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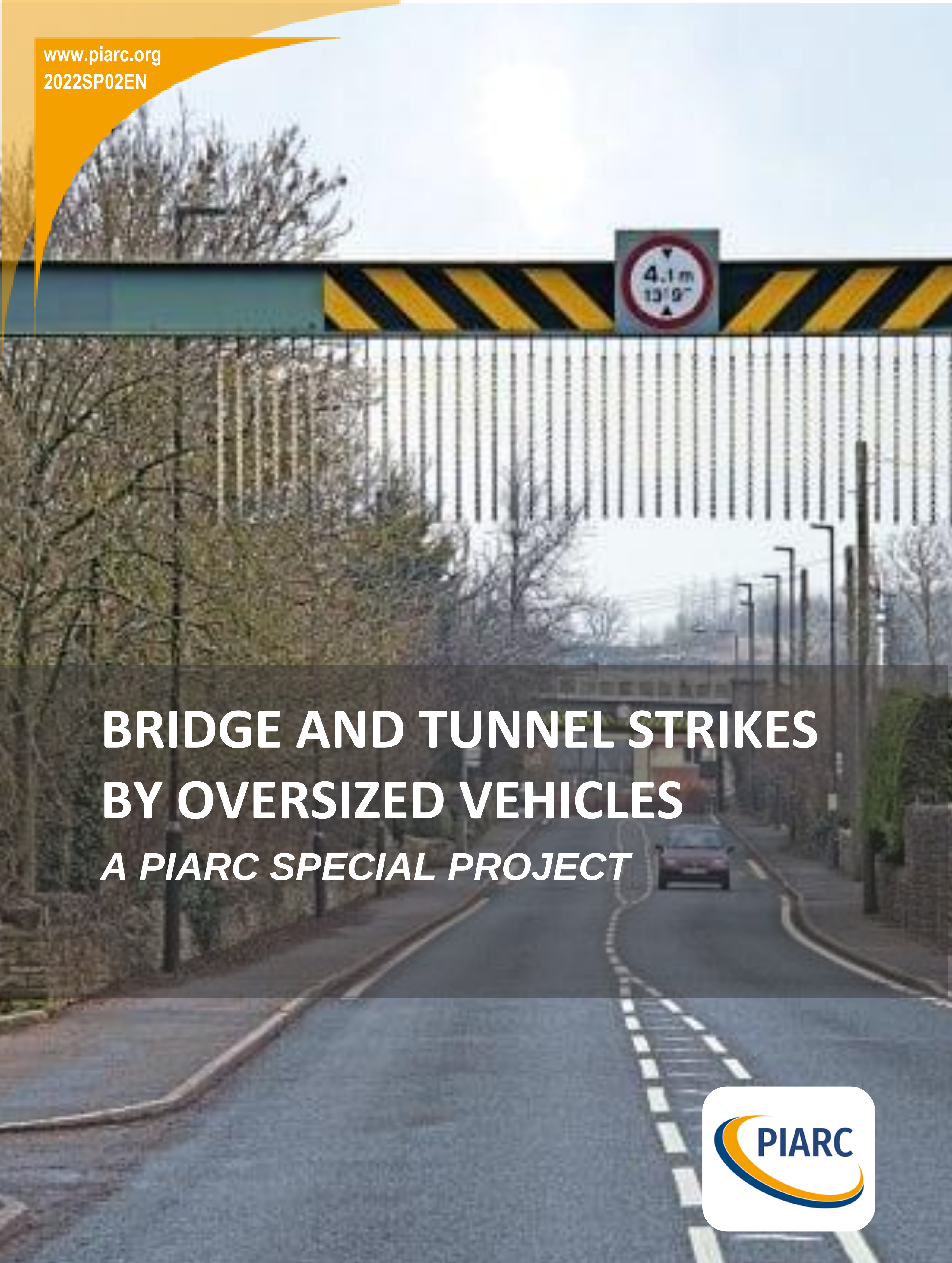

BRIDGE AND TUNNEL STRIKES BY OVERSIZED VEHICLES

A PIARC SPECIAL PROJECT

PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

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EXECUTIVE SUMMARY

2022SP02EN

BRIDGE AND TUNNEL STRIKES BY OVERSIZED VEHICLES

This report details the findings of a study carried out by Roughan & O'Donovan Ltd. (ROD) under the supervision of PIARC, in response to an open call for proposals published by PIARC to conduct the "Bridges and tunnels strikes by oversize vehicles" Special Project. The objective of the study was to examine proven countermeasures, practices, and technologies used to reduce the incidence of oversize vehicles striking bridges and tunnels along with effective processes for accurately reporting and tracking bridge strike occurrences. Specific consideration was given to LMICs, Low Middle Income Countries as per the World Bank classification (World Bank, 2021), with an aim to cater to these regions with specific recommendations.

The Special Project program aims to answer emerging or urgent issues identified by PIARC member countries in a short period of time (less than a year) within an international framework.

The study involved a detailed review of the causes, consequences and mitigation measures available in relation to the bridge and tunnel strike problem. Data was gathered through a combination of surveys, interviews and desk-based research. In order to develop a business case, the economic situation was evaluated by way of Cost Benefit Analysis (CBA). A formal CBA methodology was developed for road administrators in order to discern the best mitigation practices for a given scenario. CBA was also carried out in a global approach to demonstrate the methodology and to draw broad conclusions about effective mitigation measures.

The study made the following recommendations to PIARC:

1. PIARC should perform a sample case study, focusing on a single network or list of structures, showing how the required data can be gathered, and how to use it in a detailed risk analysis and CBA to decide on appropriate interventions.
2. PIARC should champion the development of a data capture guide for bridge and tunnel strikes, coordinating the data internationally to better describe the business case.

While various recommendations were made to HICs (High Income Countries as per the World Bank classification (World Bank, 2021)) and LMICs individually in relation to physical mitigation, the key finding of the study was that the current state of the art is to move toward driver-based mitigation practices such as better driver education, advertising of the consequences and informing legislation in relation to the bridge / tunnel strike problem. The development of a multi-sectoral panel should be formalised in both LMICs and HICs, allowing all key actors to work together to provide a coordinated response to bridge and tunnel strikes.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The World Road Association (PIARC) has established a Special Projects mechanism to enable it to respond outside the usual four years Technical Committee cycle to emerging issues and urgent priorities identified by its members. In December 2020, PIARC published an open call for proposals to conduct the "Bridges and tunnels strikes by oversize vehicles" Special Project. Roughan & O'Donovan Consulting Engineers submitted a proposal to this call and were selected as the preferred consultant to progress the project under PIARC guidance.

1.2. DEFINITIONS

In line with the call for proposals produced by PIARC, the following definitions apply:

Bridges, tunnels and other similar structures are key elements of road networks. Their structural characteristics and significance as nodes in the network make them very valuable assets.

Oversize vehicles are defined as vehicles and cargo beyond standard size limitations. They can also be standard size vehicles that are beyond a local size limitation of a specific area, road, bridge, or tunnel. These oversize vehicles can be over-height, over-width or over-dimensioned vehicles. Oversize vehicles may also include vehicles with a permit to circulate in a certain itinerary, which leave their authorized route. These vehicles may be required to be accompanied by escort vehicles.

Bridges and tunnel strikes by oversize vehicles are defined as collisions of these vehicles and cargo with bridges or tunnels or their associated equipment.

Effectiveness of mitigation measures relates to the percentage reduction in bridge / tunnel strikes due to the implementation of a mitigation measure. For example, presuming static warning signs reduces the number of bridge strikes on average per year from 10 to 8, we would state that static warning signs are 20% effective.

1.3. OBJECTIVES

Bridge and tunnel strikes by oversize vehicles are a threat to road user's safety, and the operation of highway and rail infrastructure. These incidents cause significant damage to infrastructure, injuries and fatalities, secondary crashes, traffic delays, emergency response, rerouting of traffic to remove trucks and repair damage, and economic costs related to response and recovery efforts. In the most severe cases, bridges can fail, resulting in serious injuries or fatalities and costly economic / quality of life impacts until the associated road can be reopened to traffic. In the United States, bridge strikes and overloads are the number two and three causes of bridge failures. This is also an important issue in other Higher Income Countries (HICs) and Lower Middle-Income Countries (LMICs). The causes are myriad, such as driver error, routing error and signage issues as well various other factors which will be addressed in subsequent section of this report.

The objective of this study was to examine proven countermeasures, practices, and technologies used to reduce the incidence of oversize vehicles striking bridges and tunnels along with effective processes for accurately reporting and tracking bridge strike occurrences. Some of these practices for truck routing and permitting may also be useful in preventing bridge overloads.

The study identified successful technologies, approaches, and mitigation strategies to address bridge and tunnel strikes, allowing information transfer to other countries. This includes lessons learned from around the world on deploying and operating various countermeasures, practices, and technologies. The project specifically identified practices and technologies that can be utilized in LMICs.

ROD utilised the data gathered through review of available literature, surveys specific to this project and interviews with key stakeholders in order to perform semi-quantitative Cost Benefit Analysis (CBA) of the various mitigation methods addressed. This allowed recommendations to be made on how the bridge and tunnel strike problem should be addressed in both HICs and LMICs, where LMICs include the three lower economic income classes in accordance with The World Bank definitions: Low Income Countries (LICs), Lower-Middle Income Countries (L-MICs) and Upper-Middle Income Countries (U-MICs).

1.4. Scope

The project focused on three key areas in consideration of bridge and tunnel strikes; impacts, mitigation measures and challenges and opportunities for these counter measures. A number of sources were used to determine the key drivers in these areas including a review of available literature and regulations in these areas, surveys of relevant stakeholders and focused interviews where possible. CBA was then carried out to evaluate a business case for the various mitigation measures investigated, in order to make recommendations to road administrators and PIARC members on how the problem of bridge and tunnel strike can best be addressed in different socio-economic regions.

The focus of this project was not on bridge overloading. While some of the measures investigated to avoid bridges strikes might have a secondary benefit of preventing bridge overloading, the study has not focused specifically on measures preventing solely bridge overloading. Moreover, the subject of this project was not to examine in detail the financial resources of the measures required to remedy the damage. In some countries, repairs are carried out at the expense of the responsible person's liability insurance, but in most cases the operators finance the repairs from their own budgets, or under the terms of a contract with their own insurance company. Therefore, this study is focused on providing more global recommendations that will prove useful to bridge and tunnel operators around the globe.

A different PIARC Special Project has been developed for “Impacts of overweight vehicles on road infrastructure and road safety”, which is also available at www.piarc.org

2. METHODOLOGY

2.1. Overarching Methodology

This study aimed to collect useful information through an extensive review of academic literature, industry and funding body reports aggregated through a desk study and outreach to members of PIARC and other relevant networks and supplemented by additional information gathered through surveys as deemed appropriate. Various stakeholder groups, bodies and road authorities were contacted, requesting data on bridge or tunnel strike incidents, cause and impact in the wider transport network e.g. traffic delays and congestion, public transport interruptions etc. Liaison also included links with traffic managers, truck operators and carriers, who are also important stakeholders for this issue.

The overarching methodology employed in the study is illustrated in Figure 2.1. A desk-based study was first used to inform the base understanding and international practice with regard to causes, consequences and mitigation measures for bridge strikes. A gap analysis from the desk-based study was then used in order to inform the construction of the first survey, which is described in detail in 2.2 below. The first survey acted as an initial data gathering phase and allowed identification of key stakeholders for the second survey. The second survey consisted of a more focused approach in order to obtain cost, consequence and mitigation effectiveness data. This data was then used in order to perform semi-quantitative CBA in order to make recommendations to PIARC on how the bridge strike problem should be addressed.

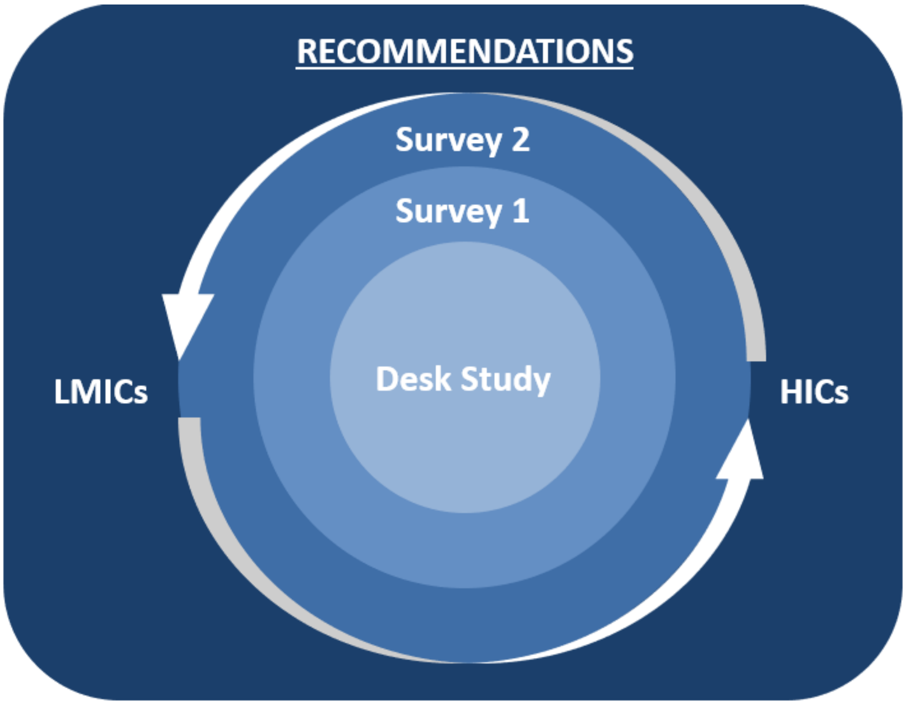

Figure 2.1: Study Methodology

The desk-based study focused not just on bridge strike causes and mitigation measures, but also on National Legislation for internal traffic as well as International agreements for cross-border traffic which are the legal basis for regulation of bridge / tunnel strike prevention. In addition to addressing solutions that are currently available on the market, various other potential future ITS-based (Intelligent Transport System) mitigation solutions will be reviewed, including the investigation of how Connected Autonomous Vehicles (CAVs) can be supplemented with an inventory of overbridge information and Vehicle2Infrastructure (V2I) communication can be employed to adapt and alter routes to avoid potential strikes. This type of technology can be used as part of higher TRL (Technology Readiness Level) future technologies, with other examples including implementation in on board navigation systems communicating with network ITS in order to inform hauliers of alternative routes prior to and during a journey. While the primary focus of the current study is proven countermeasures to bridge / tunnel strikes which can be verified through practice, recommendations will be made on how these future technologies may be brought to market to provide optimal mitigation in the future.

It is important to note that recommendations made to PIARC are based not only on the results of the CBA output after the final survey, but also on the trends from the desk-based study as well as qualitative information garnered through the first survey and project interviews.

The socio-economic impact of damage to bridges and tunnels due to over-height vehicles varies based on geographical location and the economic status of the region in question. Hence, this analysis takes account of the perspective of Infrastructure Managers (IMs) and National Road Authorities (NRAs) from both HIC and LMIC use cases. It is acknowledged that there is no “one size fits all” solution to address the issue of bridge and tunnel strikes globally. Thus, this study has established a range of potential solutions that will allow an individual body to determine the correct fit to suit their needs and end-goals. For countries that cannot provide statistics prior to implementing solutions, there is no way to quantify the effectiveness of a countermeasure in their own region prior to implementing a solution. Therefore, different regions have been clustered based on similar socio-economic backgrounds. Recommendations are then made for the most effective countermeasures for each cluster based on available data within that cluster. Moreover, it is envisaged that existing data from one organisation will be applicable to any organisation in a similar socio-economic background (including LMICs). Therefore, associated costs and benefits will similarly be able to be quantified.

2.2. Survey 1 – Overview and Response

The first survey aimed to examine proven countermeasures, practices, and technologies used to reduce the incidence of oversized vehicles striking bridges and tunnels along with effective processes for accurately reporting and tracing bridge strike occurrences.

Furthermore, the first survey was intended to establish relevant stakeholders to collaborate in addressing the issue, as well as to obtain some initial data for identifying best practice. The first survey was produced in consultation with the PIARC Project Oversight Team (POT). ROD developed a series of interrelated questions aimed at determining the relevant international legislation, data availability (type of info stored, how long data has been recorded, effectiveness of mitigation measures etc.). The survey also aimed to determine how important bridge / tunnel strikes are in comparison with other hazards. Crucially, an effort was made to determine what type of mitigation had been applied by the survey respondents, if any. The full survey is available in Appendix B.

ROD developed the list of survey 1 stakeholders in consultation with the POT. The list is available in Appendix A, and consists of a mix of road hauliers, contractors and infrastructure owners. More information is available on the respondents in the following sections. Stakeholders were obtained from ROD's extensive list of industry contacts, as well as the PIARC General Secretariat, which has over 120 stakeholders.

Following an initial upload of the survey and issue in May 2021, it was apparent that the number of respondents from LMICs was minimal. To combat this shortcoming, the PIARC POT and ROD together formulated a plan to ensure further engagement from these countries. ROD reissued the survey to a number of contacts in India and PIARC provided further specific outreach to L-MICs and U-MICs through the individual working groups / technical committees of PIARC for Tunnels and bridges. This resulted in a better uptake of the first survey from LMICs, and a greater number of potential respondents for the second survey.

The first survey consisted of 18 questions which mainly focused on bridge and tunnel strike issues and countermeasures. In the beginning of the survey, short definitions of "Bridge & Tunnel Elements", "Oversized Vehicles" and "Bridge & Tunnel Strike" were provided to a version of the survey was developed in English, French and Spanish. All three surveys were produced using the SurveyMonkey platform (SurveyMonkey, 2021).

ROD received 104 responses, 73 in English, 24 in French and 7 in the Spanish version. The English version included U-MICs to HICs including the United Kingdom (U.K.), United States (U.S.), Ireland, Australia, New Zealand, South Africa etc. The French version included responses from France, Luxembourg, Switzerland, Burkina Faso etc. The Spanish version had responses from Spain, Argentina, Colombia, Mexico etc. In the following paragraphs, the results of the first survey are analysed and discussed in detail.

In the first question, the respondents were asked to provide the name of their organisation while in the second question they were asked to classify the nature of their organisation:

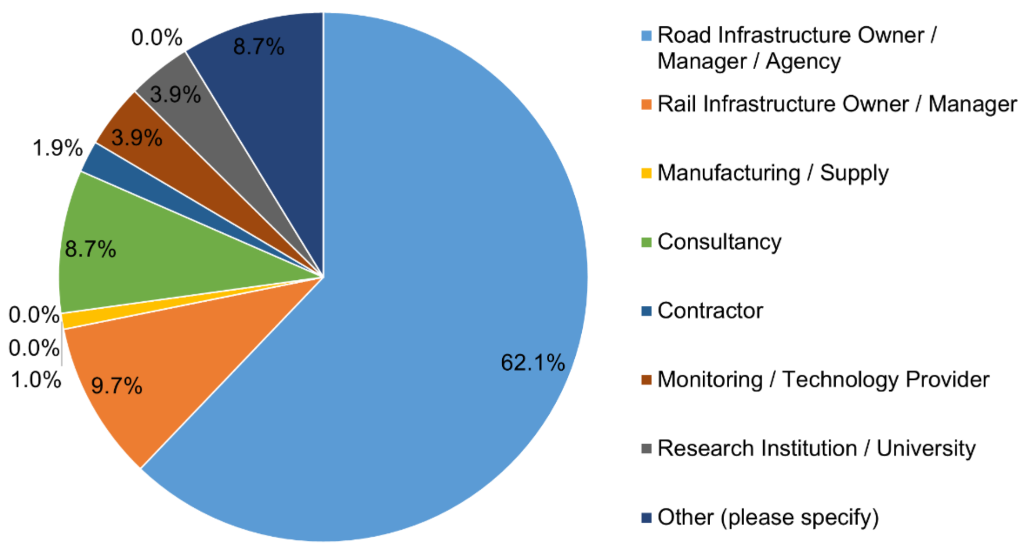

Figure 2.2: Q2 - Organisation type.

The majority of the respondents were Road Infrastructure Owners/ Managers/ Agencies (62.1%). Other responses came from Rail Infrastructure Owners/ Managers (around 9.7%), Consultancies (around 8.7%), Monitoring/ Technology Providers (around 3.9%) & Research Institutions (around

3.9%). ROD, however, received responses from various organisations e.g. contractors, International consortiums, manufacturers/ suppliers etc.

The third question determined the country and state of the respondent. ROD then clustered the responses into HICs, U-MICs, L-MICs and LICs. The clusters were made according to the World Bank classification (World Bank, 2021). The clusters are presented in Figure 2.3.

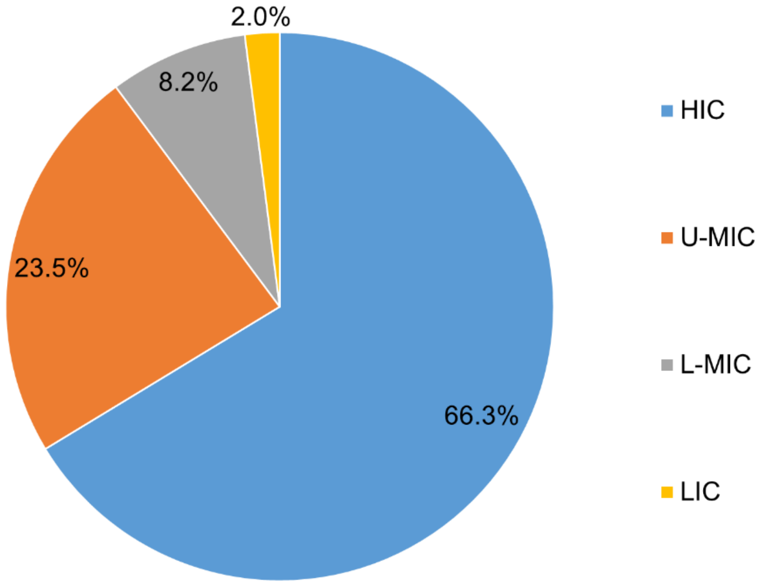

Figure 2.3: Q3 - Countries income classification.

Most of the responses were from high income countries (approx. 65.9%), followed by upper-middle income countries (approx. 23.1%) and low middle income countries (approx. 8.8%). 2 responses were received from low income countries (Burkina Faso and Mozambique), which accounted for 2.2% of the sample.

Based on the results of Q4, 61.5% of the respondents suggested that bridge and tunnel strikes by overheight vehicles have been identified as a major problem by their organisation, while approximately 23.1% believe that it is not a major issue and 15.4% stated that they are unsure. To gain a better insight, the responses are classified according to organisation type as shown in Figure 2.4. It should be noted that the percentages are taken as a percentage of the total response, in order to show the different numbers of responses from each organisation type. It can be seen that road infrastructure owners, consultancies and monitoring/ technology providers highlight bridge and tunnel strikes as a major issue while manufacturers/ suppliers and research institutions believe it is not.

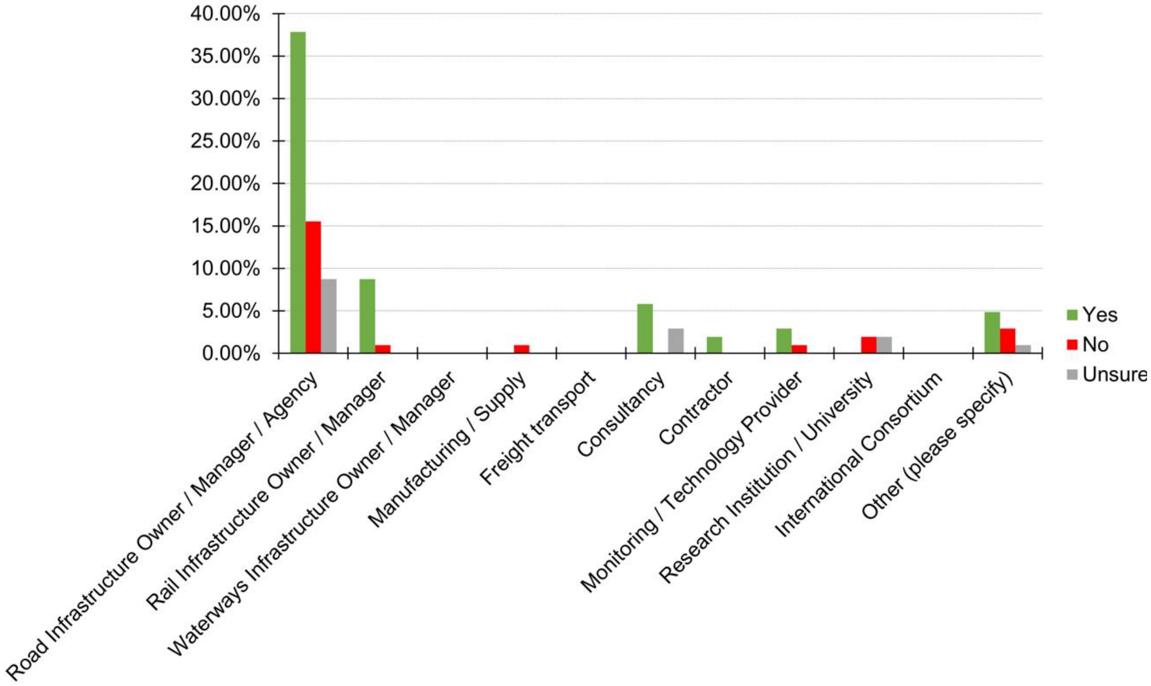

Figure 2.4: Q4 - Has your organisation identified Bridge and Tunnel Strikes by oversized vehicle as a major issue? (per organisation type Q2)

Respondents were also asked if they are aware of any legislation, protocols, guidelines etc pertinent to Bridge or Tunnel strikes.

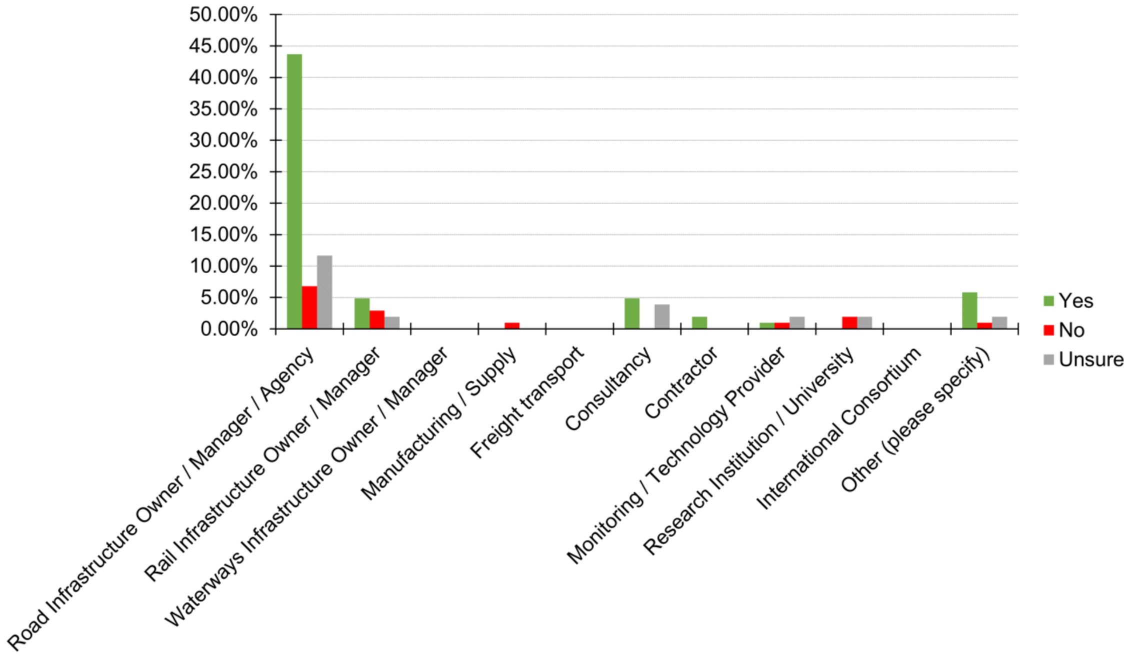

Figure 2.5: Q5 - Are you aware of State / Province / National and/or International legislation, regulation, guidelines, and protocols pertinent to Bridge and/or Tunnel Strike prevention and detection? (per organisation type Q2)

The majority replied with yes (approx. 61.5%) while 14.4% of them were unsure and 24% replied with “No”. The responses are further classified as per organisation type as shown in Figure 2.5. The majority of the “Yes” responses are again from road & rail infrastructure owners and consultancies. This highlights that while strikes are a major issue, awareness of the problem among private organisations and members of the public may be minimal.

Those who replied with “yes” in question 5 were asked to provide additional information about relevant standards etc. Their responses are shown in Table 2.1 where they have been classified by country.

Name Legislation/ Regulation/ Guideline
Argentina
Nota Circular N° 17 del 14/02/1980 con Resolución del Administrador General estableciendo Gálibo Mínimo
Manuales de Diseño Geométrico de Carreteras
Instructivos del SIGMA Puentes
Ley Nacional de Tránsito N°24449 de la República Argentina y su actualización 26363/16
Configuraciones Autorizadas para el Transporte Automotor de Cargas - Art. 27 del Decreto N° 32/18
Pesos máximos establecidos por la ley - Configuraciones vehiculares - Decreto 32/2018
Resolución N° 1003/2018 - Reglamentación para la circulación de Bitrenes
Solicitud de Permiso de Tránsito para vehículos especiales. Dirección Nacional de Vialidad (formulario online)
Alturas Maximas Admisibles Vialidad
Acuerdo de Pesos y Dimensiones del MERCOSUR Resolución GMC 65
Australia
Road Regulations NSW
Australian Road Rules https://pcc.gov.au/uniform/2019/Australian-Road-Rules-22November2019.pdf
Austroads Guidelines for Tunnels
Roads traffic Act Over dimension vehicles
Highway Structures & Bridges Design, CD 366 Design criteria for collision protection beams
Burkina Faso
Le règlement 14 de l'UEMOA
Canada
Règlement sur le permis spécial de circulation
Règlement sur les normes de charges et de dimensions des véhicules routiers
Collection Normes-Ouvrages routiers, Tome V – Signalisation, articles 3.23 et 4.29
Répertoire des hauteurs libres (Voir site internet Québec 511, onglet camionnage)
Répertoire des entraves liées aux charges et dimensions (Voir site internet Québec 511, onglet camionnage)

Name Legislation/ Regulation/ Guideline
China
Regulations on the Management of Over-limit Transport Vehicles Driving on Highways (Decree No. 62, 2016 of the Ministry of Transport)
"Regulations on the Administration of Over-limit Transport Vehicles on Highways" (Regulation of the Ministry of Transport 2016 No. 62)
Shandong Province Implementation Measures for the Administration of Over-limit Transportation Vehicles on Highways, Regulation of Shandong [2000] No. 3
Estonia
National laws
Finland
Tietunnelin turvallisuusasiakirjojen laadinta, Liikenneviraston ohjeita 9/2018
Road Traffic Act
National regulations for structures and railings
France
Notes techniques CEREMA
Notes d'informations and documents CETU sur les hors gabarits
Dossier de sécurité
Le code le la route impose au gestionnaire de signaler une hauteure libre <4,30m
L'instruction ministérielle de la signalisation routière impose une signalisation spécifique lorsqu'une route est limité a un gabarit ou un type de véhicule.
Code la route / R433 / R311 / R312 ...
Arrêtés du mai 2006
Arrêté permanent de circulation de l'ouvrage
Instruction Interministerielle (IISR) article 61
CETU note d'information n°18 sur la prise en compte des hors gabarit
Code de la voirie rotuière R131-1
Guide des dossiers de sécurité des tunnels routiers, Fascicule 3, Les analyses des risques liés au transport des marchandises dangereuses Décembre 2018
Code de la route : infraction de 5ème catégorie en cas de PL hors gabarit en tunnel
Instruction technique relative aux tunnels
Directive européenne sur la sécurité des tunnels routiers du RTE-T
Instruction interministérielle de la signalisation routière IISR
Recommandations CETU fermeture des tunnels routiers
Germany
RABT - Richtlinie für die Ausstattung und den Betrieb von Tunneln
RAA - Richtlinie für die Anlage von Autobahnen

Name Legislation/ Regulation/ Guideline
Hungary
Tunnels will be provided by risk analysis .
The current standard contains of minimum height of bridges.
All "low" bridges requiring signs warning of their height.
Tunnels and large bridges must be provided with passive and active prevention system
Iceland
Rules for road design
India
There is a mandatory provision of anti-crash barriers & height restriction gantries as requirement specified on IRC & IRS codes.
Motor Vehicles Act,1988
Indonesia
Road regulation Nos 38/2004
Government Regulation Nos 38/2006
Ireland
TII Publication DN-GEO-03036 Cross-sections and Headroom defines the design standard for vertical clearances at structures, see tiipublications.ie. There are no standards for designing vehicle detection systems at bridges with restricted vertical clearance.
Max Vehicle Height Legislation (4.65m) - Road Traffic Regs 2008 SI 366
Railway Safety Act 2005 - Penalty points and Fines for bridge strikes and failures to report
Road Traffic Act 1961. Outlines the legal duty for persons driving vehicles be aware of bridge height restrictions.
Limerick Tunnel Bye laws - tunnel height at 4.65m and restricting access only to "roadworthy" vehicles
Irish legislation - national limit of vehicles to 4.65, agricultural vehicles exempt
Road Safety Legislation
Luxembourg
Code de la Route
Loi du 14 février 1955 concernant la réglementation de la circulation sur toutes les voies publiques
New Zealand
Land Transport Vehicle Dimension and Mass Rule 2006 NZ.
Land Transport Rule: Vehicle Dimensions and Mass 2016-The rule covers requirements for dimension and mass limits to enable vehicles, in particular, heavy truck and trailer combinations, to be operated safely on New Zealand’s roads

Name Legislation/ Regulation/ Guideline
Norway
Guidelines for road signs N300, https://www.vegvesen.no/_attachment/69739/
Guidelines for clearance and crash sacrificial beams, N500
Guidelines for Bridges N400
Regulations for bridge loads, https://lovdata.no/dokument/SF/forskrift/2017-11-17-1900?q=bruer
Regulations for transport, https://lovdata.no/dokument/SF/forskrift/1990-01-25-92?q=forskrift%20om%20bruk%20av%20kj%C3%B8ret%C3%B8y
Russia
Bridges and pipes СП 46.13330.2012
Automobile roads СП 34.13330.2021
Serbia
Rulebook
South Africa
National guidelines 5,2m clearance requirements for road bridges.
We have national guidelines dictating the maximum height for a vehicle. Any vehicle taller than this requires special permission from Provincial authorities.
National Roads Act - legislates the national stds relating to overload vehicles and clearance requirements
National Road Traffic Act (Act 93 of 1996) and Regulations - Road Traffic and Road Transport Legislation
Spain
Réglementation Générale des Véhicules (Reglamento General de Vehículos): Il établit la définition des véhicules hors gabarit et leurs caractéristiques techniques.
Code de la route (Reglamento General de Circulación): Il établit les conditions de circulation des véhicules hors gabarit.
Code de circulation
Sweden
Bridges with a free clearance of less than 4,5 m are required to have necessary warning signs.
Oversized loads require special permits
Switzerland
Directive ASTRA 12008 Choc provenant de véhicules routiers (2005 V1.1)
Thailand
Announcement of Director General for Legal Loading on Highway Network in Thailand
Guidelines for Permit Load Rating for Highway Network in Thailand
AASHTO LRFR
AASHTO LRFD
Ministerial regulations No.60 (2009) according to Land Transport Act 1979
Announcement of Director General for Weight Limit of Vehicle on Highway
Guidelines for Bridge Evaluation and Permit load rating for oversize and overweight trucks

Name Legislation/ Regulation/ Guideline
Tunisia
Code de la route de la Tunisie
Décret N°147-2000 du 24 Janvier 2000 fixant les régles techniques d'équipements et d'aménagement des véhicules
U.K.
Road Vehicles (Construction & Use) Regulations 1986 (C&U) Regs
Suite of Gov guidance at https://www.gov.uk/government/publications/prevention-of-bridge-strikes-good-practice-guide
General Network Rail bridge strike standards (for reporting, examination etc)076, 176, 201, 202 etc
Prevention of Strikes on Bridges over Highways A Protocol for Highway Managers & Bridge Owners
DMRB TD27/05, now CD 127
Traffic Signs Manual and Regulations and associated guidance
Network Rail Bridge Strike Guidance
Network Rail has developed its own standards and mitigation policy
Highway & Driver Law (Offences such as dangerous driving, driving without due care etc)
Handbooks issued by government and other bridge owners
UK legal requirement to display travelling height in cab
U.S.
Federal regulations in 23 CFR 657.5 require each State to enforce vehicle size and weight laws to assure that violations are discouraged and that vehicles traversing the highway system do not exceed the limits specified by law.
Each State regulates maximum vehicle height, with maximum permitted height ranging from 13.5 feet to 14.5 feet and vehicles exceeding these heights must obtain oversized load permits from the State.
Federal regulations in 23 CFR 650.305 established the National Bridge Inspection Standards, which must be carried out by State DOTs, and many State DOTs have dedicated a section of their bridge inspection manual or procedures to bridge damage inspection, such as damage from vehicle strikes.
Federal regulations in 23 CFR 655.603, established the Manual on Uniform Traffic Control Devices (MUTCD), which is the national standard for all highway traffic control devices, including Low Clearance Signs.
The FHWA Pilot/Escort Vehicle Operators Best Practices Guidelines provides laws and rules relevant to pilot/escort operations, incident reports, and other information focused on the movement of oversize loads.

Table 2.1 Q6 – Please list the name of any relevant legislation / regulations / guidelines

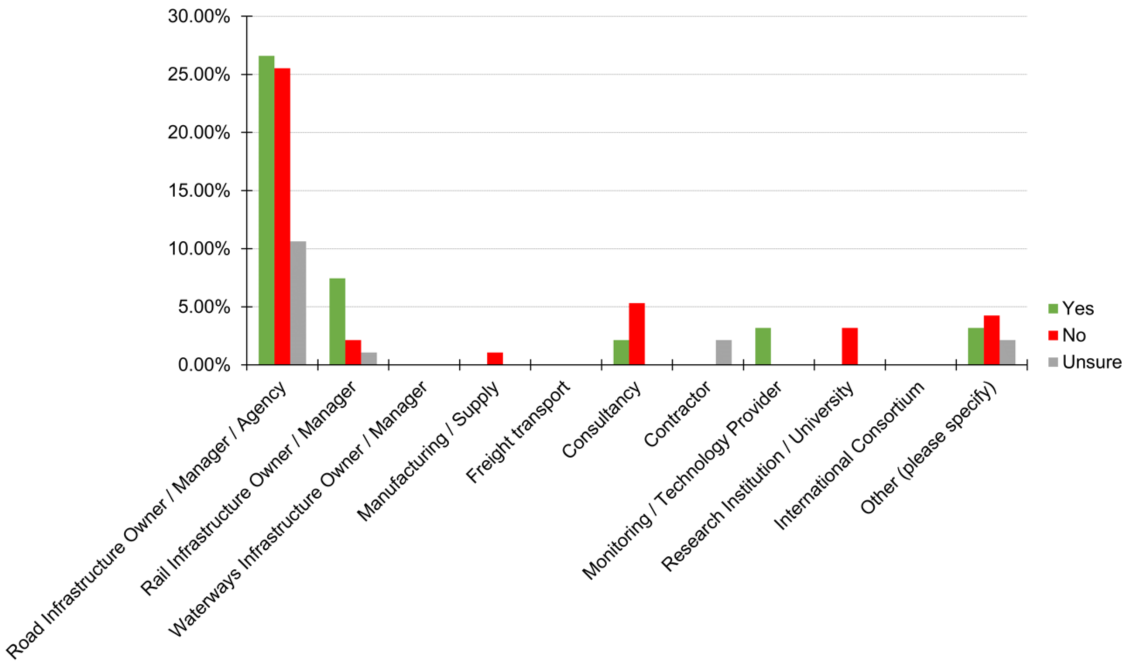

Figure 2.6: Q7 - Does your organisation record data in relation to Bridge and Tunnel Strike incidents? (per organisation type Q2)

When questioned on whether respondents record data in relation to bridge or tunnel strikes, 48.4% of the respondents replied with “yes” while 36.8% replied with “no”. Around 16.8% of respondents were unsure if their organisation recorded data. Figure 2.6 shows the results of Q7 by organisation type.

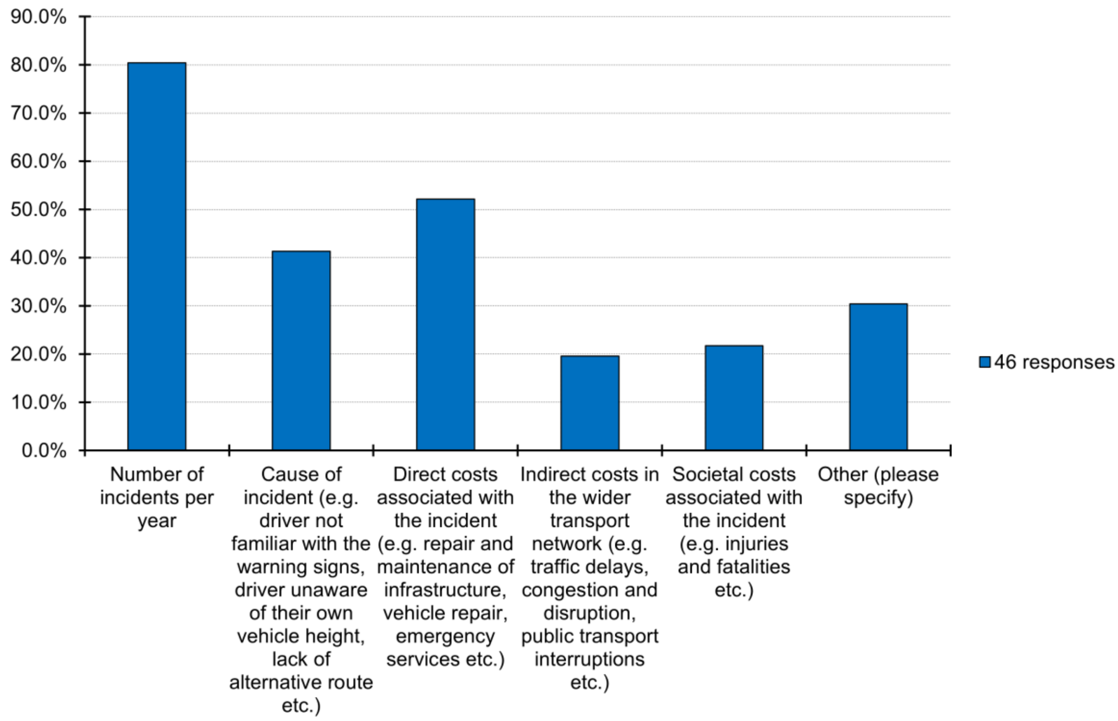

Figure 2.7: Q8 - Please indicate if your organisation stores data of the type listed.

Figure 2.7 shows the type of data recorded and noted to be available to the contacted organisations. Most respondents possess data relating to the number of incidents per year (around 80.4%), direct costs (around 52.2%) and cause of an accident (around 41.3%). However, a smaller number of respondents possess data relating to indirect costs, societal costs and other costs for example detailed incident reports (photos, videos, effects on traffic) and bridge elements that are impacted. It should be highlighted that one of the respondents indicated that his / her organisation requires data to be collected but the majority of strikes are not recorded properly or at all. This highlights the importance of detection methods as well as mitigation methods. For many infrastructure owners, the use of sensors installed on the infrastructure could be the first port of call in order to inform them if a strike has occurred. An example would be the installation of accelerometers on bridges to detect vehicle impacts.

Respondents were also asked for the history of the recorded data. The majority of recorded data has been stored for more than 10 years (approx. 48.9%) while in 17.0% of cases, data has been stored for 5 to 10 years. In around 12.8% of cases, data has been recorded for less than 5 years. A great portion of the respondents, approximately 21.3%, are unsure about the history of bridge and tunnel strike data. Results are shown in Figure 2.8 by organisation type.

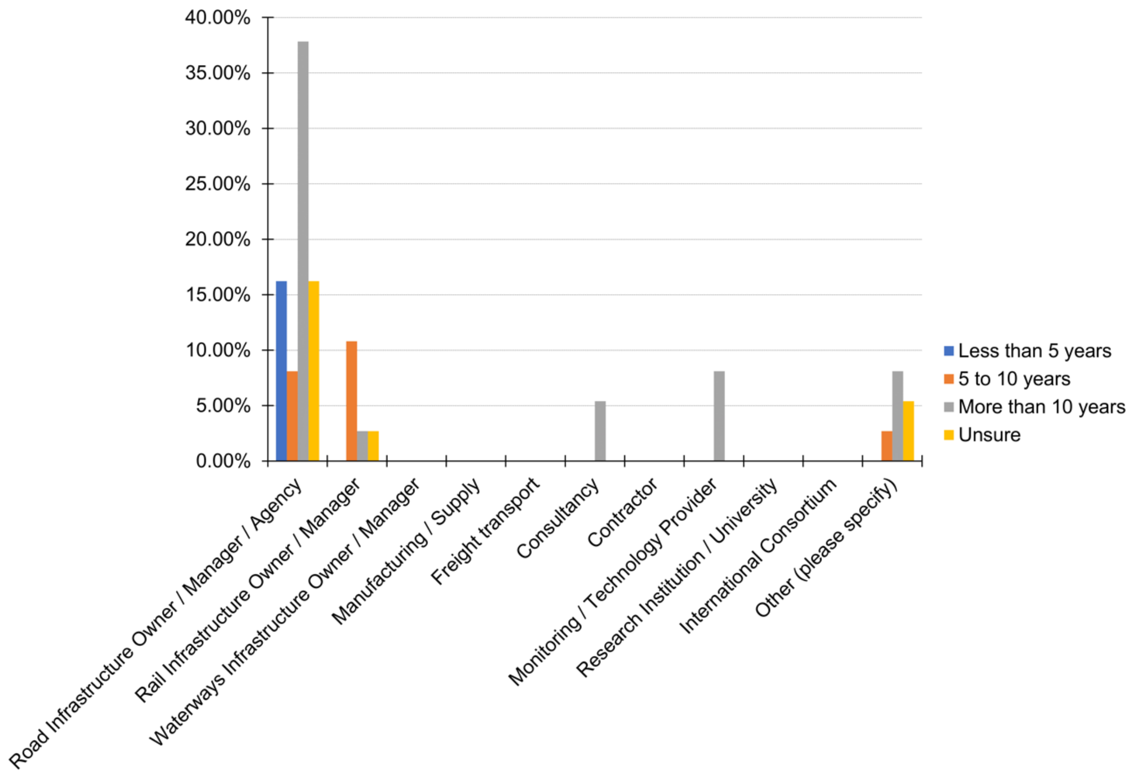

Figure 2.8: Q9 - For how long has your organisation been storing data in relation to Bridge and Tunnel Strikes? (per organisation type Q2)

Respondents were also asked to rank various transport infrastructure hazards in terms of safety and cost (1 lowest risk/cost to 7 highest risk/cost). The various transport infrastructure hazards are averaged and are shown in Figure 2.9 and Figure 2.10 for safety and cost, respectively. In Figure 2.9, the respondents believe that strikes by over height vehicles are the highest **risk** to transport infrastructure, followed by aging of infrastructure, Illegal overloading and fire incidents. Lower concerns are related to environmental deterioration / climate and civil security. Traffic growth is shown to be in a medium risk / impact. It should be noted here that scour / hydraulic issues was not provided as an option, and while some respondents may have included this under environmental deterioration, this is known to be a major cause of bridge failures in the US. In Figure 2.10 it can be seen that aging of transport infrastructure is the major concern in terms of transport infrastructure **cost**. Strikes by over height vehicles follows together with traffic growth and fire damage. Illegal overloading seems to be a medium-level concern while lower-level concerns include environmental deterioration and civil security.

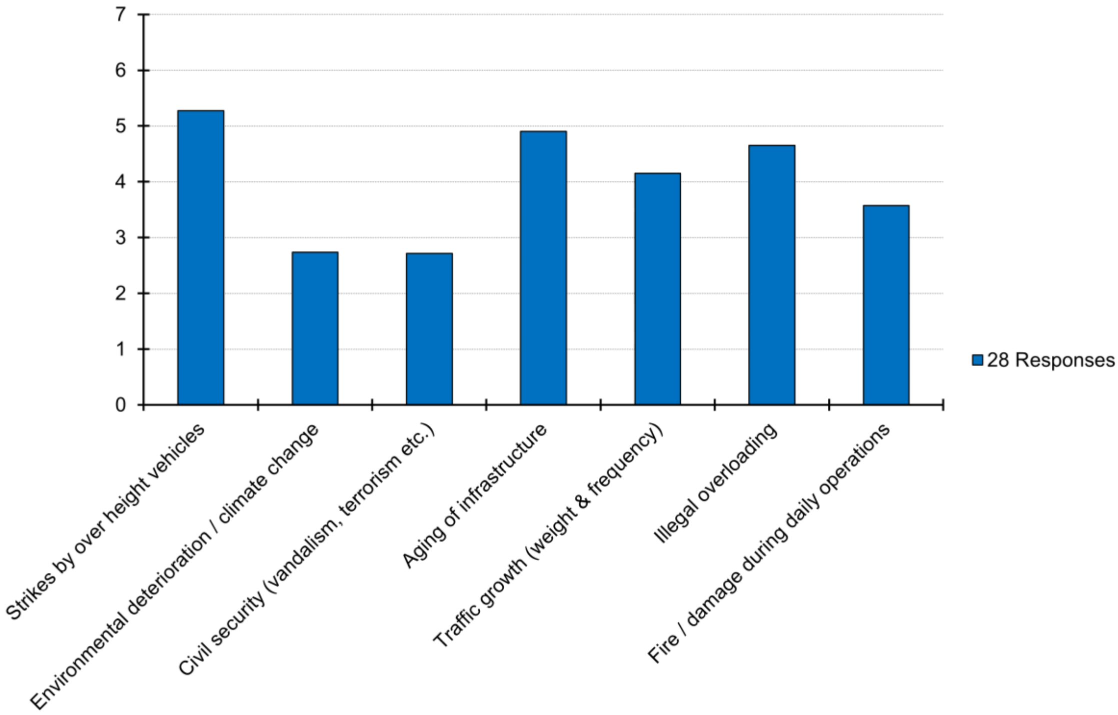

Figure 2.9: Q10 - In your opinion, please rank the following bridge / tunnel hazards by their impact on safety.

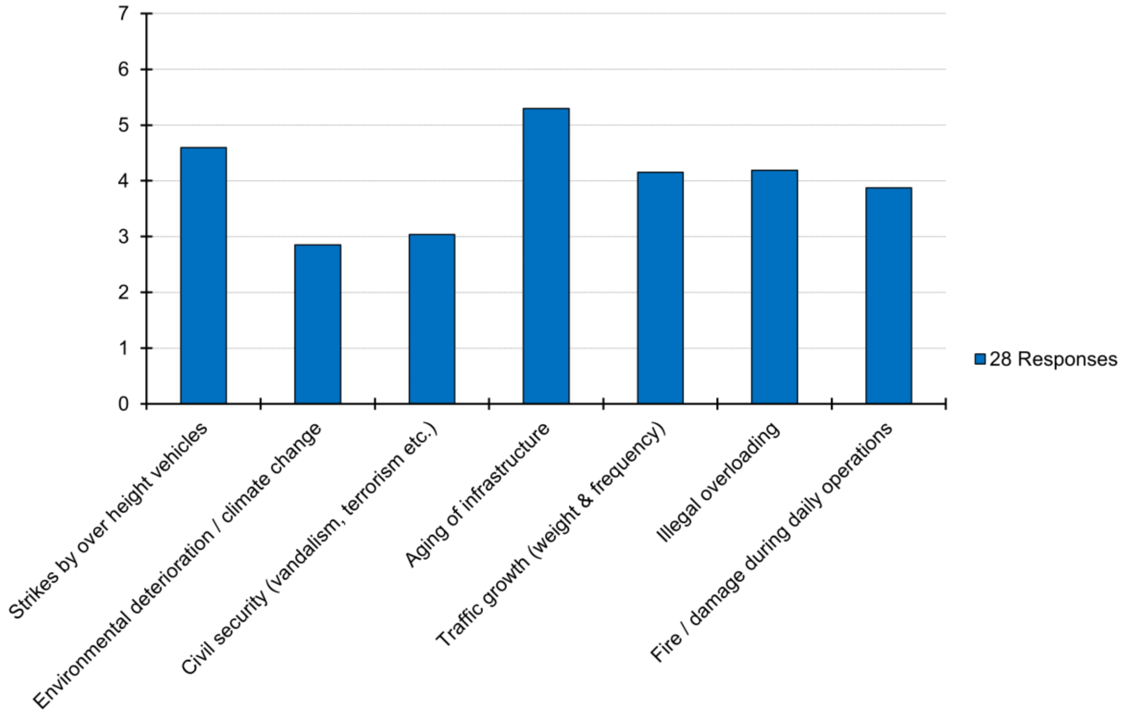

Figure 2.10: Q11 - In your opinion, please rank the following bridge / tunnel hazards by their impact on cost.

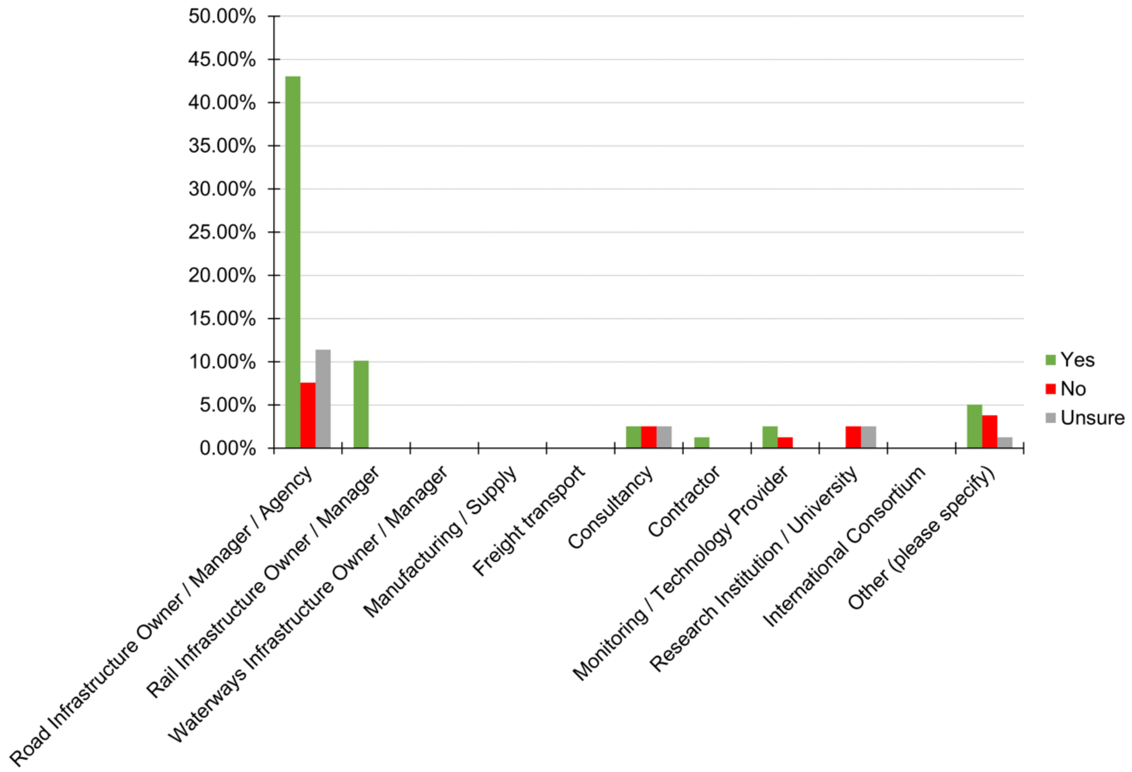

Figure 2.11: Q12 - Has your organisation ever commissioned or installed countermeasures to mitigate the issue of Bridge and Tunnel Strikes by oversize vehicles? (by organisation type Q2)

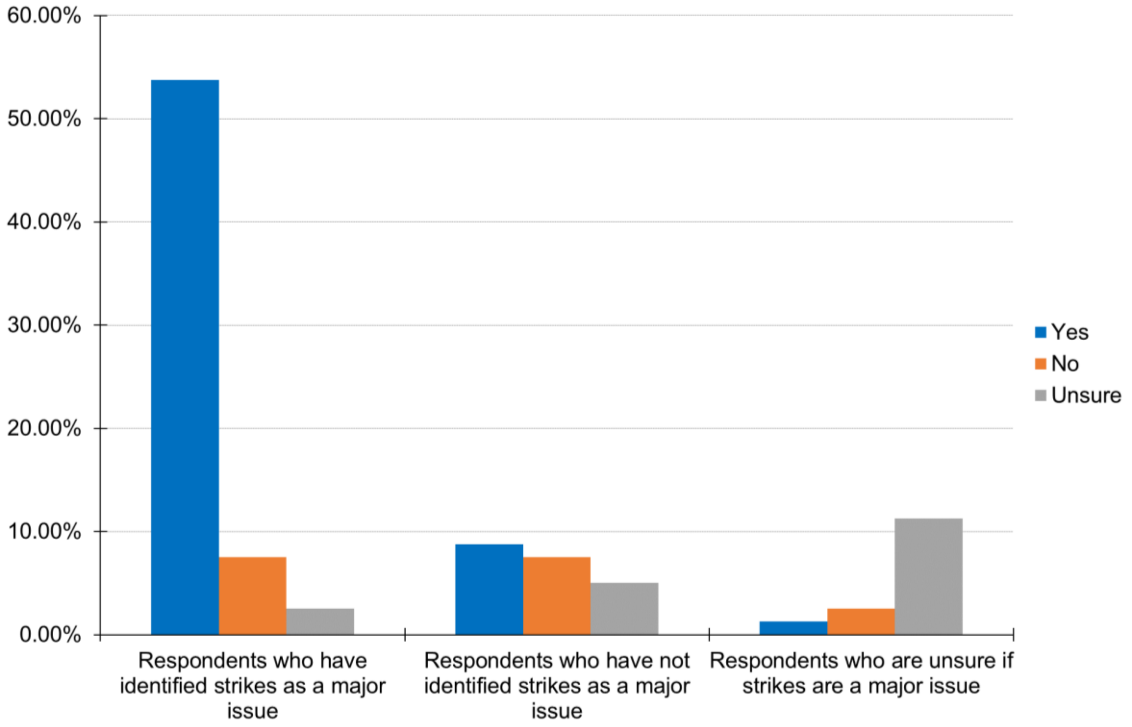

Figure 2.12: Q12 - Has your organisation ever commissioned or installed countermeasures to mitigate the issue of Bridge and Tunnel Strikes by oversize vehicles? (by whether strikes have been identified as a major issue - Q4)

In terms of countermeasures, the majority of the respondents (around 67%) replied that they have installed prevention systems to mitigate the issue of Bridge and Tunnel Strikes by oversized vehicles. Only the 13% replied with “no” while around 20% were not sure. The results are shown in Figure 2.11 and Figure 2.12, considering the response to Q2 and Q4, respectively. For example, Figure 2.11 indicates that the majority of road infrastructure managers have installed mitigation measures. Figure 2.12 indicates that 53.8% have identified bridge strikes as a major issue, and subsequently installed countermeasures. Note that this 53.8% equates to 84.3% of all participants who identified bridge and tunnel strikes as a major issue. Interestingly, 8.8% of respondents have not identified bridge and tunnel strikes as a major issue, but have installed countermeasures nonetheless.

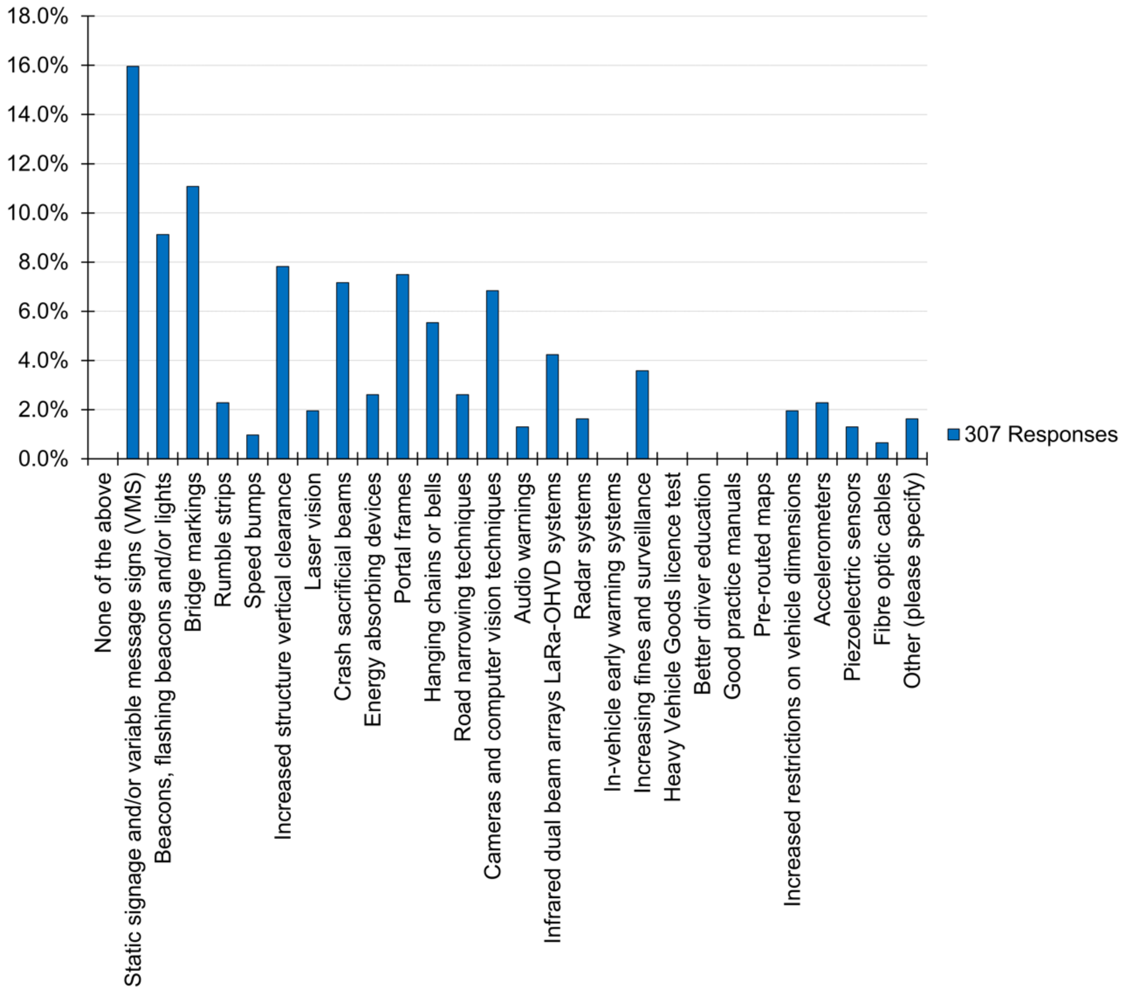

Figure 2.13: Q13 - Mitigation – Infrastructure. Please select the type of mitigation measure used from the list below. If an alternative measure has been used other than those listed, please provide details.

The chart in Figure 2.13 shows the mitigation measures which have been applied by the respondents to the infrastructure itself. It can be seen that 16% of respondents use static signages and/or variable message signs. A great portion also use beacons and bridge markings as countermeasures. Other prominent mitigation measures include increased structure vertical clearance, crash sacrificial beams and camera or computer vision techniques. Less used countermeasures include speed bumps, radar systems and fibre optic cables.

In comparison, the chart in Figure 2.14 shows the mitigation measures from the driver/ vehicle perspective. The major mitigation measure here is pre-routed maps (approx. 14.5%) while other significant countermeasures include better driver education (approx. 11.8%), pilot/ escort vehicles (approx. 10.9%), increased restriction on vehicle dimensions and increased fines.

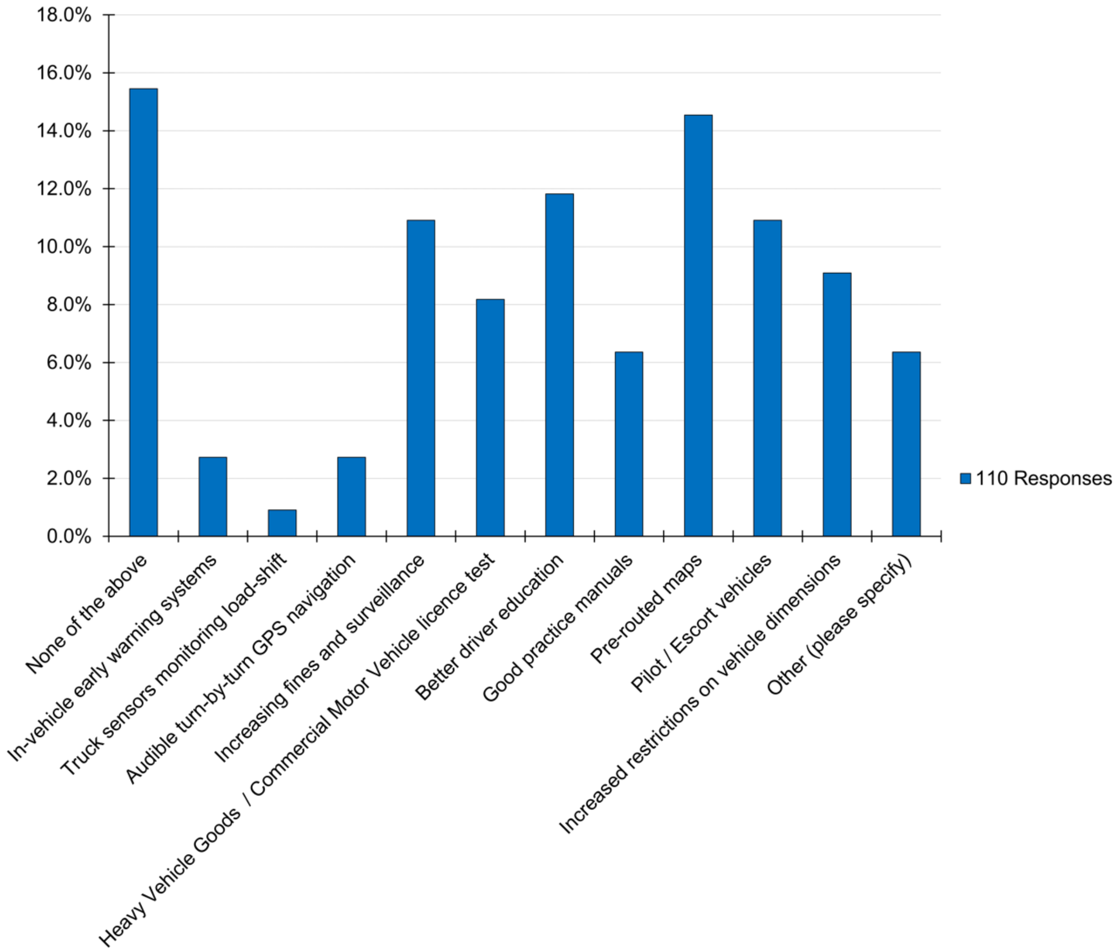

Figure 2.14: Q14 - Mitigation - Driver/Vehicle. Please select the type of mitigation measure used from the list below. If an alternative measure has been used other than those listed, please provide details.

The survey also asked the respondents if they have available data in relation to bridge and tunnel strike incidents before and/or after the countermeasures and if they are aware of their effectiveness. The results are summarised in Figure 2.15. Many respondents (approx. 28.8%) were unsure, while yes and no responses are at approx. 28.8% and 42.3%, respectively.

In addition, the chart in Figure 2.16 shows the type of data recorded. It can be seen that most of the data has relates the number of incidents per year (around 41.8%), direct costs (around 19.4%) and cause of an incident (around 17.9%). However, data also seem to be available on indirect costs, societal costs and other costs (for example length of time to detect an overheight and take action).

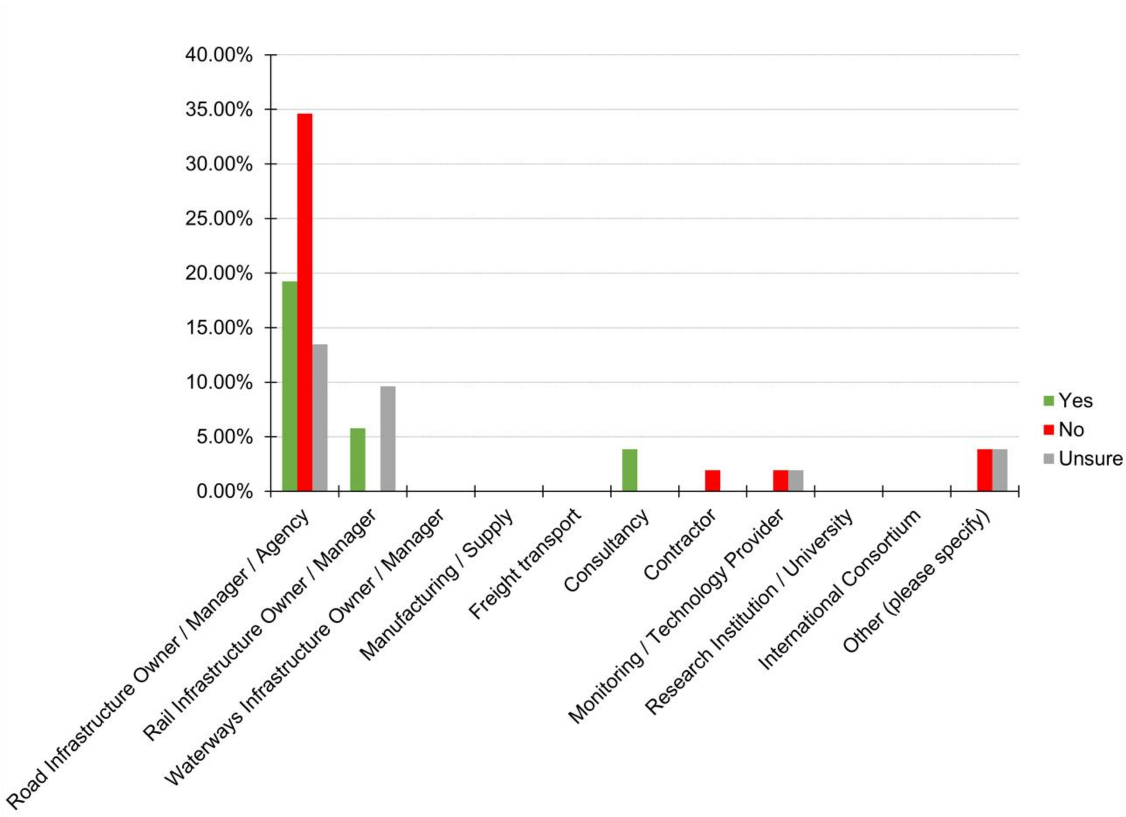

Figure 2.15: Q15 - Does your organisation have available data in relation to Bridge and Tunnel Strike incidents before and/or after the countermeasures have been installed? i.e. Are you aware of how effective countermeasures have been? (per organisation type Q2)

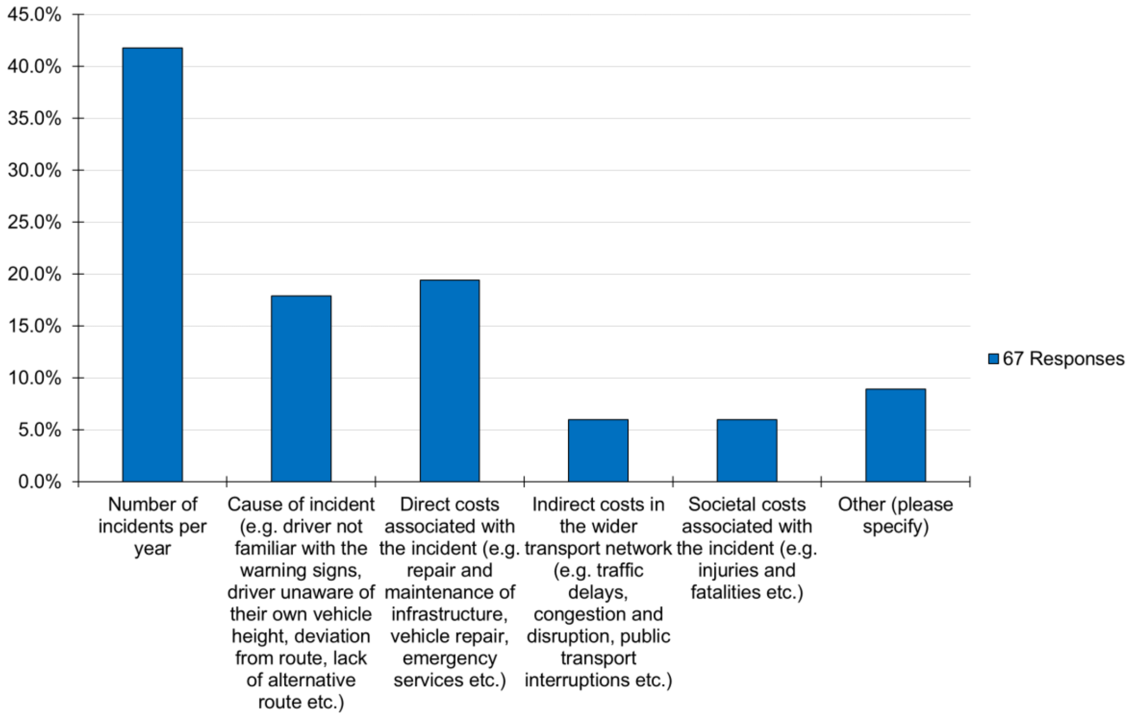

Figure 2.16: Q16 - Please indicate the type of data available for before and/or after the countermeasures have been installed from the list.

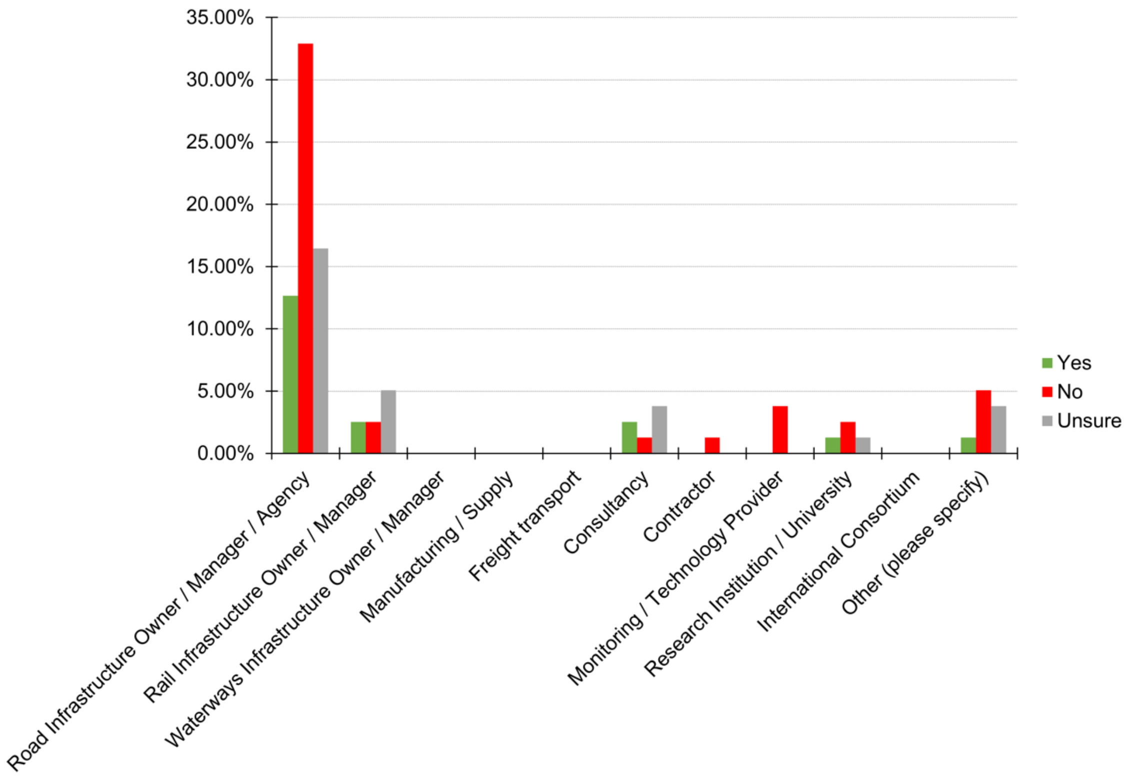

Figure 2.17: Q17 - Has your organisation ever used any decision-making tools or carried out any Cost-Benefit Analysis to select the most appropriate mitigation measures? (by organisation type Q2)

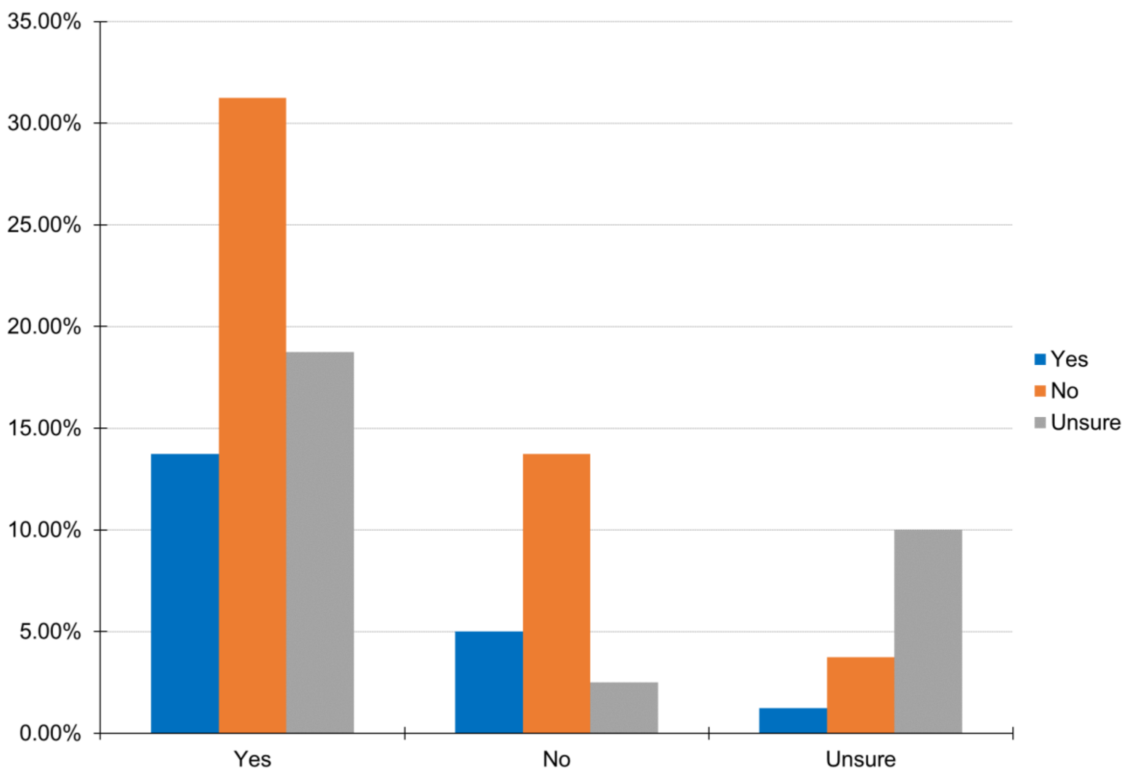

Figure 2.18: Q17 - Has your organisation ever used any decision-making tools or carried out any Cost-Benefit Analysis to select the most appropriate mitigation measures? (by whether strikes have been identified as a major issue - Q4)

In terms of the use of any decision-making tools or any cost-benefit analysis in the countermeasure selection, 31.3% of the respondents are “unsure” and approx. 48.8% did not carry out any cost-benefit analysis in the countermeasure selection. Only the 20% replied with “yes”. Figure 2.17 and Figure 2.18 show the results as per Q2 and Q4, respectively.

ROD also asked the respondents if they would like to be contacted again for further information. 37.1% replied with “no”, mainly because they do not possess enough data to provide meaningful information. 62.9% were willing to participate in the second survey.

2.3. Survey 2 – Overview and Response

The second survey aimed to obtain cost, consequences and mitigation effectiveness data that will be later used to perform a semi-quantitative CBA. Based on the conclusion obtained, recommendations on how the bridge strike problem should be addressed will be made to PIARC.

The second survey was produced in consultation with the PIARC Project Oversight Team (POT). A series of questions were developed by ROD, aiming to determine the number and cost of strikes in different countries and the relative breakdown for different categories of costs. The survey also aimed to obtain cost and effectiveness of mitigation measures to be able to identify and recommend the most relevant measures. The full survey is available in Appendix D.

Relevant stakeholders for the second survey were identified taking into account the first survey responses, on the basis of data availability and willingness to collaborate on the project. Additional key stakeholders were also separately identified by ROD and the PIARC POT for the second survey only, in which case their responses are not available for the first survey. The list of stakeholders is available in Appendix A. After the stakeholder refinement, the list consisted of mainly road and rail infrastructure owners. Moreover, as pointed out in the survey 1 overview in section 2.2, the number of respondents from LMICs was initially minimal and was an extended effort was made during the project to engage these stakeholders. More information is available on the respondents in the following sections.

The second survey consisted of 20 questions which mainly focused on bridge and tunnel strike costs and countermeasures’ effectiveness. The requested data was very detailed and specific. ROD and PIARC were aware that some questions might have been challenging for some stakeholders and blank answers were expected. Additionally, considering the type of data requested, it was assumed that respondents might have wished to provide comments or qualifications, therefore multiple opportunities were provided at the end of each question and at the end of the survey to comment / qualify any responses made.

In the beginning of the survey, short definitions of the “Bridge & Tunnel Elements”, “Oversized Vehicles”, “Bridge & Tunnel Strike” and “Effectiveness” were provided to familiarise the respondents with the survey’s key concepts. To enhance the response rate, ROD developed a version of the survey in English, French and Spanish. All three surveys have been produced using the SurveyMonkey platform (SurveyMonkey, 2021).

ROD received 43 responses, 21 in English, 12 in French and 10 in the Spanish version. The English version included L-MICs, U-MICs and HICs including U.K., U.S., Ireland, Australia etc. The French version included responses from France, Belgium, and Canada. The Spanish version had responses from Spain, Argentina, Colombia and Chile. In the following paragraphs, the results of the second survey are analysed and discussed in detail. The data presented below focuses on relevant questions and results of the survey in order to draw conclusions. The overall response from the second survey is provided in Appendix D.

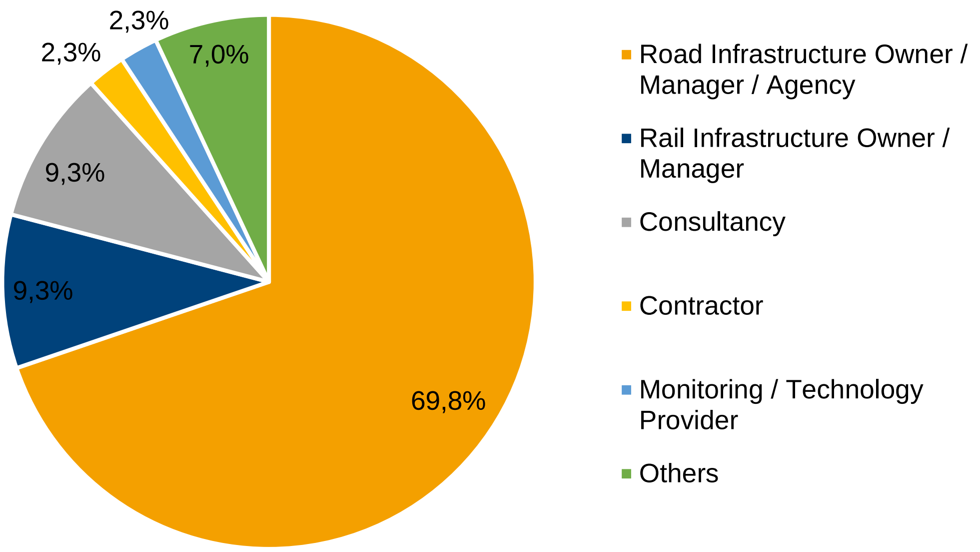

Figure 2.19: Q2 – Organisation type.

It can be seen in Figure 2.19 that the majority of the respondents were Road Infrastructure Owners/ Managers/ Agencies (69.8%), a few other responses came from Rail Infrastructure Owners/ Managers (around 9.3%), Consultancies (around 9.3%), Monitoring/ Technology Providers (around 2.3%) and Contractors (around 2.3%). 7.0% of the responses included other organisation type from Road, Rail & Maritime Owners and Maintainer, Territorial Communities and Maintenance Operators.

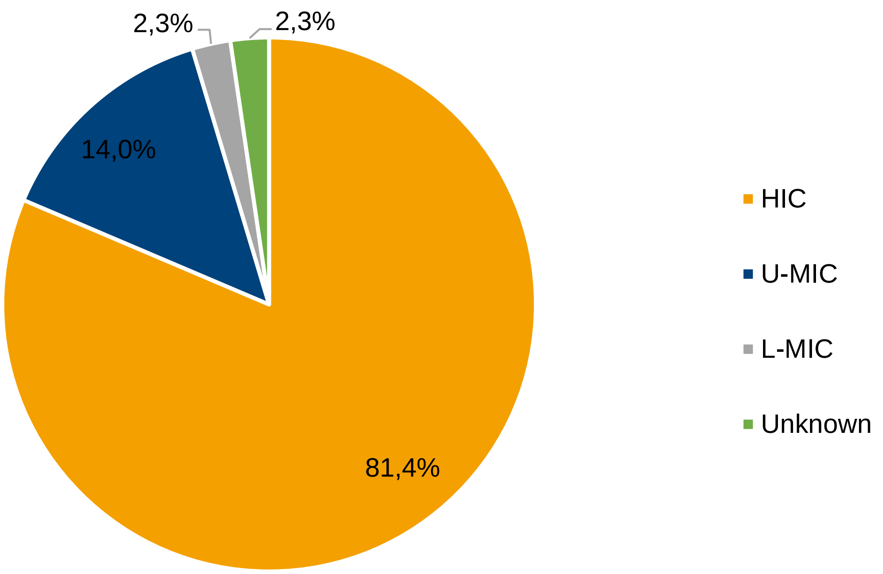

Figure 2.20: Q3 – Countries income classification.

In the third question, the respondents provided the name of their country. ROD then clustered the responses into HICs, U-MICs and L-MICs. The clusters were made according to the World Bank classification (World Bank, 2021). The clusters are presented in Figure 2.20. The majority of the responses were from income countries (approx. 81.4%), followed by upper-middle income countries (approx. 14.0%) and low-middle income countries (approx. 2.3%). One response did not provide a valid country name, and the income classification could not be identified (2.3%).

The following questions are focused on obtaining detailed data on strike and countermeasure costs and countermeasure effectiveness. Each question is repeated for bridges and tunnels separately. In general, the number of responses for bridges are higher than for tunnels, as expected since the number of stakeholders contacted that were tunnel owners / managers was smaller, and there are comparatively less tunnels than bridges on most networks.

The respondents were asked to provide data on number of strikes per year and average cost or cost range of a strike (Q4 and Q8) based on the type of strike, which were defined as:

- Small: causes minor vehicle damage and no / very slight bridge / tunnel damage
- Medium: causes major vehicle damage and minor bridge / tunnel damage that does not impact on safe use
- Large: causes major vehicle damage and major bridge / tunnel damage resulting in collapse or global movement of structure for bridges or major damages to equipment / significant interruptions to safe use for tunnels.

The number of stakeholders who responded to these questions were 11 for bridges, which represents 25.6% of the total and 4 for the tunnels (9.3% of the total). For the bridge respondents, 8 (18.6%) were HICs, 2 (4.7%) were U-MICs and 1 (2.3%) was L-MIC. For the tunnel respondents, 3 (7.0%) were HICs and 1 (2.3%) was L-MIC. The number of strikes can vary significantly for different respondents, and is clearly dependant on the region or country considered. In general, there tends to be small strikes than large strikes. The costs of a strike also varies based on the country.

Respondents were also requested to provide a percentage breakdown of the strike cost across different cost categories (Q6 and Q11). This was again divided for small, medium and large types of strike. Figure 2.21, Figure 2.22, Figure 2.23 and Figure 2.24 below show an average percentage breakdown for both HICs and LMICs. Considering the limited number of responses collected, especially for LMICs, it is difficult to draw certain conclusions. From the data available, infrastructure repair appears to be the cost category most affecting the strike cost for HICs, whereas the strike cost appears to be more equally distributed into the categories for LMICs.

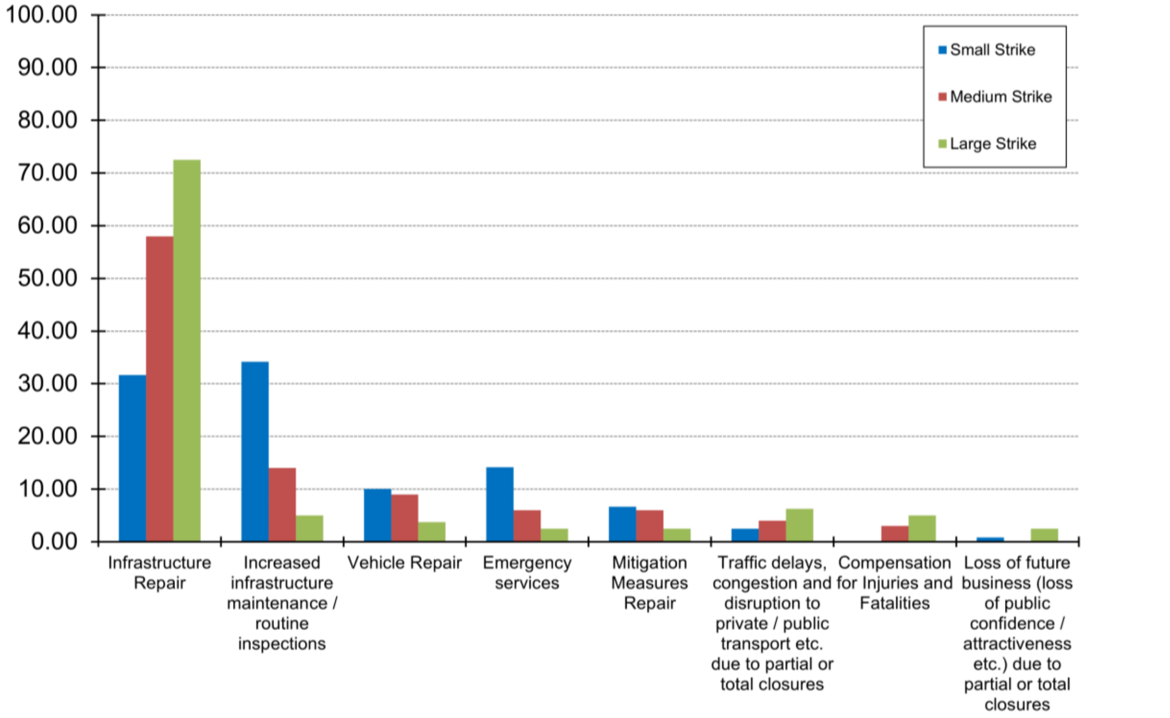

Figure 2.21: Q6 – Bridges HICs – Please indicate the percentage breakdown of the cost across the categories below.

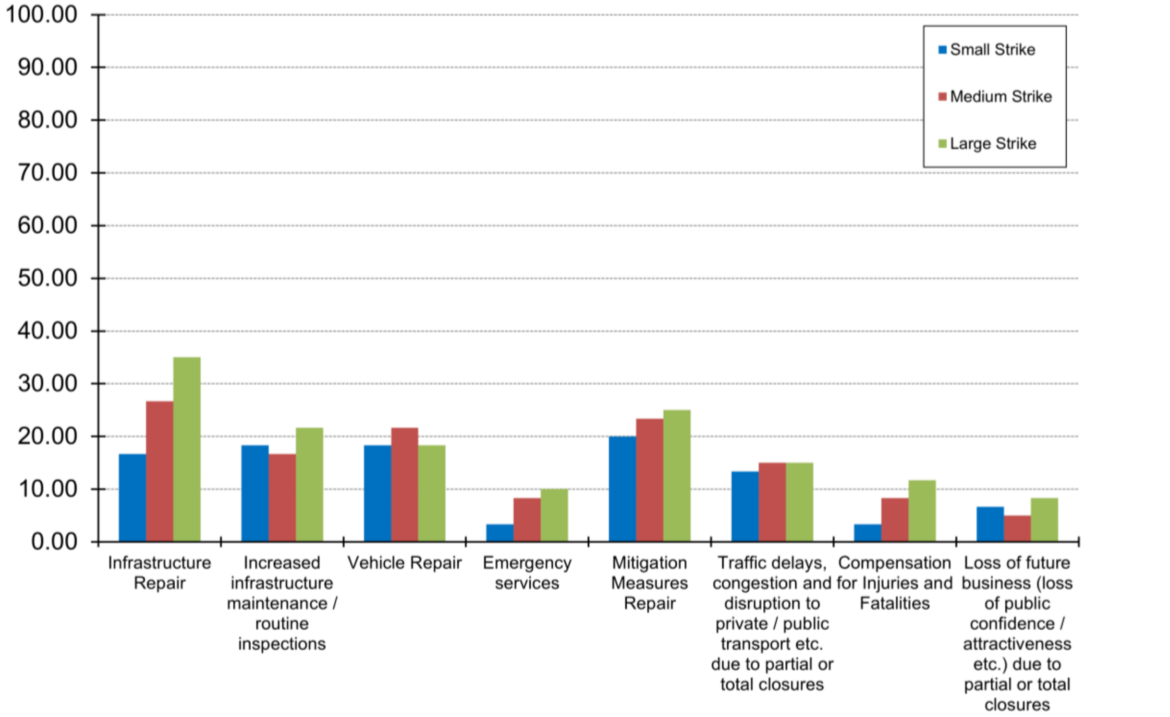

Figure 2.22: Q6 – Bridges LMICs – Please indicate the percentage breakdown of the cost across the categories below.

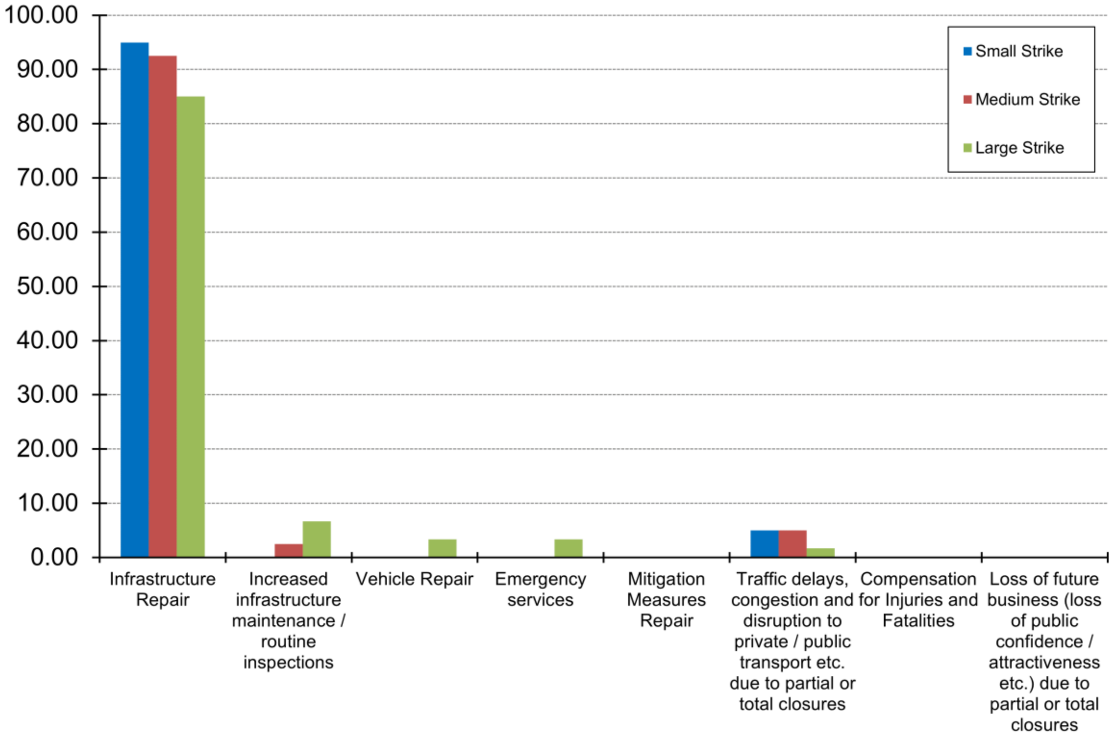

Figure 2.23: Q11 – Tunnels HICs – Please indicate the percentage breakdown of the cost across the categories below.

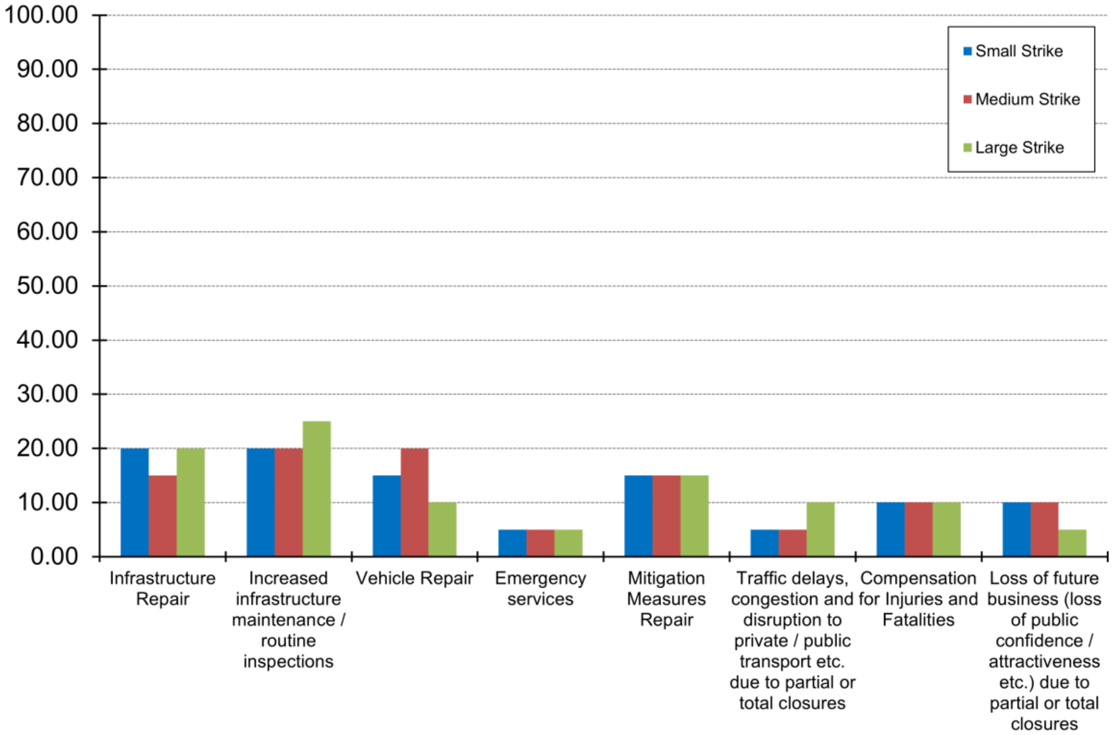

Figure 2.24: Q11 – Tunnels LMICs – Please indicate the percentage breakdown of the cost across the categories below.

The next questions aim to identify the percentage of cost that is born by the bridge / tunnel owner and that which is recovered by insurance or the road hauliers themselves (Q7 and Q12). The number of stakeholders who responded to these questions are 7 for bridges (16.3%) and 4 for tunnels (9.3%). The percentage of LMIC respondents is 7% for bridges and 2.3% for tunnels. Based on the data from the respondents, a bridge owner would on average pay 53.6% of the total strike cost, 32.8% is recovered by insurance and 13.6% is born by the haulier. For a tunnel owner, the cost to the owner is around 26.3% of the total strike cost, 56.2% is recovered by insurance and 17.5% is born by the road haulier.

The following section of the second survey focuses on the effectiveness and cost of mitigation measures. For each countermeasure, the respondents provided a level of effectiveness based on the following categories: Low Effectiveness (0%-25%), Low Medium Effectiveness (25%-50%), High Medium Effectiveness (50%-75%) and High Effectiveness (>75%). There were 12 responses for bridges (27.9%) and 6 for tunnels (14.0%). Of these, 7.0% and 4.7% were LMICs for bridges and tunnels respectively. Figure 2.25 and Figure 2.26 show the average mitigation measures effectiveness for bridges and tunnels.

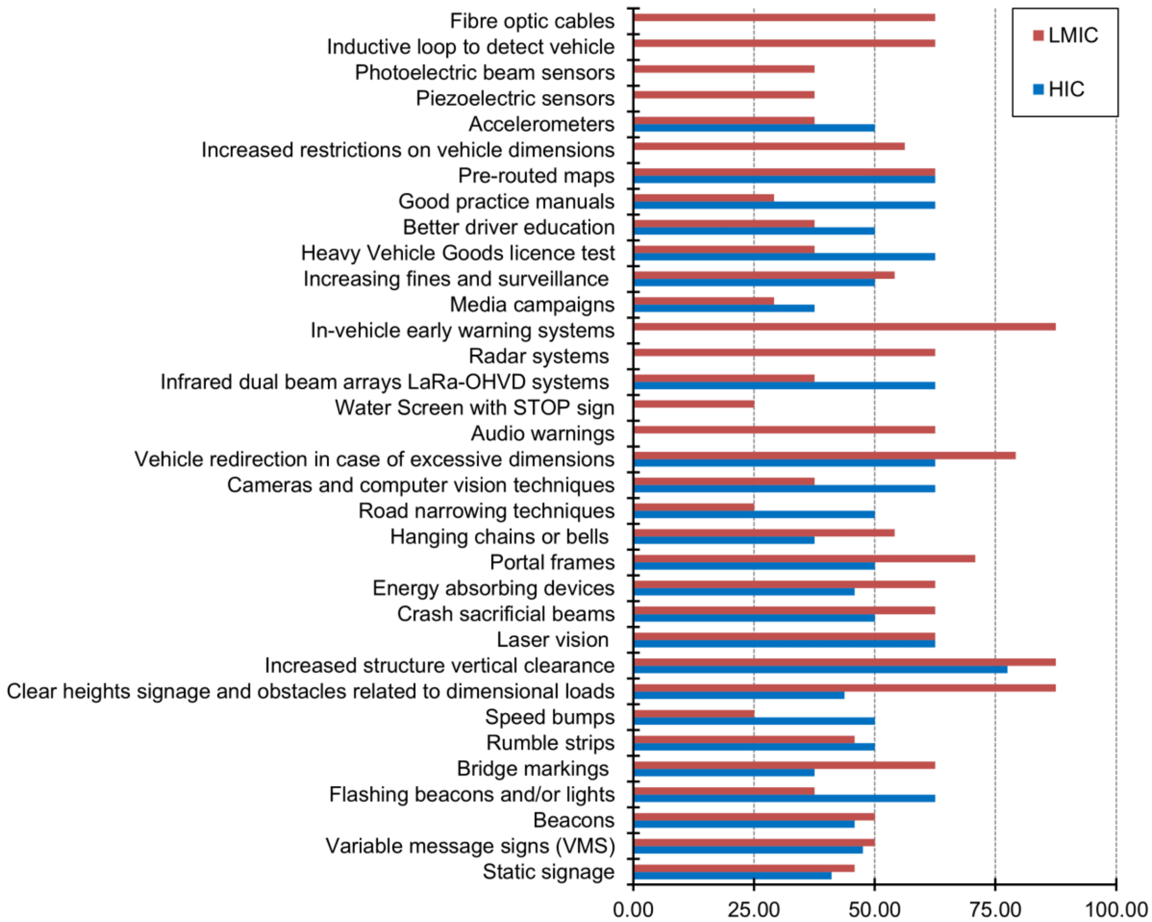

Figure 2.25: Q14 – Bridge – Please indicate the effectiveness of the following mitigation measures for bridge strikes.

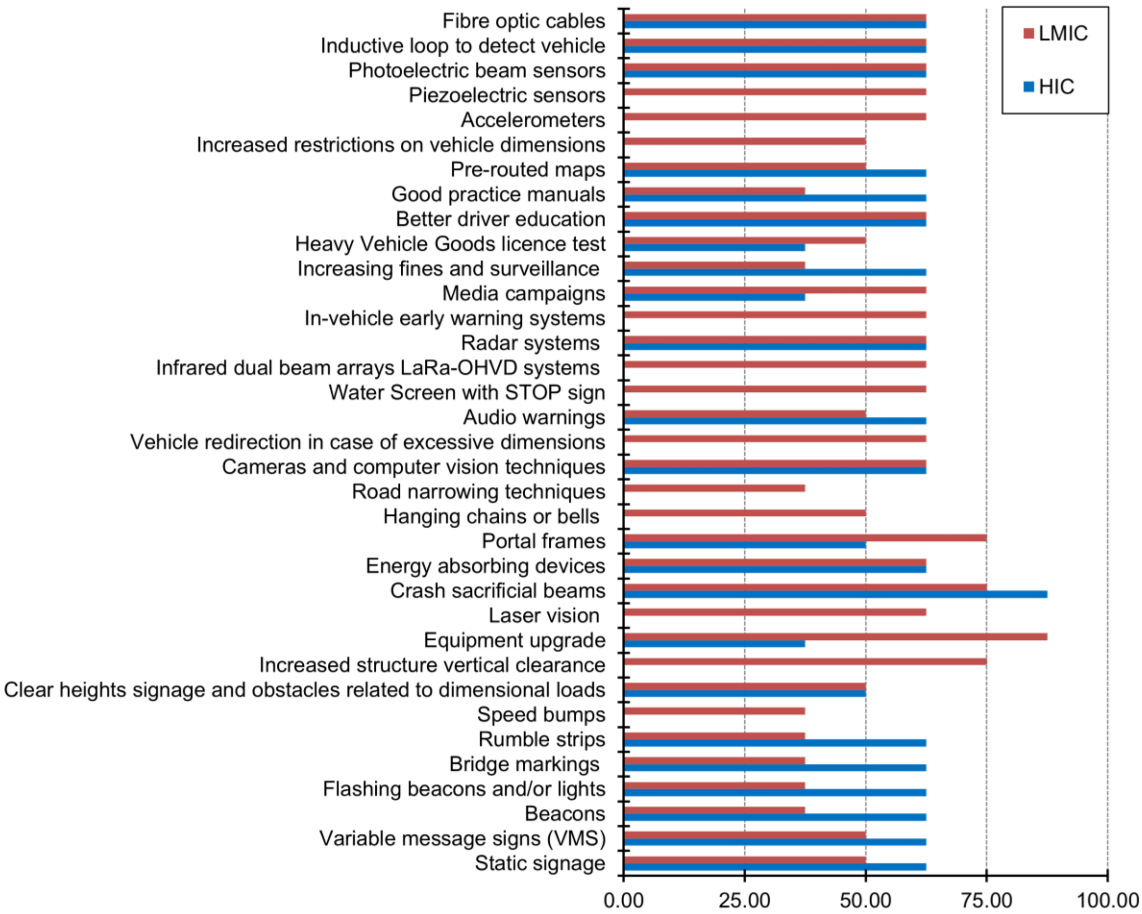

Figure 2.26: Q17 – Tunnel – Please indicate the effectiveness of the following mitigation measures for tunnel strikes.

Finally, an estimation of the cost of purchase, installation and annual maintenance was requested for the mitigation measures for bridges and tunnels (Q15 and Q18). The price ranges obtained from the survey vary noticeably from country to country. Only 5 stakeholders (11.6%) responded to the bridge question and only 2 (4.7%) to the tunnel one.

2.4. Stakeholder Interviews

As expected, the level of quantitative data obtained from the second survey was minimal, and probably insufficient to provide an extensive CBA. It should be noted that the respondents to survey 2 were specifically targeted and identified as being the key people to provide data from their organisation. Therefore, it can be stated that this is as extensive a data set as can be currently obtained for this type of an international analysis.

In order to ascertain the reason for the lack of quantitative data available, ROD carried out a series of interviews with key stakeholders from the second survey. This included contacts who were the Bridge Strike Leads of infrastructure management companies in the UK and Ireland as well as senior personnel within the UK Bridge Strike Prevention Group (BSPG). From the results of this survey, it was clear that while an extensive amount of data is available to these organisations, it is not currently possible to provide the data in the format requested by the survey, as it is not currently stored in the manner requested. For example, cost data from train delays in the UK may be available, it is not easy to attribute these delay costs directly to the cause, nor can the data be quickly aggregated for different bridge types, strike levels or consideration of the mitigation in place. This highlights a need for strike data to be stored in a uniform format by bridge and tunnel owners internationally. It is recommended that PIARC act as the international champion in standardising this process. The recommendations at the end of this report contains a sample of the data headings which should be used by operators in order to log each reported strike event in order to allow CBA to be carried out for their organisation in the future, or for international organisations of similar socio-economic background.

Recognising that a coordinated and detailed CBA is the only effective way to identify the benefits of countermeasures and to highlight the most effective means to mitigate strikes, it is recommended that a more detailed demonstration project be carried out in one or two case study regions, in order to highlight the methodology and provide a basis for other owners to address the problem effectively into the future. A number of sample demonstration sites could be chosen in an individual region where bridge strike mitigation measures have been put in place in recent years. For example, three sites could be chosen consisting of locations where low, medium and high-level interventions have been used. This will ensure measures which can be adopted by LMICs are considered in the analysis. Working at a lower level would allow the analyst to spend time investigating the various costs of the mitigation which has been adopted. In order to quantify the benefit of the associated systems, advanced risk assessment could be performed, considering the probability of failure both before and after the mitigation measures are put in place, as well as the consequences of various potential bridge / tunnel strikes, in terms of both direct (physical damage) and indirect (user delay costs) consequences. In order to evaluate long term benefits of interventions, the results can be extrapolated, and the risk calculated at different times in the assessment period. This analysis would provide an example of how designed mitigation measures can be optimized from the perspective of maximum resilience, and also provides initial considerations and data to be used by others in future studies.

3. BRIDGE AND TUNNEL STRIKE IMPACTS

3.1. DESK STUDY

3.1.1. Bridge / Tunnel Strike Costs

Accidental collisions between over height vehicles and bridges or tunnels are quite frequent and can be seen in High Income Countries (HICs) through Low-to-Middle Income Countries (LMICs). A bridge or tunnel strike can result in catastrophic and costly impacts to infrastructure such as traffic delays and congestion as well as loss of life or injury to the vehicle driver, passengers and other members of the public (Network Rail, 2007b; Agrawal 2013). In the worst-case scenario, oversized vehicles can cause train derailments, causing major injuries to the public. For example, the bridge strike incident in 1975 at Clogh Bridge, Wexford, Ireland resulted in 5 fatalities and 30 injured persons (Mac Aongusa, 2005). In addition, overheight collisions with structures can result in trucking firms paying significant amounts of money as a settlement for the victims or to cover the associated repair / delay costs.

Studies have shown that strike incidents account for a major percentage of bridge / tunnel failure. For example, bridge strikes are estimated to be the third most common cause of bridge failure in the U.S. (FHWA, 2013) and are considered to be the most common cause of damage (approximately 81%) to pre-stressed concrete bridges. Furthermore, oversized vehicles have been recorded to cause up to 90% of damage to steel bridges in the U.S (Shanafelt and Horn, 1984). A study from University of Kentucky in 1990 analysed U.S. bridge failures from 1951 to 1988 where it was found that of the 79 bridge failures, 11 were precipitated by truck collisions (14%). Equally, past research from the Michigan Department of Transportation in 1988 reported a 36% increase of overheight collisions over one year in 1988 (Span Damage Rate Rising, 1988).

The University of Maryland conducted a poll across the U.S. where 18 of the 29 states responding to the survey (62%) stated that they considered overheight collisions to be a serious problem (Fu et al. 2004). In 2001, a research study from Maryland State Highway Administration showed that 1496 bridges have clearance over roadways and of these, 309 bridges (20%) have sustained some damage from oversized vehicles (Maryland State Highway Administration, 2001). In addition, the research indicated that overheight collisions are a more severe problem in metropolitan areas in comparison to states with lower population densities and traffic volumes. Another research study by the University of Transportation Research Center at the City College of New York showed that these strike incidents are more frequent on low-vertical clearance bridges over parkways or other local roadways prohibited to truck traffic (Agrawal et al. 2012). The FHWA-HIF-20-087 report reveals that bridges in the U.S. are impacted (collision by all vehicle types) on average 15,000 times a year.

Agrawal et al. 2012 also reported that bridges in New York State experience approximately 200 strikes annually by over-height trucks. In California, the rate of bridge strikes subject to ongoing litigation is on average one per month (Yen, 2014). However, the total number of bridge strikes is expected to be higher. A later study by Wardhana, 2003 in the U.S. for the years 1989 – 2000, showed that 14 out of 503 bridge failures (3%) were due to vehicle/ structure collisions. A research study conducted by the Texas Department of Transportation (Feldman et al. 1998) reported 241 collisions of overheight vehicles from 1987 to 1992. The Texas Department of Transportation also presented that bridge strike incidents cost an average $180,000 to repair causing significant financial burden on transportation agencies (Nguyen et al. 2016). In the U.S., the average cost of repair after a bridge strike is around $200,000 (Nguyen, 2018).

In the UK, approximately 3,400 bridges are defined as high risk due to their low clearance, i.e. less than 5m. The most common height of bridges that are impacted are those with a clearance between 3.65 – 4.25 m (Department of Transport, 1993). The number of bridge strikes significantly increased from less than 300 in the 1970s to more than 700 in the early 1990s (Horberry et al. 2002). A Network Rail study revealed that a railway bridge strike occurs on average every 4.5 hours (Network Rail, 2016a). More than 12,000 incidents have been recorded during the period 1995-2003 by Network Rail and approximately 50% of these incidents involved Heavy Goods Vehicles (HGV) (Network Rail, 2007a).

Another study by Network Rail revealed that bridge strikes caused more than 12,000 minutes of delays to rail passengers in Leicestershire alone over 5 years, resulting in more than £800,000 in compensation (Network Rail, 2016b). Bridge and tunnel strikes are still a reoccurring event in the UK costing asset owners thousands of pounds in repairs, maintenance and inspection costs. The average bridge strike costs £25,000 per event (Nguyen & Brilakis, 2016).

A study in China showed that 20% of bridge damage within Beijing City stemmed from over-height vehicles (Sina, 2007; Wang, 2007). In Ireland, studies have shown that the number of bridge strikes has steadily increased from 75 incidents per year in 1979 to 140 in 2007 (Byrne 2009). A summary of past bridge strike incidents in Ireland together with their consequences can be found in Byrne (2009). This study also provided a statistical analysis to identify the most vulnerable bridges in terms of location, road class, material type etc. In Australia, an over-height truck collision with Melbourne's Burnley tunnel in 2013 resulted in a damage loss and traffic jam cost which of up to $1M (Brooks, 2013).

Bedi (2000) studied the structural reduction in load-carrying capacity due to bridge strikes. It was found that the reduction in strength was more than double that predicted by the section properties alone. Therefore, it was concluded that the damage induced by overheight vehicle collisions may be more severe than calculated using standard methods.

The severity of a bridge or tunnel strike is usually characterised as either low to medium or medium to severe damage depending on the amount of structural damage and/or injuries. Low to medium damage implies minor damage of the structure and some potential damage on the top of the oversized vehicle. In comparison, medium to severe damage implies major damage of the structure e.g. fracture of reinforcement and/or damage to concrete elements (Nguyen, 2016).

It is clear from the literature that bridge and tunnel strikes do not only result in direct impact to the affected structure and the safety of the driver, but also leads to indirect impacts on the wider transportation network around the incident. For instance, the Texas Department of Transportation estimates an average cost of repair at $180,000 while the disruption of service can last for up to a year (Kozman et al., 2014). Although direct costs can be easily calculated, the indirect costs from detours, traffic congestion and delays are difficult to be interpreted and can often be significant (Meyer, 2013).

3.1.2. Bridge / Tunnel strike causes

In order to effectively mitigate and reduce bridge and tunnel strikes, it is important to understand why they occur. Various studies have showed that inadequate vertical clearance is one of the most important factors that might contribute to overheight collisions with structures (Hilton et al. 1973; Hadipriono et al. 1985; Humphrey et al. 1988).

Despite the efforts made to reduce the number of bridge or tunnel strikes by the relevant authorities, they are steadily increasing globally every year. The most important factor appears to be that the oversized vehicle drivers fail to recognise or are unfamiliar with warning signs. For example, a study in the U.K. revealed that the 30% of over-height vehicles are driven by foreign drivers who enter the Country and are not familiar with warning sign format (Network Rail, 2007a). Clearly there is a need to standardise international road signage not just for overhead clearance but for safety related issues in general. Another important consideration is that many drivers are unaware of their own vehicle height, and they often overestimate the clearance of the structure. In this regard, a study showed that only 12% of truck drivers correctly estimated their vehicle height. Other factors may be due to the lack of an alternative route or the lack of a planned route by the transport logistics companies (Agrawal et al. 2011, Martin et al. 2004). Therefore, better driver education on the issue is clearly an important consideration.

In the U.K., an analysis of 1550 incident reports (Department of Transport, 1993), where an explanation was given by the driver, found that the most likely causes were as follows: height of vehicle not known by the driver (given as the cause in 32% of cases), equipment (e.g. on mobile cranes or tippers) left raised when driving (in 26% of cases) and poor warning signs (in 13% of cases). Galer, (1980) found that only 12% of high-sided vehicle drivers could correctly estimate the heights of their vehicles. Unsurprisingly, there have been several initiatives to tackle the problem of drivers' lack of knowledge of their vehicles' height. This implies that the driver is at fault in the majority of cases and the issue largely relates to knowledge or error. Another frequent cause seen internationally is load shift. For example, dump trucks with the bed lifted, or trucks halling cranes with the booms extended are often involved in strikes. This often occurs as a result the load not being properly secured, causing it to move during travel.

3.1.3. Case study from the United States

In 2013 there was a major bridge failure on Interstate 5 (I-5) in the United States. A truck hauling an oversized load struck the overhead structure of the Skagit River bridge causing it to fail. To gain a better insight of the cause and impact of the incident, a review was carried out by the United States National Transportation Safety Board.

A truck-tractor in combination with an Aspen flatbed semitrailer hauling an oversized load was travelling South on I-5 near Mount Vernon, Washington. The oversize combination vehicle had a permit for the route of travel and was being led by a pilot/ escort vehicle. The oversized combination vehicle was travelling in the wrong lane across the I-5 bridge above the Skagit River and the oversize load struck the bridge, damaging its structure.

As a result of contact damage, a span of the bridge collapse into the Skagit river, leading to two passenger vehicles falling into the river and damage to two other vehicles during the incident. In total, eight vehicle occupants were involved in the bridge span collapse; three received minor injuries and five were uninjured.

The National Transportation Safety Board determined that the probable cause of the bridge strike was that the oversize combination vehicle failed to travel in a lane with adequate overhead clearance due to the deficiencies in the interdependent system of safeguards for oversize load movements. These deficiencies included:

- insufficient route planning.
- failure of the certified pilot/escort vehicle driver to perform required duties and to communicate potential hazards, due in part to distraction caused by cell phone use.
- inadequate evaluation of oversize load permit requests and no provision of low-clearance warning signs in advance of the bridge by the Washington State Department of Transportation.

The following conclusions/ findings were made as part of this incident:

- The driver of the oversized vehicle did not adequately consider the vertical clearance or the reduced width of the travel lanes on the Skagit river bridge.
- The pilot/ escort vehicle driver was distracted by their hands-free phone conversation, which reduced attention to their escort duties.
- Neither the state nor the motor carrier seemed aware of the necessity to take any precautions due to the lane width reduction on the Skagit River Bridge.
- The lack of standardization of training for pilot/escort vehicle drivers among the states and the failure of the majority of states to require certification or training of such drivers leaves some pilot/escort vehicle drivers poorly prepared to carry out their duties.
- Due to their special safety responsibilities, pilot/escort vehicle drivers should not engage in distracting activities and should be prohibited from using portable electronic devices for nonemergency purposes, except to communicate safety-related information to the escorted vehicle.
- Adding roadway clearance data to navigation systems on commercial motor vehicles would be a direct and efficient method of providing drivers with safe route information for oversized loads.
- Low-clearance signs in advance of and on bridges and tunnels provide valuable and necessary warnings to drivers of vehicles carrying overheight loads to help them avoid striking overhead obstructions.
- Drivers of overheight vehicles would benefit from having a warning sign that indicates the proper lane of travel for their vehicles when traveling underneath an arched structure.

3.2. Results from stakeholder engagement

Two surveys have been developed as part of this project with the aim of collecting information of the bridge and tunnel strike issue by key stakeholders. Both surveys have been circulated to relevant stakeholders worldwide.

Valuable qualitative data was obtained from the first survey for which bridge and tunnel strikes have been recognised as one of the main issues by organisations, especially for infrastructure owners, and one of the main hazards impacting cost and safety of bridges and tunnels.

The second survey aimed to collect detailed data on strike and countermeasure costs and countermeasure effectiveness, yielding very interesting results. As mentioned previously, the level of detail requested in the survey was high and optimistic and it was often challenging for stakeholders to retrieve and provide the data requested. It was clear from the second survey comments and following stakeholder interviews that the main reason for this was the lack of data storage or the lack of standardisation making it difficult to recover information.

From the data collected in the second survey it was noticed that the quantitative data can vary considerably based on the country and organisation. The number of strikes per year for example varies a lot, since each stakeholder considered different areas of study, such as a whole country, a region or a single bridge / tunnel. Some discrepancies were also noted between survey countermeasure costs and the desk study values. This was attributed to the fact that the desk study costs did not take into account additional expenses that the infrastructure owner would have in the event that a countermeasure needs to be adopted. Additionally, the strike cost breakdown showed that there is not a typical cost breakdown, but that different countries and different types of organisations are subject to unique costs. These considerations lead to the obvious conclusion that average cost and effectiveness values are difficult to calculate and that considering the variability of the data being analysed, each value should be obtained on a case-by-case basis.

For the purpose of this project, average values of costs and effectiveness must be approximated. The data obtained from both surveys and the desk study were analysed in order to obtain an average value for strike cost, strike cost breakdown, mitigation measure costs and mitigation measure effectiveness. These values have been calculated from the HICs stakeholders' data since the data available for LMICs was considered too limited to obtain reliable values. Table 3.1, Table 3.2, Table 3.3 and Table 3.4 below present the average values obtained. Some of the mitigation measures in Table 3.4 have been grouped based on their similarity and others have been removed since little or poor information was available. These are approximate values for the purpose of this project only, and it is strongly recommended that a case-by-case analysis be carried out to evaluate an actual CBA in within an owner's network.

	Cost Percentage
Cost born by infrastructure owner	60%
Cost born by haulier	6%
Cost born by insurance	34%

Table 3.1: Strike cost associated with owner, haulier and insurance for HICs

	Total Strike Cost
Small Strike	5,500€
Medium Strike	38,400€
Large Strike	294,000€

Table 3.2: Average strike cost per structure for HICs

Type of cost	Small Strike	Medium Strike	Large Strike
Infrastructure Repair	35%	57%	65%
Increased infrastructure maintenance / routine inspections	42%	17%	7%
Vehicle Repair	4%	3%	3%
Emergency services	0%	2%	2%
Mitigation Measures Repair	8%	4%	2%
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	11%	14%	15%
Compensation for Injuries and Fatalities	0%	3%	4%
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	0%	2%

Table 3.3: Strike cost breakdown for HICs

Mitigation Measure	Purchase Cost	Installation Cost	Maintenance Cost	Effectiveness
Static signage	1,000 €	1,000 €	500 €	41.1 %
Variable message signs (VMS)	80,000 €	60,000 €	8,000 €	47.5 %
Beacons	1,000 €	1,000 €	500 €	45.8 %
Flashing beacons and/or lights	500 €	500 €	500 €	62.5 %
Bridge markings	1,000 €	4,000 €	1,000 €	37.5 %
Rumble strips	2,500 €	2,500 €	500 €	50.0 %
Speed bumps	2,500 €	2,500 €	500 €	50.0 %
Clear heights signage and obstacles related to dimensional loads	1,000 €	1,000 €	500 €	43.8 %
Increased structure vertical clearance	250,000 €	250,000 €	0 €	77.5 %
Laser vision	100,000 €	50,000 €	25,000 €	62.5 %
Crash sacrificial beams	20,000 €	35,000 €	1,000 €	50.0 %
Hanging chains or bells	15,000 €	35,000 €	1,000 €	37.5 %
Road narrowing techniques	20,000 €	80,000 €	5,000 €	50.0 %
Cameras and computer vision techniques	30,000 €	5,000 €	1,000 €	62.5 %

Mitigation Measure	Purchase Cost	Installation Cost	Maintenance Cost	Effectiveness
Vehicle redirection in case of excessive dimensions	1,000 €	1,000 €	500 €	62.5 %
Infrared dual beam arrays LaRa-OHVD systems	10,000 €	2,000 €	1,000 €	62.5 %
Media campaigns[1]	5,000 €	5,000 €	0 €	37.5 %
Increasing fines and surveillance[1]	5,000 €	5,000 €	0 €	50.0 %
Heavy Vehicle Goods licence test[1]	5,000 €	5,000 €	0 €	62.5 %
Better driver education[1]	5,000 €	5,000 €	0 €	50.0 %
Good practice manuals[1]	5,000 €	5,000 €	0 €	62.5 %
Pre-routed maps[1]	5,000 €	5,000 €	0 €	62.5 %
Increased restrictions on vehicle dimensions[1]	5,000 €	5,000 €	0 €	50.0 %
Accelerometers, Piezoelectric sensors and Fibre optic cables	7,000 €	3,000 €	1,000 €	50.0 %

[1] Mitigation measures costs do not refer to one single structure, but to the total cost of the mitigation measure implementation

Table 3.4: Mitigation measures cost per structure and effectiveness for HICs

In addition to a desk study and surveys, interviews have been carried out with stakeholders in order to provide an insight on the problem and additional data for the project.

Valuable outcomes were obtained from the interviews. In particular, the stakeholders clarified that while quantitative strike data is available, its format is not suitable to properly provide meaningful data for CBA. For example, general strike numbers and costs are accessible, but not subdivided in the categories requested. One stakeholder mentioned the use of a Strike Database that allows users to input strike data. However, the database is manually maintained and data is not always up to date and objective.

The overall cost of strikes is known, but it is not straightforward to break it down into different categories. The majority of the cost for railway operators was found to be due to delays and cancellations. Infrastructure repair costs are not usually apparent since they are often absorbed into routine maintenance, especially for small strikes.

The stakeholders also provided information about the decision-making process used to identify the best measures to reduce the strike issue: critical structures are first identified for specific regions; possible solutions are then analysed by the collaboration of different professional actors that provide distinct insights to the problem. The professionals involved are for example infrastructure owners, road/rail operators, police and road hauliers.

The stakeholders dealing with the problem on the ground also suggested that the state of the art in dealing with the bridge strike issue has moved away from individual mitigation / technology applied to the structure, and toward a policy change through stakeholder engagement, advertising the issue and highlighting the potential disasters which can occur. This type of intervention has the benefit of attacking the problem at source, while also being rolled out on a nationwide basis.

From the information collected from the stakeholder engagement it can be concluded that some improvements can be made in order to address the bridge and tunnel strike issue. First of all, a better data collection system is required, where an appropriate data format is needed in order to carry out a CBA. Data should be analysed on a case by case basis, since average values are difficult to calculate and not reliable for a large scale network. Finally, the decision-making process should include insights of a wide range of professionals, since even small changes and improvements in the network can make a huge difference on the issue resolution.

3.3. Conclusions

The desk study reveals the following causes of bridge/ tunnel strikes which can be considered for both high- and low-income countries.

1. Inadequate low-clearance signage or other mitigation measures that warn the forthcoming drivers well before any damage of the structure.
2. Guidelines, manuals, protocols and standards do not always exist and/or may be different from country to country leading to overheight collisions by foreign drivers when they cross country / state borders.
3. Better driver education is needed such as overheight vehicle driver familiarisation with signage and any mitigation technologies used to avoid collision with structures.
4. Lack of an alternative route or lack of a planned route by logistics companies.
5. Drivers are distracted during their journey (e.g. though electronic devices) or they experience fatigue or health problems and fail to recognise a forthcoming dangerous situation or they overestimate the vertical clearance of a structure.
6. Drivers are not aware of height of their overheight vehicle.
7. Improperly secured loads may shift or rise during transport.

The cost of a bridge/ tunnel strike is difficult to be interpreted since it depends on several factors and the level of damage of both the vehicle and structure, as well as the nature of the route of the vehicle and that of the infrastructure above.

1. In the U.S., it was reported that the average cost of repair of a bridge strike is around $200,000. The Texas Department of Transportation estimates an average cost of repair at $180,000. Network Rail in the U.K. also reports an average bridge strike cost at £25,000 per event.
2. The indirect costs of a bridge/ tunnel strike incident are extremely difficult to be evaluated. Nevertheless, National Rail authorities in the U.K. report delay costs of more than £800,000 in Leicestershire over 5 years. Furthermore, the indirect costs of an overheight truck collision with Melbourne's Burnley tunnel in 2013 resulted in costs of up to $1 million.
3. Unfortunately, the data for direct and indirect costs of a bridge/ tunnel strike incident could not be found from the literature for LMICs.

While much of the data from the project surveys and stakeholder engagement is in broad agreement with the desk study, some of the data recovered is spurious in nature and stakeholders cannot easily calculate or retrieve the various costs of bridge and tunnel strikes. It is therefore recommended that a formalised structure for recording bridge / tunnel strike data be developed in order to ensure international coordination of the issue. Furthermore, recent developments suggest that countries are moving toward a policy change through stakeholder engagement, advertising the issue and highlighting the potential disasters which can occur. While drivers' education and awareness can be assisted by engagement and advertising, enhancements to vehicle technologies and self-diagnostics are still required to address the knowledge-based and error-based issues. This type of intervention has the benefit of attacking the problem at source, while also being rolled out on a nationwide basis. Nevertheless, the use of on site technology does of course have a place at specific sites where the issues of strikes are pronounced and recurring, and should be evaluated on the basis of site specific CBA.

4. BRIDGE AND TUNNELS STRIKE MITIGATION MEASURES

Various prevention systems have been proposed in the past to eliminate bridge / tunnel strike incidents. These are categorised into passive, sacrificial and active systems as per Nguyen et al. (2016) and they are briefly described in sections 4.1, 4.2 and 4.3. Several detection systems have also been proposed to detect a bridge or tunnel strike incident and these are presented in section 4.4. Other alternative and driver-based countermeasures are discussed in section 4.5.

4.1. PASSIVE SYSTEMS

Passive systems are currently considered the most cost-effective systems, readily available in terms of supply chain, simple installation and low maintenance requirements. They include static signage, Variable Message Signs (VMS) (Fontaine et al. 2003), beacons (Mattingly et al., 2003) and bridge markings (Horberry et al. 2002). Other systems may include flashing beacons and lights (Manjunathan et al, 2005) to inform the oncoming driver about possible alternative routes. These systems use static signage which show the structure clearance height well in advance and they are typically used in conjunction with other preventative methods.

Variable Message Signs (VMS) are electronic traffic signs used on roadways to give travellers information about special events. The message shown is updated as required and, in this context, can warn the upcoming vehicle of its excessive height. Beacons, flashing beacons and lights are instead static devices located on the road and designed to attract the attention of the driver to notify oversized vehicles of possible detours.

Passive systems are considered the primarily and most widely used countermeasure against bridge and tunnel strikes around the World. Although these systems are inexpensive, they rely on driver education and attention and thus they are estimated to be 10-20% effective (Cawley 2002). A bridge warning sign is illustrated in Figure 4.1 where it can be noticed that damage has still been done to the concrete under the bridge. Bridge warning signs are also often required from a legal perspective from the bridge/ tunnel owner.

Figure 4.1: Bridge warning signs and damage to concrete under the bridge (Byrne, 2009).

In the survey of the University of Maryland, U.S., it was found that nine of the states increased the number of warning signs of vertical clearances as a means of reducing overheight collisions. Five states reported that this countermeasure worked to some degree (56%), three were unable to tell (33%), and one said that it was not successful (11%) (Maryland survey, 2001).

Horberry et al. (2002) researched whether warning markings on a bridge would result in a reduction of the number of strikes. It was found that bridge warning signs make bridge openings appear smaller from a distance making drivers more reluctant to pass underneath. They suggested placing low bridge warning signs at a much earlier stage on the approach to a bridge as a means to increase the level of caution as far as possible. They also indicated that bridge markings would never completely mitigate strike incidents and additional methods such as detection systems should be used. They also stressed that as long as low clearance bridges are situated over busy roads, some bridge strikes will be inevitable in the future.

In the U.K., the Department of Transport requires all bridges under 5.03m to be posted with prohibition and warning signs (Department of Transport, 2008). In 1993, the DoT experimentally attempted to reduce bridge strikes by modifying the warning markings on bridges in order to make them appear lower. This mitigation measure only partially reduced the strike incidents leading to the conclusion that additional prevention measures are required.

4.2. SACRIFICIAL SYSTEMS

Sacrificial systems involve physical contact with the upcoming vehicle. Examples of sacrificial prevention systems include crash beams, hanging chains or bells and road narrowing techniques e.g. speed bumps and rumble strips (Byrne, 2009; Nguyen, B., 2018a; Transport Asset Standards Authority, 2020). These systems can be installed close-by the structure to dissipate the energy from the vehicle impact or at a moderate distance before the bridge or tunnel to warn the driver of the forthcoming danger and ultimately protect the structure itself. Although the effectiveness of these systems is estimated to be around 30-50%, they may require either high installation costs (around $60,000 per installation) (Cawley, 2002) and/or time-consuming installation processes (Nguyen, 2018a). Additionally, the relatively low effectiveness of sacrificial crash beams is recognised to be mainly due to lack of design guidance for the appropriate impact loads on these devices. Furthermore, while these systems will alert a driver prior to striking a bridge, they may still cause damage to the vehicle itself, and associated disruptions to road traffic.

Crash beams are horizontal structural members installed at the structure location protecting the structure itself from overhead collisions from high sided vehicles (see Figure 4.2). They absorb the energy of strike and thus prevent or reduce damage to the main structure (Yang et al., 2010). If properly designed, the crash beam should absorb much of the impact energy thus reducing kinetic energy on both structure as well as the vehicle. The crash beam should remain intact without collapsing to the roadway thus minimizing disruption to existing roadway travel and safety. Although, crash beams are very effective in preventing a bridge strike, they are costly and they only act as a protective measure rather than preventative, as in reality there are additional costs associated with a vehicle striking these crash beams (albeit less than that of a bridge strike). Considering installation, maintenance and additional strike costs, it is therefore unclear as of yet if this mitigation measure is cost effective in most environments. Many railway operators utilise crash beams in the UK and Ireland. Surveys and interviewed carried out by ROD have identified that while there may be justification for crash beams at certain high-profile sites, modern research is moving away from their use as they have in some cases resulted in significant delay to road and railway users, as well as injury to the public. While these systems may be designed to provide 100% effectiveness in terms of a bridge strike, survey data indicates that the significant consequences associated with a crash-beam strike can negate the benefits, particularly for the road operators.

Figure 4.2: Crash beam for preventing bridge strikes (Guelphmercury, 2021).

The U.S. Department of Transportation is developing an energy-dissipative system using a combination of a steel box beam with aluminium honeycombs for the protection of bridge girders from overheight impacts. This system could be installed on low-clearance bridges or bridges susceptible to impact by over-height trucks to prevent significant damage to the main bridge system.

Figure 4.3: Hanging chains for preventing bridge strikes (Railway Magazine, 2021).

Alternative options include road narrowing techniques (e.g. speed bumps, rumble strips chicanes) and metal hanging chains which warn the driver in advance of the low clearance structure and ultimately reduce the speed of the vehicle. Hanging chains or bells (Figure 4.3) are chains or bells hanging from a gantry and positioned at a moderate distance from the structure. An oversized vehicle would be hit by the chaines and warned of the low clearance bridge in the distance. Speed bumps, rumble strips and other road narrowing techniques are instead simple traffic calming measures that should slow down the traffic and reduce the likely impact between a road vehicle and the bridge thereby preventing track distortions from occurring (Byrne, 2009).

Unfortunately, the effectiveness of narrowing techniques in preventing overhead collisions are difficult estimate due to lack of survey data. Sandidge, (2012) reported that hanging chains have been proven to be difficult for drivers to hear and as such, can be ineffective.

4.3. Active systems

Intelligent Transportation Systems (ITS) can be considered as an active prevention system. These include Early Warning Detection Systems (EWDS), computer vision systems etc.

Early Warning Detection Systems have been developed by Lowry et al. (1981) and are based on light beam sensors. Visual and audio warnings are activated when the transmission of a light beam is interrupted by an overheight vehicle (Solak, 2019). A signal is then sent to a control station which in turn activates a visible, flashing, electric sign indicating that the approaching vehicle is too high to clear the obstruction, and further warns the driver of the vehicle to stop or to exit from the roadway. A message concerning the overheight vehicle can be transmitted to the highway authorities simultaneously. EWDS can also advise drivers of available routes. Mattingly, (2003) reports that several Departments of Transportation in the U.S. are currently using EWDS. Further details can also be found in Nguyen, (2018a).

Various other systems exist including infrared dual beam arrays with the ability to reject ambient light and eliminate false overheight vehicle alarms (see Figure 4.4) (Nguyen et al. 2016, TRIGG, 2020), LaRa-OHVD systems (Singhal, 2020) and radar systems (see Figure 4.5) (Urazghildiiev el al. 2007) for detecting the height of oversized vehicles. In the United States, many states have started deploying warning systems using laser or infrared light (FHWA, 2011).

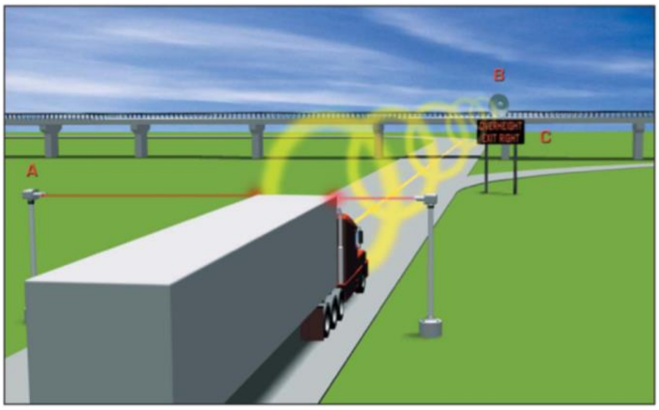

Figure 4.4: TRIGG laser. (TRIGG, 2020).

Infrared dual beam arrays are optoelectronic sensors that rely upon the interruption of a beam or sheet of light to indicate that a vehicle exceeds a predefined height threshold. This countermeasure is combined with additional measures to warn the drivers when the oversized vehicle is detected. LaRa-OHVD systems (Singhal, 2020) is an innovative laser ranging over-height vehicle detection system which is installed on the bridge being protected and detects incoming over height vehicles at a safe stopping distance. The laser detects the vehicles and warns the drivers by using a standard warning sign with flashing beacons installed on the bridge face next to the detector.

Figure 4.5: Single laser beam systems applicable to a wide variety of traffic control and law enforcement scenarios. The photo illustrates the CMP52 laser radar developed by Noptel Oy (Noptel Oy, 2021).

Radar systems, such as CMP52 laser radar developed by Noptel Oy, are eye safe sensors applied within fixed installations such as gantry, bridge or poles, and mobile systems. Based on their location, they measure several information of traffic and vehicles on single or multilanes, and approaching and/or receding vehicles.

Agrawal, (2011) reports that the installation cost of infrared light technology is in the range of $7,700 to $8,900 plus maintenance costs of approximately $50 per annum. Equally, the cost of radar systems may vary from approximately $2,000 - $2,500 per unit (Maghiar et al., 2017). While the active systems represent the lowest Technology Readiness Level (TRL) of all mitigation measures, these appear to have the most promise in terms of effectiveness and future roll out. The use of these systems in combination with emerging CAV technology and Vehicle-2-Structure communication will not only allow automated arresting of strike incidents, they will also allow the automated storing of data relating to vehicle and structure height, automating the process of route selection, which has been problematic in the past. Due to the low TRL of these technologies, a clear recommendation here would be to fund future research efforts to enhance and prove these systems.

Another innovative active system on the market is laser vision. This technology is used in the Sydney Harbour Tunnel along with a float in mid-air pseudo-holographic ‘STOP’ sign message on a water screen which warns the oversized vehicle driver to stop (Laservision, 2021) (Figure 4.6). These methods and newer computer vision methods can be very successful in preventing accidental collisions by creating the illusion of a distinguishable solid surface. However, they have several drawbacks such as significant installation cost (>$100,000) and maintenance cost (>$25,000 annually) (Nguyen, 2018a), use of large volume of water, separate water network required and pavement slippage due to the water. These lead to the conclusion that their use is not suited for LMICs.

Figure 4.6: Laser vision, pseudo-holographic “STOP” warning sign (Laservision, 2021).

Active prevention systems are usually 50-80% effective (Hanchley et al. 1990). A survey conducted by Mattingly, (2003) across the U.S. showed that active systems led to a reduction in overheight collisions. A research study in the Department of Transportation, Michigan shows that the cost of active systems is around $110,000 while the 3-year benefit is approximately $600,000 to $700,000 Cawley, (2002). However, it is uncertain how the costs were determined. In addition, the installation of loop detectors requires roadblocks causing another indirect cost of the technology. Further details can also be found in Nguyen et al. (2018a).

Alternative and less expensive systems to detect over-height vehicles have been proposed by Park et al. (2013) and Dai et al. (2015) based on cameras and computer vision techniques. In these systems, video streams are collected from a camera attached to low clearance structures and processed to detect vehicles and ultimately measure their heights. Preliminary experiments showed 96.6% accuracy of measuring vehicle heights resulting in a potential and cost-effective warning system. However, the efficiency of these systems depends on environmental conditions. For example, they are not usable during night hours and low light conditions.

4.4. DETECTION SYSTEMS

As well as prevention systems (passive, sacrificial and active), there are a number of detection systems currently in market. Detection systems are mainly structural health monitoring tools (Patil et al. 2017) such as accelerometers, piezoelectric, and fibre optic cables that are used to record the case of a bridge or tunnel strike and effectively transit warning messages to the corresponding authorities to shut down the transportation services around the incident. These sensors measure the dynamic displacement of structures due to a strike. Accelerometers sense acceleration in one to three orthogonal directions, piezoelectric transducers are subjected to force deformation such as compression or shear, and fibre optic cables measure local strain changes. For example, fibre optic cables are used in the Mass Transit Railway, Hong Kong, to inform authorities of the occurrence of a bridge strike (Ye et al. 2014). ROD-IS has designed such systems based on vibration monitoring to provide early warning to Irish Rail in the event of a bridge strike. These systems are key to addressing a different aspect of the bridge / tunnel strike problem – unreported strikes. There is potential for example for bridge strikes to cause displacement of bearings etc, and for this to go unreported to bridge owners. In this case, the continued passage of trains or vehicles over the bridge could result in a catastrophic failure. Examples of such events have resulted in train derailments internationally. Examples from Ireland include the Longford under bridge strike of 1974 and the Wexford under bridge strike of 1975, which resulted in 5 fatalities and 30 injuries (Figure 4.7). This highlights the need for detection systems in certain locations where unreported strikes are apparent.

Figure 4.7: Train derailment at Longford 1974 (left) and Wexford 1975 (right) due to undetected bridge strikes (Byrne 2009).

4.5. DRIVER-BASED MITIGATION OF BRIDGE AND TUNNEL STRIKES

There are also driver-based ways of reducing the number of bridge / tunnel strikes such as increasing fines and surveillance and/or better driver education (Wheel, 2020). Transport infrastructure owners have attempted to reduce the number of bridge / tunnel strike incidents by implementing permits, axle load restrictions, fines, driver education and awareness programs, good practise manuals and protocols. These can have a positive impact with a reasonably low cost and can be easily applied in LMICs. An alternative but more expensive prevention system is also the Geographical Positioning Systems (GPS) which helps optimising the route and identifying low clearance bridges.

Modern trends seem to be drifting toward these types of methods as opposed to infrastructure mitigation systems / technology, in an effort to reduce the impact of the problem at source.

Good Practice Guides and protocols for professional drivers are extensively available and can be used for driver training and management to increase their awareness (Network Rail, 2007a, 2007b & 2014). These best practices encourage drivers to check the height of the vehicle and display the height in their cab before commencing a journey. Equally, Transport Scotland together with the National Bridge Strike Prevention Group have produced “Strike it Out” campaign to raise the awareness of drivers though training reduce bridge strike incidents (Donnelley, 2010). In the U.S., best practices guidelines for pilot/ escort vehicle operators have been published by the Federal Highway Administration (FHWA-HOP-16-051). This document summarises the results of extensive research and advises individuals pertinent to existing pilot/ escort vehicle operator training materials, laws and rules relevant to the movement of oversize loads.

Another driver-based countermeasure focuses specifically on driver personality (e.g. their risk outlook), on the driving task (e.g. route planning to avoid low clearance bridges) and in a wider context, on the use of non-road transport methods to carry freight and passengers (i.e. using the railways to a greater extent) (Horberry et al. 2002).

In the U.S. the penalties for violation vary from $20 to $1,000 between different states (Maryland survey, 2001). However, research revealed that increased penalties for overheight violations would not significantly reduce overheight collisions. However, through stakeholder consultation in the current study, it has been identified that highlighting the extend of personal injury and liability which can occur has had a significant impact in reducing strikes. Legal precedent has recently been set in the UK which makes the road haulier more responsible for the delay costs and personal injury costs associated with bridge and tunnel strike events. Stakeholders have highlighted to ROD-IS that the advertising of the levels of fines and recent prison sentences handed down to responsible drivers can be a cheap and effective way of combatting the issue at source.

The American Association of State Highway and Transportation Officials (AASHTO) has published a policy on Geometric Design of Highways and Streets (AASHTO, 1994) which defines a minimum vertical clearance of 4.9 m for structures over freeways, but this varies from state to state. The National Transportation Safety Board investigators conducted a survey of various states to determine their statutory maximum vehicle height and low-clearance signage requirements. They found that statutory maximum vehicle heights vary from a low of 3.96 m to a high of 4.57 m. In National Transportation Safety Board, (2013), the statutory maximum vehicle height by state can be found. Some states in the U.S. also mitigate overheight collisions by increasing the vertical clearance of the existing overpasses (Maryland survey, 2001). A U.S. survey for each state revealed that the standard bridge clearance on the U.S. National Network ranges from 4.8 to 5.2 m. Some states show the actual vertical clearance on warning signs while other states under-report the clearance by up to 0.15m. Recent studies show that this under reporting can lead certain truck drivers to draw incorrect assumptions about the actual bridge / tunnel clearance, resulting in a perception that their vehicle will safely pass beneath the structure.

Irish Rail has also developed a risk model to use as a tool to monitor and assist in managing potential risks from bridge strikes. The model aids network operators by identifying the critical areas where safety investments can provide the greatest return (Byrne 2009). The model measures risk in terms of fatalities and/or the number of major and minor injuries. Irish Rail also uses the tool to estimate the overall performance of the rail network.

The U.K. Department of Transport now oblige any vehicle above 3.0 m high either to carry a sign in the cab indicating the vehicle height or to carry relevant information concerning the vehicle and its journey (Horberry et al. 2002).

GPS systems are used by overheight vehicles to indicate where low bridges are located. A small unit is installed in the vehicle cab which compares the registered vehicle height with the bridge clearance. If the height of the vehicle is greater than the vertical clearance of the structure, video and audio warnings are activated within the vehicle to warn the driver of the upcoming collision (Martin et al. 2004). A major disadvantage of these systems is that they do not always contain accurate bridge/tunnel height information leading to unexpected overheight collisions with structures. Transport for Scotland, for instance, has encouraged drivers not to trust GPS (Donnelly, 2010).

4.6. Conclusion

This section provided an overview of the various prevention measures available to mitigate bridge and tunnel strikes by overheight vehicles. Passive, sacrificial and active systems were reviewed as well as detection systems and driver-based mitigation. While passive systems are the least effective, they are often a statutory requirement and are very inexpensive to erect. Recently, the state of the art has moved away from sacrificial systems which can have significant impacts on transport networks and the public when struck. Detection systems are an extremely useful technology where un-reported strikes can lead to significant knock-on impacts to the infrastructure and the public. Active systems appear to have the most promise in terms of effectiveness, especially when the future of CAVs allows automated uptake of these systems into the industry. However, further research is needed in this area in order to prove these systems and enhance their uptake internationally.

The level of literature currently available on bridge / tunnel strike prevention systems in LMICs is very limited. However, use cases can be found for example in Egypt where Massoud, 2013 developed an over-height vehicle detection system based on mechanical, optical and image processing methods. An initial literature review suggests that the use of lower cost passive or sacrificial systems can be adopted in LMIC countries in conjunction with appropriate Cost Benefit Analysis (CBA).

Driver-based mitigation appears to be the current State of the Art among HICs which are dealing with major bridge and tunnel strike occurrences. These systems can be easily rolled out on a nationwide basis at low cost, and allow the problem to be combatted at source.

A summary of the current technologies and practises used for mitigating bridge and tunnel strike incidents can be seen in Table 4.1. An indication of the cost of the different products can be found in Maghiar, (2017).

Passive	Sacrificial	Active	Detection	Driver-based
10-20% effective	**30-50% effective**	**50-80% effective**	**-**	**-**
Static signage (purchase and installation costs: $50-100; maintenance cost: minimal).	Sacrificial beams (purchase + installation costs: $5,000-$10,000; maintenance cost: $1500).	Radar systems (purchase + installation costs: $2,000 - $2,500; maintenance costs: -)	Piezoelectric (purchase + installation costs: $100 - $2,000; maintenance costs: -)	Driver education awareness.
Flashing sign (purchase + installation costs: approx. $500; maintenance cost: minimal).	Portal frames (purchase + installation costs: $1,000 – 3,000; maintenance cost: approx. $1000).	Overheight Vehicle Detection System (purchase + installation: $5000 - $15,000)	Accelerometers (purchase + installation costs: $10 - $100; maintenance costs: -)	Heavy Vehicle Goods (HVGs) licence test.

Passive	Sacrificial	Active	Detection	Driver-based
10-20% effective	**30-50% effective**	**50-80% effective**	-	-
Variable message signs (purchase + installation costs: $1200 to $10.000; maintenance cost: minimal).	Metal strips/ bells (purchase + installation costs: $1,000 – 3,000; maintenance cost: approx. $500).	Computer vision techniques (purchase + installation costs: >$100,000; maintenance cost >$25,000.		Good Practice Manuals.
Speed bumps (purchase + installation costs: $500 to $6000 per mile; maintenance cost: minimal).	Fibre-optics (purchase + installation costs: $100 – 1,000; maintenance cost: approx. $50).	Infra-red light technology (purchase + installation costs: $7,700 to $8,900; maintenance costs: $50		GPS (purchase + installation costs: $15,000-$20,000; maintenance cost: minimal).
Rumble strips (purchase + installation costs: $500 to $6000 per mile; maintenance cost: minimal).				Fines/ Fees (U.S. penalties for violation $20 to $1,000).
				Maps.
				Policies.

Table 4.1: Summary of current bridge and tunnel strike countermeasures

5. CHALLENGES AND OPPORTUNITIES FOR MITIGATION

5.1. CHALLENGES

The biggest challenges for transport infrastructure owners regarding bridge and tunnel strike countermeasures are affordability (installation and maintenance cost) and reliability, with minimal compromise of accuracy and performance (Nguyen, 2018). As discussed in section 4, there are various systems to mitigate bridge and tunnel strikes. Passive systems appear to be the lowest cost solution although their prevention rate is only 10-20%. More advanced systems include the so-called sacrificial systems (approx. 30-50% prevention rate) which require higher installation & maintenance costs than passive systems. The third and most sophisticated systems include ITS-based systems which seem to have the highest prevention rate (approx. 50-80%). However, they are the most expensive option, prohibiting their use in LMICs. review of existing literature and survey information appears to indicate that the most effective measure for bridge strike prevention may lie in driver-based methods, including driver education, permitting and routing practices, and multi-sectoral engagement on the issue.

It should be highlighted that from the literature it is not clear how the effectiveness of each system has been measured. Moreover, there are not enough studies to validate the value of the effectiveness of a system amongst different countries and/or countries with different income (e.g. high vs low income countries). Another point to consider is the fact that various prevention systems may be used in combination, e.g. bridge markings and sacrificial beams. However, the effectiveness of combined prevention systems has not been explored in the literature.

Another important challenge faced by infrastructure owners relates to bridge / tunnel strike cost. Although, past studies have provided indications of a strike costs, it is currently unclear how the different costs (direct / indirect) have been estimated. It can be seen from the references in section 3 that different countries have reported completely different costs for bridge and tunnel strike incidents. The direct costs (e.g. bridge, tunnel and vehicle damage) can sometimes be easily calculated. However, it is apparent that the actual infrastructure repair costs are typically absorbed into routine maintenance costs, and owners do not always keep a record of specific damage relating to bridge / tunnel strikes. Moreover, the indirect costs (traffic congestion, delays etc.) are often very difficult to estimate. This presents another barrier to effective cost-benefit analysis for countermeasures. Even for organisations which do have significant amount of information on cost due to all delays, these delays are not always attributable to the events that caused them. An example would be the railway operators in the UK, Network Rail. All delays and associated costs are stored, as these are paid in penalties to the (separate) train companies. However, the database of delay costs does not always accurately or comprehensively store information on causes of delay. This means that obtaining the annual costs due to bridge strike in order to perform CBA, would be a huge undertaking in itself.

The aforementioned points constitute the current challenges in the mitigation of the bridge and tunnel strike incidents as well as the selection of the most appropriate system for their elimination.

5.2. OPPORTUNITIES

The business case for bridge / tunnel strike mitigation can be easily evaluated from the opportunities in terms of strike reduction, and associated cost savings. There is a need for infrastructure managers to address the current challenges discussed in the previous section, in order to facilitate the reduction of bridge/ tunnel strikes incidents. The average initial mitigation measure cost per structure is around €40,000, with the average annual maintenance of mitigation around €2,000. Considering the data available, the average cost of a bridge strike in Europe appears to be around €25,000 per strike. Therefore, there is a clear opportunity for a rapid return on investment for high-profile, frequently struck structures. This is of course coupled with significant safety and reliability enhancements for operators and society as a whole.

Bridge / Tunnel strike incidents are required to be properly recorded to generate a reliable database which can be used for the selection of the most appropriate mitigation measure. Examples of data that could be recorded include number of incidents per year, cause of incident, direct & indirect costs, societal costs etc. Site specific information such as structure location, structure type, countermeasures in place, structure clearance, legal truck height, traffic volume, roadway normal travel speed, damage severity, vehicle type, etc. could also be recorded and would be fundamental for an accurate CBA to support bridge-level decisions and relative prioritizing.

The industry needs to take a multi-sectoral approach to bridge the gap between cost-effective yet efficient solutions in terms of prevention rate. A similar approach has been adopted by the Bridge Strike Prevention Group (BSPG) in the UK, where various actors (railway operators, road operators, hauliers, police etc.) work together to address the issue. This can be supplemented with input from industry and academia. For example, Nguyen (2018) developed a novel vision-based system that utilises a single camera to accurately detect over-height vehicles by using a set of optimised parameters. The system uses a camera installed at the offending height, which acts as an "over-height plane" formed by the averages of the maximum allowable heights across all lanes in a given traffic direction. The precision rate is reported to be around 95% and the purchase cost less than £3,000 making it as a promising "smart" system for prevention of bridge and tunnel strikes in the future with a reasonably low cost.

Another promising ITS-based system from the driver perspective may derive from the forthcoming deployment of automated driving (FHWA, 2021). Automated vehicles will be able to use their embedded sensors in conjunction with computer vision techniques/ algorithms to estimate the vertical clearance of a structure. This is anticipated to transfer any in-site mitigation measures (e.g. bridge markings) directly to the vehicle. This will result in two major advantages:

1. the installation and maintenance cost of the on-site sensors, signs or other countermeasures will be minimised into critical areas.
2. Bridge/ tunnel strike data will be properly recorded allowing infrastructure managers to take better decisions to enhance the safety of their networks.

While the development of these currently low TRL technologies is extremely promising, this project is aimed at current recommendations to tackle the bridge strike problem. Moreover, there is a specific focus given by PIARC to LMICs, for whom these low TRL may prove to be unrealistic or out of reach. Therefore, the authors of this report recommend that the real opportunity associated with countermeasures can only be quantified in a measurable way through CBA.

6. COST-BENEFIT ANALYSIS

Cost Benefit Analysis (CBA) is a decision-making process that allows analysis of a problem to make rational decisions through the evaluation of strengths and weaknesses. In this project, ROD will utilise the data gathered through review of available literature, surveys and interviews with key stakeholders in order to perform CBA of various mitigation methods to rationally analyse the bridge and tunnel strike issue.

In the following sections a definition and description of the CBA process is provided, a methodology is developed for this project and subsequently applied for different socio-economic regions. The methodology provided will allow road administrators to perform ad hoc CBAs and identify the best technologies, approaches, and mitigation strategies for customised cases.

6.1. CBA Review

'Cost-benefit analysis (CBA) is the systematic and analytical process of comparing benefits and costs in evaluating the desirability of a project or programme – often of a socio-economic nature. It attempts to answer such questions as whether a proposed project is worthwhile, the optimal scale of a proposed project and the relevant constraints', (Mishan & Quah, 2020). CBA is an essential decision-making tool to government and businesses and is recognised as a formal technique for making informed decisions. Benefits, defined as the potential rewards expected from an action or project, are compared to costs, the total expenses associated with taking that action or launching that project. The outcome of the analysis will determine whether the project is financially feasible or if the project should not be pursued. Different CBA outcomes can also be compared to identify the best project or option to be pursued.

Regardless the type of organisation, business, or government performing CBA, a common process can be identified, as shown in Figure 6.1 below.

Figure 6.1: Cost-Benefit Analysis process

Definition of the CBA objective

The definition of the CBA objective is a very important step in the CBA process. As pointed out by (Brent, 2006), while developing a CBA some questions might arise such as 'Which costs and which benefits are to be included?'. The answer to this question depends on whose welfare is to be maximized. Depending on the set objective and on the business or organisation which would benefit from the project or action, different cost and benefit categories can be determined, and their related values can change. Therefore, the CBA's outcome could completely differ based on the set objective.

Identification of different CBA cases

This step of the CBA process is primarily relevant when multiple projects or options are being considered and compared. A CBA can be performed to determine if a single project is beneficial for the organisation or not, in which case only two scenarios can be examined: launching of the project or not. If multiple scenarios are evaluated in the analysis, the CBA process can assist on the selection of the best and most profitable option.

Identification of cost and benefit categories

Costs and benefits should be disaggregated into their constituent parts, which will facilitate the calculation of their values in the next step. Costs and benefits can be primarily categorised into direct and indirect costs. **Direct costs** can be defined as costs directly dependent on the project, whereas **indirect costs** are more subtle costs. Considering Bridge and Tunnel Strikes as an example, a direct cost might be the purchase cost of a mitigation measure, whereas an indirect cost might be the traffic delay caused by the countermeasure installation.

Calculation of cost and benefit values

Once cost and benefit categories are defined, their overall values can be calculated. Costs and benefits can be defined as **tangible** if they are easy to measure and quantify, or **intangible** if they are difficult to identify and estimate in monetary terms. Examples of how to calculate intangible costs are provided in (Brent, 2006). Intangible values can always be subject to interpretation, and often require more indirect valuation methods. Despite their demanding estimation, it is better to provide one's best estimate of these intangible effects, rather than omit them completely. Examples of intangible costs might be the valuation of human life or customer satisfaction.

Cost and benefit values for each category can be estimated from historical data, available data, or data obtained through surveys and interviews. If information is missing for a particular category, alternative valuation methods need to be adopted. In the literature, several theoretical and experimental formulas are available to assist in cost and benefit calculation. If literature is not available, more indirect and complex valuation methods can be used. Examples are provided in (Brent, 2006)

It is important to consider costs and benefits across the assumed life of a project and to take both the short and long term into consideration. Costs and benefits will evolve over time and projections should be made based on the life of the program or initiative. Especially for large projects with a long-term time horizon, a CBA might fail to account for important financial concerns such as inflation, interest rates, and the **net present value (*NPV*)** of money. The concept of present value states that an amount of money or cash in the present day is worth more than receiving that amount in the future since today's money could be invested and earn income. Saying that a unit today is worth more than a unit next year is equivalent to saying that a unit next year is worth less than a unit this year. In other words, the future unit has to be discounted to make it comparable to a current unit. An amount of money m in n years, will have a net present value today of:

$$NPV = \frac{m}{(1+r)^n}$$

where ***r*** is the **discount rate**, expressed in %, e.g. for a discount rate of 5%, the *r* value is equal to 0.05. The NPV of a series of benefits or costs CB from next year ($t = 1$) to the end of the project ($t = T$) can therefore be summarised as:

$$NPV = \sum_{t=1}^{t=T} \frac{CB}{(1+r)^t}$$

To take into consideration cost and benefit components with different significances, unequal **weights** w_c and w_b can be applied, so that the overall cost is $w_c \cdot C$ and the overall benefit is $w_b \cdot B$. Specifying the weights makes explicit the value judgements regarding the priority of objectives. Weights may also be applied to individual components of benefits and costs before aggregation so that specific factors can can be weighted differently. Unit weights can also be applied if different components are considered of equal significance.

Comparison of costs and benefits

CBA is a decision-making tool which aims to determine if and/or which project is worthwhile to be pursued. The outcome of a CBA is a comparison of the benefits and costs of the project and can be expressed as:

- *economic efficiency*, difference between benefits B and costs C
$$B - C \quad \text{or} \quad w_b \cdot B - w_c \cdot C \quad \text{or}$$
$$(w_{b1} \cdot B_1 + w_{b2} \cdot B_2 + \cdots + w_{bx} \cdot B_x) - (w_{c1} \cdot C_1 + w_{c2} \cdot C_2 + \cdots + w_{cy} \cdot C_y),$$
- *benefit-cost ratio*, ratio between benefits B and costs C
$$B/C \quad \text{or} \quad (w_b \cdot B)/(w_c \cdot C) \quad \text{or}$$
$$(w_{b1} \cdot B_1 + w_{b2} \cdot B_2 + \cdots + w_{bx} \cdot B_x)/(w_{c1} \cdot C_1 + w_{c2} \cdot C_2 + \cdots + w_{cy} \cdot C_y).$$

In both cases, the aim is to maximise the difference or ratio between benefits and costs. CBAs with positive economic efficiency and/or benefit-cost ratio higher than 1 can be considered as profitable. If different CBAs are compared, the project with higher economic efficiency and/or benefit-cost ratio is the most profitable.

6.2. Proposed Methodology

The proposed Cost-Benefit Analysis framework aims to give guidance to road administrators and owners to perform an assessment on their own networks through the CBA process. This methodology has been developed from the point of view of the abovementioned categories and aims to compare different mitigation measure scenarios. The list of cost and benefit categories considered below might not be exhaustive, as additional and/or different categories could be identified by the users, who might avail of additional data or have different objectives.

6.2.1. Definition of the CBA objective

As previously explained, the definition of the CBA objective is an important step of the process. The aim of this project is to make recommendations on the best mitigation measures for different socio-economic regions, based on road administrators and owners' point of view.

This objective can be adapted based on the user's goal in the CBA process. Different perspectives might be taken into account and more or less restrictive study areas might be considered. Studies might be focused on a country, town or one isolated case study, or might consider a wider territory.

6.2.2. Identification of different CBA cases

Several countermeasure scenarios will be analysed to provide recommendations on the most suitable mitigation methods. For each countermeasure, costs and benefits associated with its adoption will be calculated and evaluated. Each of these scenarios will be compared to a do-nothing scenario, which assumes that no mitigation measures have been installed and the bridge or tunnel status is unchanged. The scenarios can also be compared to each other. In the first case, the countermeasure scenario can be categorised as worth pursuing or not, whereas in the second one the most profitable solution can be identified. A more detailed explanation is provided in the following sections.

In this project the do-nothing and mitigation measure scenarios are analysed for different socio-economic regions separately, in order to make recommendations for each one of them considering each context distinctively. The flowchart in Figure 6.2 below gives a representation of the CBA cases identified.

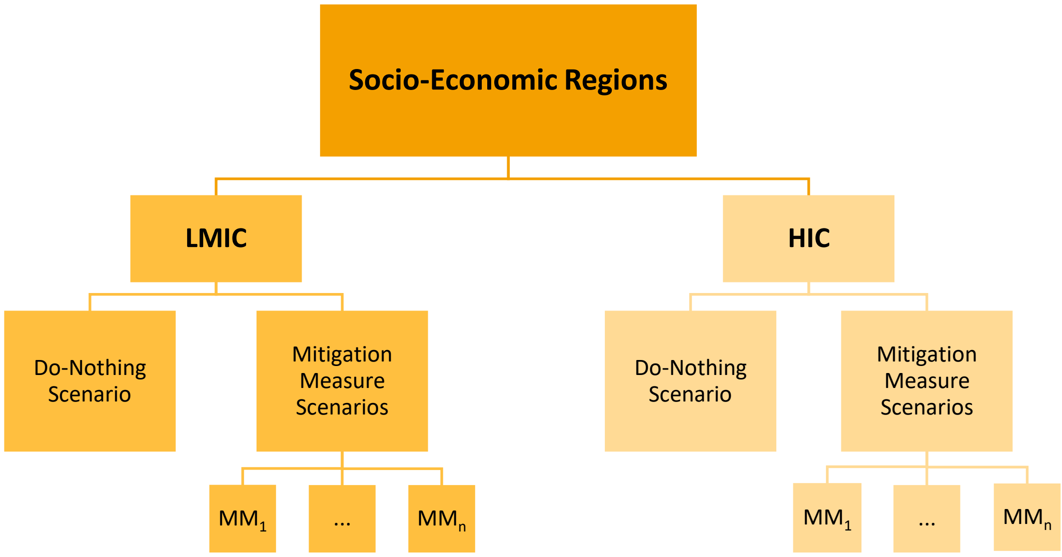

Figure 6.2: Cost-Benefit Analysis cases

6.2.3. Identification of cost and benefit categories

The various scenarios identified in the flowchart in Figure 6.2 can be summarised in two main CBA cases: the do-nothing scenario and the mitigation measure scenario. Although the latter is applied multiple times for several countermeasures, the cost and benefit categories identified are the same.

The do-nothing scenario will act as a reference scenario. Costs and benefits in this scenario are forced to have the same overall value, so that the economic efficiency and the benefit-cost ratio have a value equal to 0 and 1, respectively. No cost and benefit categories need to be identified in this scenario, as the economic efficiency and the benefit-cost ratio values are predetermined and assigned by the user.

The mitigation measure scenario will include different cost and benefit categories and economic efficiencies and benefit-cost ratios will be calculated based on their values. A scenario with a positive economic efficiency and a benefit-cost ratio higher than 1 will be more profitable than the do-nothing scenario and can be considered worth pursuing. If multiple mitigation measure scenarios have favourable outcomes, the most profitable scenario can be determined by comparing their economic efficiencies and benefit-cost ratios and identifying the one which maximises the outcomes.

One question might arise: how is the cost of a strike considered in the CBA? An intuitive answer might be that the cost of a strike should be considered in the do-nothing scenario, since no mitigation measures are being adopted, and strike events are occurring undisturbed. So, how is the cost of a strike to be taken into account if cost and benefit categories of the do-nothing scenario are forced to have the same overall value, and economic efficiency and benefit-cost ratio values are predetermined? The cost of a strike is not considered in the do-nothing scenario but is instead indirectly included in the mitigation measure scenario as benefits, interpreted as saved cost due to the countermeasure adopted.

Table 6.1 and Table 6.2 below list and describe the cost and benefit categories identified for the mitigation measure scenario. These categories can be extended or simplified based on the requirements of the user and the data available. Some of the categories included below might not be relevant for all countermeasures or might not be significant for some road administrators, in which case they shall be assumed to be zero.

Cost Category	Description	Unit(1)
Mitigation measure purchase cost	Represents the initial cost of purchase of the countermeasure.	**€**
Mitigation measure installation cost	Represents the installation cost of the countermeasure. It includes the cost of the labour and the traffic disruption due to its installation.	**€**
Mitigation measure maintenance cost	Represents the annual maintenance cost of the countermeasure, including occasional repairs due to malfunctions. It includes the cost of labour and the traffic disruption due to its maintenance.	**€/year**
Mitigation measure repair due to strike	Represents the annal repair cost of the countermeasure due to strikes. It includes the cost of the labour and the traffic disruption costs due to the repair.	**€/year**

(1) Unit of measurement specified is defined for this project and can be changed based on the country and project needs.

Table 6.1: Cost categories.

Benefit Category	Description	Unit[1]
Saved cost for infrastructure repair	Represents the cost saved of repairing the infrastructure after strikes. The cost saving is due to a reduction in strikes after installing mitigation measures.	**€/year**
Saved cost for vehicle repair	Represents the cost saved of repairing damaged vehicles after strikes. The cost saving is due to a reduction in strikes after installing mitigation measures.	**€/year**
Saved cost for increased infrastructure maintenance	Represents the cost saved of additional maintenance required after strikes. The cost saving is due to a reduction in strikes after installing mitigation measures.	**€/year**
Saved cost for emergency services	Represents the cost saved of emergency services in the event of a strike.	**€/year**
Saved cost for fines applied to driver	Represents the cost saved of fines applied to the vehicle driver in the event of strikes.	**€/year**
Saved cost for traffic disruption	Represents the cost saved of traffic disruption due to strikes.	**€/year**
Saved cost for loss of business	Represents the cost saved associated with loss of future business for infrastructure owners in the event of a strike, due to a change in public perception etc.	**€/year**
Saved cost for injuries & fatalities	Represents the cost of injuries & fatalities in the event of strikes.	**€/year**
Saved environmental costs	Represents the saved environmental costs due strikes.	**€/year**

[1] Unit of measurement specified is defined for this project and can be changed based on the country and project needs.

Table 6.2: Benefit categories.

6.2.4. Calculation of cost and benefit values

This step of the CBA process aims to quantify the cost and benefit categories, in order to merge them and obtain their overall values. These values might be directly available to the user or might require alternative methods to be calculated. Surveys and stakeholder interviews are effective tools to gather the necessary data. Additional missing information can be obtained from literature or by making reasonable assumptions.

Short-term and long-term influences need to be taken into account by considering a discount rate *r* which varies based on the country / region, usually being higher for developing countries (8%-15%) than developed ones (3%-7%), (Asian Development Bank, 2013). Some of the considered categories are present costs and benefits, referring to the starting time of the project and being a one-time rate. Others are future rates, referring to one or multiple years, recurring annually or periodically and applied to the whole length of the project or to only some years.

In the following paragraphs cost and benefit categories are analysed in detail, considering a time period of n years, where year 0 is the year in which mitigation is installed.

Costs & Benefits

The total cost of a mitigation measure scenario is defined as $\boldsymbol{C_{tot}}$ and is equal to:

$$\boldsymbol{C_{tot} = C_p + C_i + C_m + C_r},$$

where:

- $\boldsymbol{C_p}$ is the mitigation measure purchase cost. C_p is a present cost paid in year *0*, so that
$$C_p = C_{p,0}.$$
- $\boldsymbol{C_i}$ is the mitigation measure installation cost, which includes the labour C_{il} and the traffic disruption costs due to the installation, C_{it}. C_i is a present cost paid in year *0*, so that
$$C_i = C_{il,0} + C_{it,0}.$$
- $\boldsymbol{C_m}$ is the mitigation measure maintenance cost including occasional repair costs due to malfunctions, which includes labour (C_{ml}) and traffic disruption (C_{mt}) costs due to maintenance. C_m is an annual cost which must consider a discount rate r from year *0* to *n*, so that
$$\boldsymbol{C_m} = \sum_{t=0}^{t=n} \frac{(C_{ml,t} + C_{mt,t})}{(1+r)^t}.$$
- $\boldsymbol{C_r}$ is the mitigation measure repair cost due to strike damage, which includes labour (C_{rl}) and traffic disruption (C_{rt}) costs due to repair. C_r can be assumed as an annual or a sporadic cost: in the first case costs and discount rates r are considered for each year from 0 to *n*, whereas in the second case costs and discount rate are considered only for relevant years. The repair cost depends on the average number of strikes per year after the mitigation measure installation, which can be defined as $N_s \cdot (100\% - E_{MM})$, where N_s is the average number of strikes per year before the mitigation measure installation, and E_{MM} is the countermeasure effectiveness as defined in section 1.2. Additionally, the repair cost depends on the probability of required repair due to strike $\%_{repair}$: for example, a crash sacrificial beam has a higher probability of required repair after a strike than road markings, whose probability of repair can be assumed to be *0%*. If the $\%_{repair}$ value is equal to *0%*, the C_r value goes automatically to zero since no cost would be required for the repair. In the formula below only costs of relevant years should be considered, assuming a cost of 0 for the excluded years.

$$\boldsymbol{C_r} = N_s \cdot (100\% - E_{MM}) \cdot \%_{repair} \cdot \sum_{t=0}^{t=n} \frac{(C_{rl,t} + C_{rt,t})}{(1+r)^t}$$

The total benefit of a mitigation measure scenario is defined as $Btot$ and is equal to:

$$\boldsymbol{B_{tot} = E_{MM} \cdot S_{MM} \cdot C_{s,tot}},$$

where:

- $\boldsymbol{E_{MM}}$ is the mitigation measure effectiveness, as defined in section 1.2.
- $\boldsymbol{S_{MM}}$ is the mitigation measure suitability, expressed in %, defined as the appropriateness of a mitigation measure to be adopted in a specific socio-economic region or country. This variable aims to consider that a countermeasure might not be the most suitable for

a country, for example due to its advanced technology. In a low-income country, basic methods might be preferred.

- $\boldsymbol{C_{s,tot}}$ is the total cost due to strikes to be born by the road administrator for n years. $C_{s,tot}$ is an annual cost that needs to consider a discount rate r from year 0 to n. It depends on N_s which is the number of strikes per year without mitigation, C_s which is the cost for a single strike and $\%_{recover}$ which is the percentage of money recovered by the road administrator for example through insurance or from the vehicle owner / manager.

$$\boldsymbol{C_{s,tot}} \;=\; N_s \cdot (100 - \%_{recover}) \cdot \sum_{t=0}^{t=n} \frac{C_{s,t}}{(1+r)^t}.$$

$\boldsymbol{C_s}$ represents the cost of a single strike, which can be defined as:

$$\boldsymbol{C_s = C_{sri} + C_{srv} + C_{sm} + C_{ses} + C_{sf} + C_{st} + C_{sb} + C_{sc} + C_{sen},}$$

where:

- C_{sri} is the infrastructure repair cost due to a strike, including labour and traffic disruption / delay,
- C_{srv} is the struck vehicle repair cost,
- C_{sm} is the increased infrastructure maintenance cost due to a strike,
- C_{ses} is the emergency services cost,
- C_{sf} is the cost of fines applied to the driver,
- C_{st} is the cost of traffic disruption & delays due to the strike,
- C_{sb} is the cost of loss of business for infrastructure owners in the event of a strike,
- C_{sc} is the cost of fatalities and injuries in the event of a strike,
- C_{sen} is the environmental cost caused by a strike.

There must be a reasonable amount of flexibility in how these costs are considered. Owners may wish to apply percentages of recovery to the individual categories of $\boldsymbol{C_s}$, where one category may be more likely to have cost recovery than others. Of course, only costs which are of interest to the organisation carrying out CBS should be considered, although this may not necessarily be representative of actual costs applied to the organisation. For example, the cost of fines applied to the driver may not need to be considered by infrastructure owners, and in fact could be considered as a cost recovery method. Additionally, it is clear that certain cost categories may overlap and it is important not to double count. An example would be in the rail industry where trains are often operated externally to the infrastructure managers. Penalties may be applied by the train operators to the infrastructure owner due to strikes, and this can often be considered to represent the total delay cost (including the value of wasted time by train users), plus any loss of future business associated with the delay.

Cost and benefit categories and additional variables described above (N_s, E_{MM}, S_{MM}, $\%_{repair}$ and $\%_{recover}$) might be subject to variation based on the socio-economic region considered and potentially also for different countries of similar economics, but different social situations and perceptions of risk. These values can also differ based on the type of strike considered, defined as small, medium or large based on the vehicle and infrastructure damage and safety consequences on the infrastructure. If sufficient data is available, category values could also be calculated for different strike types, where costs and benefits could be defined as follows:

$$\boldsymbol{C_{tot}} = \boldsymbol{C_{tot,small}} + \boldsymbol{C_{tot,medium}} + \boldsymbol{C_{tot,large}}$$

$$\boldsymbol{B_{tot}} = \boldsymbol{B_{tot,small}} + \boldsymbol{B_{tot,medium}} + \boldsymbol{B_{tot,large}}$$

Alternative cost and benefit estimation

In the case where the user does not possess sufficient data to estimate cost and benefit values, alternative methods need to be applied. In the literature, several empirical ways of calculating costs and benefits are provided. For example, Design Manual CD355 (Highways England, 2019) and WebTAG[1] supply a series of formulas for the calculation of costs such as travel delay and vehicle operating costs. Formulas provided in these documents might not be appliable to all countries / regions and circumstances.

The Design Manual CD355 (Highways England, 2019), for example, provides the following formula for calculating traffic delay costs due to restrictions imposed on the network, in the absence of a more refined method. Tabulated values are given for each variable allowing for a cost assessment.

$$TVD = \frac{(DT_c + CRD_c) - (DT_n + CRD_n)}{60} \cdot EV \cdot EF$$

Where:

- TVD is the total vehicle delay in vehicle hours
- DT_c is the expected drive time in lane closure conditions over the length of the restriction (min)
- DT_n is the expected drive time in normal conditions over the length of the restriction (min)
- CRD_c is the Capacity Related Delay time in lane closure conditions (min)
- CRD_n is the Capacity Related Delay time in normal conditions (min)
- EV is the expected equivalent hourly volume of traffic for each period
- EF is an economic factor to be applied to the cost to take account of the extent of planning and forewarning that has been provided prior to imposition of the lane closure(s).

6.2.5. Comparison of costs and benefits

For each case considered, cost and benefits have been calculated and can now be compared. The flowchart in Figure 6.3 summarises the cases considered in this project and respective outcomes.

Both economic efficiency and benefit-cost ratio provide relevant information on the case being analysed, but it is important to use reason in the result interpretation. The economic efficiency represents the net profit of the project and the additional resources available, whereas the benefit-cost ratio represents the overall relationship between the relative costs and benefits.

[1] Transport analysis guidance (TAG) from the Department for Transport (https://www.gov.uk/guidance/transport-analysis-guidance-tag)

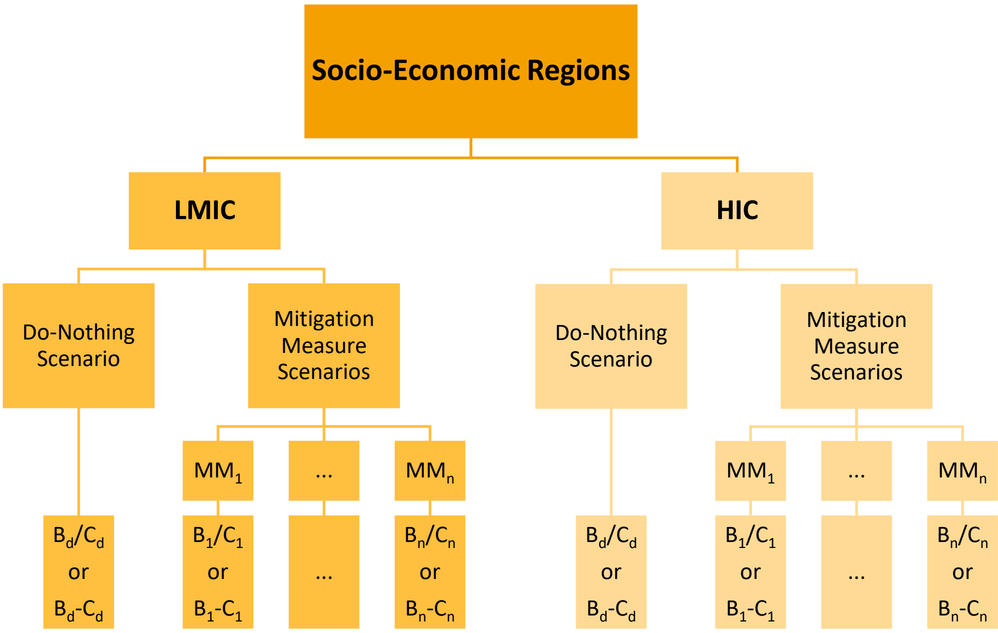

Figure 6.3: Cost-Benefit Analysis cases and outcomes

Considering for example a project for which two options are being analysed in order to identify the most profitable one. In the first option the overall benefit is equal to €10,000 and the overall cost is equal to €8,000. The economic efficiency and benefit-cost ratio are respectively €2,000 and 1.25. Both the outcomes suggest that this option is profitable and worth pursuing. Considering then the second alternative, this has an overall benefit and cost of €15,000 and €13,000, respectively. Economic efficiency is then equal to €2,000 and benefit-cost ratio is 1.15. This option is also cost-effective. If the economic efficiencies of both options are compared, it can be seen that they both have the same net profit, and it might be concluded that they have an equal level of profitability. However, analysing the benefit-cost ratios the first option has a higher ratio which makes it the most profitable and preferred alternative.

The same process should be carried out by the road administrator when comparing mitigation measure scenarios when the profitable scenarios are being identified in comparison with the do-nothing scenario. This process also allows for comparison across different bridge and / or tunnel sites to prioritise where mitigation measures should be put in place.

6.3. APPLIED FRAMEWORK AND RECOMMENDATIONS

Based on the framework provided in the previous sections, a Cost-Benefit Analysis has been carried out with the aim to make broad recommendations on the best mitigation measures for a given socio-economic region, based on road administrators' and owners' point of view. These recommendations aim to inform different socio-economic regions on the mitigation measures that may most commonly be applied, but should not prevent the individual region from considering and evaluating the use of other measures at certain sites. It is indeed suggested that a CBA is carried out on a case by case basis to better take into consideration the unique factors characterising the analysed site.

The data being used in the CBA was collected from the first and second surveys or obtained from the desk study. As mentioned previously, the second survey aimed to collect very detailed data and it was often challenging for the stakeholders to provide the data requested. Average values of strike costs, strike cost breakdown, mitigation measure costs and mitigation measure effectiveness were calculated in section 3.2 and shown in Table 3.1, Table 3.2, Table 3.3 and Table 3.4. In addition, the probability of a mitigation measure repair due to a strike and the related mitigation measure repair cost have been assumed based on survey data, desk study and engineering judgement (Table 6.3).

Mitigation Measure	Probability of repair	Repair Cost
Static signage	5.0%	500 €
Variable message signs (VMS)	0.0%	0 €
Beacons	0.0%	0 €
Flashing beacons and/or lights	0.0%	0 €
Bridge markings	0.0%	0 €
Rumble strips	0.0%	0 €
Speed bumps	0.0%	0 €
Clear heights signage and obstacles related to dimensional loads	0.0%	0 €
Increased structure vertical clearance	0.0%	0 €
Laser vision	0.0%	0 €
Crash sacrificial beams	50.0%	40,000 €
Hanging chains or bells	70.0%	750 €
Road narrowing techniques	0.0%	0 €
Cameras and computer vision techniques	0.0%	0 €
Vehicle redirection in case of excessive dimensions	0.0%	0 €
Infrared dual beam arrays LaRa-OHVD systems	0.0%	0 €
Media campaigns	0.0%	0 €
Increased fines and surveillance	0.0%	0 €
Heavy Vehicle Goods licence test	0.0%	0 €
Better driver education	0.0%	0 €
Good practice manuals	0.0%	0 €
Pre-routed maps	0.0%	0 €
Increased restrictions on vehicle dimensions	0.0%	0 €
Accelerometers, Piezoelectric sensors and Fibre optic cables	50.0%	1,000 €

Table 6.3: Probability of repair and repair cost for mitigation measures per structure in HICs.

The data provided in the tables just mentioned has been calculated based on HIC data, considering the lack of data available for LMICs. The following CBA is carried out with averages representing typical situations for a typical structure strike in HICs. Recommendations for both HICs and LMICs will be based on the outcome of the CBA. As mentioned previously, these values are calculated only for the purposes of this project, and it is suggested that a CBA be carried out on a case-by-case basis to obtain more reliable results and draw specific conclusions for an individual structure or network.

The CBA carried out in this section has considered a time study of 10 years, assuming a total number of strikes per structure per year of 0.12, where 60% are small type strikes, 30% medium type strikes and 10% large type strikes. The discount rate has been assumed as 5% for HICs based on available literature. A discount rate of 12% is suggested for LMICs. The mitigation measure suitability has been assumed as 100% for all mitigation measures in HICs, but a lower value is suggested for more advanced mitigation measures in LMICs. Table 6.4 lists the calculated costs and benefits for each countermeasure analysed in HICs and the relative benefit-cost ratio assuming costs and benefit relevance to be the same by considering overall unit weights w_c and w_b.

Category	Mitigation Measure	Cost	Benefit	Benefit-Cost Ratio
Low benefit-cost ratio	Increased structure vertical clearance	500,000.0 €	11,217.0 €	0.02
	Laser vision	263,648.8 €	9,046 €	0.03
	Variable message signs (VMS)	176,367.6 €	6,875 €	0.04
	Road narrowing techniques	122,729.8 €	7,236.8 €	0.06
	Hanging chains or bells	54,724.9 €	5,427.6 €	0.10
Medium benefit-cost ratio	Crash sacrificial beams	65,001.1 €	14,473.6 €	0.22
	Cameras and computer vision techniques	39,546.0 €	9,046 €	0.23
	Accelerometers, Piezoelectric sensors and Fibre optic cables	14,682.3 €	7,236.8 €	0.49
	Infrared dual beam arrays LaRa-OHVD systems	16,546.0 €	9,046 €	0.55
	Bridge markings	9,546.0 €	5,427.6 €	0.57
	Rumble strips	7,273.0 €	7,236.8 €	0.99
	Speed bumps	7,273.0 €	7,236.8 €	0.99

Category	Mitigation Measure	Cost	Benefit	Benefit-Cost Ratio
High benefit-cost ratio	Static signage	4,281.0 €	5,944.5 €	1.39
	Clear heights signage and obstacles related to dimensional loads	4,273.0 €	6,332.2 €	1.48
	Beacons	4,273.0 €	6,633.7 €	1.55
	Flashing beacons and/or lights	4,273.0 €	9,046 €	2.12
	Vehicle redirection in case of excessive dimensions	4,273.0 €	9,046 €	2.12

Table 6.4: Benefit-Cost Ratio for mitigation measures in HICs.

Analysing the results obtained in the table above, the mitigation measures can be subdivided into three categories based on the benefit-cost ratio:

- High benefit-cost ratio: benefit-cost ratio is higher than 1
- Medium benefit-cost ratio: benefit-cost ratio is between 0.2 to 1
- Low benefit-cost ratio: benefit-cost ratio is below 0.2

The mitigation measures which were found to be in the high benefit-cost ratio category are static signage, beacons / flashing beacons and lights, clear heights signage and obstacles related to dimensional loads, and vehicle redirection in case of excessive dimensions. These mitigation measures have low purchase, installation and maintenance costs and are often mandatory measures at a low height structure location. It is not then surprising that these measures are strongly recommended solutions to prevent and reduce the bridge and tunnel strike issue.

The mitigation measures which were found to be in the medium benefit-cost ratio category are bridge markings, rumble strips, speed bumps, crash sacrificial beams, cameras and computer vision techniques, infrared dual beam arrays LaRa-OHVD and radar systems, accelerometers, piezometric sensors and fibre optic cables. In general, these mitigation measures can be more expensive, less effective or require more maintenance and repair. For example, crash sacrificial beams are very effective in avoiding the infrastructure being struck, but are not effective in avoiding strike events, which have additional costs and disruptions. A combination of some of these mitigation measures may prove beneficial in order to have a higher effectiveness and reduce installation, maintenance and repair costs by simultaneously carrying out these works.

Mitigation measures found to be in the low benefit-cost ratio category are variable message signs (VMS), increased structure vertical clearance, laser vision, hanging chains or bells and water screens with STOP signs and road narrowing techniques. Hanging chains or bells are rather expensive and have a relatively low effectiveness since they do not avoid the strike but only warn the driver of the danger ahead. If used in combination with other countermeasures however, hanging chains or bells could be cost-effective for particular scenarios. The other mitigation measures in this category are very expensive, and even though their effectiveness is high, the CBA suggests these measures not to be cost-effective. However, it must be noted that the CBA carried out in this section refers to a typical structure. These types of mitigation measures are recognised to be best suited for more important and critical nodes on the network and are also normally only appropriate for sites that are prone to strikes and severe damage, as evidenced by prior occurrences. In these scenarios a customised CBA would be likely to show cost-effectiveness. One example of these technologies effectively applied is the float in mid-air pseudo-holographic 'STOP' sign message which warns the oversized vehicle driver to stop in Sydney Harbour Tunnel.

Finally, consideration should be given to the prominent driver-based mitigation measures including media campaigns, increased fines and surveillance, heavy vehicle goods licence test, better driver education, good practice manuals, pre-routed maps, and increased restrictions on vehicle dimensions. These mitigation measures were not included in the CBA results since they are not implemented for a single structure, but for an entire network. The benefit-cost ratio for these categories is very high since the purchase and installation costs are diluted for the whole network, resulting an extremely cost-effective solution.

Based on the results obtained by the CBA for HICs, some conclusions and recommendation can be drawn for LMICs. Considering the different type of economy in LMICs, mitigation measures in the high benefit-cost ratio category described above are the most recommended. These countermeasures are basic and primary measures that are low-cost and reasonably effective. Mitigation measures in the low benefit-cost ratio category are not recommended for LMICs, considering their high costs and their possible lack of availability in LMICs. Again, it is suggested that a case-by-case CBA be carried out to identify the best mitigation measures to be adopted at an individual network or structure. A minimum adoption of static mitigation measures is clearly a good recommendation to infrastructure owners and managers, since this can limit their liability in the event of a strike. Driver-based mitigation including driver education, increased fines and restrictions, better route guidance and good practice manuals are clearly also a highly recommended measure that in several cases have been demonstrated to be effective.

6.4. SITE-SPECIFIC COST-BENEFIT ANALYSIS EXAMPLES

Based on the applied framework in section 6.3 above, a series of observations were made in relation to the mitigation measures analysed. As explained above some assumptions and generalisations needed to be made which led to some limitations on the applied framework. A typical structure was considered as representative of the whole network, inevitably excluding more critical structures. Additionally, each mitigation measure was considered to be individually applied to the structure, which might not be representative of what happens in reality where a combination of countermeasures is instead adopted. It is indeed highly recommended to carry out a CBA on a case by case basis, to better represent the system analysed.

The examples described in the following sections aim to demonstrate how different assumptions and /or different sites can affect the result of the CBA and to emphasize that the results obtained in the applied framework above are more general and indicative values to be interpreted and used carefully.

The following examples consider two different sites in high-income countries where a customised combination of mitigation measures are proposed. A description of each site is provided in the following sections 6.4.1 and 6.4.2. It can be noted that the number of strikes assumed in the following sections is much higher than those considered in section 6.3. In the previous applied framework, the total number of strikes was assumed to be applied to the whole network considered and was averaged for all the structures in the network itself, obtaining an average number of strikes per structure. In reality, not all of the structures in the network are struck by oversized vehicles, increasing the actual number of strikes per year per structure and justifying the number assumed in the following sections.

A cost-benefit analysis has been carried out for each sample site in accordance with the process described in the previous sections. Costs and benefits have been calculated for a period of 5 years (year 0 to year 4) and are assigned with unit weights w_c and w_b, assuming an equal level of relevance for the purposes of these examples. In both examples a discount rate of 5% is assumed.

Costs and benefits have been calculated based on the categories described in sections 6.2.3 and 6.2.4.

Costs include purchase, installation, maintenance and repair costs, whose values have been taken from Table 3.4. Installation and maintenance costs have been considered with a reduced value, so that the total installation / maintenance cost per year is not equal to the sum of the cost for each mitigation measure, but is reduced based on the assumption that installation / maintenance is carried out for all mitigation measures together, lowering the overall cost. A discounted cost percentage (dcp) is provided in the following sections for each cost category, so that for a dcp of 70%, the category cost for all mitigation measures would be 70% of the sum of the category cost of each mitigation measure.

Benefits depend on the strike cost, whose value is calculated differently in the following examples relative to the type of structure being analysed. The cost percentage associated with the owner and strike cost breakdown are however assumed equal for both examples as defined in Table 3.1 and Table 3.3: Strike cost breakdown for HICs, respectively. The suitability of each mitigation measure is assumed as 100%.

Both costs (specifically repair cost) and benefits are dependent on the considered mitigation measure effectiveness value. Both of the examples below analyse a combination of mitigation measures in the CBA. The system of countermeasures can be assigned with an overall effectiveness which has an overall higher value than each of the measures considered, based on the assumption that their collaboration would guarantee a more effective system. The combined effectiveness is calculated assuming the mitigation measures as a parallel system, which fails only if all parts fail. The combined effectiveness E_{comb} can be calculated as follows:

$$\boldsymbol{E_{comb} = 1 - \prod_{1}^{n}(1 - E_{MM,n})}$$

where :

- $E_{MM,x}$ is the individual effectiveness for mitigation measure *x*,
- n is number of mitigation measures considered in the system,
- ∏ represent the product over multiple terms.

6.4.1. Typical bridge site

The site considered in this example is a typical bridge located in an urban setting with medium level traffic. The bridge is struck multiple times per year, causing medium level damage to the structure itself and related costs to the infrastructure owner. The relatively high number of strikes per year requires the adoption of mitigation measures on site in order to reduce the number of events. It is assumed that on average the bridge is struck 8 times per year, where 5 are small strikes, 2 are medium strikes, and 1 is a large strike.

A combination of more standard passive mitigation measures as a minimum requirement and more advanced active mitigation measures to increase the effectiveness of the system has been considered in this example. The passive countermeasures considered are static signage, speed bumps and variable message signs (VMS), whereas the active countermeasure considered is a radar detection system. The effectiveness of each mitigation measure is defined in Table 3.4 and is equal to 41.1% for static signage, 50.0% for speed bumps, 47.5% for variable message signs (VMS) and 62.5% for the radar system. A combined effectiveness is calculated based on the definition above and is equal to 94.2%.

Table 6.5 and Table 6.6 below show respectively the costs and benefits breakdown for this example. In Table 6.5 installation and maintenance costs are assigned with a discounted cost percentage (dcp) equal to 70%. Additionally, purchase and installation costs are assumed to be present costs applied only to year 0, whereas maintenance and repair are costs recurring annually and applied to the whole 5 years. The total cost obtained for a period of 5 years is equal to 171,224,39 €.

<table>
<tr><th colspan="2"></th><th>Static Signage</th><th>Speed Bumps</th><th>Variable Message Signs (VMS)</th><th>Radar Systems</th><th>Years considered</th></tr>
<tr><td rowspan="2">Purchase</td><td>Cost</td><td>1,000 €</td><td>2,500 €</td><td>80,000 €</td><td>10,000 €</td><td rowspan="2">Year 0</td></tr>
<tr><td>dcp</td><td colspan="4">100%</td></tr>
<tr><td rowspan="2">Installation</td><td>Cost</td><td>1,000 €</td><td>2,500 €</td><td>60,000 €</td><td>2,500 €</td><td rowspan="2">Year 0</td></tr>
<tr><td>dcp</td><td colspan="4">70%</td></tr>
<tr><td rowspan="2">Maintenance</td><td>Cost</td><td>500 €</td><td>500 €</td><td>8,000 €</td><td>1,000 €</td><td rowspan="2">Years 0 to 4</td></tr>
<tr><td>dcp</td><td colspan="4">70%</td></tr>
<tr><td rowspan="4">Repair</td><td>Cost</td><td>500 €</td><td>0 €</td><td>0 €</td><td>0 €</td><td rowspan="4">Years 0 to 4</td></tr>
<tr><td>Probability of repair</td><td>5%</td><td>0%</td><td>0%</td><td>0%</td></tr>
<tr><td>Combined Effectiveness</td><td colspan="4">94.2%</td></tr>
<tr><td>dcp</td><td colspan="4">100%</td></tr>
<tr><td colspan="2">Total</td><td colspan="5">171,224.39 €</td></tr>
</table>

Table 6.5: Cost breakdown for typical bridge site.

The total benefit depends on the strike costs assumed. Since this example is considering a typical bridge structure, it is reasonable to assume that the strike costs obtained from the stakeholder engagement (shown in Table 3.2) are suitable for this structure. Table 6.6 shows the strike cost values for small strikes, medium strikes and large strikes which are respectively 5,500 €, 38,400 € and 294,000 €. The total benefit obtained for a period of 5 years is equal to 1,023,372.07 €.

	Small Strike	Medium Strike	Large Strike
Vehicle repair	250 €	1,200 €	9,000 €
Infrastructure repair	2,100 €	22,900 €	195,900 €
Increased maintenance	2,500 €	6,900 €	21,300 €
Emergency services	0 €	800 €	6,000 €
Delays / Disruptions	650 €	5,400 €	43,800 €
Loss of business	0 €	0 €	6,000 €
Fatalities / Injuries	0 €	1,200 €	12,000 €
Owner percentage	60%		
Suitability of mitigation measures	100%		
Effectiveness	94.2%		
Total	**1,023,372.07 €**		

Table 6.6: Benefit breakdown for typical bridge site.

Considering overall unit weight for both costs and benefits, the obtained Benefit-Cost Ratio and Benefit-Cost Efficiency are respectively equal to **5.98** and **852,147.68 €**.

6.4.2. Critical tunnel site

The site considered in this example is a tunnel at a critical node of a network with a high traffic volume. The tunnel is struck a relatively low number of times per year, but the damage, disruption and related costs are high considering the significance of the structure. The adoption of mitigation measures on site is fundamental in order to reduce the number of events and limit traffic disruptions. It is assumed that on average the tunnel is struck 3 times per year, where the average number of small, medium and large strikes is 1.8, 0.9 and 0.3 respectively.

A combination of standard passive mitigation measures and advanced active mitigation measures is as also considered in this example. The passive countermeasures considered are static signage, flashing beacons and/or lights and variable message signs (VMS), whereas the active countermeasure included is a laser vision system. The effectiveness of each mitigation measure is defined in Table 3.4 and is equal to 41.1% for static signage, 62.5% for flashing beacons, 47.5% for variable message signs (VMS) and 62.5% for laser vision. A combined effectiveness is calculated based on the definition above and is equal to 95.6%.

Table 6.7 and Table 6.8 below show respectively the costs and benefits breakdown for this example. Installation and maintenance costs are again assigned in Table 6.7 with a discounted cost percentage (dcp) equal to 70%. Purchase and installation costs are assumed to be present costs applied only to year 0, whereas maintenance and repair are costs recurring annually and applied across the 5 years. The total cost obtained for a period of 5 years is equal to 368,608.46 €.

<table>
<tr><th colspan="2"></th><th>Static Signage</th><th>Flashing beacons and/or Lights</th><th>Variable Message Signs (VMS)</th><th>Laser Vision</th><th>Years considered</th></tr>
<tr><td rowspan="2">Purchase</td><td>Cost</td><td>1,000 €</td><td>1,000 €</td><td>80,000 €</td><td>100,000 €</td><td rowspan="2">Year 0</td></tr>
<tr><td>dcp</td><td colspan="4">100%</td></tr>
<tr><td rowspan="2">Installation</td><td>Cost</td><td>1,000 €</td><td>1,000 €</td><td>60,000 €</td><td>50,000 €</td><td rowspan="2">Year 0</td></tr>
<tr><td>dcp</td><td colspan="4">70%</td></tr>
<tr><td rowspan="2">Maintenance</td><td>Cost</td><td>500 €</td><td>500 €</td><td>8,000 €</td><td>25,000 €</td><td rowspan="2">Years 0 to 4</td></tr>
<tr><td>dcp</td><td colspan="4">70%</td></tr>
<tr><td rowspan="4">Repair</td><td>Cost</td><td>500 €</td><td>0 €</td><td>0 €</td><td>0 €</td><td rowspan="4">Years 0 to 4</td></tr>
<tr><td>Probability of repair</td><td>5%</td><td>0%</td><td>0%</td><td>0%</td></tr>
<tr><td>Combined Effectiveness</td><td colspan="4">95.6%</td></tr>
<tr><td>dcp</td><td colspan="4">100%</td></tr>
<tr><td colspan="2">Total</td><td colspan="5">368,608.46 €</td></tr>
</table>

Table 6.7: Cost breakdown for critical tunnel site.

	Small Strike	Medium Strike	Large Strike
Vehicle repair	3,200 €	4,500 €	13,500 €
Infrastructure repair	28,100 €	85,800 €	293,800 €
Increased maintenance	33,800 €	25,800 €	32,000 €
Emergency services	0 €	3,000 €	9,000 €
Delays / Disruptions	8,500 €	20,400 €	65,700 €
Loss of business	0 €	0 €	9,000 €
Fatalities / Injuries	0 €	4,500 €	18,000 €
Owner percentage	60%		
Suitability of mitigation measures	100%		
Effectiveness	95.6%		
Total	**1,028,899.96 €**		

Table 6.8: Benefit breakdown for critical tunnel site.

The structure considered in this example is a critical node on the network for which the strike costs are assumed to be higher than a typical structure. Based on individual responses obtained from the stakeholder engagement, strike costs for small strikes, medium strikes and large strikes were assumed, and the values are shown in Table 6.8. The total benefit obtained for a period of 5 years is equal to 1,028,899.96 €.

Considering an overall unit weight for both costs and benefits, the obtained Benefit-Cost Ratio and Benefit-Cost Efficiency are respectively equal to **2.79** and **660,291.50 €**.

6.4.3. Conclusions

Both the typical bridge and the critical tunnel examples described in sections 6.4.1 and 6.4.2 result in a Benefit-Cost Ratio higher than 1 and a positive Benefit-Cost Efficiency, concluding that both mitigation measure systems are cost-efficient in the respective cases considered. The Benefit-Cost Ratios obtained in these two examples for a period of 5 years are over 2.5. Realistically the mitigation measure systems would be in place longer than the assumed 5 years, which would result in an overall higher ratio and higher profit. Furthermore, unit weights were assumed for the overall cost and benefit. Unequal weights may be used to emphasise the relevance of the benefit against the cost, on the basis that for example safety, life loss and environmental impact have a priority over upfront cost. This would again increase the overall cost-effectiveness of the system.

The examples presented confirm that it is highly recommended to carry out a CBA on a case-by-case basis to properly analyse the site system. Likewise, this analysis also highlight that it is important to correctly interpret the results obtained in section 6.3 .

7. CONCLUSIONS

In response to an open call for proposals published by PIARC to conduct the “Bridges and tunnels strikes by oversize vehicles” Special Project, Roughan & O’Donovan carried out a detailed desk study and analysis into international best practice on the issue. The objective of the study was to examine proven countermeasures, practices, and technologies used to reduce the incidence of oversize vehicles striking bridges and tunnels along with effective processes for accurately reporting and tracking bridge strike occurrences. Specific consideration was given to LMICs, with an aim to cater to these regions with specific recommendations.

The study included two detailed surveys. A focused effort was made to engage LMICs in responding to these surveys. After an initial engagement of stakeholders for each survey, ROD and PIARC noticed a lack of responses from the LMIC organisations contacted. ROD and PIARC then made further efforts to engage members of these countries to ensure their needs were captured in the data.

The first survey consisted of a wide outreach of stakeholders on the issue, with the aim to obtain public and private perception of the issue, form an initial understanding and discern relevant stakeholders for further survey and interview. The second survey was focused to stakeholders who were known to have quantitative data available in relation to bridge / tunnel strike consequences and mitigation measures. A range of quantitative information was obtained and is contained within Appendix E. It was found that the survey 2 responses were often limited in terms of the quantitative data received. In order to discern the reason for this, ROD engaged a number of stakeholders in interviews to determine the reason for the lack of data being provided. It was found that although many organisations have data available, the data is not stored in a coordinated way in order to perform CBA. This led to the primary recommendation to PIARC from this study: a formalised method of recording data strikes should be provided by PIARC, showing how each reported bridge strike should be logged and indicating the data that should be gathered for each strike in the future to streamline the process of designing mitigation. Additionally, due to the variation in the data internationally, ROD recommend that PIARC perform a sample case study, focusing on a single network or list of structures, showing how he required data can be gathered, and how to use it in a detailed risk analysis and CBA to decide on appropriate interventions.

In addition to the data gathered in this work, a desk study was carried out and a detailed description was provided of the likely costs and causes of bridge and tunnel strikes. A review of the currently available mitigation practices was also carried out, summarising the expected effectiveness and cost of each mitigation measure type including passive systems, sacrificial systems, active systems, detection systems and driver-based mitigation practices. The review indicated that while active systems and technology have promise in effectively dealing with this issue in the future, further research is needed to demonstrate their effectiveness and reduce cost of installation. Furthermore, driver-based countermeasures such as driver training, legislation and improved route guidance appear to be the single most effective measure to address the issue at present.

The final chapter in this work developed a detailed CBA methodology to be performed by road infrastructure owners in order to discern the most appropriate mitigation measures for a given structure / set of structures. The data readily available to jurisdictions and captured by the project was found to be sufficient to perform a CBA on a broad level aiming to identify the relative appropriateness of various countermeasures applied globally. Different results might be obtained at particular sites when different assumptions are considered, as demonstrated by the CBA examples analysed. The CBA process was demonstrated using the gathered data for HICs, with LMICs not having provided sufficient data for analysis. The data showed that lower cost systems such as static signage, beacons / flashing beacons and lights, clear heights signage and obstacles related to dimensional loads, and vehicle redirection in case of excessive dimensions appear to be the most universally recommended physical solutions for mitigation. Mitigation measures which were found to be in the medium benefit-cost ratio category are bridge markings, rumble strips, speed bumps, crash sacrificial beams, cameras and computer vision techniques, infrared dual beam arrays and radar systems. While a number of systems were found to be in a low benefit-cost ratio category, this is due mainly to the global nature of the analysis performed, and cannot be considered a realistic interpretation of the value of these high cost systems. The same data allowed investigation of sample CBAs at an individual bridge / tunnel level. A combination of mitigation measures in the high, medium and low benefit-cost ratio categories were adopted. Both examples showed that the adoption of an appropriate combination of mitigation measures at a problem site can be extremely cost-effective. This emphasises the need to carry out case by case CBAs and to carefully interpret the CBA conclusions obtained. Recommendations on data storage have been provided in section 8.2 to improve the capability to discern the cost-benefit of alternative countermeasures, allowing for ranking alternative countermeasures at a site as well as ranking different sites.

8. RECOMMENDATIONS

8.1. Recommendations to Road Administrations

8.1.1. HICs

Recommendations to road administrators from HICs are provided in the short and long term.

Short term recommendations

The CBA performed in this study has highlighted mitigation measures that are universally effective in HICs right now. It is therefore recommended that HICs continue to ensure adequate and accurate overheight clearance signage be installed on all structures, in addition to mitigation measures such as flashing beacons and obstacles related to dimensional loads, and providing adequate advanced warning allowing drivers to redirect in case of excessive dimensions. This initial study also found that currently available technology such as laser-based overheight detection in combination with variable message signs (VMS) will be beneficial in certain high-profile sites. An appropriate combination of mitigation measures will be essential based on the site. Crucially, it is important that road administrators adopt a CBA methodology similar to that presented herein when discerning appropriate mitigation measures.

The key short-term recommendation to road administrators and governments in HICs would be the development of a multi-sectoral panel to address and share / disseminate knowledge on the issue. Involvement from road administrators, hauliers, government, and police in a collaborative way is essential. The primary goal of the panel would be to provide better driver education, advertising of the consequences and informing legislation in relation to the bridge / tunnel strike problem. Adoption of mitigation measures is still recognised as essential and required in vulnerable sites.

Long term recommendations

In the majority of strike cases, it appears that the driver is at fault. While drivers' education, advertising and engagement are essential to address the issue, enhancements to vehicle technologies are required. For example, accurate low clearance bridge information should be gathered by road agencies and included in the drivers GPS/Navigation Systems.

Future technologies such as on-board navigation systems in combination with CAV technology and vehicle-2-infrastructure communication were found to have significant promise in tackling the bridge / tunnel strike problem. For this reason, it is recommended that more research funding be made available in these areas in order to demonstrate the effectiveness and enhance the TRL of these systems.

8.1.2. LMICs

Recommendations to road administrators from LMICs are provided in the short and long term.

Short term recommendations

The CBA and qualitative review performed as part of this study has highlighted mitigation measures that may be beneficial and applicable in LMICs. It is recommended that LMICs ensure adequate and accurate overheight clearance signage be installed on all structures, in addition to mitigation measures such as flashing beacons and obstacles related to dimensional loads, and providing adequate advanced warning allowing drivers to redirect in case of excessive dimensions. The qualitative review also indicated that while LMICs already install overheight clearance signage at structures, this signage is often outdated, obscured or damaged. Hence, it is recommended that further efforts be made to ensure signage is maintained and legible, particularly at high-risk structures. Adoption of a CBA methodology is recommended to road administrators similar to that presented herein, even in a simplified form and particularly for critical nodes that have experienced previous strikes of high severity damage.

Long term recommendations

The key long-term recommendation to road administrators and governments in LMICs would be the development of a multi-sectoral panel to address and share / disseminate knowledge on the issue. Involvement from road administrators, hauliers, government, and police in a collaborative way is essential. The primary goal of the panel would be to provide better driver education, advertising of the consequences and informing legislation in relation to the bridge / tunnel strike problem. Some HICs already have panels of this type in place, which would provide a good starting point for LMICs to initialise the approach.

8.2. Recommendations to PIARC

The study has highlighted the importance of two specific areas, which can be best addressed by PIARC directly:

1. It is recommended that PIARC publish a guideline for recording of bridge / tunnel strike data. This can be a relatively short guideline that includes data allowing the estimate of strike costs and benefits, as described in section 6.2.4, and strike and severity probability. Data should support both broad and site-specific CBA. The guideline should outline that a primary individual in each member organisation should act as the bridge strike champion, inputting the data in the list below after each reported strike:
    a. Date / time of strike
    b. Vehicle data (type, dimensions, registration, company etc)
    c. Structure data (location, structure type, girder type, clearance, mitigation in place etc.). This data may be provided as a link to an infrastructure management system.
    d. Road data (traffic volume, travel speed, region legal truck height etc.)
    e. Cause of strike
    f. Damage severity (structure, vehicle and third parties)
    g. Load and permits
    h. Costs of strike, under the headings of the CBA provided in section 6.2.

    A separate database may be maintained for structure specific data relating to the bridge / tunnel strike problem. This would contain, for example, costs of mitigation measures installed at a bridge / tunnel. This can then be linked to other transportation network data such as functional classification, truck volumes, and asset management data.
2. It is further recommended that PIARC perform a sample case study, focusing on a single network or list of structures, showing how he required data can be gathered, and how to use it in a detailed risk analysis and CBA to decide on appropriate interventions.

Both recommendations could be implemented by the PIARC Technical Committees on Bridges and Tunnels.

9. GLOSSARY

Term	Definition
AADF	Average Annual Daily Flow
AC	Alternating Current
APS	Aesthetic Power Supply
B	Magnetic Field
BM	Business Model
BMS	Battery Management System
CAN	Controller Area Network
CBA	Cost Benefit Analysis
CO_2	Carbon Dioxide
CRF	Centro Ricerche Fiat
CWD	Charge While Driving
DBFO	Design Build Finance Operate
DC	Direct current
DEFRA	Department for Environment, Food and Rural Affairs
DWPT	Dynamic Wireless Power Transfer
eBus	Electric Bus
EC	European Commission
ECU	Electronic Control Unit
EFC	Emissions Forecasting Tool
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
ERS	Electric Road System
IM	Infrastructure Manager
ITS	Intelligent Transport System
LIC	Low Income Country
LMIC	Lower and Middle Income Country

Term	Definition
L-MIC	Lower-Middle Income Country
NRA	National Road Authority
HIC	High Income Country
TPF	Transportation Pooled Fund
TRL	Technology Readiness Level
U-MIC	Upper-Middle Income Country

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APPENDIX A

SURVEY 1&2 – CONTACT LIST

The table below lists the stakeholders contacted during the project for both survey 1 and survey 2. Relevant stakeholders have been identified by ROD in collaboration with the PIARC POT, aiming to circulate the surveys to a worldwide network and specifically to LMICs.

Most of the contacts below were contacted during the first survey. The survey was also circulated to several road hauliers, but no responses were obtained so their contacts were not included in the table. Key stakeholders for the second survey were then identified based on their responses to the first survey and additional stakeholders were contacted separately for the second survey.

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Asociación Argentina de Carreteras (AAC)	Non-profit non-governmental association	Argentina	LMIC	Y	Y		
Direccion Nacional de Vialidad	Road Infrastructure Manager	Argentina	LMIC	Y	Y	Y	Y
Ing.Civil Tomás A. del Carril	Consultancy	Argentina	LMIC			Y	Y
ITS Argentina Non-Profit Civil Association	Non-Profit Civil Association	Argentina	LMIC	Y	Y	Y	
Austroads	Road Association	Australia	HIC	Y	Y		
Sydney Harbour Tunnel Company	Road Infrastructure Manager	Australia	HIC	Y	Y	Y	Y
Transport & Main Roads, Queensland	Road Infrastructure Manager	Australia	HIC	Y	Y	Y	Y

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Transport for New South Wales	Multimodal infrastructure manager	Australia	HIC	Y	Y	Y	Y
Transurban	Road Infrastructure Manager	Australia	HIC	Y	Y	Y	Y
Ventia	Road Infrastructure Manager	Australia	HIC	Y	Y		
Republic of Austria Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology	Road Infrastructure Manager	Austria	HIC	Y	Y		
Service Public de Wallonie	Road Infrastructure Manager	Belgium	HIC			Y	Y
AGEIM-IC	Consultancy	Burkina Faso	LMIC	Y	Y	Y	
Direction Generale de l'Entretien Routier (DGER)	Road Infrastructure Manager	Burkina Faso	LMIC	Y	Y		
Ministère des transports du Québec	Road Infrastructure Manager	Canada	HIC	Y	Y	Y	Y

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Deparamento de Puentes - Ministerio de Obras Publicas Chile	Road Infrastructure Manager	Chile	HIC			Y	Y
Dirección de Vialidad	Road Infrastructure Manager	Chile	HIC			Y	Y
China Academy of Transportation Sciences	Research Institution / University	China	LMIC	Y	Y		
China Highway Planning and Design Institute Co.Ltd (CCCC Highway Consultants Co.Ltd)	Consultancy	China	LMIC	Y	Y	Y	
JSTI Group	Consultancy	China	LMIC	Y	Y		
INVIAS	Road Infrastructure Manager	Colombia	LMIC			Y	Y
Pavifnra Pavimentos e Infraestructura	Consultancy	Colombia	LMIC	Y	Y		

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
HZ INFRASTRUKTURA	Rail Infrastructure Manager	Croatia	HIC	Y			
UZ	Research Institution - Rail	Croatia	HIC	Y			
Ministry of Transport	Road Infrastructure Manager	Czech Republic	HIC	Y	Y		
Banedanmark	Rail Infrastructure Manager	Denmark	HIC	Y			
Transpordiamet	Road Infrastructure Manager	Estonia	HIC	Y	Y		
Finnish Transport Infrastructure Agency	Road Infrastructure Manager	Finland	HIC	Y	Y	Y	
APRR	Road Infrastructure Manager	France	HIC	Y	Y	Y	Y
CD38	Road Infrastructure Manager	France	HIC			Y	Y
COFIROUTE	Road Infrastructure Manager	France	HIC	Y	Y		
Collectivité européenne d'Alsace	Road Infrastructure Manager	France	HIC	Y	Y	Y	

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
A member of the Comité Tunnels	Network of local authorities operating tunnels	France	HIC	Y	Y	Y	Y
Conseil départemental de l'Essone	Road Infrastructure Manager	France	HIC	Y	Y		
Conseil Departemental des Alpes Maritimes	Road Infrastructure Manager	France	HIC			Y	Y
DIR Centre Ouest	Road Infrastructure Manager	France	HIC	Y	Y	Y	
DIR Centre-Est	Road Infrastructure Manager	France	HIC	Y	Y	Y	Y
DIRMC	Road Infrastructure Manager	France	HIC	Y	Y		
A member of the GTFE	Road Tunnel Operators	France	HIC	Y	Y	Y	Y
Metropole Aix-Marseille	Territorial community	France	HIC			Y	Y
Metropole de Lyon	Road Infrastructure Manager	France	HIC	Y	Y		

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Metropole Nice Cote d'Azur	Road Infrastructure Manager	France	HIC	Y	Y	Y	
Paris La Defense	Road Infrastructure Manager	France	HIC			Y	
SE BPNL	Road Infrastructure Manager	France	HIC	Y	Y	Y	
Federal Ministry of Transport and digital Infrastructure	Road Infrastructure Manager	Germany	HIC	Y	Y	Y	Y
Magyar Államvasutak Zrt	State Railway	Hungary	HIC	Y			
Magyar Közút NZrt	State Road Operator	Hungary	HIC	Y	Y		
Unnamed	Consultancy	Hungary	HIC			Y	Y
Icelandic Road and Coastal Administration	Road Infrastructure Manager	Iceland	HIC	Y	Y		
Afcons Infrastructure Ltd	Contractor	India	LMIC	Y	Y	Y	Y
Ministry of Road Transport &	Road Infrastructure Manager	India	LMIC	Y	Y	Y	

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Highways, Government of India							
Rodic Consultants Private Limited	Consultancy	India	LMIC	Y	Y	Y	
Indonesian Road Development Association (IRDA)	Road Infrastructure Manager	Indonesia	LMIC	Y	Y		
PIARC General Secretariat	120 International contacts	International	HIC & LMIC	Y			
PIARC members LMIC TCs	99 International contacts	International	HIC & LMIC	Y			
Siemens Rail Services	Manufacturer	International	HIC	Y			
Celtic Road Group	Road Construction Consortium	Ireland	HIC	Y			
Colas Roadbridge	Motorway Maintenance Manager	Ireland	HIC	Y	Y		
Egis Lagan	Motorway Maintenance Manager	Ireland	HIC	Y	Y	Y	Y
ERTO	Tunnel Managers	Ireland	HIC	Y			

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
GSJ	Motorway Maintenance Manager	Ireland	HIC	Y			
Irish Rail	Rail Infrastructure Manager	Ireland	HIC	Y	Y	Y	Y
Midlink / Southlink	M7/M8/M25 Road Maintenance	Ireland	HIC	Y			
Murphy Group	Monitoring Contractor	Ireland	HIC	Y	Y	Y	
Northlink	M1 Road Maintenance	Ireland	HIC	Y	Y	Y	
NVM	Monitoring Contractor	Ireland	HIC	Y	Y		
TII	Road Infrastructure Manager	Ireland	HIC	Y	Y	Y	Y
TII	Light Rail Infrastructure Manager	Ireland	HIC	Y			
DATUM	Monitoring Contractor	Ireland/UK	HIC	Y	Y	Y	Y
Ferrovie dello Stato Italiane	Rail Infrastructure Manager	Italy	HIC	Y			

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Administration des ponts et chaussées	Road Infrastructure Manager	Luxembourg	HIC	Y	Y	Y	
ciaO	Road Infrastructure Manager	Mexico	LMIC	Y	Y	Y	
National Administration of Roads	Road Infrastructure Manager	Mozambique	LMIC	Y	Y		
ProRail	Rail Infrastructure Manager	Netherlands	HIC	Y			
Rijkswaterstaat	Road Infrastructure Manager	Netherlands	HIC	Y			
TU Delft / InGEO	University/Geotechnical Consultancy	Netherlands	HIC	Y			
Vertas & PSJ Advies	Security Specialist	Netherlands	HIC	Y	Y	Y	Y
Znapz	Asset Management Consultant	Netherlands	HIC	Y			
New Zealand Transport Agency	Road Infrastructure Manager	New Zealand	HIC	Y	Y	Y	
Waterview Tunnel Joint Operation	Road Infrastructure Manager	New Zealand	HIC	Y	Y		

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Bane Nor	Rail Infrastructure Manager	Norway	HIC	Y	Y		
Norwegian public roads administration	Road Infrastructure Manager	Norway	HIC	Y	Y		
NTNU	Research Institution - Rail	Norway	HIC	Y	Y		
IP - Infraestructureas de portugal, S.A.	Road Infrastructure Manager	Portugal	HIC			Y	Y
AO «Institute «Stroyproekt» JSC	Consultancy	Russia	LMIC	Y	Y	Y	Y
Russian road research institute	Research Institute	Russia	LMIC	Y	Y		
Ministry of Construction, Transport and Infrastructure	Ministry	Serbia	LMIC	Y	Y		
ZAG	Research Institution - Rail	Slovenia	HIC	Y			
eThekwini Municipality -	Road Infrastructure Manager	South Africa	LMIC	Y	Y		

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Roads Provision Dept							
SANRAL	Road Infrastructure Manager	South Africa	LMIC	Y	Y	Y	
Dirección General de Carreteras-MITMA	Road Infrastructure Manager	Spain	HIC			Y	Y
Ministère de Transport	Road Infrastructure Manager	Spain	HIC	Y	Y	Y	
Tunnel du Somport	Operator	Spain	HIC	Y	Y	Y	Y
KTH	University	Sweden	HIC	Y			
Swedish Rail	Infrastructure Manager	Sweden	HIC	Y			
Swedish Transport Administration	Rail Infrastructure Manager	Sweden	HIC	Y	Y	Y	
Trafikverket	Rail Infrastructure Manager	Sweden	HIC	Y	Y		
ASTAG	Swiss Association of Road Transport	Switzerland	HIC	Y			
Office Fédéral des Routes (OFROU)	Road Infrastructure Manager	Switzerland	HIC	Y	Y	Y	

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Ministry of Works and Transport	Road Infrastructure Manager	Tanzania	LMIC	Y	Y		
Department of Highways	Road Infrastructure Manager	Thailand	LMIC	Y	Y		
Ministère de l'équipement, de l'Habitat et de l'Infrastructure	Road Infrastructure Manager	Tunisia	LMIC	Y	Y	Y	
Devon Council	Local Authority Engineer	UK	HIC	Y			
Full Scale Dynamics	Monitoring Contractor	UK	HIC	Y			
Highways England	Road Infrastructure Manager	UK	HIC	Y			
James Fisher Testing Services	Monitoring Institution	UK	HIC	Y	Y	Y	
London Underground	Underground Rail Operator	UK	HIC	Y	Y	Y	Y
Network Rail	Rail Infrastructure Manager	UK	HIC	Y	Y	Y	Y
Nprime	Monitoring Contractor	UK	HIC	Y			

Organisation	Organisation Type	Country / Region	Socio-Economic Region	Survey 1	Response Survey 1	Survey 2	Response Survey 2
Transport for Wales	Infrastructure Manager	UK	HIC	Y			
Transport Scotland	Road Infrastructure Manager	UK	HIC	Y	Y	Y	Y
TRL	Research Institution - Rail	UK	HIC	Y			
American Association of State Highway and Transportation Officials (AASHTO)	National Association of Transportation Agencies	USA	HIC	Y			
FMCSA - Federal Motor Carrier Safety Administration	US Department of Transportation	USA	HIC	Y			
SENSR	Monitoring Contractor	USA	HIC	Y			
United States Department of Transportation	Road Infrastructure Manager	USA	HIC	Y	Y	Y	Y

APPENDIX B

SURVEY 1

BRIDGE AND TUNNEL STRIKES

Thank you for taking the time to complete this survey. The survey takes approximately **7 minutes** to complete.

Respondents can edit their response up to 28th May 2021, even after completing the survey.

Bridge and tunnel strikes by oversize vehicles are a threat to road user's safety, and the operation of transport infrastructure. These incidents cause significant damage to infrastructure, injuries and fatalities, secondary crashes, traffic delays, emergency response, rerouting of traffic to remove trucks and repair damage, and economic costs related to response and recovery efforts.

This survey is part of an international study being carried out by **Roughan & O'Donovan Ltd.** on behalf of **PIARC – World Road Association www.piarc.org**, which aims to examine proven countermeasures, practices, and technologies used to reduce the incidence of oversize vehicles striking bridges and tunnels along with effective processes for accurately reporting and tracking bridge strike occurrences.

The survey below is intended to establish relevant stakeholders to collaborate in addressing the issue, as well as to obtain some initial data for identifying best practice.

The inputs of the survey will serve to produce a technical report including recommendations which will be available free of charge once the study is concluded.

Definitions

Bridges, tunnels and other similar structures are key elements of transport networks. Their structural characteristics and significance as nodes in the network make them very valuable assets.

Oversize vehicles are defined as vehicles beyond standard size limitations. They can also be standard size vehicles that are beyond a local size limitation of a specific area, road, bridge, or tunnel. These oversize vehicles can be over-height, over-width or over-dimensioned vehicles. Oversize vehicles may also include vehicles with a permit to circulate in a certain itinerary, which leave their authorized route. These vehicles may be required to be accompanied by escort vehicles.

Bridges and tunnel strikes by oversize vehicles are defined as collisions of these vehicles with bridges or tunnels or their associated equipment.

1. Organisation name:

2. Organisation type:
    - Road Infrastructure Owner / Manager / Agency,
    - Rail Infrastructure Owner / Manager,
    - Waterways Infrastructure Owner / Manager,
    - Freight transport
    - Consultancy
    - Contractor
    - Manufacturing / Supply
    - Monitoring / Technology Provider
    - Research Institution / University
    - International Consortium
    - Other (please specify)

3. Country / State / Province:

4. Has your organization identified Bridge and Tunnel Strikes by oversize vehicles as a major issue?

    ◯ Yes

    ◯ No

    ◯ Unsure

5. Are you aware of State / Province / National and/or International legislation, regulation, guidelines, and protocols pertinent to Bridge and/or Tunnel Strike prevention and detection?

    ◯ Yes

    ◯ No

    ◯ Unsure

6. Please list the name of any relevant legislation / regulations / guidelines below and / or provide a one sentence summary:
    1.
    2.
    3.
    4.
    5.

7. Does your organisation record data in relation to Bridge and Tunnel Strike incidents?

    ◯ Yes

    ◯ No

○ Unsure

8. Please indicate if your organisation stores data of the type listed below

   ☐ Number of incidents per year

   ☐ Cause of incident (e.g. driver not familiar with the warning signs, driver unaware of their own vehicle height, deviation from route, lack of alternative route etc.)

   ☐ Direct costs associated with the incident (e.g. repair and maintenance of infrastructure, vehicle repair, emergency services etc.)

   ☐ Indirect costs in the wider transport network (e.g. traffic delays, congestion and disruption, public transport interruptions etc.)

   ☐ Societal costs associated with the incident (e.g. injuries and fatalities etc.)

   ☐ Other (please specify)

9. For how long has your organisation been storing data in relation to Bridge and Tunnel Strikes?

   ○ Less than 5 years

   ○ 5 to 10 years

   ○ More than 10 years

   ○ Unsure

10. In your opinion, please rank the following bridge / tunnel hazards by their impact on safety (7 = highest risk / impact, 1 = lowest risk / impact):
    - Strikes by over height vehicles
    - Environmental deterioration / climate change
    - Civil security (vandalism, terrorism etc.)
    - Aging of infrastructure
    - Traffic growth (weight & frequency)
    - Illegal overloading
    - Fire / damage during daily operations
    - Other (please specify description and ranking)

11. In your opinion, please rank the following bridge / tunnel hazards by their impact on cost (7 = highest cost, 1 = lowest cost):
    - Strikes by over height vehicles
    - Environmental deterioration / climate change
    - Civil security (vandalism, terrorism etc.)
    - Aging of infrastructure
    - Traffic growth (weight & frequency)
    - Illegal overloading
    - Fire / damage during daily operations

- Other (please specify description and ranking)

12. Has your organisation ever commissioned or installed countermeasures to mitigate the issue of Bridge and Tunnel Strikes by oversize vehicles?

◌ Yes

◌ No

◌ Unsure

13. Mitigation – Infrastructure
Please select the type of mitigation measure used from the list below. If an alternative measure has been used other than those listed, please provide details

☐ Static signage and/or variable message signs (VMS)

☐ Beacons, flashing beacons and/or lights

☐ Bridge markings

☐ Rumble strips

☐ Speed bumps

☐ Increased structure vertical clearance

☐ Laser vision

☐ Crash sacrificial beams

☐ Energy absorbing devices

☐ Portal frames

☐ Hanging chains or bells

☐ Road narrowing techniques

☐ Cameras and computer vision techniques

☐ Audio warnings

☐ Infrared dual beam arrays LaRa-OHVD systems

☐ Radar systems

☐ Increasing fines and surveillance

☐ Increased restrictions on vehicle dimensions

☐ Accelerometers

☐ Piezoelectric sensors

☐ Fibre optic cables

☐ Others (please specify)

☐ None of the above

14. Mitigation – Driver/Vehicle
Please select the type of mitigation measure used from the list below. If an alternative measure has been used other than those listed, please provide details

☐ In-vehicle early warning systems

☐ Truck sensors that monitor load-shift

☐ Audible turn-by-turn GPS navigation

☐ Increasing fines and surveillance

☐ Heavy Vehicle Goods/Commercial Motor Vehicle licence test

☐ Better driver education

☐ Good practice manuals

☐ Pre-routed maps

☐ Pilot/escort vehicles

☐ Increased restrictions on vehicle dimensions

☐ Other (please specify)

☐ None of the above

15. Does your organisation have available data in relation to Bridge and Tunnel Strike incidents before and/or after the countermeasures have been installed? i.e. Are you aware of how effective countermeasures have been?

◯ Yes

◯ No

◯ Unsure

16. Please indicate the type of data available for before and/or after the countermeasures have been installed from the list below:

☐ Number of incidents per year

☐ Cause of incident (e.g. driver not familiar with the warning signs, driver unaware of their own vehicle height, deviation from route, lack of alternative routes etc.)

☐ Direct costs associated with the incident (e.g. repair and maintenance of infrastructure, vehicle repair, emergency services etc.)

☐ Indirect costs in the wider transport network (e.g. traffic delays, congestion and disruption, public transport interruptions etc.)

☐ Societal costs associate with the incident (e.g. injuries and fatalities etc.)

☐ Other (please specify)

17. Has your organisation ever used any decision-making tools or carried out any Cost-Benefit Analysis to select the most appropriate mitigation measures?

    ◯ Yes

    ◯ No

    ◯ Unsure

18. We intend to conduct further correspondence with relevant stakeholders in order to obtain more specific data, where available. Please indicate below if you are happy to be included in this correspondence.

    ◯ No, I do not wish to be contacted again

    ◯ Yes, I'm happy to stay in touch. Please provide email address:

Thank you for taking the time to complete this survey. If you can suggest any colleagues or other professionals who may be willing to take part in this survey or future surveys, please feel free to share the link below with them.

https://www.surveymonkey.com/r/BridgeAndTunnelStrikes

APPENDIX C

RAW DATA FROM SURVEY 1

Q2: Organisation type

	Percentage (%)	Number of respondents
Road Infrastructure Owner / Manager / Agency	62.1%	64
Rail Infrastructure Owner / Manager	9.7%	10
Waterways Infrastructure Owner / Manager	0.0%	0
Manufacturing / Supply	1.0%	1
Freight transport	0.0%	0
Consultancy	8.7%	9
Contractor	1.9%	2
Monitoring / Technology Provider	3.9%	4
Research Institution / University	3.9%	4
International Consortium	0.0%	0
Other (please specify)	8.7%	9

Other (please specify)

- Ministry
- Road association
- Road, rail & Maritime infrastructure manager / Agency
- Security specialist & decision support
- Retired from rail infrastructure owner
- Exploitant
- Asociación no gubernamental sin fines de lucro
- Non-profit civil association
- Asociación sin fines de lucro

Q3: Organisation country

	Percentage (%)	Number of respondents
High income countries (HICs)	65.9%	60
Upper-Middle income countries (U-MICs)	23.1%	21
Lower-Middle income countries (L-MICs)	8.8%	8
Lower income countries (LICs)	2.2%	2

	Percentage (%)	Number of respondents	Country income classification
Argentina	4.1%	4	U-MIC
Australia	8.2%	8	HIC
Austria	1.0%	1	HIC
Burkina Faso	1.0%	1	LIC
Canada	1.0%	1	HIC
China	3.1%	3	U-MIC
Colombia	1.0%	1	U-MIC
Czech Republic	1.0%	1	HIC
Estonia	1.0%	1	HIC
Finland	2.0%	2	HIC
France	14.3%	14	HIC
Germany	1.0%	1	HIC
Hungary	1.0%	1	HIC
Iceland	1.0%	1	HIC
India	4.1%	4	L-MIC
Indonesia	1.0%	1	L-MIC
Ireland	12.2%	12	HIC
Luxembourg	1.0%	1	HIC
Mexico	1.0%	1	U-MIC
Mozambique	1.0%	1	LIC

	Percentage (%)	Number of respondents	Country income classification
Netherlands	1.0%	1	HIC
New Zealand	3.1%	3	HIC
Norway	3.1%	3	HIC
Russia	2.0%	2	U-MIC
South Africa	8.2%	8	U-MIC
Spain	3.1%	3	HIC
Sweden	2.0%	2	HIC
Switzerland	1.0%	1	HIC
Tanzania	1.0%	1	L-MIC
Thailand	3.1%	3	U-MIC
Tunisia	2.0%	2	L-MIC
UK	7.1%	7	HIC
USA	1.0%	1	HIC

Q4: Has your organisation identified Bridge and Tunnel Strikes by oversized vehicles as a major issue?

	Percentage (%)	Number of respondents
Yes	61.5%	64
No	23.1%	24
Unsure	15.4%	16

Q5: Are you aware of State / Province / National and/or International legislation, regulation, guidelines, and protocols pertinent to Bridge and/or Tunnel Strike prevention and detection?

	Percentage (%)	Number of respondents
Yes	61.5%	64
No	14.4%	15
Unsure	24.0%	25

Q7: Does your organisation record data in relation to Bridge and Tunnel Strike incidents?

	Percentage (%)	Number of respondents
Yes	42.1%	40
No	41.1%	39
Unsure	16.8%	16

Q8: Please indicate if your organisation stores data of the type listed below

	Percentage (%)	Number of respondents
Number of incidents per year	32.7%	37
Cause of incident (e.g. driver not familiar with the warning signs, driver unaware of their own vehicle height, lack of alternative route etc.)	16.8%	19
Direct costs associated with the incident (e.g. repair and maintenance of infrastructure, vehicle repair, emergency services etc.)	21.2%	24
Indirect costs in the wider transport network (e.g. traffic delays, congestion and disruption, public transport interruptions etc.)	8.0%	9
Societal costs associated with the incident (e.g. injuries and fatalities etc.)	8.8%	10
Other (please specify)	12.4%	14

Other (please specify)

- Type of vehicle, time of day
- Detailed incident report for all cases detailing times, photos, videos in some cases, effects on traffic.
- National Bridge Inventory includes bridge condition data that would include damage from strike.
- Detailed incident report for all cases detailing times, photos, videos in some cases, effects on traffic.
- Our organisation requires data to be collected but the majority of strikes are not recorded properly or at all.
- Data captured for rail bridges only. Bridge elements that are impacted.
- Acceleration on impact, Impact energy, displacement of structure, date/time, video footage.
- Le Ministère de Transport compile les données relatives aux incidents dans les tunnels.
- Pas de compilation de données.
- Nombre de fermetures de tunnels pour détection de hors gabarits.
- Les incidents touchant les structures sont compilés dans leur dossier spécifique, lorsque l'incident est connu, sans toutefois entrer dans les détails. Peut-être que les autres

données sont compilées, mais nous avons encore des vérifications à effectuer, donc nous ne sommes pas en mesure de répondre pour le moment.

- Identificación de lesionados y muertos, franja etaria, clase y modelo de vehiculo, características de la locación.
- no llevamos registro.
- Muchos de los miembros de la AAC, en las Instituciones donde trabajan, tienen información sobre estos temas.

Q9: For how long has your organisation been storing data in relation to Bridge and Tunnel Strikes?

	Percentage (%)	Number of respondents
Less than 5 years	12.8%	6
5 to 10 years	17.0%	8
More than 10 years	48.9%	23
Unsure	21.3%	10

Q10: In your opinion, please rank the following bridge / tunnel hazards by their impact on safety (averaged values).

	Percentage (%)
Strikes by over height vehicles	18.8%
Environmental deterioration / climate change	9.8%
Civil security (vandalism, terrorism etc.)	9.7%
Aging of infrastructure	17.5%
Traffic growth (weight & frequency)	14.8%
Illegal overloading	16.6%
Fire / damage during daily operations	12.8%
Other (please specify description and ranking)	0.00%

Q11: In your opinion, please rank the following bridge / tunnel hazards by their impact on cost (averaged values).

	Percentage (%)
Strikes by over height vehicles	16.4
Environmental deterioration / climate change	10.2
Civil security (vandalism, terrorism etc.)	10.8
Aging of infrastructure	18.9
Traffic growth (weight & frequency)	14.8
Illegal overloading	15.0
Fire / damage during daily operations	13.8

Q12: Has your organisation ever commissioned or installed countermeasures to mitigate the issue of Bridge and Tunnel Strikes by oversize vehicles?

	Percentage (%)	Number of respondents
Yes	63.8%	51
No	17.5%	14
Unsure	18.8%	15

Q13: Mitigation – Infrastructure. Please select the type of mitigation measure used from the list below. If an alternative measure has been used other than those listed, please provide details

	Percentage (%)	Number of respondents
None of the above	0.0%	0
Static signage and/or variable message signs (VMS)	16.0%	49
Beacons, flashing beacons and/or lights	9.1%	28
Bridge markings	11.1%	34
Rumble strips	2.3%	7
Speed bumps	1.0%	3
Increased structure vertical clearance	7.8%	24
Laser vision	2.0%	6
Crash sacrificial beams	7.2%	22
Energy absorbing devices	2.6%	8
Portal frames	7.5%	23
Hanging chains or bells	5.5%	17
Road narrowing techniques	2.6%	8
Cameras and computer vision techniques	6.8%	21
Audio warnings	1.3%	4
Infrared dual beam arrays LaRa-OHVD systems	4.2%	13
Radar systems	1.6%	5
In-vehicle early warning systems	0.0%	0
Increasing fines and surveillance	3.6%	11
Heavy Vehicle Goods licence test	0.0%	0
Better driver education	0.0%	0
Good practice manuals	0.0%	0
Pre-routed maps	0.0%	6
Increased restrictions on vehicle dimensions	2.0%	7
Accelerometers	2.3%	4

	Percentage (%)	Number of respondents
Piezoelectric sensors	1.3%	2
Fibre optic cables	0.7%	5
Other (please specify)	1.6%	5

Other (please specify)

- Photoelectric beam sensors, inductive loop to detect vehicle, camera to photograph vehicle, detection systems that notify law enforcement.
- Water Screen with STOP sign.
- Camera systems to detect number plates. Track sensors to check rail geometry.
- Impact detection, energy calculation.
- Revisión periódica de las alturas mínimas existentes.

Q14: Mitigation - Driver/Vehicle. Please select the type of mitigation measure used from the list below. If an alternative measure has been used other than those listed, please provide details

	Percentage (%)	Number of respondents
None of the above	15.5%	17
In-vehicle early warning systems	2.7%	3
Truck sensors monitoring load-shift	0.9%	1
Audible turn-by-turn GPS navigation	2.7%	3
Increasing fines and surveillance	10.9%	12
Heavy Vehicle Goods / Commercial Motor Vehicle licence test	8.2%	9
Better driver education	11.8%	13
Good practice manuals	6.4%	7
Pre-routed maps	14.5%	16
Pilot / Escort vehicles	10.9%	12
Increased restrictions on vehicle dimensions	9.1%	10
Other (please specify)	6.4%	7

Other (please specify)

- Media campaigns from CCTV footage.
- The road is not recommended on the GPS.
- Les véhicules d'escorte sont utilisés dans les cas d'excès des dimensions.

- Répertoire des hauteurs libres et des entraves liées aux charges de dimensions (Québec 511).
- Campañas de educación vial incluidas dentro de algunos pliegos de obras.

Q15: Does your organisation have available data in relation to Bridge and Tunnel Strike incidents before and/or after the countermeasures have been installed? i.e. Are you aware of how effective countermeasures have been?

	Percentage (%)	Number of respondents
Yes	28.8%	15
No	42.3%	22
Unsure	28.8%	15

Q16: Please indicate the type of data available for before and/or after the countermeasures have been installed from the list below.

	Percentage (%)	Number of respondents
Number of incidents per year	41.8%	28
Cause of incident (e.g. driver not familiar with the warning signs, driver unaware of their own vehicle height, deviation from route, lack of alternative route etc.)	17.9%	12
Direct costs associated with the incident (e.g. repair and maintenance of infrastructure, vehicle repair, emergency services etc.)	19.4%	13
Indirect costs in the wider transport network (e.g. traffic delays, congestion and disruption, public transport interruptions etc.)	6.0%	4
Societal costs associated with the incident (e.g. injuries and fatalities etc.)	6.0%	4
Other (please specify)	9.0%	6

Other (please specify)

- The USDOT does not own bridges, they are owned by State/local agencies and railroads. If we have data, it would be affiliated with a research project. The State/local agencies and railroads that own bridges may have data. There is a need to survey how effective is countermeasures are in protecting or preventing bridge strikes, e.g. if a sacrificial beam was installed, did it work or it became a flying object causing additional damages or fatalities, etc. Information is also needed on the typical repair strategies or methods on the bridge components that were damaged due to the strikes.

- Length of time to detect an overheight and take action.
- Aucune.
- Cambios o evolución en las causas y en indicadores de riesgos después de las contramedidas.

Q17: Has your organisation ever used any decision-making tools or carried out any Cost-Benefit Analysis to select the most appropriate mitigation measures?

	Percentage (%)	Number of respondents
Yes	20.0%	16
No	48.8%	39
Unsure	31.3%	25

Q18: We intend to conduct further correspondence with relevant stakeholders in order to obtain more specific data, where available. Please indicate below if you are happy to be included in this correspondence.

	Percentage (%)	Number of respondents
No, I do not wish to be contacted again	37.1%	26
Yes, I'm happy to stay in touch.	62.9%	44

APPENDIX D

SURVEY 2

BRIDGE AND TUNNEL STRIKES – QUANTITATIVE SURVEY

Thank you for taking the time to complete this survey.

Respondents may save their survey and return to make changes at a later date, even after completing the survey.

Bridge and tunnel strikes by oversize vehicles are a threat to road user's safety, and the operation of transport infrastructure. These incidents cause significant damage to infrastructure, injuries and fatalities, secondary crashes, traffic delays, emergency response, rerouting of traffic to remove trucks and repair damage, and economic costs related to response and recovery efforts.

This survey is part of an international study being carried out by **Roughan & O'Donovan Ltd.** on behalf of **PIARC - The World Road Association (www.piarc.org)**, which aims to examine proven countermeasures, practices, and technologies used to reduce the incidence of oversize vehicles striking bridges and tunnels along with effective processes for accurately reporting and tracking bridge / tunnel strike occurrences.

This is the second survey in response to this study. While you may or may not have answered the first general survey, your organisation has been selected to take part based on your particular experience / data availability to provide answers to some or all of the questions herein.

Note that there may be some questions which your organisation does not have any specific data or experience with. Please feel free to leave these questions blank.

We note that survey respondents may wish to provide comments or qualifications while responding to this survey. An opportunity is provided at the end of each question and at the end of the survey to comment / qualify any responses made.

The inputs of the survey will serve to produce a technical report including recommendations which will be available free of charge once the study is concluded.

Definitions

Bridges, tunnels and other similar structures are key elements of transport networks. Their structural characteristics and significance as nodes in the network make them very valuable assets.

Oversize vehicles are defined as vehicles beyond standard size limitations. They can also be standard size vehicles that are beyond a local size limitation of a specific area, road, bridge, or tunnel. These oversize vehicles can be over-height, over-width or over-dimensioned vehicles. Oversize vehicles may also include vehicles with a permit to circulate in a certain itinerary, which leave their authorized route. These vehicles may be required to be accompanied by escort vehicles.

Bridges and tunnel strikes by oversize vehicles are defined as collisions of these vehicles with bridges or tunnels or their associated equipment.

Effectiveness of mitigation measures relates to the percentage reduction in bridge / tunnel strikes due to the implementation of a mitigation measure. For example, presuming static warning signs reduces the number of bridge strikes on average per year from 10 to 8, we would state that static warning signs are 20% effective.

19. Organisation name:

20. Organisation type:
    - Road Infrastructure Owner / Manager / Agency,
    - Rail Infrastructure Owner / Manager,
    - Waterways Infrastructure Owner / Manager,
    - Freight transport
    - Consultancy
    - Contractor
    - Manufacturing / Supply
    - Monitoring / Technology Provider
    - Research Institution / University
    - International Consortium
    - Other (please specify)

21. Country / State / Province:

Bridge Strike Consequences / Costs

22. Based on your available data, please estimate the number and overall average cost range of a small, medium and large **bridge** strike, considering every cost attributable to the event. Please specify the currency.

Level of **bridge** strike	Number per year	Cost range
Small (minor vehicle damage, no / very slight **bridge** damage)		
Medium (major vehicle damage, minor **bridge** damage that does not impact on safe use)		
Large (major vehicle damage, major **bridge** damage resulting in collapse or global movement of structure)		

23. Please specify any additional information and / or comments below in relation to question 4 above.

24. For the cost ranges specified in question 4 above, please indicate the percentage breakdown of the cost across the categories below (Note: the sum of the percentages in each column should be 100).

Cost type	Small **bridge** Strike	Medium **bridge** Strike	Large **bridge** Strike
Infrastructure Repair			
Increased infrastructure maintenance / routine inspections			
Vehicle Repair			
Emergency services			
Mitigation Measures Repair			
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures			
Compensation for Injuries and Fatalities			
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures			
Others (please specify item and percentage)			

Please specify any additional categories and related cost percentages and / or comments below.

25. On average, what percentage of the cost associated with a **bridge** strike is recovered (through the haulier / insurance etc.), and what percentage is born by the bridge owner? Please provide comment and be as descriptive as possible.

% Cost born by bridge owner:

% Cost born by haulier:

% Cost born by insurance:

26. Please specify any additional information and / or comments below in relation to question 7 above.

Tunnel Strike Consequences / Costs

27. Based on your available data, please estimate the number and overall average cost range of a small, medium and large **tunnel** strike, considering every cost attributable to the event. Please specify the currency.

Level of **tunnel** strike	Number per year	Cost range
Small (minor vehicle damage, no / very slight **tunnel** damage)		
Medium (major vehicle damage, minor **tunnel** damage that does not impact on safe use)		
Large (major vehicle damage, major **tunnel** damage resulting in major damages to equipment (e.g. lights, fans, etc.) or significant interruptions to safe use)		

28. Please specify any additional information and / or comments below in relation to question 9 above.

29. For the cost ranges specified in question 7 above, please indicate the percentage breakdown of the cost across the categories below (Note: the sum of the percentages in each column should be 100).

Cost type	Small **tunnel** Strike	Medium **tunnel** Strike	Large **tunnel** Strike
Infrastructure Repair (including electrical / mechanical equipment etc.)			
Increased infrastructure maintenance / routine inspections (including electrical / mechanical equipment etc.)			
Vehicle Repair			
Emergency services			
Mitigation Measures Repair			
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures			
Compensation for Injuries and Fatalities			
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures			
Others (please specify item and percentage)			

Please specify any additional categories and related cost percentages and / or comments below.

30. On average, what percentage of the cost associated with a **tunnel** strike is recovered (through the haulier / insurance etc.), and what percentage is born by the tunnel owner? Please provide comment and be as descriptive as possible.

    % Cost born by tunnel owner:

    % Cost born by haulier:

    % Cost born by insurance:

31. Please specify any additional information and / or comments below in relation to question 12 above.

Bridge strike mitigation measures – effectiveness and cost

32. Based on your available data, please indicate the effectiveness of the following mitigation measures for **bridge** strikes. If your organisation has made use of a combination of the

following mitigation measures, please specify them and the related effectiveness in the comment below.

	Low Effectiv. 0-25%	Low Medium Effectiv. 25-50%	High Medium Effectiv. 50-75%	High Effectiv. >75%	
• Static signage	○	○	○	○	
• Variable message signs (VMS)	○	○	○	○	
• Beacons	○	○	○	○	
• Flashing beacons and/or lights	○	○	○	○	
• Bridge markings	○	○	○	○	
• Rumble strips	○	○	○	○	
• Speed bumps	○	○	○	○	
• Clear heights signage and obstacles related to dimensional loads	○	○	○	○	
• Increased structure vertical clearance	○	○	○	○	
• Laser vision	○	○	○	○	
• Crash sacrificial beams	○	○	○	○	
• Energy absorbing devices	○	○	○	○	
• Portal frames	○	○	○	○	
• Hanging chains or bells	○	○	○	○	
• Road narrowing techniques	○	○	○	○	
• Cameras and computer vision techniques	○	○	○	○	
• Vehicle redirection in case of excessive dimensions	○	○	○	○	
• Audio warnings	○	○	○	○	
• Water Screen with STOP sign	○	○	○	○	
• Infrared dual beam arrays LaRa-OHVD systems	○	○	○	○	
• Radar systems	○	○	○	○	
• In-vehicle early warning systems	○	○	○	○	
• Media campaigns	○	○	○	○	
• Increasing fines and surveillance	○	○	○	○	
• Heavy Vehicle Goods licence test	○	○	○	○	
• Better driver education	○	○	○	○	
• Good practice manuals	○	○	○	○	
• Pre-routed maps	○	○	○	○	
• Increased restrictions on vehicle dimensions		○	○	○	○
• Accelerometers	○	○	○	○	
• Piezoelectric sensors	○	○	○	○	
• Photoelectric beam sensors		○	○	○	○
• Inductive loop to detect vehicle	○	○	○	○	
• Fibre optic cables	○	○	○	○	

Please specify any additional mitigation measures / combination of mitigation measures and related effectiveness and / or any comments below.

33. Based on your available data, please estimate the cost of purchase, installation and annual maintenance of the following mitigation measures for **bridge** strikes. Note that installation and maintenance costs should include cost of delays / disruption due to the works. Cost ranges can be inserted, if necessary. Please specify the currency.

	Purchase	Installation	Annual maintenance
• Static signage			
• Variable message signs (VMS)			
• Beacons			
• Flashing beacons and/or lights			
• Bridge markings			
• Rumble strips			
• Speed bumps			
• Clear heights signage and obstacles related to dimensional loads			
• Increased structure vertical clearance			
• Laser vision			
• Crash sacrificial beams			
• Energy absorbing devices			
• Portal frames			
• Hanging chains or bells			
• Road narrowing techniques			
• Cameras and computer vision techniques			
• Vehicle redirection in case of excessive dimensions			
• Audio warnings			
• Water Screen with STOP sign			
• Infrared dual beam arrays LaRa-OHVD systems			
• Radar systems			
• In-vehicle early warning systems			
• Media campaigns			
• Increasing fines and surveillance			
• Heavy Vehicle Goods licence test			
• Better driver education			
• Good practice manuals			
• Pre-routed maps			
• Increased restrictions on vehicle dimensions			
• Accelerometers			
• Piezoelectric sensors			
• Photoelectric beam sensors			

- Inductive loop to detect vehicle
- Fibre optic cables

34. Please specify any additional mitigation measures and related cost and / or any comments below.

Tunnel strike mitigation measures – effectiveness and cost

35. Based on your available data, please indicate the effectiveness of the following mitigation measures for **tunnel** strikes: If your organisation has made use of a combination of the following mitigation measures, please specify them and the related effectiveness in the comment below.

	Low Effectiv. 0-25%	Low Medium Effectiv. 25-50%	High Medium Effectiv. 50-75%	High Effectiv. >75%
Static signage				
Variable message signs (VMS)				
Beacons				
Flashing beacons and/or lights				
Tunnel markings				
Rumble strips				
Speed bumps				
Clear heights signage and obstacles related to dimensional loads				
Increased structure vertical clearance (e.g. by lowering of road level)				
Equipment upgrade				
Laser vision				
Crash sacrificial beams				
Energy absorbing devices				
Portal frames				
Hanging chains or bells				
Road narrowing techniques				
Cameras and computer vision techniques				
Vehicle redirection in case of excessive dimensions				
Audio warnings				
Water Screen with STOP sign				
Infrared dual beam arrays LaRa-OHVD systems				
Radar systems				
In-vehicle early warning systems				
Media campaigns				
Increasing fines and surveillance				

- Increased restrictions on vehicle dimensions
- Heavy Vehicle Goods licence test
- Better driver education
- Good practice manuals
- Pre-routed maps
- Accelerometers
- Piezoelectric sensors
- Photoelectric beam sensors
- Inductive loop to detect vehicle
- Fibre optic cables

Please specify any additional mitigation measures / combination of mitigation measures and related effectiveness and / or any comments below.

36. Based on your available data, please estimate the cost of purchase, installation and annual maintenance of the following mitigation measures for **tunnel** strikes. Note that installation and maintenance costs should include cost of delays / disruption due to the works. Cost ranges can be inserted, if necessary. Please provide the currency.

	Purchase	Installation	Annual maintenance
• Static signage			
• Variable message signs (VMS)			
• Beacons			
• Flashing beacons and/or lights			
• Tunnel markings			
• Rumble strips			
• Speed bumps			
• Clear heights signage and obstacles related to dimensional loads			
• Increased structure vertical clearance (e.g. by lowering of road level)			
• Equipment upgrade			
• Laser vision			
• Crash sacrificial beams			
• Energy absorbing devices			
• Portal frames			
• Hanging chains or bells			
• Road narrowing techniques			
• Cameras and computer vision techniques			
• Vehicle redirection in case of excessive dimensions			
• Audio warnings			
• Water Screen with STOP sign			
• Infrared dual beam arrays			

LaRa-OHVD systems

- Radar systems
- In-vehicle early warning systems
- Media campaigns
- Increasing fines and surveillance
- Heavy Vehicle Goods licence test
- Better driver education
- Good practice manuals
- Pre-routed maps
- Increased restrictions on vehicle dimensions
- Accelerometers
- Piezoelectric sensors
- Photoelectric beam sensors
- Inductive loop to detect vehicle
- Fibre optic cables

37. Please specify any additional mitigation measures and related cost and / or any comments below.

Additional Considerations

38. It is noted that there are various external factors which can affect the consequences, costs and effectiveness against bridge or tunnel strikes which may not be identified in this high level survey. Please provide below any additional considerations which should be born in mind when reading the results of your survey.

APPENDIX E

RAW DATA FROM SURVEY 2

In this Appendix the responses from the second survey are listed in detail. A total of 43 responses have been collected and a number from 1 to 43 has been assigned to each respondent and specified in the following tables in order to easily identify and track the responses.

Q2: Organisation type

	Percentage (%)	Number of respondents
Road Infrastructure Owner / Manager / Agency	69.8%	30
Rail Infrastructure Owner / Manager	9.3%	4
Waterways Infrastructure Owner / Manager	0.0%	0
Manufacturing / Supply	0.0%	0
Freight transport	0.0%	0
Consultancy	9.3%	4
Contractor	2.3%	1
Monitoring / Technology Provider	2.3%	1
Research Institution / University	0.0%	0
International Consortium	0.0%	0
Other (please specify)	7.0%	3

Other (please specify)

- Road, Rail & Maritime infrastructure manager / Agency
- Territorial Community
- Maintenance operator

Q3: Organisation country

	Percentage (%)	Number of respondents
High income countries (HICs)	81.4%	35
Upper-Middle income countries (U-MICs)	14.0%	6
Lower-Middle income countries (L-MICs)	2.3%	1
Lower income countries (LICs)	0.0%	0
Unknow	2.3%	1

	Percentage (%)	Number of respondents	Country income classification
Argentina	7.0%	3	U-MIC
Australia	9.3%	4	HIC
Belgium	7.0%	3	HIC
Canada	2.3%	1	HIC
Chile	4.7%	2	HIC
Colombia	4.7%	2	U-MIC
France	16.3%	7	HIC
Germany	2.3%	1	HIC
Hungary	2.3%	1	HIC
India	2.3%	1	L-MIC
Ireland	16.3%	7	HIC
Netherlands	2.3%	1	HIC
Portugal	2.3%	1	HIC
Russia	2.3%	1	U-MIC
Spain	7.0%	3	HIC
UK	7.0%	3	HIC
Unknown	2.3%	1	-
USA	2.3%	1	HIC

Q4: Based on your available data, please estimate the number and overall average cost range of a small, medium and large bridge strike, considering every cost attributable to the event. Please specify the currency

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	18.6%	8
	U-MIC	4.7%	2
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	74.4%	32

No.	Small bridge strike		Medium bridge strike		Large bridge strike		Country income classification
	Number per year	Cost range	Number per year	Cost range	Number per year	Cost range	
2	Up to 5	€2,000 per incident based on visual inspection of damage, reporting and no repair.	Up to 5	€15,000 per incident based on inspection, design of repair spec and contractor costs for traffic management and repairs	0	-	HIC
4	10	€5,000 - €20,000	0.5	€20,000-€50,000	0.05	10	HIC
7	-	-	-	-	1	-	HIC
12	55	€0 - €5,000	25	€5,001 - €20,000	1-2	€20,001+	HIC
16	700-900	-	500-700	$180,000 average	Up to 200	$500,000 average	HIC
17	1	$0 - $30k	-	-	-	-	HIC
18	6	€1,000	3	€5,000	1	€50,000	HIC
20	2	€100,000 €	6	€1 million	15	€2.5 million	U-MIC
21	100	10,000 INR	20	100,000 INR	1	10 million INR	L-MIC
33	6	1,000€ - 10,000€	1	10,000 € - 350,000€	-	-	HIC
41	10	-	6	-	2	-	U-MIC

Q5: Please specify any additional information and / or comments below in relation to question 4 above.

No.	Additional information / comments	Country income classification
2	We have not experienced any bridge collapses. We experienced one very significant costly bridge strike in the last twenty years where a steel composite structure crossing a major route required repairs. The cost of design and construction of structural steel repairs, traffic management and ancillary costs exceeded €1 million.	HIC
4	It is very difficult to accurately respond to the questions posed. On our network there has been one major bridge strike in 20 years, the cost of repair of which exceeded €500,000. It is difficult to provide accurate estimates as to the number of strikes (some bridges ae struck multiple times without severe damage. Usually the cost of remediation of a small strike is primarily governed by the traffic management costs rather than the actual repair cost.	HIC
16	Recommend reviewing New York State DOT Report on Bridge Vehicle Impact Assessment and Maryland Study, Vehicle Collisions with Highway Bridges.	HIC
17	We do not own bridges, these are state assets that go over our asset. We supply traffic management below.	HIC
21	A lot of minor incidences may not get recorded also.	L-MIC
41	No se dispone de costes. Los números de colisiones/año están estimados y referidos al 3° Distrito DNV (Tucumán), que posee 165 puentes en servicio.	U-MIC

Q6: For the cost ranges specified in question 4 above, please indicate the percentage breakdown of the cost across the categories below (Note: the sum of the percentages in each column should be 100).

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	14.0%	6
	U-MIC	4.7%	2
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	79.1%	34

Small bridge strike									
No.	2	12	16	17	18	20	21	33	41
Infrastructure Repair	0%	10%	100%	0%	50%	25%	10%	30%	15%
Increased infrastructure maintenance / routine inspections	100%	65%	0%	0%	10%	20%	30%	30%	15%
Vehicle Repair	0%	0%	0%	0%	20%	10%	20%	40%	25%
Emergency services	0%	0%	0%	85%	0%	0%	50%	0%	5%
Mitigation Measures Repair	0%	20%	0%	0%	20%	30%	15%	0%	15%
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	0%	5%	0%	10%	0%	15%	10%	0%	15%
Compensation for Injuries and Fatalities	0%	0%	0%	0%	0%	0%	5%	0%	5%
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	0%	0%	5%	0%	0%	15%	0%	5%
Country income classification	HIC	HIC	HIC	HIC	HIC	U-MIC	L-MIC	HIC	U-MIC

Medium bridge strike									
No.	2	12	16	17	18	20	21	33	41
Infrastructure Repair	80%	50%	100%	-	30%	50%	5%	30%	25%
Increased infrastructure maintenance / routine inspections	20%	30%	0%	-	10%	15%	20%	10%	15%
Vehicle Repair	0%	0%	0%	-	15%	30%	20%	30%	15%
Emergency services	0%	0%	0%	-	10%	10%	5%	20%	10%
Mitigation Measures Repair	0%	10%	0%	-	10%	40%	20%	10%	10%
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	0%	10%	0%	-	10%	15%	20%	0%	10%
Compensation for Injuries and Fatalities	0%	0%	0%	-	15%	10%	5%	0%	10%
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	0%	0%	-	0%	5%	5%	0%	5%
Country income classification	HIC	HIC	HIC	HIC	HIC	U-MIC	L-MIC	HIC	U-MIC

Large bridge strike									
No.	2	12	16	17	18	20	21	33	41
Infrastructure Repair	95%	75%	100%	-	20%	65%	5%	-	35%
Increased infrastructure maintenance / routine inspections	5%	10%	0%	-	5%	20%	25%	-	20%
Vehicle Repair	0%	0%	0%	-	15%	30%	15%	-	10%
Emergency services	0%	0%	0%	-	10%	20%	5%	-	5%
Mitigation Measures Repair	0%	0%	0%	-	10%	50%	20%	-	5%
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	0%	15%	0%	-	10%	15%	20%	-	10%
Compensation for Injuries and Fatalities	0%	0%	0%	-	20%	25%	5%	-	5%
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	0%	0%	-	10%	10%	5%	-	10%
Country income classification	HIC	HIC	HIC	HIC	HIC	U-MIC	L-MIC	HIC	U-MIC

Please specify any additional categories and related cost percentages and / or any comments below

No.	Additional categories and related costs / comments	Country income classification
2	We do not retain any information on costs other than the top two rows.	HIC
3	NR does not categorise bridge strike in this manner (small, medium, large). Bridge strike as a whole has cost £5.5million in delay and cancellation costs in the past year2020/21, down from almost £11million in the previous year. Repair and maintenance costs are more difficult to reconcile to specific bridge strike events. A total of 1605 bridge strike events occurred across the network in the year 2020/21, down from 1728 in the previous year. In the year 2019/20 it was estimated that bridge strike cost in the region of £23million in total to Network rail.	HIC
4	The question presumes that a road administration captures much more granular data on bridge strike incidents than is actually the case. As an organisation we do not have the breakdown of costs sought. Emergency services costs are typically borne by the emergency services - not be the roads administration. Delay costs are a function of the duration of an incident. Such costs are not borne by the roads administration.	HIC
12	Don’t have visibility of, or capture, road vehicle costs. Other cost to consider is the administrative cost associated with claims, attempts to recoup costs from offenders, bringing cases to court and so on.	HIC
14	We do not have any percentages of the indicated topics.	HIC
17	Note that main cost is traffic management services. Listed as Emergency Services.	HIC

Q7: On average, what percentage of the cost associated with a bridge strike is recovered (through the haulier / insurance etc.), and what percentage is born by the bridge owner? Please provide comment and be as descriptive as possible.

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	9.3%	4
	U-MIC	4.7%	2
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	83.7%	36

No.	Cost born by bridge owner	Cost born by haulier	Cost born by insurance	Country income classification
2	100%	0%	0%	HIC
12	65%	15%	20%	HIC
13	Depends on type of incident but average of 25%	0%	At least 75% in a usual incident	HIC
18	50%	15%	35%	HIC
20	10%	50%	40%	U-MIC
21	40%	10%	50%	L-MIC
41	85%	5%	10%	U-MIC

Q8: Please specify any additional information and / or comments below in relation to question 7 above.

No.	Additional information / comments	Country income classification
2	Generally when an overhead bridge strike occurs the vehicle is not identified. We often have bridge parapet impacts and in about 30% of such cases the vehicle is identified and the insurers pay for all costs.	HIC
3	In the year 2019/20 bridge strikes in total were estimated to have cost NR £23million, of this around £9million was recovered in insurance claims by the performance team. the most up to date figures are not available at present.	HIC
4	In the culprit is identified and the police are involved, then the cost will be borne by the haulier or his insurance. From a roads administration perspective it doesn't matter whether the cost is borne by the haulier or insurance. In most cases the roads administration does not have visibility on as to the source of the compensation.	HIC
12	This is an active area where we are trying to retrieve more costs from hauliers. I anticipate this figure to change in years ahead as enforcement eg penalty points etc becomes clearer. It can be difficult as it is a lengthy process and in a lot of instances we do not know/capture the offender.	HIC
14	We do not have any percentages. In the first case the bridge owner covers all the costs. In a second step cost might be covered by an insurance.	HIC
16	State Departments of Transportation will attempt to recover costs from the motor carrier company and the motor carrier’s insurance.	HIC
33	Si le responsable du dégât est identifié : cout supporté à 80 % par les assurances et ou transporteur, le reste par le propriétaire. si le responsable du dégât n'est pas identifié 100 % du coût pour le propriétaire.	HIC
41	En general, la propietaria no suele recuperar el costo del daño causado a la infraestructura, incluso cuando la culpa de la colisión haya sido del transportista. El seguro suele hacerse cargo del coste relacionado con los daños al vehículo y personas, salvo franquicia.	U-MIC

Q9: Based on your available data, please estimate the number and overall average cost range of a small, medium and large tunnel strike, considering every cost attributable to the event. Please specify the currency

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	7.0%	3
	U-MIC	0.0%	0
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	90.7%	39

No.	Small tunnel strike		Medium tunnel strike		Large tunnel strike		Country income classification
	Number per year	Cost range	Number per year	Cost range	Number per year	Cost range	
1	4	> €1,000	0.5	€5,000	0.25	€250,000	HIC
21	100	20,000 INR	15	200,000 INR	2	15,000,000 INR	L-MIC
22	6	€6,000	4	€30,000	1	€40,000	HIC
33	0	-	0	-	7	2,000€ - 30,000€	HIC

Q10: Please specify any additional information and / or comments below in relation to question 9 above.

No.	Additional information / comments	Country income classification
41	No poseo túneles en mi stock de obras de paso.	U-MIC

Q11: For the cost ranges specified in question 7 above, please indicate the percentage breakdown of the cost across the categories below (Note: the sum of the percentages in each column should be 100).

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	7.0%	3
	U-MIC	0.0%	0
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	90.7%	39

Small tunnel strike				
No.	1	21	22	33
Infrastructure Repair	90%	20%	100%	-
Increased infrastructure maintenance / routine inspections	0%	20%	0%	-
Vehicle Repair	0%	15%	0%	-
Emergency services	0%	5%	0%	-
Mitigation Measures Repair	0%	15%	0%	-
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	10%	5%	0%	-
Compensation for Injuries and Fatalities	0%	10%	0%	-
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	10%	0%	-
Country income classification	HIC	L-MIC	HIC	HIC

Medium tunnel strike				
No.	1	21	22	33
Infrastructure Repair	90%	15%	95%	-
Increased infrastructure maintenance / routine inspections	0%	20%	5%	-
Vehicle Repair	0%	20%	0%	-
Emergency services	0%	5%	0%	-
Mitigation Measures Repair	0%	15%	0%	-
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	10%	5%	0%	-
Compensation for Injuries and Fatalities	0%	10%	0%	-
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	10%	0%	-
Country income classification	HIC	L-MIC	HIC	HIC

Large tunnel strike				
No.	1	21	22	33
Infrastructure Repair	95%	20%	90%	70%
Increased infrastructure maintenance / routine inspections	0%	25%	10%	10%
Vehicle Repair	0%	10%	0%	10%
Emergency services	0%	5%	0%	10%
Mitigation Measures Repair	0%	15%	0%	0%
Traffic delays, congestion and disruption to private / public transport etc. due to partial or total closures	5%	10%	0%	0%
Compensation for Injuries and Fatalities	0%	10%	0%	0%
Loss of future business (loss of public confidence / attractiveness etc.) due to partial or total closures	0%	5%	0%	0%
Country income classification	HIC	L-MIC	HIC	HIC

Please specify any additional categories and related cost percentages and / or any comments below.

No.	Additional categories and related costs / comments	Country income classification
14	We do not have any percentages in total. All in all we do not have that many breakdowns.	HIC
41	Especifique a continuación las categorías adicionales y los porcentajes de coste correspondientes y/o los comentarios.: No poseo túneles en mi stock de obras de paso.	U-MIC

Q12: On average, what percentage of the cost associated with a tunnel strike is recovered (through the haulier / insurance etc.), and what percentage is born by the tunnel owner? Please provide comment and be as descriptive as possible.

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	7.0%	3
	U-MIC	0.0%	0
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	90.7%	39

No.	Cost born by tunnel owner	Cost born by haulier	Cost born by insurance	Country income classification
1	0%	5%	95%	HIC
21	35%	15%	50%	L-MIC
22	20%	0%	80%	HIC
33	50%	50%	0%	HIC

Q13: Please specify any additional information and / or comments below in relation to question 12 above.

No.	Additional information / comments	Country income classification
14	We do not have any percentages.	HIC
22	Montant de vétusté déduit (Amount of obsolescence deducted)	HIC
33	Transporteur => son assurance.	HIC
41	No poseo túneles en mi stock de obras de paso.	U-MIC

Q14: Based on your available data, please indicate the effectiveness of the following mitigation measures for bridge strikes. If your organisation has made use of a combination of the following mitigation measures, please specify them and the related effectiveness in the comment below.

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	20.9%	9
	U-MIC	4.7%	2
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	72.1%	31

No.	2	3	7	11	12	13	14	16	21	33	41	43
Static signage	High Effectiveness >75%	Low Medium Effectiveness 25-50%	High Effectiveness >75%	-	Low Medium Effectiveness 25-50%	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	High Effectiveness >75%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%
Variable message signs (VMS)	-	Low Medium Effectiveness 25-50%	-	-	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	High Effectiveness >75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Beacons	-	Low Medium Effectiveness 25-50%	-	-	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	-	-	High Effectiveness >75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Flashing beacons and/or lights	High Effectiveness >75%	Low Medium Effectiveness 25-50%	High Effectiveness >75%	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Bridge markings	-	Low Medium Effectiveness 25-50%	-	-	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	High Effectiveness >75%	Low Effectiveness 0-25%	High Effectiveness >75%	Low Effectiveness 0-25%
Rumble strips	-	-	-	-	-	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Speed bumps	-	-	-	-	-	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%
Clear heights signage and obstacles related to dimensional loads	Low Medium Effectiveness 25-50%	-	Low Medium Effectiveness 25-50%	-	Low Medium Effectiveness 25-50%	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	-	High Effectiveness >75%	Low Medium Effectiveness 25-50%	High Effectiveness >75%	High Effectiveness >75%

No.	2	3	7	11	12	13	14	16	21	33	41	43
Increased structure vertical clearance	High Effectiveness >75%	-	High Effectiveness >75%	-	High Effectiveness >75%	High Effectiveness >75%	Low Medium Effectiveness 25-50%	-	High Effectiveness >75%	Low Effectiveness 0-25%	High Effectiveness >75%	High Effectiveness >75%
Laser vision	-	-	-	-	High Medium Effectiveness 50-75%	-	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	High Effectiveness >75%	-	-
Crash sacrificial beams	-	Low Medium Effectiveness 25-50%	-	-	High Medium Effectiveness 50-75%	-	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	High Effectiveness >75%	-	High Effectiveness >75%
Energy absorbing devices	-	Low Medium Effectiveness 25-50%	-	-	High Medium Effectiveness 50-75%	-	Low Medium Effectiveness 25-50%	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
Portal frames	-	Low Medium Effectiveness 25-50%	-	-	Low Medium Effectiveness 25-50%	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	High Effectiveness >75%
Hanging chains or bells	-	Low Medium Effectiveness 25-50%	-	-	Low Medium Effectiveness 25-50%	-	-	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%
Road narrowing techniques	-	Low Medium Effectiveness 25-50%	-	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Cameras and computer vision techniques	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	-	High Effectiveness >75%	-	High Medium Effectiveness 50-75%	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%

No.	2	3	7	11	12	13	14	16	21	33	41	43
Vehicle redirection in case of excessive dimensions	-	-	High Effectiveness >75%	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	-	High Effectiveness >75%	Low Effectiveness 0-25%	-	High Medium Effectiveness 50-75%
Audio warnings	-	-	-	-	-	-	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
Water Screen with STOP sign	-	-	-	-	-	-	-	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Infrared dual beam arrays LaRa-OHVD systems	Low Effectiveness 0-25%	-	-	-	High Medium Effectiveness 50-75%	-	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Radar systems	-	-	-	-	-	-	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
In-vehicle early warning systems	-	-	-	-	-	-	-	-	High Effectiveness >75%	Low Effectiveness 0-25%	-	-
Media campaigns	-	Low Medium Effectiveness 25-50%	-	-	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	Low Effectiveness 0-25%	Low Effectiveness 0-25%
Increasing fines and surveillance	High Effectiveness >75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	-	High Medium Effectiveness 50-75%	High Effectiveness >75%	High Effectiveness >75%	Low Effectiveness 0-25%

No.	2	3	7	11	12	13	14	16	21	33	41	43
Heavy Vehicle Goods licence test	-	-	-	-	Skipped	High Medium Effectiveness 50-75%	-	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%
Better driver education	-	-	-	-	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	Low Effectiveness 0-25%	Low Medium Effectiveness 25-50%
Good practice manuals	-	-	-	-	Skipped	High Medium Effectiveness 50-75%	-	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	Low Effectiveness 0-25%	Low Medium Effectiveness 25-50%
Pre-routed maps	-	-	-	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
Increased restrictions on vehicle dimensions	-	-	-	-	-	High Medium Effectiveness 50-75%	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%
Accelerometers	-	-	-	High Effectiveness >75%	Low Effectiveness 0-25%	-	-	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	-	-
Piezoelectric sensors	-	-	-	-	-	-	-	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	-	-
Photoelectric beam sensors	-	-	-	-	-	-	-	-	Low Medium Effectiveness 25-50%	Low Effectiveness 0-25%	-	-

No.	2	3	7	11	12	13	14	16	21	33	41	43
Inductive loop to detect vehicle	-	-	-	-	-	-	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
Fibre optic cables	-	-	-	-	-	-	-	-	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
Country income classification	HIC	HIC	HIC	HIC	HIC	HIC	HIC	HIC	L-MIC	HIC	U-MIC	U-MIC

Please specify any additional mitigation measures / combination of mitigation measures and related effectiveness and / or any comments below

No.	Additional mitigation measures / combination and related effectiveness / comments	Country income classification
11	Acceleration sensors are extremely useful to ascertain if a bridge strike occurs. This provides asset owners with data to analyse on the severity of the strike and to pre plan actions for remediation. Camera systems that are combined within the hardware setup, allows for quick review on bridge integrity. This evidence can be used for legal proceedings showing license plate of the vehicle.	HIC
16	There is limited national data on the effectiveness of bridge strike prevention systems. Active systems tend to be more effective, but this varies based upon the location and other factors. The most effective applications are with a combination of measures with laser detection, VMS, flashing beacons, cameras, and enforcement. The Georgia Department of Transportation (DOT) Research Project 15-21, Warning Systems Evaluation for Overhead Clearance Detection, provides an overview of systems being used in the US and State DOT experience with the systems.	HIC
41	Se dejó sin marcar aquellas medidas de las cuales no se tiene experiencia, aunque pudieran ser más o menos efectivas. Las cadenas colgantes se suelen utilizar en conjunto con los portales marco.	U-MIC

Q15: Based on your available data, please estimate the cost of purchase, installation and annual maintenance of the following mitigation measures for bridge strikes. Note that installation and maintenance costs should include cost of delays / disruption due to the works. Cost ranges can be inserted, if necessary. Please specify the currency.

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	9.3%	4
	U-MIC	0.0%	0
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	72.1%	38

No.		11	12	16	21	33
Static signage	Purchase	-	€1,000	-	1,000,000 INR	€2,000
	Installation	-	€1,000	-	100,000 INR	€1,000
	Maintenance	-	€500	-	50,000 INR	€0
Variable message signs (VMS)	Purchase	-	€100,000	-	1,000,000 INR	€40,000
	Installation	-	€80,000	-	100,000 INR	€40,000
	Maintenance	-	€10,000	-	100,000 INR	€500
Beacons	Purchase	-	-	-	500,000 INR	-
	Installation	-	-	-	50,000 INR	-
	Maintenance	-	-	-	50,000 INR	-
Flashing beacons and/or lights	Purchase	-	-	-	500,000 INR	-
	Installation	-	-	-	50,000 INR	-
	Maintenance	-	-	-	75,000 INR	-
Bridge markings	Purchase	-	€1,000	-	2,000,000 INR	-
	Installation	-	€4,000	-	200,000 INR	-
	Maintenance	-	€1,000	-	300,000 INR	-
Rumble strips	Purchas	-	-	-	200,000 INR	-
	Installation	-	-	-	20,000 INR	-
	Maintenance	-	-	-	20,000 INR	-

No.		11	12	16	21	33
Speed bumps	Purchase	-	-	-	300,000 INR	-
	Installation	-	-	-	30,000 INR	-
	Maintenance	-	-	-	30,000 INR	-
Clear heights signage and obstacles related to dimensional loads	Purchase	-	€1,000	-	500,000 INR	-
	Installation	-	€1,000	-	50,000 INR	-
	Maintenance	-	€500	-	50,000 INR	-
Increased structure vertical clearance	Purchase	-	€250,000	-	1,000,000 INR	-
	Installation	-	€250,000	-	100,000 INR	-
	Maintenance	-	0	-	100,000 INR	-
Laser vision	Purchase	-	-	$15,000-20,000	20,000,000 INR	-
	Installation	-	-	-	200,000 INR	-
	Maintenance	-	-	-	20,000 INR	-
Crash sacrificial beams	Purchase	-	€100,000	-	20,000,000 INR	€2,000
	Installation	-	€150,000	-	200,000 INR	€1,000
	Maintenance	-	€1,000	-	200,000 INR	€0
Energy absorbing devices	Purchase	-	€100,000	-	10,000,000 INR	-
	Installation	-	€150,000	-	1,000,000 INR	-
	Maintenance	-	€1,000	-	100,000 INR	-

No.		11	12	16	21	33
Portal frames	Purchase	-	-	-	5,000,000 INR	-
	Installation	-	-	-	500,000 INR	-
	Maintenance	-	-	-	50,000 INR	-
Hanging chains or bells	Purchase	-	€10,000	-	500,000 INR	-
	Installation	-	€90,000	-	50,000 INR	-
	Maintenance	-	€5,000	-	50,000 INR	-
Road narrowing techniques	Purchase	-	€20,000	-	100,000 INR	-
	Installation	-	€80,000	-	10,000 INR	-
	Maintenance	-	€5,000	-	10,000 INR	-
Cameras and computer vision techniques	Purchase	€5,000	-	$12,000-50,000	200,000,000 INR	-
	Installation	€5,000	-	-	2,000,000 INR	-
	Maintenance	€6,000	-	$1,500-6,000	2,000,000 INR	-
Vehicle redirection in case of excessive dimensions	Purchase	-	€5,000	-	3,000,000 INR	-
	Installation	-	€45,000	-	300,000 INR	-
	Maintenance	-	€5,000	-	300,000 INR	-
Audio warnings	Purchas	-	-	-	5,000,000 INR	-
	Installation	-	-	-	500,000 INR	-
	Maintenance	-	-	-	500,000 INR	-

No.		11	12	16	21	33
Water Screen with STOP sign	Purchase	-	-	-	1,000,000 INR	-
	Installation	-	-	-	100,000 INR	-
	Maintenance	-	-	-	100,000 INR	-
Infrared dual beam arrays LaRa-OHVD systems	Purchase	-	-	-	200,000,000 INR	-
	Installation	-	-	-	20,000,000 INR	-
	Maintenance	-	-	-	2,000,000 INR	-
Radar systems	Purchase	-	-	-	10,000,000 INR	-
	Installation	-	-	-	1,000,000 INR	-
	Maintenance	-	-	-	1,000,000 INR	-
In-vehicle early warning systems	Purchase	-	-	-	10,000,000 INR	-
	Installation	-	-	-	100,000 INR	-
	Maintenance	-	-	-	100,000 INR	-
Media campaigns	Purchase	-	€5,000	-	10,000,000 INR	-
	Installation	-	€5,000	-	1,000,000 INR	-
	Maintenance	-	0	-	1,000,000 INR	-
Increasing fines and surveillance	Purchase	-	€5,000	-	5,000,000 INR	-
	Installation	-	€5,000	-	500,000 INR	-
	Maintenance	-	0	-	500,000 INR	-

No.		11	12	16	21	33
Heavy Vehicle Goods licence test	Purchase	-	-	-	2,000,000 INR	-
	Installation	-	-	-	250,000 INR	-
	Maintenance	-	-	-	250,000 INR	-
Better driver education	Purchase	-	-	-	5,000,000 INR	-
	Installation	-	-	-	500,000 INR	-
	Maintenance	-	-	-	500,000 INR	-
Good practice manuals	Purchas	-	-	-	2,000,000 INR	-
	Installation	-	-	-	200,000 INR	-
	Maintenance	-	-	-	200,000 INR	-
Pre-routed maps	Purchase	-	€5,000	-	1,000,000 INR	-
	Installation	-	€5,000	-	100,000 INR	-
	Maintenance	-	€5,000	-	100,000 INR	-
Increased restrictions on vehicle dimensions	Purchase	-	-	-	200,000 INR	-
	Installation	-	-	-	20,000 INR	-
	Maintenance	-	-	-	20,000 INR	-
Accelerometers	Purchase	€4,000	€5,000	-	500,000 INR	-
	Installation	€5,000	€5,000	-	50,000 INR	-
	Maintenance	€4,000	€1,000	-	50,000 INR	-

No.		11	12	16	21	33
Piezoelectric sensors	Purchase	-	-	-	1,000,000 INR	-
	Installation	-	-	-	100,000 INR	-
	Maintenance	-	-	-	100,000 INR	-
Photoelectric beam sensors	Purchase	-	-	-	2,000,000 INR	-
	Installation	-	-	-	200,000 INR	-
	Maintenance	-	-	-	200,000 INR	-
Inductive loop to detect vehicle	Purchase	-	-	-	5,000,000 INR	-
	Installation	-	-	-	500,000 INR	-
	Maintenance	-	-	-	500,000 INR	-
Fibre optic cables	Purchase	-	-	-	5,000,000 INR	-
	Installation	-	-	-	500,000 INR	-
	Maintenance	-	-	-	500,000 INR	-
Country income classification		HIC	HIC	HIC	L-MIC	HIC

Q16: Please specify any additional mitigation measures and related cost and / or any comments below.

No.	Additional mitigation measure and related cost / comments	Country income classification
2	We have a small number of structures which are below regulatory height requirements. We do not record the costs of maintaining signage. Last year we received a cost estimate for purchasing and installing a laser vision system for two structures. The total cost was €380,000 ie €190,000 per structure.	HIC
16	Cost vary significantly between types of systems and configurations (e.g. number of sensors, signage, etc.). Recommend reviewing Georgia DOT Research Project 15-21 Warning Systems Evaluation for Overhead Clearance Detection.	HIC
41	No se dispone de costes de las medidas de mitigación (es otra área de la Organización la que implementa las medidas).	U-MIC

Q17: Based on your available data, please indicate the effectiveness of the following mitigation measures for tunnel strikes: If your organisation has made use of a combination of the following mitigation measures, please specify them and the related effectiveness in the comment below.

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	9.3%	4
	U-MIC	2.3%	1
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	86.0%	37

No.	14	21	22	33	42	43
Static signage	High Medium Effectiveness 50-75%	High Effectiveness >75%	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%
Variable message signs (VMS)	High Medium Effectiveness 50-75%	High Effectiveness >75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%
Beacons	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%
Flashing beacons and/or lights	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Bridge markings	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%

No.	14	21	22	33	42	43
Rumble strips	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%
Speed bumps	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Clear heights signage and obstacles related to dimensional loads	Low Medium Effectiveness 25-50%	High Effectiveness >75%	-	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%
Increased structure vertical clearance	-	High Effectiveness >75%	-	Low Effectiveness 0-25%	-	High Medium Effectiveness 50-75%
Equipment upgrade	Low Medium Effectiveness 25-50%	High Effectiveness >75%	-	Low Effectiveness 0-25%	-	-
Laser vision	-	High Medium Effectiveness 50-75%	-	High Effectiveness >75%	-	-

No.	14	21	22	33	42	43
Crash sacrificial beams	-	High Medium Effectiveness 50-75%	High Effectiveness >75%	High Effectiveness >75%	-	High Effectiveness >75%
Energy absorbing devices	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	High Medium Effectiveness 50-75%
Portal frames	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Medium Effectiveness 25-50%	-	-	High Effectiveness >75%
Hanging chains or bells	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%
Road narrowing techniques	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Cameras and computer vision techniques	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Vehicle redirection in case of excessive dimensions	-	High Effectiveness >75%	-	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%

No.	14	21	22	33	42	43
Audio warnings	High Medium Effectiveness 50-75%	High Effectiveness >75%	-	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Water Screen with STOP sign	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Infrared dual beam arrays LaRa-OHVD systems	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Radar systems	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	High Medium Effectiveness 50-75%	-
In-vehicle early warning systems	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Media campaigns	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	Low Effectiveness 0-25%	-	-
Increasing fines and surveillance	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	High Effectiveness >75%	-	Low Effectiveness 0-25%

No.	14	21	22	33	42	43
Heavy Vehicle Goods licence test	Low Medium Effectiveness 25-50%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%
Better driver education	High Medium Effectiveness 50-75%	High Effectiveness >75%	-	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%
Good practice manuals	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Effectiveness 0-25%
Pre-routed maps	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%
Increased restrictions on vehicle dimensions	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	Low Medium Effectiveness 25-50%
Accelerometers	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Piezoelectric sensors	-	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-

No.	14	21	22	33	42	43
Photoelectric beam sensors	-	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	Low Effectiveness 0-25%	-	-
Inductive loop to detect vehicle	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Fibre optic cables	High Medium Effectiveness 50-75%	High Medium Effectiveness 50-75%	-	Low Effectiveness 0-25%	-	-
Country income classification	HIC	L-MIC	HIC	HIC	HIC	U-MIC

Please specify any additional mitigation measures / combination of mitigation measures and related effectiveness and / or any comments below.

No.	Additional mitigation measures / combination and related effectiveness / comments	Country income classification
12	N/a for tunnels in Irish Rail	HIC

Q18: Based on your available data, please estimate the cost of purchase, installation and annual maintenance of the following mitigation measures for tunnel strikes. Note that installation and maintenance costs should include cost of delays / disruption due to the works. Cost ranges can be inserted, if necessary. Please specify the currency.

	Country income classification	Percentage (%)	Number of respondents
Responses	HIC	2.3%	1
	U-MIC	0.0%	0
	L-MIC	2.3%	1
	LIC	0.0%	0
No response	-	95.3%	41

No.		21	22
Static signage	Purchase	10,000,000 INR	-
	Installation	1,000,000 INR	-
	Maintenance	100,000 INR	-
Variable message signs (VMS)	Purchase	10,000,000 INR	-
	Installation	1,000,000 INR	-
	Maintenance	100,000 INR	-
Beacons	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Flashing beacons and/or lights	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Bridge markings	Purchase	20,000,000 INR	-
	Installation	200,000 INR	-
	Maintenance	200,000 INR	-
Rumble strips	Purchas	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-

No.		21	22
Speed bumps	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Clear heights signage and obstacles related to dimensional loads	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Increased structure vertical clearance	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
	Purchase	50,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Laser vision	Purchase	2,000,000 INR	-
	Installation	200,000 INR	-
	Maintenance	200,000 INR	-
Crash sacrificial beams	Purchase	50,000,000 INR	€7,000
	Installation	500,000 INR	€1,500
	Maintenance	500,000 INR	-

No.		21	22
Energy absorbing devices	Purchase	30,000,000 INR	€1,000
	Installation	3,000,000 INR	500
	Maintenance	3,000,000 INR	-
Portal frames	Purchase	5,000,000 INR	€2,000
	Installation	500,000 INR	€1,000
	Maintenance	500,000 INR	-
Hanging chains or bells	Purchase	2,000,000 INR	-
	Installation	200,000 INR	-
	Maintenance	200,000 INR	-
Road narrowing techniques	Purchase	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Cameras and computer vision techniques	Purchase	2,000,000 INR	-
	Installation	200,000 INR	-
	Maintenance	200,000 INR	-
Vehicle redirection in case of excessive dimensions	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-

No.		21	22
Audio warnings	Purchas	3,000,000 INR	-
	Installation	300,000 INR	-
	Maintenance	300,000 INR	-
Water Screen with STOP sign	Purchase	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Infrared dual beam arrays LaRa-OHVD systems	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Radar systems	Purchase	20,000,000 INR	-
	Installation	2,000,000 INR	-
	Maintenance	2,000,000 INR	-
In-vehicle early warning systems	Purchase	2,500,000 INR	-
	Installation	250,000 INR	-
	Maintenance	250,000 INR	-
Media campaigns	Purchase	50,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-

No.		21	22
Increasing fines and surveillance	Purchase	2,000,000 INR	-
	Installation	200,000 INR	-
	Maintenance	200,000 INR	-
Heavy Vehicle Goods licence test	Purchase	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Better driver education	Purchase	5,000,000 INR	-
	Installation	500,000 INR	-
	Maintenance	500,000 INR	-
Good practice manuals	Purchas	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Pre-routed maps	Purchase	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Increased restrictions on vehicle dimensions	Purchase	10,000,000 INR	-
	Installation	1,000,000 INR	-
	Maintenance	1,000,000 INR	-

No.		21	22
Accelerometers	Purchase	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Piezoelectric sensors	Purchase	1,000,000 INR	-
	Installation	100,000 INR	-
	Maintenance	100,000 INR	-
Photoelectric beam sensors	Purchase	25,000,000 INR	-
	Installation	2,500,000 INR	-
	Maintenance	2,500,000 INR	-
Inductive loop to detect vehicle	Purchase	2,000,000 INR	-
	Installation	200,000 INR	-
	Maintenance	200,000 INR	-
Fibre optic cables	Purchase	50,000,000 INR	-
	Installation	5,000,000 INR	-
	Maintenance	5,000,000 INR	-
Country income classification		L-MIC	HIC

Q19: Please specify any additional mitigation measures and related cost and / or any comments below

No.	Additional mitigation measure and related cost / comments	Country income classification
12	N/a	HIC
33	Coûts identiques que pour les ponts.	HIC
41	No poseo túneles en mi stock de obras de paso.	U-MIC

Q20: It is noted that there are various external factors which can affect the consequences, costs and effectiveness against bridge or tunnel strikes which may not be identified in this high level survey. Please provide below any additional considerations which should be born in mind when reading the results of your survey.

No.	Additional mitigation measure and related cost / comments	Country income classification
2	Traffic management costs are often significant. We do not record the costs of other factors noted in the survey headings. My input relates to bridges only, a colleague will complete the survey for tunnels.	HIC
3	As a rail operator, control over signage, clearance etc at low structures over highways is not within our gift.	HIC
11	Vandalism and theft. Calibration of sensors. Frequency of recordings and transfer of high volume data. Communications (3G/4G/5G) in rural areas.	HIC
12	Enforcement costs are a factor	HIC
21	Local conditions many times govern the possibility of such strikes which can't be covered in such global level surveys.	L-MIC
41	Un factor que en el medio en que trabajo afecta bastante es el robo y vandalismo (de señales y de barandas, por ejemplo). Además del problema cultural que esto refleja, no hay punición por incapacidad de ejercer el poder de policía. Esto disuade a la implementación de tecnologías más modernas y de coste más elevado.	U-MIC

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