EXCEEDING THE EXPOSURE ACTION VALUE? A FIELD SURVEY OF HAND-ARM VIBRATION IN THE UK UTILITIES SECTOR

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ABSTRACT

Purpose: This paper reports upon field research analysis of the hand-arm vibration (HAV) exposure levels of utility workers in the UK construction sector when operating hand held vibrating power tools. Excessive exposure to HAV can lead to hand-arm vibration syndrome (HAVS) which is a major health and wellbeing issue that can irreparably damage to the neurological, vascular and muscular skeletal system.

Methodology: An empirical epistemological lens was adopted to analyse primary quantitative data on the management of hand held tool trigger times (seconds) collected from field studies. To augment the analysis further, an interpretivist perspective was undertaken to qualitatively analyse interviews held with the participating company's senior management team post field study results. This approach sought to provide further depth and perspective on the emergent numerical findings.

Findings: The findings reveal that none of the operatives were exposed above the exposure limit value (ELV) and that 91.07% resided under the exposure action value (EAV). However, the Burr four parameter model probability model (which satisfied the Anderson-Darling, Kolmogorov-Smirnov and Chi-squared goodness of fit tests at α 0.01, 0.02, 0.05, 0.1 and 0.2 levels of significance) illustrated that given the current data distribution pattern, there was a 3% likelihood that the ELV will be exceeded. Model parameters could be used to: forecast the future probability of HAV exposure levels on other utility contracts; and provide benchmark indicators to alert senior management to pending breaches of the ELV.

Originality: HAV field trials are rarely conducted within the UK utilities sector and the research presented is the first to develop probability models to predict the likelihood of operatives exceeding the ELV based upon field data. Findings presented could go some way to preserving the health and wellbeing of workers by ensuing that adequate control measures implemented (e.g. procuring low vibrating tools) mitigate the risk posed.

KEYWORDS

Health and wellbeing, hand-arm vibration, probability models, utilities industry

INTRODUCTION

The Organisation for Economic Co-operation and Development state that preserving workers' health and well-being represents a major socio-economic challenge for governments globally (OECD, 2016). This is because healthy people are more productive, live longer and cost less; whereas the converse is also true (Howell, 2016). Within the United Kingdom (UK), the government commissioned report by Black (2008) found that the annual economic cost of workplace sickness and absence was estimated to be in excess of £100 billion, UK sterling. This monetary figure was later increased to £180 billion by 2015 and underscores the growing issue within British industry (Pretty *et al.,* 2015). More recently, the UK's Health and Safety Executive (HSE) reported that the annual cost of workplace injuries and ill health (between 2016 and 2017) was estimated to be circa £15 billion (excluding cancer); where 65% of this cost was attributable to ill health and 35% was attributed to injury (HSE, 2018). In 2017, the Office for National Statistics (ONS) reported that 131 million days were lost to sickness absence with prominent reasons being: minor colds with 34.3 million days lost (26.1% of the total days lost); musculoskeletal conditions with 28.2 million days lost (21% of sickness absences); and mental health issues with 15 million days lost (11.4% of sickness absences) (ONS, 2017). Musculoskeletal conditions *"includes back pain, neck and upper limb problems and other musculoskeletal problems"* (*ibid*), which would include hand-arm vibration related conditions.

Such compelling statistics have engendered a plethora of research investigation in related areas such as: healthy eating and diet (Velardo, 2015); exercise (Oja, 2017); reducing mental health related stigma and discrimination (Thornicroft *et al.,* 2016); community health and well-being support programmes (Ebenso, 2019); and how contact with nature can support human health (Roe and Aspinall, 2011).

Despite these concerted efforts, the issue of 'health and well-being' has received comparatively insufficient academic attention within the construction and civil engineering industry when compared to the more established issue of 'safety' (Love *et al.,* 2010; Langdon and Sawang, 2017). Indeed, there is not even a consistent definitions of what is meant by wellbeing (Smyth *et al.,* 2019), with both academic and practical focus remaining primarily on 'safety'. In particular, health issues stemming from hand-arm vibration (HAV) via the use of hand-held vibrating powered tools and/or work processes continue to cause concern throughout industry (cf. Edwards and Holt, 2006; Edwards and Love, 2016). Although the overall trend of reported

incidents between 2008 and 2017 appears to be reducing (HSE, 2019a) post-introduction of the Control of Vibration at Work Regulations (CVWR) 2005 (CVWR, 2005), new claims remain unacceptably high viz: 7,115 new claims for hand-arm vibration syndrome (HAVS) were registered (20 for women and 7,095 for men) and 3.285 new claims for carpal tunnel syndrome (CTS) (255 for women and 3,285 for men) (HSE, 2019a). The origin of some of these recent claims may pre-date the 2005 Regulations, but nevertheless each represents a significant impact upon the health and wellbeing of an individual.

Within the utilities sector of the UK construction industry, as in other industry sectors involved with civil engineering construction, maintenance and repair activities, a range of power tools are utilised (often in combination) for service excavation (e.g. hydraulic, electric or pneumatic breakers; floor saws; and hand held disc cutters) and reinstatement works (e.g. vibration tampers; and compaction plates) (cf. Edwards *et al.,* 2003). Utility workers predominantly work as two or three man teams that work largely in isolation to site management and frequently, have to attend emergency services work (such as burst water pipes or cable strikes) (Edwards and Love, 2016). As a consequence, keeping abreast of exposure to vibration can be difficult to manage and control remotely, and hence, the teams themselves are largely responsible for their own health and well-being monitoring.

Given the aforementioned prevailing circumstances, this research sought to undertake field study research to measure whether the HAV risk exposure from power tools operated by utility workers is within permissible tolerances and using this field data, develop a probability model to predict the likelihood of excessive HAV exposure occurring. Concomitant objectives are to: ensure that control measures implemented to mitigate the risk of developing HAVS are effective; assess whether current systems and processes for recording HAV exposure are adequate; and ultimately, preserve the health and well-being of utility workers.

HAND-ARM VIBRATION

Exposure to HAV *per se* may not automatically lead to the development of HAVS or carpal tunnel syndrome (CTS) as several ill-health issues (such as Raynaud's disease – more commonly known as vibration 'white finger') are prevalent within society irrespective of exposure (Palmer *et al.,* 2002; Edwards and Holt, 2006). Neither can it be assumed that vibration related ill-health develops because of work activities alone as for example, non-work activities (e.g. operating a lawnmower) and life style (e.g. smoking) can impact upon a person's

health and well-being (Edwards and Holt, 2007a; 2007b). Rather, it is prolonged or repeated occupational exposure to unmanaged HAV emissions that represents a serious health risk that must be assessed and controlled (CVWR, 2005). HAVS and CTS are preventable but failure to control the risk posed can lead to the onset of v*ascular, neurological* and *musculoskeletal damage* (HSE, 2014). Common symptoms include: tingling or numbness of the fingers signifying vascular and neurological damage (Brammer *et al.,* 1987); fingers changing colour when exposed to cold temperatures indicating vascular damage (Bovenzi, 2008); and loss of manual dexterity or grip strength as a result of both muscle and nerve damage (Rashid *et al.,* 2018). Moreover, any damage incurred is currently irreparable using existing medical techniques and continued exposure to HAV will further exacerbate the condition.

Legal Duties and Measurement of Exposure

Employers' are legally required to ensure that the risks of HAV exposure are assessed and that robust control measures are implemented (HSE, 2012). There are three aspects to 'HAV exposure', namely: i) first, *how much vibration the tool generates* and ii) second *how much of the generated vibration is subsequently absorbed into the hands and forearms of operators*. In previous research work, the international standard ISO 5349 parts 1 and 2 (ISO, 2001 and 2015) were used to measure vibration of hand held power tools (Edwards and Holt, 2005). However, such work illustrated that vibration is extremely variable and dependent upon for example, the maintenance of the tool, the appendage selected, the operator's grip force and feed force etc. (*ibid*). Hence, differences between original equipment manufacturer (OEM) type approval or standardised vibration measurements (which are specifically designed to be repeatable) and field data (which is often variable) were apparent (Rimell *et al.,* 2008). For this reason, anecdotal evidence suggests that while some practitioners within the construction and civil engineering industry do use bolt-on sensors to measure 'true' vibration of tools, these can measure different levels of vibration from the same tool dependent on where the sensor is fitted. For simplicity, it appears that practitioners more predominantly use original equipment manufacturer (OEM) tri-axial data readings 'as an approximate estimate of the risk posed'.

The third factor which determines HAV exposure is iii) *the trigger time duration*. This is the amount of time that the operator has a finger on the trigger of the machine or power tool. Cumulatively, the tool vibration, vibration absorption and the trigger time constitute *vibration exposure*.

Whilst not exhaustive, common control measures may include: use of low/lower vibration tools, job rotation (to share the vibration risk and thus lower individual exposure), selecting the correct tool type for the task, ensuring that tools are well maintained and using the correct appendage for the tool and task (Edwards, 2006).

The CVWR include an Exposure Action Value (EAV) and Exposure Limit Value (ELV). The EAV is a daily exposure defined as A(8), that if exceeded, requires control measures to be taken to reduce the risk. The EAV is 2.5m/s2 A(8); where A(8) units of metres per second, per second, reflect the fact that vibration is a form of acceleration (refer to Equation 1 below). Edwards and Holt (2006) state that the Exposure Limit Value (ELV) is a daily exposure, i.e. 5m/s2 A(8) that must not be exceeded. A(8) increases with vibration magnitude and/or duration of exposure such that:

$$A(8) a_{hv} \sqrt{\frac{T}{T_0}} \qquad \text{Eq. 1}$$

where a_{hv} is the (source) vibration magnitude expressed in m/s^2; T is the duration of exposure to the vibration magnitude a_{hv}; T_0 is the reference duration of eight hours (28800 seconds); and a_{hv}, is a function of:

$$a_{hv} = \sqrt{a_{hwx}^2} + a_{hwy}^2 + a_{hwz}^2 \qquad \text{Eq. 2}$$

where a_{hwx}, a_{hwy} *and* a_{hwz} are the root-mean-square acceleration magnitudes (m/s^2), measured in three orthogonal directions, *x, y and z*, at the vibrating surface in contact with the hand, and frequency weighted using the weighting W_h. The definition for W_h is provided in ISO 5349-1 (ISO, 2001, 2015). If an operator's daily exposure comprises two or more tools, with different vibration magnitudes, then:

$$A(8) = \sqrt{\frac{1}{T_0} \sum_{i=1}^{n} a_{hvi}^2 T_i} \qquad \text{Eq. 3}$$

where n is the number of individual tools; a_{hvi} is the vibration magnitude for tool i; and T_i is the duration of exposure to tool i. By simple transposition of Equation 1, maximum exposure time (T) may be calculated given *A(8)* and a known vibration magnitude (a_{hv}).

Because of the formal educational qualifications (particularly maths) of the average worker, the HSE introduced a points based system that could be readily understood by all; the exposure action value (2.5 m/s2 A(8)) is equal to 100 points; and the exposure limit value (5 m/s2 A(8)) is equal to 400 points (HSE, 2019b). HSE points can be calculated via equation 4 viz:

$$HSE\ Points = \left(\frac{(a_{hvi} \times a_{hvi}) \times 2}{3{,}600\ (secs)}\right) \times T(secs) \quad \text{Eq. 4}$$

where a_{hvi} is the vibration magnitude for tool *i*; and *T* is the duration of exposure to tool *i* in seconds. Within industry, tool tags are often attached to tools that use OEM vibration data to indicate how long a tool can be used up until the EAV (100 points) and ELV (400 points) values. However, even with measures to simplify the management of HAV risks, operators and managers often fail to record the accurate measurement of HAV exposure (Devine, 2016). Anecdotally, if questioned operatives may report total working time rather than the trigger time, significantly over-estimating HAV exposure. Consequently, field study observations are needed to secure a more accurate assessment of the risks posed within the workforce.

Hand-arm vibration research in the construction industry

A review of the Scopus database (using the specific search terms '*hand-arm vibration in the construction industry'*) reveals that a mere 47 research articles (including conferences and peer reviewed journal articles) have been published since 1989 (refer to Figure 1). Moreover, although academic interest in this important area of employee health and wellbeing research has increased slightly since the publication of the CVWR 2005 (CVWR, 2005), the rate of publications remains low (peaking at a maximum of five publications per annum) and appears sporadic with wild perturbations between one to five publications per annum.

<Insert Figure 1 about here>

Table 1 provides a breakdown of publications by discipline area and illustrates that 26 articles involve cross-disciplinary collaboration and hence, the number of total disciplines represented is 73. Of these, *medicine* unsurprisingly (given the subject area) makes the greatest contribution to the field with 25 articles (accounting for 34.25% of the population). *Engineering* then makes the next largest contribution with 20 publications (27.4%) and then *social sciences* with publications (15.06%). These three discipline categories alone constitute 76.71% of the sample

with the remainder being covered by: *physics and astronomy; business, management and accounting; health professions; chemical engineering; computer science; environmental science; nursing; and other.* Figure 2 reveals that the two highest published authors in the construction and civil engineering discipline are Edwards, D.J. (with five publications) and Holt, G.D. (with four publications) - at the time of publication, both worked at Loughborough University, UK. Interestingly, these two authors last published together in this area in 2010 (Edwards and Holt, 2010) and Edwards published one further paper later in 2008 (Notini *et al.,* 2008). Much of this body of knowledge has tended either to focus either on: the ailments of HAVS; the measurement of independent tools; and/or the measurement of appendages within tools. Since then, construction and civil engineering academics have been surprisingly underrepresented in this area of health and wellbeing despite the fact that the sector increasingly adopting automation and automated tools and processes to complete projects (cf. Edwards *et al.,* 2017). Cumulatively these findings underscore the urgent need for field research to determine how HAV is being managed within the workplace and measure whether the ELV and possibly the EAV are being exceeded in practice.

<Insert Table 1 and Figure 2 about here>

METHODOLOGY

This research predominantly employed an empirical epistemological lens (Edwards *et al.,* 2019) to analyse primary quantitative data on the management of hand held tool trigger times collected from a major contractor working within the UK utilities industry. To augment the ensuing analysis, an interpretivist perspective (Roberts *et al.,* 2018) was also undertaken to provide further depth and perspective on the emergent numerical findings. Within this overarching methodological design, a three stage 'operational research process' was implemented viz: *Stage one – data mining* employed summary statistical analysis (e.g. measures of central tendency and distribution) to search for patterns and trends within the trigger time data which was converted into Health and Safety Executive points – where 100 points (2.5 m/s^2) equals the EAV and 400 points (5 m/s^2) equals the ELV. Specifically, this data sought to explore the validity of data collected and determine whether operators had been exposed to excessive vibration energy; *Stage two – probability modelling* conducted sought to determine the probability that operators would remain within the ELV; and Stage three – *senior management interviews* were convened via telephone conference calls and sought to generate further qualitative debate and discussion on the findings presented.

Research context and setting

The participating company is a leading utility services provider in the UK and Ireland with a turnover of circa £700 million (UK sterling 2018) and a workforce of 4,234 employees. The company resides within a larger group of companies worth 1.2 billion and hires machinery from a separate plant and equipment hire business unit within the group. The utility company works in collaboration with utility asset owners in the water, gas and electricity sectors to help them repair, renew, refurbish and maintain their infrastructure. For this research 13 contracts spread throughout the UK were randomly sampled as part of field trials using pseudo random numbers between the period 3rd October 2018 to 8th January 2019. A total of 50 operators were observed and three of these appeared twice in the studies. Four operators used more than one tool (ranging between two to four tools) in one day. A total of 60 observations were recorded but four observations did not have trigger times recorded due to incomplete or erroneous entries. Field studies were observed by 20 health and safety advisors (two observations were recorded by two health and safety advisors), and one observation was self-administered by a member of the contract gang consisting of two brothers. A total of 45 items of subcontractor equipment was recorded, eight items belonged directly to the utility company, two items were provided by a hire contactor and four items were not recorded.

18 different makes and models of machinery was used and this consisted of 11% angle grinders; 15% drills and breakers; 26% compaction equipment (tampers/rammers and compaction plates); 48% hand held disc cutters (cut off saws) and floor saws. Four tool entries listed (constituting four tools – where a vibrating poker was used twice) were classed as non-specific because an exact make and model was not listed in field reports. In this case, a worst case estimate of the vibration emission (from similar tools within the company's inventory) was used to calculate HSE points. Eight operations were in gas; 38 in water; 13 in electricity and 11 reinstatement giving a total of 70 – this was because 4 operations were relevant to all four sectors (giving 16 operational sector – reducing the total by 12); one was in two operational sectors (reducing the total by 1); and 3 operations were not attributed to a sector thus giving a total of 57 observations (refer to Table 2).

<Insert Table 2 about here>

STAGE ONE – DATA MINING

Data within Table 3 illustrates that the data distribution (for both cumulative trigger time and HSE points) is positively skewed (von Hippel, 2005), that is, very few higher observations were recorded leading to a longer tail on the right half of the distribution. 91.07% of HSE points observations are under the EAV and 8.93% are under the ELV (rounded to 2 decimal places (d.p.)). 85.71% of trigger times ($f = 48$) are under 1 hour, 5.36% ($f = 3$) are just over 1 hour and 8.93% ($f = 5$) are greater than 2 hours but less than 4 hours. The shortest trigger time recorded was 12 seconds (to fix four screws using an 18 volt battery drill with a vibration emission of 2.5m/s^2 - the tool used accrued only 0.041 HSE points). The greatest cumulative trigger time duration was 3.5 hours (to grind steel using a 115mm angle grinder with a vibration emission of 7.5 m/s^2 - the tool used accrued 393.75 HSE points which is very close to the limit value of 400 points). Several observations recorded (particularly the five observations for the angle grinder which had HSE points above the action value) were exactly on the hour – there is a suspicion that these were either rounded up to the nearest hour or may have been guesstimates.

<Insert Table 3 about here>

STAGE TWO - PROBABILITY MODELLING

The probability density function (PDF) represents a continuous probability distribution where the integral in the interval (α, b) yields the probability that a given random variable with the given density is contained in the interval provided. This can be expressed as:

$$P\int_{\alpha}^{b} f(x)dx = P(\alpha \leq X \leq b) \qquad \text{[Eq. 5]}$$

A cumulative distribution function (CDF) is the probability that a variate takes on a value less than or equal to x. For continuous distributions, the CDF is expressed as a curve and denoted by:

$$F(x) = \int_{-\infty}^{x} f(t)dt \qquad \text{[Eq. 6]}$$

The empirical CDF is displayed as a stepped discontinuous line depending upon the number of bins and is denoted by:

$$F_n(x) = \frac{1}{n}.[Number\ of\ observations \leq x] \quad \text{[Eq. 7]}$$

Where bins are the number of equal vertical bars contained within a CDF histogram, each representing the number of sample data values (that are contained within each corresponding interval), divided by the total number of data points. This analytical technique has been used extensively within academic literature and has been shown to be particularly useful when modelling the 'risk of an event occurring' (cf. Pärn *et al.,* 2018).

The PDF, CDF and distribution parameters (e.g. $\alpha, \beta, \gamma, \mu, k, m, \sigma, \xi$) for 36 different continuous distributions, including *Beta*, *Error Function, Levy, Power Function and Weibull* were examined using the estimation method Maximum Likelihood Estimates. The best fit distribution was then determined using three goodness of fit tests, namely the: 1) Kolmogorov-Smirnov statistic (D); 2) Anderson-Darling statistic (A^2); and 3) Chi-Squared at the 99%, 98%, 95%, 90% and 80% confidence interval (e.g. α = 0.01, 0.02, 0.05, 0.1 and 0.2 respectively). Combined, these goodness of fit tests measure how well the distribution fits the data.

The *Kolmogorov-Smirnov statistic (D)* is based on the largest vertical difference between the theoretical and empirical CDF. It is defined as:

$$D = \max_{1 < i < n} \left(F(x_i) - \frac{i-1}{n}, \frac{i}{n} - f(x_i)\right) \quad \text{[Eq. 8]}$$

The *Anderson-Darling statistic (A^2)* is a general test to compare the fit of an observed CDF to an expected CDF. The test provides more weight to a distribution's tails than the *Kolmogorov-Smirnov* test. The Anderson-Darling statistic is defined as:

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\cdot\left[InF(x_i) + In\left(1 - F(x_{n-i+1})\right)\right] \quad \text{[Eq. 9]}$$

The *Chi-squared test (χ^2)* is used to determine if a sample comes from a population with a specific distribution. The Chi-Squared statistic is defined as:

$$\chi 2 = \sum_{i-1}^{k} \frac{(O_i - E_i)^2}{(E_i)} \quad \text{[Eq. 10]}$$

Where: O_i is the observed frequency for bin *I;* and E_i is the expected frequency for bin *i* calculated by:

$$E_i = F\,(x_2) - F(x_1) \qquad \text{[Eq. 11]}$$

Where: F is the CDF of the probability distribution being tested; and x_1, x_2 are the limits for bin *i*. The hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the test statistic is greater than the critical value defined as:

$$\chi 2\ 1 - \alpha, k - 1 \qquad \text{[Eq. 12]}$$

meaning the Chi-Squared inverse CDF with *k-1* degrees of freedom and a significance level of α.

These three goodness of fit tests were used to test the null (H_o) and alternative hypotheses (H_1) of the datasets: H_0 - follow the specified distribution; and H_1 - do not follow the specified distribution. The hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the statistic *D,* A^2 and $\chi 2$ are greater than the critical value. For the purposes of this research, 0.01, 0.02, 0.05, 0.1 and 0.2 significance levels were used to evaluate the null hypothesis.

The *p*-value, in contrast to fixed α values, is calculated based on the test statistic and denotes the threshold value of significance level, in the sense that H_o will be accepted for all values of α less than the *p*-value. Once the 'best fit' distribution was identified, the probabilities for cycle times (seconds) were calculated using the CDF.

Distribution Fitting: HSE Points

All 56 data points were analyzed and the results reported upon in Table 4 illustrates that the best fit probability distribution for the HSE points was the four parameter Burr (Burr 4P) distribution at α = 0.01, 0.02, 0.05, 0.1 and 0.2 confidence intervals. The four parameters are:

$$k = 0.36096;\ \alpha = 2.1199;\beta = \ 3.2989 \text{ and } \gamma = -0.3647$$

Where: k is a continuous shape parameter ($k > 0$); α is a continuous shape parameter (α > 0); β continuous scale parameter (β > 0); and γ is a continuous location parameter (γ ≡ 0 yields the three-parameter Burr distribution).

<Insert Table 4 about here>

The PDF (Figure 3) and CDF (Figure 4) for the Burr 4P fitting are defined in equations 13 and 14 respectively as:

$$f(x) = \frac{\alpha k(\frac{x-y}{\beta})^{\alpha-1}}{\beta(1+(\frac{x-y}{\beta})^{\alpha})^{k+1}} \quad \text{[Eq. 13]}$$

$$F(x) = 1 - (1 + (\frac{x-y}{\beta})^{\alpha})^{-k} \quad \text{[Eq. 14]}$$

The domain for this distribution is $y \leq x \leq +\infty$

<Insert Figures 3 and 4 about here>Using the Burr (4P) model parameters, two delimiters (X1 and X2) were used to calculate the probabilities of obtaining a discrete category of HSE points ranging from 0-100 points, 101-200 points, 201-300 points, 301-400 points and 401- ≤ 500 points (refer to Table 5). These incremental HSE points categories represent equal interval steps (constituting 100 points per steps) between the EAV and 100 points beyond the ELV (to represent a worst case scenario. This decision was based upon the prevailing EAV and ELV values with some leeway for these values to be exceeded. This discrete analysis revealed that 92.34% of observations accrued ≤ 100 HSE points and 97.04% accrued ≤ 400 HSE points. Although 0.38% exceeded the 401 HSE points ≤ 500 HSE points, it is apparent that overall there is a 3% likelihood that the ELV will be exceeded. This risk is due to the positively skewed shape of the HSE points distribution due to the five outlier observations (incurred by sub-contractors) which elongate the tail and increase the probability of exceeding the ELV. In the absence of these outliers, the data distribution, type probability model and predictions made would have been very different. That is, the probability of exceeding the ELV would have been reduced demonstrably.

<Insert Table 5 about here>

STAGE THREE – SENIOR MANAGEMENT INTERVIEWS

Expert interviews were conducted via telephone conference calls with five senior health and safety advisors, the safety, health, environment and quality (SHEQ) Director and a Senior SHEQ plant manager within the company's own equipment hire provider (set up as a separate business unit within the wider group of companies). These participating professionals were deemed 'experts' because they had all undertaken relevant Institution of Occupational Safety and Health (IOSH) training and professional development courses, had accrued at least ten years field experience of managing HAV in the workplace and had direct line management responsibility for managing health, safety and wellbeing in the workplace. Telephone calls were made on an individual basis so as to ensure that each person contacted had sufficient opportunity to express their own views in confidence without feeling any peer pressure from other senior members of the team – indeed, this approach was requested from the SHEQ Director who requested total transparency and honesty from his team members and colleagues – whose anonymity would be preserved. The data collected and analysis results were first presented to the participants ahead of the conference call so that they could digest the contents and offer their informed insights. Three lines of enquiry were pursued around the issues of: i) HSE points accrued; ii) selection of, and usage of tools; and iii) internal management protocols for recording trigger times.

HSE Points Accrued

All participating interviewees confirmed that they had presupposition about the results but all were delighted to see that the ELV had not been exceeded. One senior health and safety advisor said:

> *"Our crews work as small teams of typically two-three people and we do actively encourage job sharing of the tools as a control measure to mitigate the risk posed by HAV. Reducing the trigger time and exposure to HAV is key and so we always use lower vibrating tools within our own hire company. Most of the guys are sensible about sharing the workload and it seems that our core messages are getting out there at the coalface."*

However, some anomalies were apparent particularly around a small cluster of five outlier values at the far right of the distribution of HSE points recorded (all >300 HSE points but < 500 HSE points). The SHEQ Director said:

"It was interesting to note that these observations were from our subcontractors – if we are going to have any problems, it always seems to come from them. It's challenging within the business at present because we're growing significantly and taking on new businesses all the time - and so controlling what tools they use and educating their workers about the risks of HAV and our [the participating company's] risk mitigation measures is a constant battle."

In taking a closer look at these five outlier values, another senior health and safety advisor said:

"I'm genuinely surprised at the amount of trigger time spent using these high vibrating tools. I would have to question the tool selection process involved but also the work method adopted to see whether this could be changed to remove the use of these tools in the first place. That's an awful amount of vibration exposure there and so further investigation is needed."

These comments suggest that although HSE points accrued are under the ELV value and the company has had some success in mitigating risks posed, challenges remain in terms of managing tools used, changing working processes, educating the subcontractor workforce, providing effective oversight of subcontractor activities and assurance of subctontractor competence. These challenges are further exacerbated by growth within the business which has allowed a large influx of subcontractor workforce who at present do not share the company's health and well-being policies, systems and procedures (e.g. low vibrating tool selection, job rotation etc.). When asked whether the data should be remodelled with the outliers excluded, the SHEQ Director said:

"Of course not – this work is about identifying the risks posed – additional theoretical/academic modelling might give us a better fit but the aim now for us [the company] is to see how we can now eradicate these instances of high HSE points occurring. It's best we know about them."

Selection of, and Usage of Tools

At the very peak of the HAV risk mitigation hierarchy, is the need to engineer-out the usage of hand-held vibrating tools in working processes. This can present a challenge in terms of both cost and flexibility in operations, as it may not be practicable to eliminate use of hand-held vibrating tools in many situations.

Below this, where the use of hand-held vibrating tools cannot be eliminated, is the need to procure low vibrating tools (preferably below the EAV) and here, considerable efforts have been made by the company. The SHEQ Director said:

> *"I work very closely with our Senior SHEQ plant manager and the business has replaced older makes and models of machinery and replacing with new low vibrating tools and equipment. We also make every effort to buy good low vibrating appendages as we know that cheap products could increase the vibration levels of an otherwise excellent tool."*

The Senior SHEQ plant manager concurred with this observation but noted some caution. Specifically, there was a concern that not every part of the business or people within it fully understood the company's HAV policy and the rationale behind it, so that they apply the policy such that HAV risk is reduced . The Senior SHEQ plant manager said:

> *"I believe that there are some parts of the business that are using equipment (e.g. drills, impact drivers) which we haven't done trigger time measurements on. And some of this equipment has been procured by the contracts rather than through the official plant department. I suspect that some managers are going to buy tools that are cost effective – rather than look at the whole product in terms of quality, safety, vibration, noise and so on. In terms of drills you're looking for a free release chuck one that does not damage the persons wrists and hands – a feature that is not available on cheaper products."*

The Senior SHEQ plant manager's comments identify that in some quarters of the business a culture of 'buying the lowest cost product' prevails vis-à-vis taking a more holistic assessment of overall tool performance. This may be misunderstood as lack of knowledge of the HAV policy and rationale, but if tool procurement choices are more strongly influenced by factors other than the HAV policy (such as budget or convenience of supply), these will drive selection. It is therefore important to procure tools based upon a holistic risk assessment that takes into consideration all risks posed, not just vibration (e.g. noise, weight and so on) as well as understanding business factors such as ease of supply, repair and spares availability. For example, further discussions revealed that several workers hand received a broken wrist as a result of using drills that did not include the free release feature (that is, one without a chuck key).

Internal Management Protocols for Recording Trigger Times

All participants, questioned whether current internal management protocols to mitigate the risks of workers developing HAVS (e.g. management of subcontractors, procurement of tools and so forth). In particular, issues such as management of sub-contractors, recording of trigger times and tools standards development were discussed. For the management of subcontractors, one senior health and safety advisor felt that there should be a common set of tools recommended for procurement throughout the sub-contractor supply chain. This is not without its challenges, not least the potential for blurring the client-designer role boundary in terms of the Construction (Design and Management) Regulations 2015 (TSO, 2015) if a client starts to specify to a sub-contractor precisely how a task should be completed. However, setting clear expectations to sub-contractors around expected risk management outcomes demonstrates a clear client-designer-contractor role boundary, as well showing as a shared commitment to health, safety and wellbeing and reduction of harm.

The Senior SHEQ plant manager concurred with the common tools approach and moreover stated that plans were underway to standardise tool procurement and usage viz:

> *We have now produced a vehicle plant and equipment standards document – within that document there will be sections regards noise, HAV, dust and all other risk exposure sources. This will cover our standard, and it will also have our preferred supplier standard (the standard that we expect from them [the original equipment manufacturers]) and then also the subcontractors standard (again what we expect from them). There will also be a standard that we will have that we expect our contracts to meet within a set period to time – so that when they renew equipment that they meet our standards and have time to prepare for meeting them."*

Benchmarking tool procurement criteria in this manner will contribute towards reducing the number of 'non-specific' or high vibrating tools currently being used in the business and should also help in lowering operator's exposure to HAV. In turn, such measures will mitigate the risk of operator ill-health and injury whilst simultaneously mitigating the risk of financial loss through lost production and/ or legal expenditure. Setting clear and time-bound expectations is a key part of raising operating standards within industry, as without this performance will continue to be dominated by the cost vs safety balance. However, to fully realise these palpable benefits requires good management of tool usage on site including regular monitoring and here the views and opinions of participants differed. The Senior SHEQ plant manager said:

"I think that we need to educate the guys that are conducting the trigger times because the instructions given to them is that we need to do the trigger times for a set period of time – instead we should be telling them to carry out the trigger time recordings for how long the tool is being used for. There is no evidence to suggest that the times have been manipulated and rounded up.

Put simply, this view suggests that trigger times are sampled within set time periods vis-à-vis recording the total trigger time. Hence, four the five outliers, all values are rounded up to the nearest second. However, another senior health and safety advisor disagreed and said:

"If that were the case (i.e. recording trigger times within set periods of time) then surely all times recorded [for the five outlier observations under scrutiny] would have the same time period? I suspect that someone has just rounded the times up [to the nearest minute] for simplicity – I would like to think that there was no malevolent urge here to hide unsafe tool usage as the values are too close to the ELV for comfort."

The reasons underpinning this phenomenon will require further investigation to determine what instructions have been given to health and safety advisors and/ or determine whether any inappropriate practices have been inadvertently (or deliberately) adopted. In either event, the ability for the company to openly debate such issues and willingness to implement further investigation cumulatively demonstrates a real passion and enthusiasm to tackle the HAV management conundrum with gusto.

CONCLUSIONS

The management of HAV has moved beyond the tri-axial measurement of power tools and today, practitioners focus more upon using OEM tri-axial emissions data as a reasonable first approximation of the risk. Greater attention is given to employing robust risk mitigation measures (such as changing working practices to remove the use of vibratory work processes or power tools) and ensuring compliance with these within the organisation. This case study reveals the HAV management initiatives of a large UK utility company working within the construction and civil engineering sector of industry. A healthy, robust and at times 'frank' discussion on HAV management within the company prevails and a refreshing open admission is made that more could be done to mitigate the risks posed by using vibratory work processes or power tools.

Interestingly the results of summary statistical analysis revealed that none of the work processes sampled exceeded the ELV and from this perspective no further action or investigation is required by the company. However, the Burr (4P) model adopted (that was validated at all confidence intervals sampled and across three goodness of fit tests) reveals that given the presence of five extreme outlier observations, there is a 3% probability of exceeding the ELV. Sub-contractors were identified as using high vibrating tools for extended periods of time and hence, were the cause of these outliers recorded. This finding engendered a meaningful discourse amongst prominent safety advisors who cumulatively concur that the development of benchmark procurement standards presents the best opportunity to remove high vibrating (and hence, high risk) tools from operators in the workplace. However, concerns were also raised regards the validity of some data observations collected and future work is required to investigate questionable data entries.

Perhaps more importantly, the study demonstrates two core advancements that have resulted as a natural consequence of the Physical Agents Directive, namely: i) the development and refinement of risk mitigation 'control measures' within the construction and civil engineering industry and a genuine willingness to mitigate HAV risks posed, ideally by elimination of risk at source where it is practicable to do so; and ii) innovative mechanical engineering design orchestrated by OEMs who continue to lower vibration emissions through the use of for example, vibration damping systems. Ultimately, and at the given the current rate of technological development, it would appear that hand held power tools design and manufacturer will continue to drive down vibration emissions – where such drop below 2.5m/s^2 the risk of developing HAVS will be negated but not totally removed. This is because appendage quality, tool selection, tool maintenance and safe operation will still require consideration and management no matter how low vibrating the tool may be when new – age and usage will still wear rotating and reciprocating parts thus increasing vibration emission over time and usage. Given this realisation, future work must be conducted to determine how tool components degrade over time/ usage in order to optimise scheduled maintenance and/ or tool replacement policies.

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Figure 1 – Publications per Annum 1998 to present.

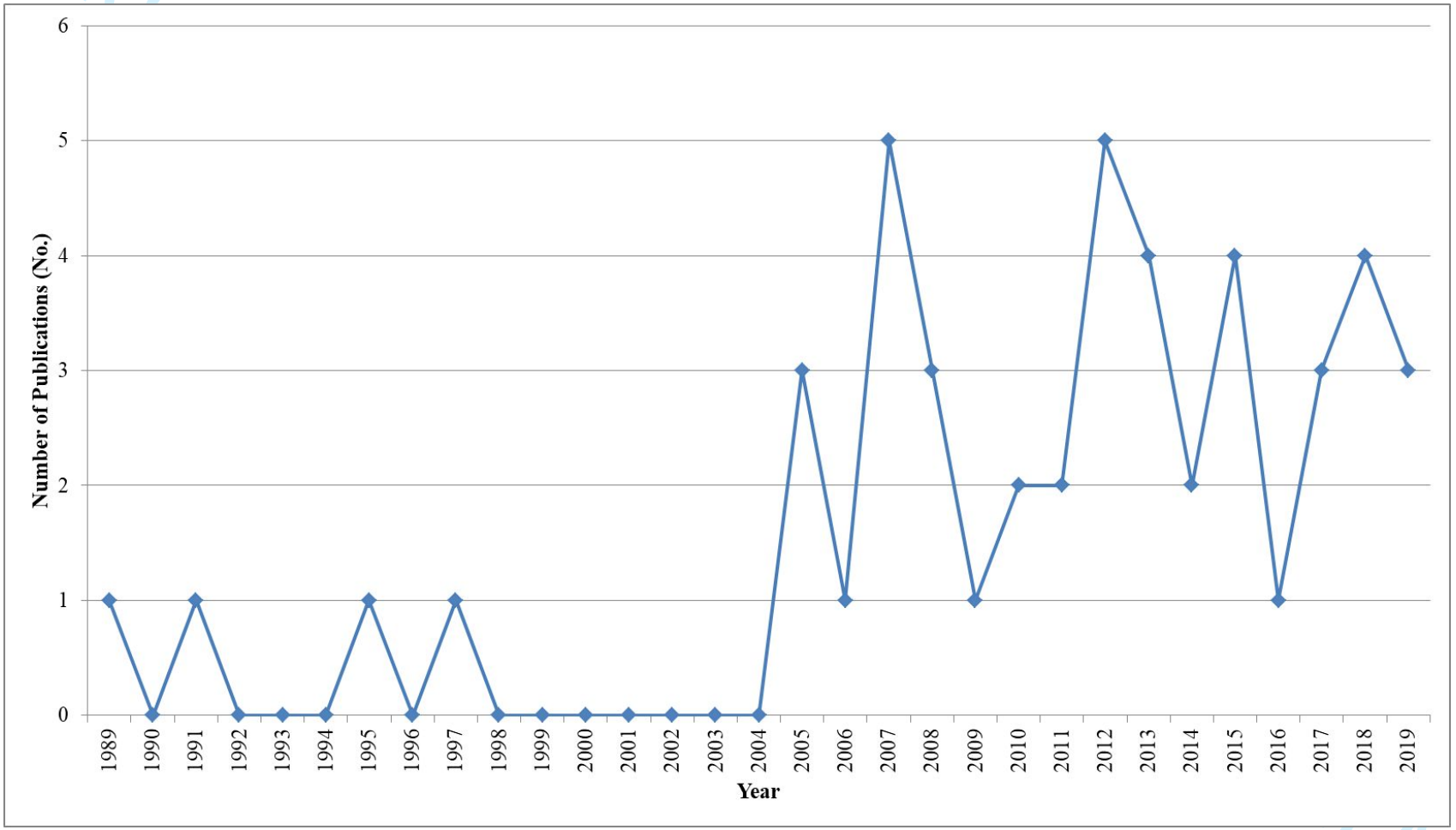
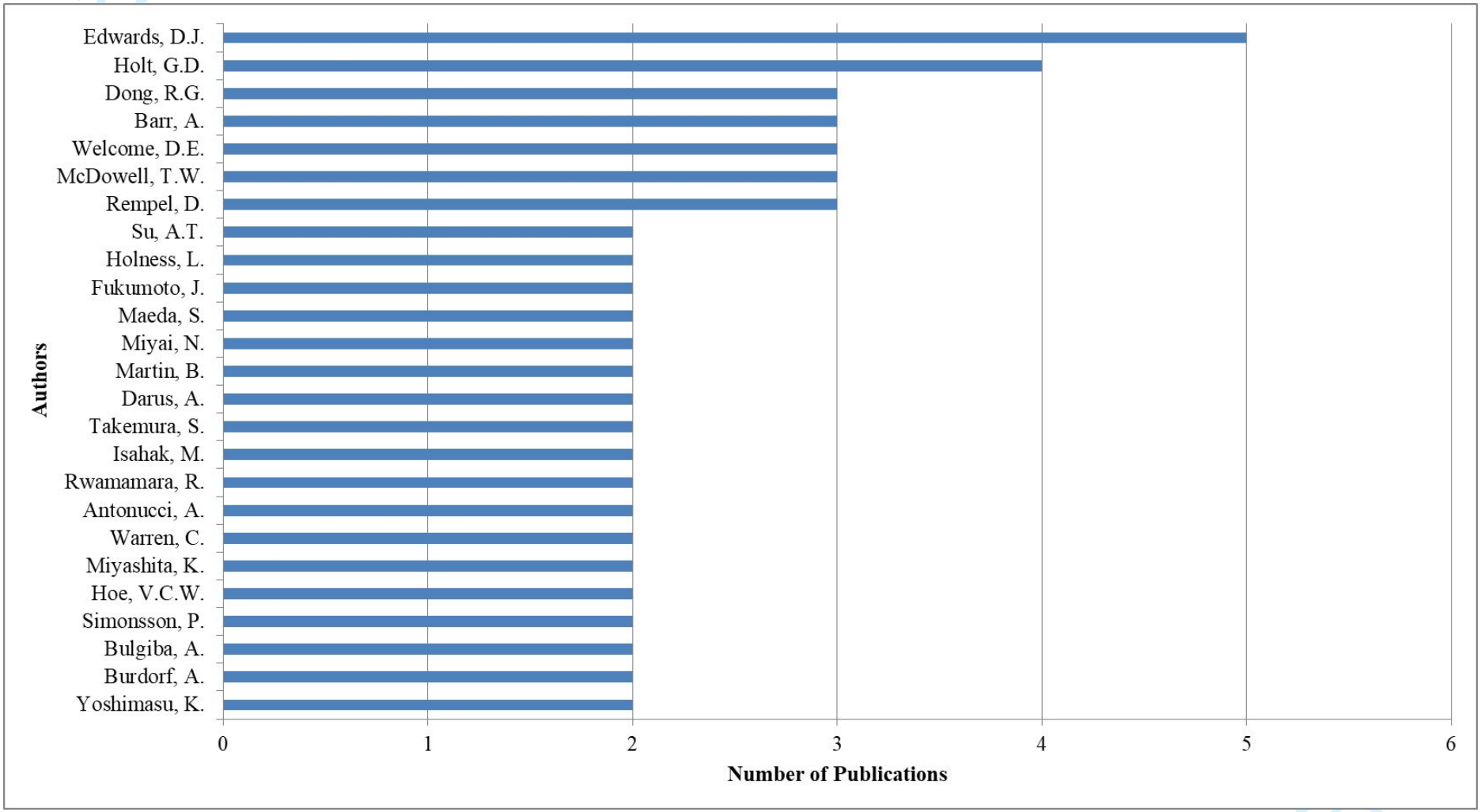


Table 1 – Publications by Discipline

Discipline	Number of publications (No.)	Percentage Frequency (%)
Medicine	25	34.25
Engineering	20	27.40
Social Sciences	11	15.06
Physics and Astronomy	5	6.85
Business, Management and Accounting	3	4.11
Health Professions	3	4.11
Chemical Engineering	2	2.74
Computer Science	1	1.37
Environmental Science	1	1.37
Nursing	1	1.37
Other	1	1.37

NB: Rounded to 2 dp.

Figure 2 – Leading Authors



NB: Authors with one publication only have been excluded from this chart purely for brevity.

Table 2 – Tools Used, Trigger Times and HSE Point

Tool make and model	Vibration m/s2	Trigger time Mins	Trigger time Secs	Trigger time (total secs) Secs	HSE Points
Floor Saw CS451	1.9	35	0	2100	4.211667
Rammer BS50.2	5.4	15	0	900	14.58
Rammer BS50.2	5.4	15	0	900	14.58
Rammer BS50.2	5.4	40	0	2400	38.88
Hand held disk cutter TS410	3.9	18	10	1090	9.2105
Hand held disk cutter TS410	3.9	7	20	440	3.718
Hand held disk cutter TS410	3.9	10	45	645	5.45025
Hand held disk cutter TS410	3.9	15	0	900	7.605
Hand held disk cutter TS411/ Floor Saw CS451	3.9	*Error*	*Error*	*Error*	*Error*
Hand held disk cutter TS411/ Floor Saw CS452	3.9	*Error*	*Error*	*Error*	*Error*
Hand held disk cutter TS410	3.9	8	30	510	4.3095
Rammer BS50.2	5.4	60	0	3600	58.32
Hand held disk cutter TS410	3.9	7	30	450	3.8025
Rammer BS50.2	5.4	15	48	948	15.3576
Hand held disk cutter TS410	3.9	4	50	290	2.4505
Hand held disk cutter TS410	3.9	10	19	619	5.23055
Compaction plate - VP112	2.5	25	39	1539	5.34375
Single drum vibrating roller - Terex MBR71	3.6	18	20	1080	7.776
Floor Saw CS451	1.9	14	40	880	1.764889
Floor Saw CS451	1.9	7	45	465	0.932583
Hand held disk cutter TS410	3.9	5	55	355	2.99975
Floor Saw CS451	1.9	35	58	2158	4.327989
Rammer BS50.2	5.4	33	18	1998	32.3676
Floor Saw CS451	1.9	14	5	845	1.694694
Rammer BS50.2	5.4	18	38	1118	18.1116
Hand held disk cutter TS410	3.9	8	50	530	4.4785
Hand held disk cutter TS410	3.9	6	39	399	3.37155
Dewalt (Model: DCD785M1)	15	4	0	240	30
Hand held disk cutter TS410	3.9	30	0	1800	15.21
Compaction plate - VP112	2.5	30	0	1800	6.25
Single drum vibrating roller - Terex MBR71	3.6	35	0	2100	15.12
Rammer BS50.2	5.4	15	0	900	14.58
Electric breaker (Makita HR3210c) – chiselling	7	10	16	616	16.76889
*Non-specific oscillating tool	16.1	7	31	451	64.94651
Hand held disk cutter TS420	3.9	61	0	3660	30.927
Atlas Copco AY47	2.13	64	0	3840	9.67872
*Non-specific vibrating poker	4	12	8	728	6.471111
*Non-specific vibrating poker	4	15	46	946	8.408889
Hand held disk cutter TS400	3.9	41	50	2510	21.2095

Newson Wacker BS60-4	6.5	16	37	997	23.40181
Hand held disk cutter TS410	3.9	11	41	701	5.92345
Rammer BS50.2	5.4	2	26	146	2.3652
Compaction plate - VP112	2.5	3	26	206	1.001389
Single drum vibrating roller - Mecolae MBR71	3.6	5	39	339	2.4408
Makita 9557NBZ	7.5	*Error*	*Error*	*Error*	*Error*
Makita GA9020s	5.5	*Error*	*Error*	*Error*	*Error*
Makita 9557NBZ	7.5	195	0	11700	365.625
Makita 9557NBZ	7.5	170	0	10200	318.75
Makita 9557NBZ	7.5	170	0	10200	318.75
Makita 9557NBZ	7.5	180	0	10800	337.5
Makita 9557NBZ	7.5	210	0	12600	393.75
*Non-specific 18v battery drill	2.5	0	12	12	0.041667
Floor Saw CS451	1.9	10	20	620	1.243444
Hand held disk cutter TS400	3.9	13	7	787	6.65015
Petrol breaker - Wacker Neuson BH55RW	4.5	9	58	598	6.7275
Hand held disk cutter TS400	3.9	12	24	744	6.2868
Husqvarna K760	2.5	18	10	1090	3.784722
Husqvarna K760	2.5	15	30	930	3.229167
Husqvarna K760	2.5	10	5	605	2.100694
Husqvarna K760	2.5	3	10	190	0.659722

Table 3 – Summary Statistics for the Trigger Time

Trigger Times (Seconds)		**HSE Points**	
Statistic	*Value*	*Statistic*	*Value*
Mean	1968.13	Mean	41.26209
Standard Error	403.952	Standard Error	13.07248
Median	900	Median	6.560631
Mode	900	Mode	14.58
Standard Deviation	3022.9	Standard Deviation	97.8255
Sample Variance	9137907	Sample Variance	9569.828
Kurtosis	5.86289	Kurtosis	7.044945
Skewness	2.62142	Skewness	2.914987
Range	12588	Range	393.7083
Minimum	12	Minimum	0.041667
Maximum	12600	Maximum	393.75
Sum	110215	Sum	2310.677
Count	56	Count	56

Figure 3 – Probability Density Function - Burr (4P)

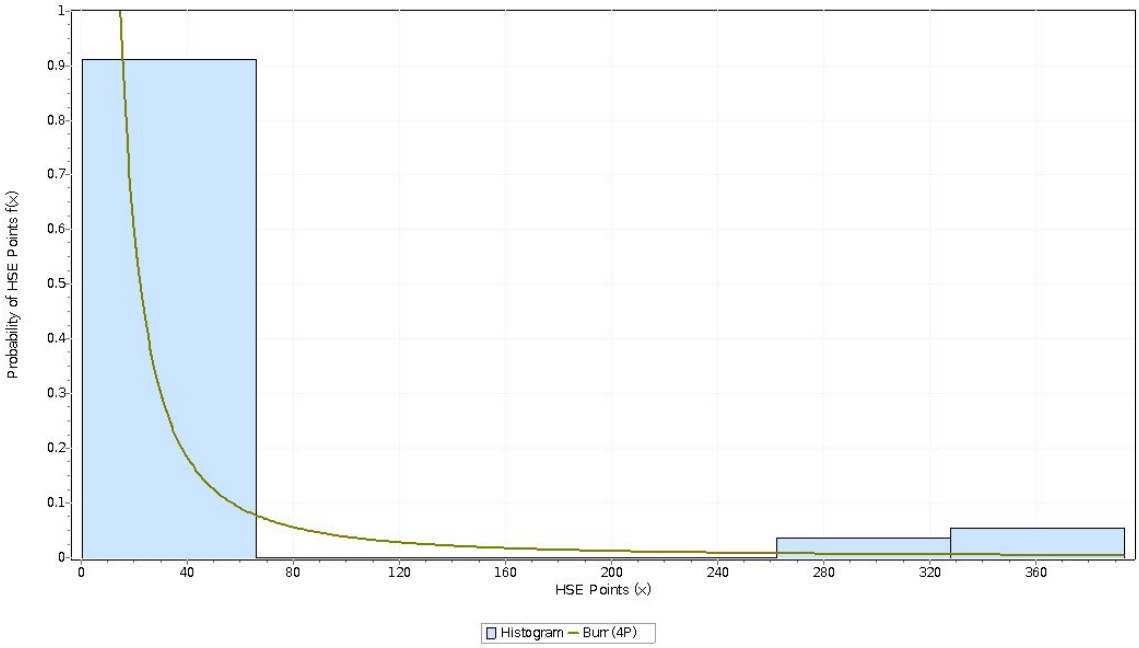


Figure 4 – Cumulative Distribution Function – Burr (4P)

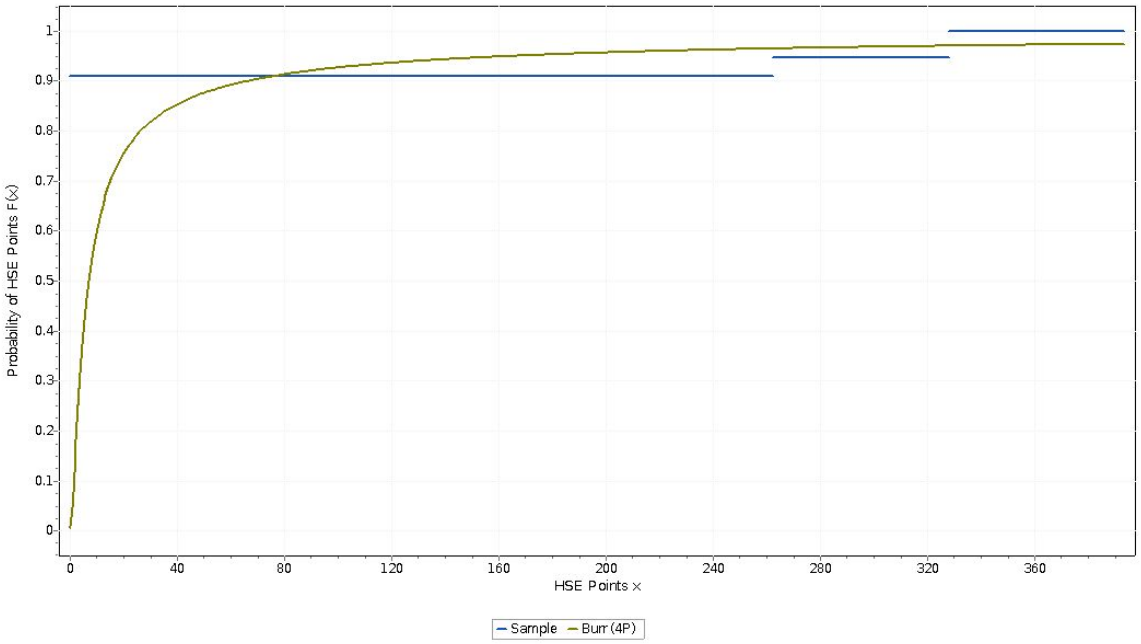


Table 4 – Goodness of Fit Tests

Test Statistics					
Kolmogorov-Smirnov					
Sample Size	56				
Statistic	0.06477				
P-Value	0.96083				
Rank	2				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.1404	0.16044	0.17823	0.1993	0.21384
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size	56				
Statistic	0.23753				
Rank	1				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom	5				
Statistic	3.1752				
P-Value	0.673				
Rank	2				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	7.2893	9.2364	11.07	13.388	15.086
Reject?	No	No	No	No	N

Table 5 – Probabilities of HSE Points (0- >400)

Probability of HSE Points incurring	P(X < X1)	P(X > X1)	P(X1< X < X2)	P(X < X2)	P(X >X2)
0 - ≤100	0.00337	0.99663	0.92336	0.92673	0.07327
101 - ≤200	0.92728	0.07272	0.02954	0.95682	0.04318
201 - ≤300	0.95698	0.04302	0.01134	0.96832	0.03168
301 - ≤400	0.9684	0.0316	0.00617	0.97458	0.02542
401 - ≤500	0.97462	0.02538	0.00394	0.97856	0.02144