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Transportation Research Procedia 14 (2016) 3915 – 3924

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

Understanding the problem of bridge and tunnel strikes caused by over-height vehicles

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Abstract

A bridge or tunnel strike is an incident in which a vehicle that is taller than the clearance underneath the structure (over-height), typically a lorry or double-decker bus, collides with the structure causing damage. This can lead to injuries, fatalities and/or, in worst case scenario, train derailments. Bridge and tunnel strikes are costly and expensive. The annual maintenance costs to repair and service the structure have been reported to range in the tens-to-hundreds of thousands (£) while the average cost per strike ranges between £5,000 to £25,000. In this paper, we present a comprehensive synthesis of the nature and scope of the problem of bridge and tunnel strikes, followed by the current state of practice and current state of research. Bridge and tunnel strikes still occur with high frequency, and prevention systems (passive, sacrificial and active) available on the market are often too expensive. Bridge-owners are seeking an affordable yet reliable system that is cheap enough for widespread installation without compromising the accuracy and performance of such a system.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Over-height detection; over-height vehicle; bridge strike; tunnel strike; bridge collision

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.481

1. Introduction

1.1. Nature & scope of the problem

A bridge or tunnel strike (henceforth BrTS) is an incident in which a vehicle, typically a lorry or double-decker bus, tries to pass under a bridge or tunnel that is lower than their vehicle, therefore colliding with the bridge or tunnel. According to the US Federal Highway Administration, the third most common cause of bridge failure is bridge-vehicle collision damage (FHWA, 2013). Accidental collisions between over-height vehicles (OHV) and bridge superstructures are a globally frequent phenomenon (Xu et al., 2012). There are a number of reasons why BrTS occur, and why drivers of heavy goods vehicles (HGVs) sometimes fail to recognise the warning signs, consequently striking the bridge or tunnel. In sum, BrTS are a major issue occurring throughout transportation networks worldwide.

In the UK, there are more than 10,000 railway bridges crossing over roadways. Of these, 3,400 are considered ‘at risk’, due to their low clearance height (below 5.03 m) (Horberry, Halliday & Gale, 2002). Network Rail (2007a) reports that a vehicle strike with a railway bridge occurs on average once every four and a half hours. In Beijing, China, roughly 20% of bridge damage is caused by OHVs (Sina, 2007). BrTS have a massive impact, not just in terms of damage to the infrastructure, but also on the public transportation system. In the US, Texas is the largest bridge owner, with 51,000 bridges and overpasses. According to the Texas Department of Transportation, each incident costs an average $180,000 USD to repair, and can take a bridge or overpass out of service for up to a year. Texas State reports that repair costs are easy to quantify, but the cost to the public from inconvenience, detours, and congestion is not (Meyer, 2013). In this paper, we present a comprehensive synthesis of the nature and scope of the problem of bridge and tunnel strikes, followed by the current state of practice and current state of research. Benefits and limitations are presented followed by concluding recommendations and remarks.

1.2. Further BrTS statistics: an increasingly frequent scourge

Bridge engineers cited OHVs as the leading cause of damage (81%) to pre-stressed concrete bridges and over a five-year period, 95% of damage to steel bridges in the US was caused by an OHV Shanafelt & Horn (1984). A study by Fu, Burhouse & Chang (2004) surveyed 29 states about OHV collisions, and 62% reported them to be a significant problem, although few were able to provide more detailed statistics. Agrawal (2011) continued the study on the seriousness of BrTS across the US. Of those states, 61% across the country consider BrTS to be a major problem. It is unclear in the report how those state departments measured the level of ‘seriousness’ of the BrTS problem as opposed to other problems. There is a lack of baseline against which to measure seriousness or frequency. For instance, Nebraska perceive BrTS to be a major problem even though there have been only 20 instances whereas Missouri has had 1,691 instances but do not perceive BrTS as a serious problem. This difference is so extreme that it calls into question the whole study. The study hinges on the semantics of a single word (‘serious’), which everyone treats differently. The study is subjective although it adds value by gathering multiple statistics in one place. The significant point to take away is that strikes are still occurring, with great prospects of increasing frequency. In the UK, Network Rail reported 12,829 incidents for the period of 1995 to 2003. In their most recent statistics, National Rail reported 1,708 bridge strikes at underline bridges in 2014; an increase of 9.9% on the previous year.

1.3. Why do BrTS occur?

As the previous section made clear, incidences of OHVs striking low bridges have increased steadily. Galer (1980) investigated two possible reasons for the accidents. Figure 1 depicts a recent scene of a bridge strike collision in Canada. These were drivers' knowledge of their vehicle heights, and drivers' understanding of the low bridge warning signs. Only 12% of drivers were correct in their estimate of their vehicle height and just 27% were within 76 mm of the correct height. In the UK, ‘low clearance height’ warning signs are posted at least 76 mm less than the measured height to allow for a safety margin. In the US, some states post the actual vertical clearance on warning signs, while other states under-report the clearance by up to 304.8 mm. This can have negative effects as drivers are likely to ignore clearance signs knowing that clearance are under-reported causing drivers to question the posted height on the warning signs. According to the 2012 Transport Statistics of Great Britain, there are approximately 260,000 registered UK HGV drivers and approximately 130,000 foreign HGV drivers that enter the UK each year, with a total of 1.5 million journeys. Foreign drivers may be unfamiliar with prohibition and warning signs therefore resulting in further BrTS. Other studies have indicated similar BrTS motivations: 1) Drivers not knowing the height of their vehicles; 2) lack of provision of alternative routes at low bridges; and 3) lack of route planning by hauliers; inadequate signing at and on the approach to low bridges (Agrawal, 2011; Martin & Mitchell, 2004). Other possibilities which are out of the scope of the study are: taller truck heights, more trucks on the roadway and better reporting/logging of strikes, such as access to a mobile device and database recording.

Fig. 1. BrTS, dump truck hit scaffolding after leaving bucket raised on the Burlington Skyway Bridge (Canada), Toronto Sun (2014).

1.4. *The impact & consequences of BrTS*

At the low end of the spectrum (in terms of amount of structural damage and injuries), yet still disruptive, are the traffic congestion and delays caused by BrTS. Strikes can bring traffic to a standstill for several hours while the OHV is removed from the bridge or tunnel, and debris (if any) is cleared. At the low-to-medium end of the spectrum, the top of the vehicle may just scrape the underside of the structure. With medium to severe incidents the structure itself may be damaged, i.e. breaking the reinforcement, exposing the pre-stressing steel and damaging the concrete element. Bridges under railways are critical points on rail networks, and any congestions or blockages have widespread ramifications for railway services. When BrTS occur, services are delayed until the bridge or tunnel has been inspected to determine if the structure has been compromised and whether it is safe to resume operations. If there is any doubt of structural instability, traffic on and under it must be stopped pending the outcome of the structural inspection. Offending drivers are charged and responsible for the recovered costs of damages caused to the bridge, road infrastructure, vehicle and any other damages caused by the strike. This may lead to increased insurance premiums, direct compensation claims and legal fees associated with the strike for the offending vehicle. Some companies may terminate the employee. This causes revenue losses to the railway companies, as track access agreements require reimbursement of train operating companies for the hindrance to track access.

Fig. 2. BrTS accidents based on severity.

Fig. 2 illustrates the levels of severity of BrTS accidents on the transportation network. The spectrum ranges from minor (no casualties) to severe (many casualties). The severe end of the spectrum under ‘fatalities’ can involve an OHV collision with a bridge or tunnel structure resulting in one or more fatal casualties. In most cases, railway services run above the bridge structure, posing a risk to drivers themselves. BrTS have the potential to cause horizontal and vertical displacement of the railway track. This can bring down a bridge completely or, in the worst-case scenario, result in derailment of the train. BrTS are thus a serious problem in the transportation and infrastructure industry, and adequate research directed at prevention has so far been lacking. At first glance, it may seem like the problem of BrTS is a fairly easy problem to solve; however, no matter how well-planned a road system may be; driver error is an ever-present risk. Increasing fines and surveillance may be a partial solution to the BrTS problem, yet such strategies still do not eradicate the problem of human fallibility. This raises the question - Why is the current state of practice insufficient for BrTS prevention?

2. Review of current state of practice

As vehicle heights are continually increasing, and bridge heights built for low traffic areas are often inadequate today, the problem of BrTS is an ongoing nuisance for bridge owners and policy-makers. A multitude of BrTS systems are available for consumer purchase today. Current state of practice is best divided into three categories: prevention, detection and reporting as depicted in Figure 3. To clarify: 1) Prevention treats methods used to prevent BrTS from occurring; 2) Detection treats recognition of occurring BrTS; 3) Reporting treats the way BrTS are reported to authorities.

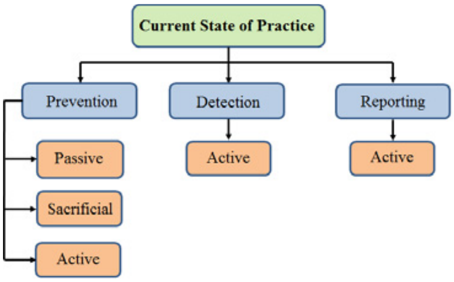

Fig. 3. BrTS current state of practice.

2.1. Prevention systems

Most BrTS technology that currently exists on the market is targeted towards preventing BrTS from occurring in the first place; very few systems are designed to mitigate BrTS impact, as bridge owners are interested in protecting the structure and limiting any risk of structural instability. Under the prevention heading, there are three basic BrTS protection schemes: passive, sacrificial and active systems. According to Cawley (2002), passive signing is estimated to be 10-20% effective in preventing incidents; the sacrificial system is estimated to be 30-50% effective, and the active warning system is estimated to be 50-80% effective. The cost of installing an OHV early warning detection system at bridges is typically much less than the cost of repairing damages due to BrTS (Hanchey & Exley, 1990).

2.1.1. Passive systems

Passive systems are the most common and cost effective type of system that exists. Two common passive methods exist: physical and non-physical. Examples of physical methods include static signage, variable message signs, beacons/flashing signs and bridge markings. The non-physical methods relate to strategic policy mandates including OHV and axle load restrictions, OHV permits, mandatory display of cab height in vehicles. Drivers of OHVs are charged with driver negligence and fined when a truck-bridge collision occurs. In the UK, the Department of Transport (2008) requires all bridges under 5.03m to be posted with prohibition and warning signs. Variable message signs are another commonly used device to warn drivers of low bridges. Horberry, Halliday & Gale (2002) tested various types of bridge markings. The primary function of bridge markings is to make bridge openings appear smaller from a distance. The study used new designs of bridge markings and concluded that the new markings appeared more conspicuous, making drivers more reluctant to pass underneath.

Laservision recently developed an innovative warning system, first installed at the Sydney Harbour Tunnel. The system produces a pseudo-holographic image that appears to float in mid-air, commanding the attention of the motorist and making the ‘STOP’ message impossible to miss (Figure 4). For the average low bridge, the system is expensive (> $100,000) to purchase due to the hydraulic water screens, critical pressure levels to mitigate distortion from wind currents, rapid start techniques, and monitor loops. Other passive systems include flashing beacons and flashing lights to notify OHV drivers of detours. Although the passive systems are a quick fix and easily installed, they do not provide a holistic solution to the problem of BrTS prevention. Such passive systems will need to be used in conjunction with other BrTS prevention systems such as the case with the Sydney Harbour Tunnel.

Fig. 4. Laservision, pseudo-holographic warning sign.

2.1.1.1. Driver education, policies and manuals

At the policy level, bridge owners have attempted to manage the problem of BrTS by implementing permits and enforcing fines to drivers of OH vehicles. In addition, drivers are encouraged to check the height of the vehicle and to display the height in their cab before beginning a journey. According to HM Revenue & Customs, a vehicle over 3.0 m tall must display a notice in the cab showing its full height. From 2002-2012, National Rail [UK] ran a campaign to increase awareness and offer advice regarding low bridges and preventing BrTS. Extensive and comprehensive manuals exist: ‘Good Practice Guides’, protocols for passengers, professional drivers, transport managers and bridge owners. Organisations such as Transport for Scotland have paired up with the National BrTS Prevention Group to develop a ‘Strike it Out’ Campaign. This group include members of road and rail bridge organisations across the UK, as well as freight groups, police and policy makers with various transport bodies. Although these strategies may not directly prevent BrTS from occurring, the aim of the group is to raise BrTS awareness amongst anyone involved with driver training and management; increasing awareness plays a positive role and can be effective for passengers, professional drivers and transport managers.

2.1.2. Sacrificial systems

The second type of BrTS prevention scheme involves physical notification, i.e. sacrificial systems. Sacrificial systems consist of crash beams (also known as collision protection beams, impact beams, bridge bumpers, or cushion systems), hanging chains/strips/bells/headache bars, portal frames and road narrowing techniques such as speed bumps and rumble strips. Crash beams are an effective method of mitigating structural damage to bridge structures from OHV impact (Qiao, Yang, & Mosallam, 2004; Yang & Qiao, 2010). The beam is designed to dissipate the energy from vehicle impact when a BrTS occurs; this in turn will protect the structure itself. However, injury risk still holds. Crash beams may be an effective mitigation strategy but they too only solve part of the problem. Crash beams provide no advance warning to drivers, and act as a last resort for drivers who fail to notice the low bridge warnings. The cost of constructing crash beams can range from £50,000 to £1,500,000 for each approach London Underground (p.c.). Crash beam installation requires permit approvals involving technical expertise from architects, engineers and construction managers. This process can be lengthy and time-consuming.

Hanging metal chains are commonly seen as a modern variant of the typical overhead portal frame used for drive-thru and low parking garages. For vehicles travelling at lower speeds, the metal chains are effective at warning drivers as vibrations are enhanced; however, at higher speeds, the moving vehicle and other background noise decreases the overall effectiveness and can be drowned out by the loud engine noise making it more difficult for the driver to hear the chains (Sandidge, 2012). Sacrificial structures or metal strips cost in the range of $60,000 – $100,000 USD per installation. Road narrowing techniques are commonly used as a preventative method, forcing drivers to cut their speed but alternatively to prevent bridge strikes. The techniques include speed bumps, rumble strips, and chicanes. The installation of such traffic calming techniques may require total or partial road reconstruction leading to congestion and other disruptions to traffic.

2.1.3. Active systems

A third BrTS prevention type is the intelligent transportation system or active warning alternative. At the basic end of active system types, Geographical Positioning Systems (GPS) are used by HGV drivers to locate low bridges. A small unit is installed in the vehicle cab, and as vehicles approach a low bridge, visual and audio warnings are activated within the cab if the vehicle is too high for the bridge. Transport for Scotland has actively encouraged drivers not to trust satellite navigation, as the systems may not contain accurate bridge height information.

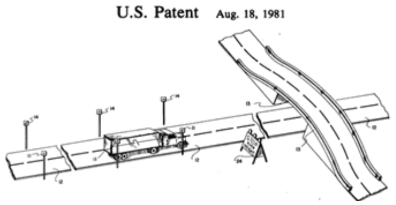

Fig. 5. First OHVDS and warning system, US patent 1981.

Active systems, also known as Early Warning Detection Systems (EWDS), detect and notify drivers ahead of the presence of low structures. This method uses sensors to detect OHVs, provides a visible and/or audible warning, and guides the driver to an alternative route. Lowry & Forster patented the first OHV detection system (OHVDS) in 1981. The system uses a pair of light sources, spaced at a distance from each other, in advance of the low bridge (Figure 5). If the light beam is interrupted, a signal is sent to activate an alert 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 OHV can be transmitted to the highway authorities simultaneously. A study by Mattingly (2003) reports that 38% of the departments of transportation are currently using EWDS. Another system uses a patented Z-Pattern red/infrared dual beam array with the ability to reject ambient light, and eliminates false OHV alarms. A fault detection and alert function also notifies authorities in the event of a power failure. The systems have been reported to cost in the range of $150,000 - $200,000 USD per installation per direction and States (Table 1) with installed over-height systems are generally satisfied with the overall performance, reliability and effectiveness of the system (Agrawal, 2011). Limited literature exists regarding the accuracy of true vehicle height measurements, number of false detections and actual performance of over-height warning systems. However, of the limited literature, Maryland State reported that 20 (during May to July, 2001) and 1584 (January to June, 2001) over-height vehicles were detected by their over-height systems at West Friendship Weigh Station and Port of Baltimore, respectively. However, the sensor data does not include the ratio of over-height versus non-over-height vehicles during these periods (University of Maryland, 2001). In a study by the Michigan Department of Transportation (MDOT) to evaluate the use of OHVDS and warning systems, the cost of an active detection and warning system is estimated to be $110,000 USD, and the estimated 3-year benefit to be $609-000 - $674,000 USD (Cawley, 2002). It is unclear how the cost and savings calculations were determined.

Tab. 1. Agrawal (2011) investigated the effectiveness and overall satisfaction of active systems.

	Missouri	Maryland	Texas	Hawaii	Minnesota	Maine	Alaska	Virginia
System type	Z-Pattern	Optic	Pipes on cable	Infra-red/ LED/ IR	Infra-red	Z-Pattern	Laser	Dual beam
Satisfaction with overall performance (out of 10)	9	8	8	9	8	9	1 (complications with false detections)	8.5
Operational issues with system	Lightening, vehicle strikes	Insufficient space for installation	low speed/ volume roadways only	Difficult to access for maintenance	Damaged by lightening	No	Many, too complex mechanisms, poor truck discrimination	False detections due to sun and bird activity
False detection occurrences	None	Sparse	N/A	1/mth	N/A	1/3mths	Frequent (very sensitive)	Frequent (caused by environmental factors)

2.2. Detection systems

Devices used for collision detection are forms of structural health monitoring tools. The following sensors described in this section are potential solutions for BrTS detection purposes. These tools include active sensors such as accelerometers, piezoelectric, and fibre optic cables used to monitor the activity caused by the strike. Companies such as Strainstall and Trimble provide structural monitoring tools for real-time monitoring and reporting. The systems provide real-time access to the data via mobile and web connections. The sensors are used as a data acquisition system, collecting data at each single nodes for subsequent centralised processing. Based on impact frequency, the sensor can notify authorities if a BrTS has occurred. Accelerometers such as piezoelectric technology are another form of the active sensors, used to parameterise a model of the structure: when damage occurs on the bridge structure, the parameters of this model are measured. The sensor is able to produce measurable electrical output signal without the use of an external power source. Available wireless solutions include wireless sensor network (WSN/Wisden), WiMMS (battery-operated wireless, Modular Monitoring System), advanced micro-electro-mechanical (MEMS) and Macro-Motes, all of which can be used to monitor the vibration characteristics in structural elements and send signals to a remote location for processing and decision-making.

Other methods exist, such as fibre optic cables installed on parapets. Fibre optic sensors have many advantages such as its small size and light weight, accuracy, and affordability, along with its long-term stability and corrosion-resistance form, the cables can be embeddable into composite structures without affecting the mechanical properties of the housing material. In addition, fibre optic cables are insensitive to electromagnetic interference and can withstand high temperatures. The Mass Transit Railway (MTR) system in Hong Kong uses fibre optic cables to notify the station if a bridge has been struck. The technology uses a collision notification system to relay the message back to the control room. Other available sensors include Fabry-Perot sensors (which have high sensitivity tolerances, can be repaired if damaged and have up to 1000 Hz sampling rate), long gauge sensors (which calculates deformation over average gauge lengths), and distributed sensors (which measure changes in light waves at various frequencies over long distances).

2.3. Reporting systems

Many BrTS accidents that occur today are not reported, and bridge owners are left to remedy the damages caused by drivers. Bridge owners have been installing closed circuit television (CCTV) cameras near their structures, to capture the license plate of the offending driver. CCTV technology can be used in combination with communications to view incident detection and verification, weather and roadway conditions monitoring. The images can be sent through wireless communication to a remote location or server using network signals. The city of Dublin installed a pilot CCTV system on a bridge that experiences frequent strikes. Footage is recorded and, if notification of a BrTS is received, the videos can identify the offending vehicle. Data acquisition systems are another form of reporting, often used on-site and connected to sensors. The systems can be accessed through remote communication, and transmitted continuously to the central maintenance office (Mehrani, Ayoub, Ayoub, 2008). Other reliable data transferring methods include wireless sensor system that uses end-to-end, hop-by-hop recover, and low-overhead data time-stamping that does not require clock synchronisation. The benefits of the wireless approach are less interference with the structure, inexpensive (~ $100) and easy to install.

2.4. Benefits & limitations of state of practice

The overall picture suggests the availability of many effective detection and reporting systems for BrTS. On the preventative side, effective methods are sparser. BrTS still occur with high frequency, and BrTS prevention systems (passive, sacrificial and active) available on the market are often too expensive to encourage widespread implementation. Passive systems may be a ‘quick fix’ and cost effective, but these passive systems are not sufficiently effective, as scrape marks are often evident on the underside of bridges in the UK. Bridge owners aim to minimise the occurrences of BrTS and, as a consequence, to minimise inspection, maintenance and repair costs. The need to develop an affordable yet reliable solution is crucial to prevent future strikes posing risks to public civil infrastructure. The solution should be affordable for the average low bridge, not just targeted at problematic cases.

3. **Review of current state of research**

This section presents the latest developments in bridge and tunnel strike research. The current state of research in BrTS may be classified into two categories: passive computer vision methods, and active sensing methods. Computer vision methods include imaging and vision-based sensing, which passively measures the ambient electromagnetic radiation - the standard video camera being the main example. The active sensing methods include sensor and laser methods consisting of optoelectronic single- or dual-eye infrared, visible beam, or laser beam detection system. The active method triggers a warning to the driver either by visual or audible alert when the beam is interrupted or broken by a vehicle. The following section reviews the current state of research, with a focus on computer vision and sensing methods from the perspective of performance but also cost efficiency.

3.1. Computer vision methods (Passive)

Several intelligent transportation systems use passive computer vision-based methods for vehicle detection, vehicle classification and license plate recognition. As part of these systems, important functions such as frame differencing and motion detection are essential in OHV detection. The use of such passive methods has not been widely explored; however, the limited research helpfully exposes the gaps in computer vision methods. Currently, there are no real-time computer vision systems on the market for OHV detection. A study by Khorramshahi, Behrad, & Kanhere (2008) presents a method for OHV detection. Their algorithm uses features selected and tracked using Kanade-Lucas-Tomasi (KLT) and blob extraction algorithms. The system uses a cubic detection zone to obtain vertical projection of a feature point on the road using blobs in 2D coordinates. Limitations of the study showed that height estimations of feature points are less accurate when occlusions and shadows occur. Other approaches use the single view metrology algorithm to find an upper and lower bound on the image to extract the height measurements of objects and vehicles. Shao, Zhou, & Chellappa (2010) uses a similar framework, however, the detection accuracy suffers when the vehicle is partially occluded in the scene. For example, when the wheels are occluded, the algorithm is not able to accurately determine the top and bottom boundaries of the truck therefore unable to compute the height. A reliable OHV system must be able to detect all overheight vehicles (despite its shape and size), to provide sufficient warning to the driver, therefore the accuracy of the system plays a crucial role in determining the appropriate system for installation.

In similar work, Park et al. (2015) use single view metrology to find the orthogonal axes in the image view to locate the upper and lower boundaries of box-shaped trucks in the scene. The research demonstrated promising initial results; however, major refinements are still required for occlusions, shadows and inaccurate line detections. Inaccurate height measurements of vehicle heights can be attributed to incorrect upper and lower reference points selected. This occurs when the algorithm encounters noise due to imperfections of the blob detection and line segmentation. In addition, when occlusions and shadows are present, upper and lower boundaries may not be fully visible for the algorithm to perform a height measurement of the moving vehicle in the scene.

Computer vision methods, although ripe for improvement, already constitute low cost and high performance alternatives to current laser and infrared beam systems. Imaging and vision-based solutions have shown great potential and advancement in recent years, and vision-based technologies can be purchased and installed at a fraction of the cost of traditional methods, making them potentially highly desirable for bridge owners. However, the methods have not been adequately tested in real time, and further research is needed to be competitive with current systems.

3.2. Sensor and laser methods (Active)

In this section, three methods are described using active sensor, light and radar technology. First, Song, Olmi, & Gu (2007) develop an OHV bridge collision detection and evaluation system using piezoceramic transducers for bridge impact detection and health monitoring purposes. A circuit was designed to detect impact and activate a digital camera to take photos of OHVs as they collide with a concrete bridge. The proposed system has shown potential to provide monitoring and accident notification, however, the sensor only solves part of the problem. When paired with prevention and reporting tools, the impact sensor is a good option as a detection tool. Massoud (2013) presents an alternative approach, using the laser & light sensing modality in conjunction with a camera to transmit license plate numbers of OHVs to traffic administration bodies. The laser system was shown to function well, however, such sensing technology methods are representative of those currently on the market, and they provide little incentive for asset owners, as the outdoor infrastructure installation requirements are financially prohibitive (> \$100,000 per direction). The latest contribution is the LaRa-OHVD (Laser Ranging Over-Height Vehicle Detection) sensing modality mounted on the bridge structure. Although the device shows great potential in accurately providing height measurements of trucks, its physical location on the structure renders it susceptible to damage or destruction in the event of a strike, which is less than optimal.

The radar type active method consists of a more complex sensing mechanism, used to measure the range or distance of objects passing through its field of view. For example, Urazghildiiev et al. (2007) propose overhead installation of a radar system for detecting both the height and the vertical profile of passing vehicles in the sensing lane. The vehicle profile is used to classify vehicle types. Their radar technology performs well under most weather and illumination conditions. However, depending on the shape and size, the single radar beam may not provide an accurate height measurement of the vehicle. Consider the scenarios in Figure 6, a flatbed carrying an excavator and a dump truck with an extended muffler in the scene, the radar may not provide a true representation of the vehicle height in non-box-shaped cases. In cases of irregularly shaped vehicles, the radar beam may not be aligned with the highest point of the vehicle, thereby eliciting false negatives in the detection process. In addition, the approach requires expensive additional outdoor infrastructure, as one unit is required for each lane of traffic.

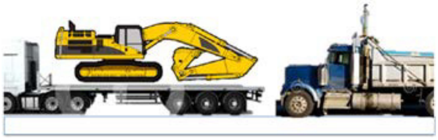

Fig. 6. Irregularly shaped vehicles.

4. **Conclusions and recommendations**

In this paper, we have presented a comprehensive synthesis of the nature and scope of the problem of bridge and tunnel strikes, followed by the current states of practice and research. We have noted that effective OHV prevention measures exist in the form of passive and sacrificial systems, but we emphasise that they do not suffice for a holistic solution. Passive systems, for example, are considered to be ‘quick fixes’ but regardless of the number of warning signs put in place, some drivers will continue to collide with the bridge; this is evident from the obvious fact that most low bridges have at least some warning in place, yet strikes persist. Scrape marks are visible on the underside of bridges; therefore the available BrTS data may only manifest a fraction of the problem, as many strikes go unreported. Therefore, in such instances, detection and reporting tools are crucial components, not only to prevent such strikes from occurring, but also as evidence to identify the responsible vehicle. Sensors and accelerometers are recommended as an additional component to classify the frequencies of BrTS and to determine the level of severity caused by strikes. In practice, especially in rural and low-traffic areas, BrTS may not be reported, leading to a potentially unsafe bridge continuing to operate. Authorities have generally taken limited action in such matters, and the consequences can be catastrophic; a bridge assessment system is ideal to handle instances such as these. The system would notify and provide authorities with an assessment of each strike; categorised by severity. Bridge owners can then use this information as guidance to determine the appropriate course of action. This will in turn minimise the number of strikes that go unreported and prevent unsafe structures from continuing to operate.

Laser and infrared beam systems have been shown to be largely reliable yet generally unaffordable. Bridge owners have chosen not to use EWDS at non-critical low bridge locations due to high installation and maintenance costs. The biggest issues for bridge owners are affordability and reliability of a BrTS system that is cheap enough for widespread implementation, without compromising accuracy and performance. Vision-based methods have so far received little attention as a potential solution to the problem of BrTS management. Despite their potential significance, there has been limited research conducted in computer vision on OHV detection, and no vision-based system exists on the market. If we were able to retain the benefits of the laser beam system in an affordable single camera set-up, this would eliminate the need for additional outdoor infrastructure. It would also decrease the overall installation costs by an order of magnitude less than traditional systems by making poles, transmitters/receivers, and looping systems superfluous. Videos can be time-stamped and used as evidence in the event of a strike. We hypothesise that a vision-based approach able to accurately detect OHVs using a single camera is the most affordable solution for bridge owners, providing a holistic answer to the problem of BrTS, especially when paired with detection and reporting tools.

Acknowledgements

This material is based upon work supported by Transport for London. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the institutes mentioned above.

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