Safety Devices and Machinery Accident Prevention: An Enigmatic Conundrum

D.J. Edwards[1], E.A. Pärn[2] and Owusu-Manu, D[3] and Sing, M.C.P.[4]

[1]David J. Edwards, (corresponding author) Birmingham City University, Birmingham, B5 5JU, UK. Email: drdavidedwards@aol.com

[2]Erika A. Pärn, Birmingham City University, Birmingham, B5 5JU, UK. Email: Erika.Pärn@bcu.ac.uk

[3]De-Graft Owusu-Manu, Kwame Nkrumah University of Science and Technology,Ghana Email: d.owusumanu@gmail.com

[4]Michael, C.P. Sing, City University of Hong Kong, Hong Kong SAR Email: mcpsing@outlook.com

ABSTRACT

Fatalities and near fatal accidents relating to construction plant and machinery continue to plague industry despite stringent safety regulations and draconian enforcement that frequently imprisons the operator but not site management. Against this backdrop, technological advancements have seduced practitioners to procure additional aids and devices to bolster safe systems of working when operating machinery. This research first reviews current provisions for the supply and manufacture of machinery within continental Europe and exposes ambiguity between legislation and enforcement regulation. To address this ambiguity and with a desire to improve machinery safety, additional retrofit safety devices have been manufactured and are frequently fitted to machinery. Yet even with such devices, accidents persist and several fatal or near fatal case study incidents are reported upon to give a rare glimpse into accident causation. A discussion of the findings suggests that a broad range of causal factors are involved and that the operator and site manager are pivotal to ensuring that safe system of working are adhered to. The work concludes by presenting a new theory of operator cognitive over-processing and sensory overload, and questions whether less emphasis should be placed upon technological advancements in exchange for basic management, training, competence and supervisory arrangements.

KEYWORDS

Construction safety, safety aids and devices, construction plant and machinery and case studies.

INTRODUCTION

Types of off-highway plant and machinery are myriad and include road rollers, articulated or rigid dump trucks, cranes and excavators. Each machine shares a symbiotic linkage with the operator and represents a mechanical extension of human physicality and cognitive ability in undertaking an operation (Edwards *et al.*, 2016). However, as globalization intensified over recent decades, an insatiable drive for improved productivity performance and concomitant profitability grew also. Reacting to customers' demands, original equipment manufacturers (OEMs) acknowledged that human intervention impacted upon machinery productivity performance in various ways and sought to better understand these through work study (*ibid*). Modelling of work study data revealed the extent to which operator performance, and other environmental factors (such as soil type and meteorological conditions), impacted upon machine performance – including safety performance.

A renewed focus upon operator training and competence development followed but new knowledge acquired on human behaviour revealed that maximizing machinery safety whilst simultaneously raising productivity efficiency was a persistent issue. The natural extension was to engineer-out human error or introduce new technological developments to mitigate risks posed. Despite this intensive period of activity, innovation and advanced technological development, fatal and near fatal accidents continue to plague industry and have led to stringent regulations and draconian enforcement. Often the operator bears the brunt of enforcement and is subjected to heavy fines, or even imprisonment, whereas site managers are prosecuted under the guise of the organisation.

Against this backdrop, this initial inductive investigation seeks to re-examine why fatal or near fatal accidents persist. The research aims are present a brief overview of legislation and regulation pertinent to the manufacture of plant and machinery to European standards of conformity as a prelude to discussing the various types of safety devices that can be fitted (as standard or retrofitted) to augment safety. The research then presents additional insight on accident causation via case study analysis of four incidents that were either fatal or near fatal. The objectives of the work are to: raise awareness of causal factors that lead to accidents; assess whether current technological or engineered-out safety solutions are effective in reducing accident occurrence; and generate new theoretical perspectives on the safe operation of plant and machinery on site.

LEGISLATION AND REGULATION: A VEXATIOUS ISSUE

Within continental Europe, new items of mobile construction plant and machinery are produced by OEMs to exacting quality controls that dictate minimum levels of conformance, as stipulated under the Supply of Machinery (Safety) Regulations 1998 (as amended) which implement the European Machinery Directive 2006/42/EC ((HMSO, 2011). These machines are CE (Communauté Européenne) marked to inform customers that they meet all relevant essential health and safety requirements and that they are fit for intended purpose (HSE, 2011). The regulations are enforced via relevant safety legislation such as Section 6 of the Health and Safety at Work etc Act (1974) which places a duty on: *"…any person who designs, manufactures, imports or supplies any article for use at work...to ensure, so far as is reasonably practicable, that the article is so designed and constructed that it will be safe and without risks to health..."*

The legislative requirements also apply to retrofit manufacturers who may install additional aids and devices onto a machine, for example, a 'quick hitch' latching device fitted to an excavator which allows quick fitting of attachments to the dipper arm. However, there is some discrepancy between legislation and regulation in certain areas, for example relating to an operator's field of view. Whilst the European Machinery Directive 2006/42/EC states that conformant machines are safe, regulation 28[e] within the The Provision and Use of Work Equipment Regulations 1998 (HMSO, 1998) states that: *"Where the driver's field of vision is inadequate to ensure safety then visibility aids or other suitable devices should be provided so far as is reasonably practicable."* This implies that a CE marked machine provided by OEMs may require retrofitting for it to be safe and indeed, should a 'struck by machine' incident occur, the operator/ owner could well face prosecution under this PUWER 1998 regulation.

SENSORS AND SAFETY DEVICES

Off-highway plant and machinery items are incredibly sophisticated in terms of types available and modes of operation and maintenance; for an operator to become truly competent takes years of practical machine operation under good supervision. Unfortunately, this is not the case within the construction and civil engineering industries where operator competency cards can be acquired in a matter of days or weeks. Additional sensors and safety devices have been primarily developed to assist the operator perform plant operations efficiently and effectively but also safely. Amongst the proliferation of devices available, the following are the most common and widely adopted – whilst an excavator serves to illustrate the implementation of these devices, other machines could equally implement many of them.

Condition based monitoring

Maintenance is a necessity for sustaining machinery availability and reliability, thus preserving a machine's working life and extending its residual value (Edwards *et al.*, 2003; Edwards and Holt, 2009). On-board condition monitoring techniques have capitalized upon sensor technology to provide direct, on-line streaming of mechanical health (or otherwise) of critical components within a machine's compartment (Heng *et al.*, 2009; Turner and Huff, 2003; Choy *et al.*, 2003). The major beneficial ramification of on-board condition monitoring is that safety is improved demonstrably whilst simultaneously parts and components are no longer replaced on a time-usage basis thus extending their useful life and reducing concomitant costs.

Telematics

Telematics is an interdisciplinary field that includes mobile communications, software engineering and electrical engineering. Applications on plant and machinery are varied but include global positioning to accurately perform excavation and highway works, autonomous vehicles and cloud-based monitoring of machinery health/ performance (Edwards *et al.*, 2003).

Automatic operation capabilities

Automatic operation capabilities include various means of adjusting machine performance to account for operator error and optimise machine performance. Predefined computer programmes can be used but increasingly sophisticated machine learning algorithms intelligently adjust machine operation and performance.

Safe load indicators

Safe load indicators essentially provide either an audible alarm or visual display unit to inform the operator if the machine is working within its safe working load (SWL) at various boom or arm geometries and is particularly useful for cranes and other lifting equipment (including excavators when used as cranes).

Stability indicators

Machine instability remains a persistent problem and each year operators are killed as a result of machinery overturn (c.f. Lezon, 2015; Akers, 2015; Pourramedani, 2016). Stability indicators monitor the machine's centre of gravity and how this changes under various operational conditions (including those relating to lift height, rated capacity, speed of travel and ground conditions). A number of commercial products are available from companies such as Prolec (http://www.prolec.co.uk/en/home/), Spillard Safety Systems (http://www.spillard.com) and Equipment Safety Systems (http://www.eqss.com.au) but research institutes are currently looking to develop telematics/ cloud based devices that integrate machine learning to holistically monitor a broad range of dynamic operational parameters (Edwards *et al.,* 2016).

Visibility aids

Machine visibility incorporates technologies that increase the plant operator's field of vision (FOV) and alert other workers and members of the public to the machine's operation. Almost a quarter of all deaths involving vehicles at work (struck-by or crushing) occur during reversing (Edwards *et al.,* 2004; HSE, 2009; HSE, 2017). To expand FOV a number of aids and devices are available but the most common are: a) *pencil beam mirrors* – these are fitted as standard by the OEM and are CE marked; b) *convex mirrors* – these are often retrofitted by the machine owner/ operator and are designed to give a wider FOV but are not currently CE marked, so must not be used to replace pencil beam mirrors because the modification would breach conformance under the European Machinery Directive 2006/42/EC; c) *rear-view cameras* – these are often retrofitted by the machine owner/ operator and allow the driver to see obstructions or pedestrians at the rear of the vehicle; and d) *image splicing* – this represents an extension of the singular rear view camera and involves a number of cameras being placed around a machine at strategic viewpoints with accompanying software that blends images taken into one 360 degree view around the machine. To alert site workers of machines in operation, flashing mast or canopy lights in distinctive colours (often red, amber or green) are fitted to the machine.

Audible alarms

Audible alarms not only alert pedestrians to a moving plant item (for example, by use of a reversing alarm) but can also notify the operator of pedestrians walking within the operating envelope of the machine or any stationary obstructions that could damage, or be damaged by, the machine (for example, sonar and radar systems). Radio frequency identification tags (RFID) worn by site personnel and fitted to other machines produce an audible alarm inside the operator's cab when the machine's safe operational envelope is breached.

Deadman switches

Deadman switches are primarily designed to isolate the machine and come in two key variants – *remote* and *on-board*. A *remote* deadman is operated by a banksman if operator error, unsafe operation or incapacitation is anticipated, essentially acting as a failsafe back-up procedure. An *on-board* deadman is usually fitted to the operator's seat to deactivate the machine when the operator leaves the seat to exit the machine, but can also be fitted to safety-covers and guards that protect rotating and reciprocating parts – when the guard is opened, the engine and moving parts stop to prevent the operator from becoming entrapped or entangled.

Safety-locking lever

A safety-locking lever is fitted by the OEM to reduce the risks associated with operators entering and exiting the cab of some machines such as excavators (HSE, 2014). The safety-locking lever has to be raised to allow cab access and egress and when in the raised position, the hydraulics are isolated within the main joystick controls. This avoids inadvertent operation of the machine which has occurred with plant items such as telescopic handlers and led to several prominent fatal accidents, grotesquely labelled as 'scissoring incidents.' Scissoring occurs when an operator leans out of a broken boom-side window and inadvertently operates the controls with other parts of their body or clothing; a raised boom descends and crushes the operator beneath it.

Fully automatic quick hitches

A quick hitch is a device designed to facilitate the efficient connection and removal of attachments to plant and equipment with a primary purpose of increasing safe production on site. It is often affixed to the end of the dipper arm of an excavator, as a means of enabling different types and sizes of attachment (such as buckets, grapples and rock breakers) to be changed at will (Edwards, 2008). The fully automatic hitch system not only retains the attachment with a hydraulically operated latch but also engages a safety device as part of the hydraulic function. This safety device may take the form of a hydraulic check valve and/ or sprung mechanism to stop the retaining latch from inadvertently opening (*ibid*). Although a fully-automatic hitch can be operated entirely from inside the cab, human inspection to ensure a safe connection and to conduct regular maintenance is advised.

CASE STUDY INCIDENTS

Four recent case studies of fatal or near fatal accidents are examined to identify potential contributory causal factors and determine whether safety sensors and devices could have mitigated the risk of the incident occurring.

Case study #1: *A 14 tonne wheeled excavator being utilised to lift a concrete skip (alternatively known as a 'hopper') to place wet concrete into a foundation overturns.*

The site foreman that decided to lift the concrete skip (which was within the machine's load rating) did so without a lifting plan for the operation and furthermore, was unlicensed to operate the machine. Anecdotal interviews with site witnesses suggested that the foreman slewed the machine to the dump target at a high speed and lost control of the machine's stability, causing it to overturn. Fortuitously, the foreman escaped with only minor injury and the machine incurred just slight damage. One observer stated: "*He [the foreman] should not have been on the machine and you could tell that he didn't know how to operate it."* Having turned the machine over, the site foreman then ordered an operator of a 20 tonne tracked excavator to lift the 14 tonne machine back to an upright position. For this impulsive second lift, there was again no lifting plan and it is by sheer luck that the 14 tonne machine was recovered despite it exceeding the load capacity of the 20 tonne machine. As a result of these two incidents, all staff involved (including site safety supervisory staff) were dismissed from employment. A senior safety advisor for the company said: *"This simple task was a disaster from start to finish and we're very fortunate that no one was killed. We have a strict zero policy on these incidents and all our guys are aware that in the event of a machine overturning, we have specialist equipment to recover the machine. There was no excuse for this behaviour. The real problem stems from the fact that the wrong machine was initially selected - a concrete pump should have been hired. The foreman should have known better as he was an experienced worker and site safety personnel on site should never have allowed this to happen."*

Case study #2: *A 20 tonne tracked machine being used to grade the side of an embankment had the bucket detach from the fully automatic quick hitch.*

A tracked excavator fitted with a quick hitch device was being used for both breaking concrete with an impact hammer and undertaking mass excavation works with a bucket. A dangerous occurrence occurred and an investigation was launched. An eye witness stated: "*We saw the operator attach the impact hammer to the quick hitch and crowd the hammer into the dipper arm of the machine. He then slewed over the heads of site management who were on site discussing* *site progress and oblivious to the imminent danger. As the operator straightened out the impact hammer [estimated to weigh 15-20 tonnes] to commence concrete breaking – it fell off within feet of site management!"* Despite being a 'fully automatic' hitch it failed to connect to the pins attached to the breaker. The inspection was inconclusive but two possible causes were apparent: either the operator had failed to correctly engage the pins before slewing to the point of breakout; or clay and other substrata material had prevented the hitch from connecting correctly. Further investigation also revealed that the retaining bolts (used to hold bucket pins into position) had been sheared off and welding around the pins attached to the impact hammer was severely worn – incipient and catastrophic engineering failure could have caused a fatality or major accident. More significantly, the quick hitch attachment alarm (that notifies the operator when the attachment is securely attached) had been tampered with and was inoperable.

Case study #3: *A rough terrain masted forkilift truck overturns when used by an untrained operator on an unloading task.*
A sub contracted transport driver delivering timber to site narrowly escaped serious injury when he decided to use a 'parked up' rough terrain masted forklift truck to unload the timber from his trailer (Figure 1). The driver was neither authorised nor trained to operate the machine and whilst attempting to unload the timber he drove too close to an open excavation which caused the excavation edge to collapse and the forklift to subsequently overturn. A review of this incident revealed that the driver was also not wearing the seatbelt (in accordance with manufacturer's instructions) and that the incident occurred early in the morning when other operatives were not on site. This incident highlights several issues (e.g. the provision of adequate transportation routes, operator training and competence, site security and management and lone working).

Figure 1 – Overturned masted forklift truck

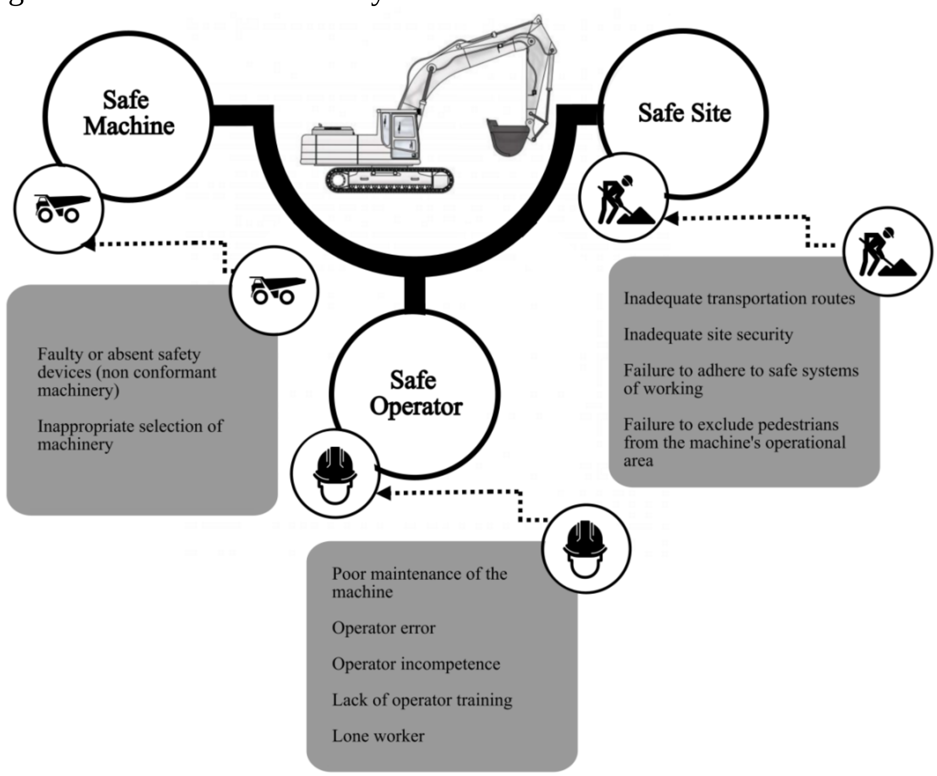
Case study #4: *An operator is killed whilst conducting maintenance on a top cutter.*
A top cutter is a popular and useful piece of equipment employed within the roadworks and utilities industries because it can provide accurate cutting depth, dust suppression and high productivity rates. It is essentially a milling machine, consisting of a housing that contains a rotating drum fitted with numerous tungsten carbide mingling picks which can cut trenches through asphalt, concrete or reinforced concrete for utility lines and pipes. A worker was fatally injured when he became entrapped between the rotating drum and housing of a top cutter. A senior manager within the

company said: *"We suspect that the operator got off the machine to conduct routine maintenance on the drum – several teeth were missing and needed to be replaced. The drum itself was very slowly rotating and the operator would have to have used a special tool to remove and then replace the missing teeth. We are not certain but we think that the operator must have had a piece of his clothing become entangled on the drum and was slowly drawn into the inner workings of the drum. This would have been an excruciatingly painful and slow death."* Subsequent Health and Safety Executive (HSE) investigations revealed that a number of safety devices that prevent access to the rotating drum whilst in motion may not have been working as intended by the Original Equipment Manufacturer (OEM). Also a significant factor was that the machine did not have a working deadman switch on the operator's driving seat.

DISCUSSION

These four case studies presented highlight that it is a multitude of interrelated factors coalesce to create conditions that lead to a fatal or near fatal incident. These factors include operator incompetence, inadequate site supervision, inadequate site security and poor maintenance of the machine (refer to Figure 2). It would be impossible to determine whether more accidents would have occurred within industry with or without additional safety devices being fitted to the machine. However two important findings are apparent.

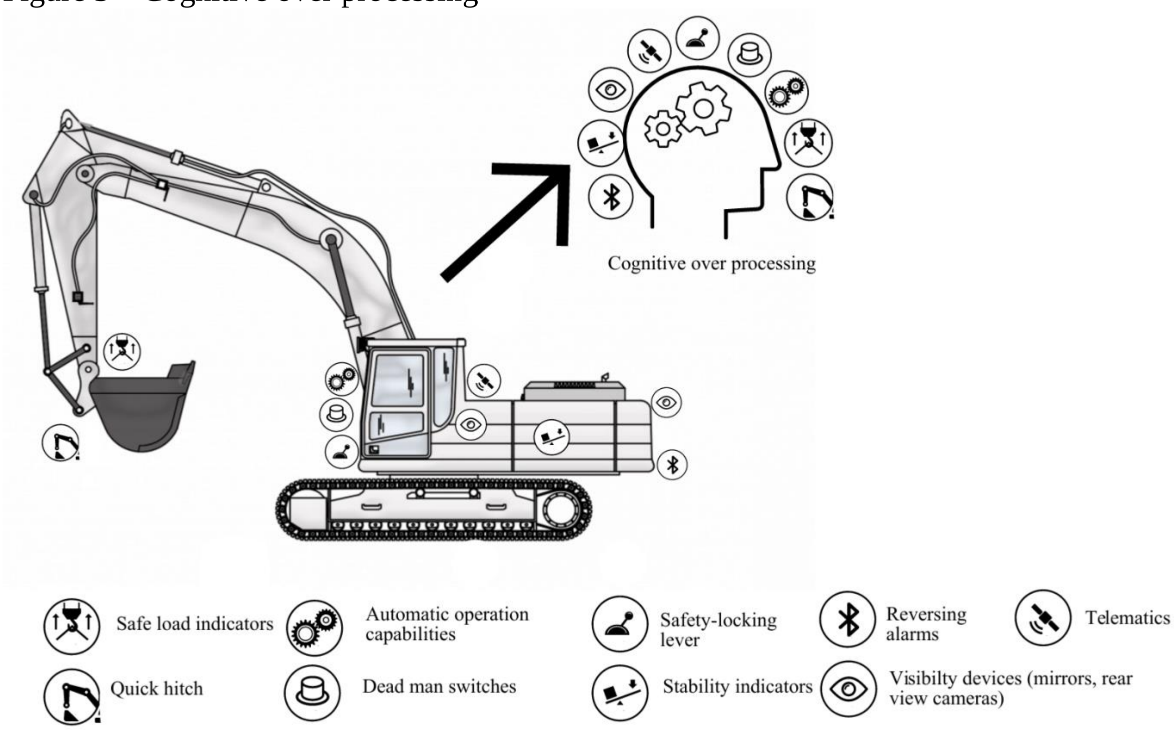
Figure 2 – Causes of case study fatalities/ near fatalities



First, the evidence suggests that human error, poor judgement, inexperience, unmitigated incompetence and a belligerent disregard for safe systems of working (on behalf of operators and site supervisors) were significant factors in all cases. Behavioural education and training may well mitigate these risk factors but not all because in some instances the operator and site management lacked basic knowledge of safe machine operation – such represents a fundamental building block in operator competence development. Second, in two of the cases, safety devices had been tampered with and were inoperable. Although it would be difficult to assert that this was a sole causal factor, it would have certainly contributed to the accident and provides further evidence of a general disregard for personal safety and the safety of others working on site. Moreover, it illustrates how easy it is to deliberately vandalise safety devices or manipulate them so that they appear to be fully functional when in reality they are inoperable. It would seem that whilst advantaged technological and engineered-out solutions are becoming increasingly sophisticated, operators are becoming equally adept at disabling the device! These issues are further exacerbated by inexperienced and ill-informed site management who are often ill-prepared to manage a complex array of machinery – each with their own bespoke set of operation and maintenance requirements.

One emergent theory is that modern operators are subjected to *cognitive over processing*. An amorphous range of safety related macro-level legislation, management protocols and procedures must be complied with - in addition, micro level company procedures, site safety controls and audible, visible and functional controls and devices integral to the machine itself must be safely managed and operated (refer to Figure 3).

Figure 3 – Cognitive over processing



The exponential pace of technological advancement further expands the machine's capabilities via retrofit devices to add further cognitive stimulation and additional devices to monitor and control. Against this backdrop of burdensome challenges with regards operator safety compliance – lest it be forgotten that a physical job must also be completed under production pressures! So against a constant barrage of sounds, visual display screens and regimented orders from site management, an operator with indomitable spirit must persevere to meet escalating production demands and generate profits for the organisation. At some juncture, those in charge of management and the procurement of technologically advanced machines and devices must consider the old cliché *"just because we can do it, doesn't mean that we should do it."*

CONCLUSIONS

A holistic safe system of work is founded upon aspects pertinent to achieving a safe site, safe machine and safe operator. An organisation's management systems, procedures and protocols must be developed around these broad considerations; at this juncture any additional safety aids and devices fitted to the machinery augment company policy and represent the last line of defence. Yet despite the ubiquitous managerial, technological, legislative and educational advancements within practice and academia, plant and machinery fatalities and near fatalities continue to plague the construction and civil engineering industry. The case studies presented within this research provide a mere glimpse of accident causation to stimulate wider academic and industry debate in this important area of construction management science. However the work does illustrate that whilst *errare humanum est* may apply, new theories are required to explain causal factors in greater detail and pragmatic solutions are needed to curtail this tragic waste of life. There is much to extol about the virtues of basic management, training, competence and supervisory arrangements and less reliance upon the seductive qualities of technology or magic bullet solutions to complex safety issues. A hard-line luddite stance is not being taken here, rather it is acknowledged that safety sensors and devices can improve operator safety and machine performance but these must be rationalised or converged into more intelligent systems that self-gauge environmental and operational parameters. This would be preferable to the current menagerie of devices that work and operate independently to each other and cause operator cognitive over processing which in turn could lead to deliberate vandalism of the device. Ultimately, advanced intelligent technology will enable a true symbiosis between man and machine to be achieved and consequential safety equilibrium but before reaching this point a far more extensive examination of such incidents and the lessons learnt is required.

REFERENCES

Akers, T. (2015) Man Sustains Fatal Injuries After Excavator he was Driving Overturned and Crushed Him, The Courier Mail, Brisbane, Australia. Available via: http://www.couriermail.com.au/news/queensland/man-sustains-fatal-injuries-after-excavator-he-was-driving-overturned-and-crushed-him/news-story/f0174819b787e781a3bc8edd683263dd (Accessed on: 15th May 2016)

Choy, F.K., Mugler, D.H. and Zhou, J. (2003) Damage Identification of a Gear Transmission Using Vibration Signatures, Journal of Mechanical Design, Vol. 125, No. 2, pp. 394-403

Edwards, D.J., Harris, F.C. and McCaffer, R. (2003) Management of Off-highway Plant and Equipment, E and FN Spon: London.

Edwards, D.J., Robinson, B. and Loxton, N. (2004) A Practical Guide to All Round Awareness (ARA), Off-highway Plant and Equipment Research Centre (OPERC). OPERC Publication: Dudley. ISBN 0 947974 26 1.

Edwards, D.J. (2008) Guidance on the Safe Use of Excavator Quick-hitch Devices, Off-highway Plant and Equipment Research Centre (OPERC), Dudley, UK. ISBN: 978-1-906977-01-6

Edwards, D. J. and Holt, G. D. (2009) Construction Plant and Equipment Management Research: Thematic Review, The Journal of Engineering, Design, and Technology. Vol.7, No. 2, pp. 186-206

Edwards, D.J., Pärn, E.A., Love, P.E.D. and El-Gohary, H. (2016) Machines, Manumission and

Economic Machinations, Journal of Business Research, Vol. 70 pp. 391-394. DOI: http://dx.doi.org/10.1016/j.jbusres.2016.08.012
Heng, A., Zhang, S., Tan, A.C.C. and Mathew, J. (2009) Rotating Machinery Prognostics: State of the Art, Challenges and Opportunities, Mechanical Systems and Signal Processing, Vol., 23, No. 3, pp. 724–739.
HSE (2009) The Safe Use of Vehicles on Construction Sites: A Guide for Clients, Designers, Contractors, Managers and Workers Involved with Construction Transport, HSG 114, 2nd Ed., London: HSE Books. Available via: http://www.hse.gov.uk/pubns/priced/hsg144.pdf (Accessed: 18th January, 2017).
HSE (2009) Workplace Transport Safety: A Brief Guide, INDG 199, Health and Safety Executive, London. Available via: http://www.hse.gov.uk/pubns/indg199.pdf (Accessed: 18th January 2017).
HSE (2011) Supplying New Machinery, INDG 270, Health and Safety Executive, London. Available via: http://www.hse.gov.uk/pubns/indg270.pdf (Accessed: 18th January 2017).
HSE (2014) Inadvertent Operation of Controls in Excavator Plant - Insight, Analysis and Recommendations for Prevention by Design, Health and Safety Executive, London. Available via: http://www.hse.gov.uk/research/rrpdf/rr1000.pdf (Accessed: 18th January 2017)
HSE (2017) Accident Case Studies, Health and Safety Executive, London. Available via: http://www.hse.gov.uk/workplacetransport/sitesafe/casestudies/c-lessons-learnt.pdf (Accessed: 18th January 2017).
HMSO (1974) The Health and Safety etc. Work Act 1974. London: HMSO. Available via: http://www.legislation.gov.uk/ukpga/1974/37/pdfs/ukpga_19740037_en.pdf (Accessed: 18th January 2017).
HMSO (1998) The Provision and Use of Work Equipment Regulations. London: HMSO. Available via: http://www.legislation.gov.uk/uksi/1998/2306/contents/made (Accessed: 18th January 2017).
HMSO (2011) The Supply of Machinery (Safety) (Amendment) Regulations. London: HMSO. Available via: http://www.legislation.gov.uk/uksi/2011/2157/contents/made (Accessed: 18th January, 2017)
Lezon, D. (2015) Overturned Excavator Pins Construction Worker, Chron, Houston, Tx. Available via: http://www.chron.com/houston/article/Overturned-excavator-pins-construction-worker-6696836.php (Accessed on: 15th May 2016)
Pourramedani, A. (2016) Man has Lost his Life in an Excavator Accident in Lom, Norway Today, Oslo, Norway. Available via: http://norwaytoday.info/news/man-lost-life-excavator-accident-lom/ (Accessed on: 16th May 2016)
Turner, I.Y. and Huff, E.M. (2003) Analysis of Triaxial Vibration Data for Health Monitoring of Helicopter Gearboxes, Journal of Vibration Acoustics, Vol. 125, No. 1, pp 120-128.