
# A FIELD SURVEY OF HAND-ARM VIBRATION EXPOSURE IN THE UK UTILITIES SECTOR


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| Journal: | *Engineering, Construction and Architectural Management* |
| Manuscript ID | ECAM-09-2019-0518.R2 |
| Manuscript Type: | Original Article |
| Keywords: | Case Study, Construction Equipment, Construction Safety |
| Abstract: | |

**Ref:** Manuscript ID ECAM-09-2019-0518.R1
**Journal:** Engineering Construction and Architectural Management
**Title:** A field survey of hand-arm vibration exposure in the UK utilities sector

## REVIEWERS' COMMENTS AND AUTHORS' RESPONSE

The authors wish to extend thanks to the first referee for further constructive comments and suggestions given and to the second referee for recommending acceptance of the paper. These minor comments have been addressed (refer below) and a final file resubmitted for your consideration using the 'tracked changes' feature within MS Word. Once again, thank you.

| No. | Editor's Comments | Author's Response |
|---|---|---|
| 1 | This reviewer(s) have some important comments that would further improve the quality of the paper and should therefore be addressed within a minor revision. | Thank you for considering this paper for publication and for the very positive feedback and suggestions for minor amendment that will improve the quality of narrative. I do hope that these latest edits are satisfactory. |
| | **Review No. 1 Comments** | |
| 2 | **Recommendation:** Minor revision | Thank you for your recommendation. |
| 3 | The authors choose a non-traditional section format. This makes reading and understanding the manuscript very unclear to your potential readers. Using traditional titles/sections such as "Introduction", "Literature review", "Research Methods", "Results", "Discussion", and 'Conclusions' would be helpful. With these main sections, the authors can further provide and discuss appropriate subsections | Thank you for your constructive suggestion. The authors deliberately attempted to avoid using titles such as 'literature review' as we would prefer to name the section after the content of that section - because we contend that the narrative itself is indicative of the subject matter. That said, we do concede that for some readers, this may not be immediately apparent and hence, various revisions have been made to make the sections' titles and sub-titles more explicit. Specifically:<br><br>The section previously entitled: '*HAND_ARM VIBRATION*' is now entitled '*A REVIEW OF HAND_ARM VIBRATION*' – such indicates that this is the 'literature review' section.<br><br>The operational stage process has also been revised to include a four stage process (increased from three formerly) that now advises the reader that stage one presents the research context and setting, stages two and three represent data analysis sections, and stage four represents the discussion viz:<br><br>*"Within this overarching methodological design, a four stage 'operational research process' was implemented viz: Stage one - research context and setting provided key information about the company, tools used and industrial setting (i.e. gas, electricity, water and reinstatement contracts). Stage two – data mining and summary analysis represented the first stage of quantitative data* |

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|---|---|---|
| | | *analysis and 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/s2) equals the EAV and 400 points (5 m/s2) 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 three – probability modelling represented the second stage of quantitative data analysis conducted and sought to determine the probability that operators would remain within a theoretical distribution of the ELV. Stage four – discussion of data analysis results via senior management interviews were convened via telephone conference calls and sought to generate further qualitative debate and discussion on the findings presented. This latter stage gave the participating company and its employees with an important opportunity to reflect upon the findings and practices employed within the organisation as well as stimulate discussion on how such practices could be modified and improved."*<br><br>Note that stage titles have also been edited accordingly to better reflect changes made. We do hope that these far more explicit references to what each section represents satisfies the reviewer. Thank you for your consideration and advice. |
| | **Review No. 2 Comments** | |
| 4 | Recommendation: Accept. Thank you for adding the limitations sections and the discussion of the international relevance! | Thank you very much for your support and encouragement here – it is very much appreciated. |

# A FIELD SURVEY OF HAND-ARM VIBRATION EXPOSURE IN THE UK UTILITIES SECTOR


## ABSTRACT

**Purpose:** Excessive exposure to HAV can lead to hand-arm vibration syndrome (HAVS) which is a major health and well-being issue that can irreparably damage to the neurological, vascular and muscular skeletal system. 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.

**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 $\alpha$ 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 well-being of workers by ensuing that adequate control measures implemented (e.g. procuring low vibrating tools) mitigate the risk posed.



## KEYWORDS

Health and well-being, hand-arm vibration, probability models, utilities industry, Industry 4.0

**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 well-being (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 well-being 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 (to safeguard worker health) and using this field data, develop a probability model to predict the likelihood of excessive HAV exposure occurring. Such knowledge will allow management to gain a better insight into the risks posed and ensure that control measures implemented to mitigate the risk of developing HAVS are effective. Concomitant objectives are to: assess whether current systems and processes for recording HAV exposure are adequate for reducing risks posed; and ultimately, preserve the health and well-being of utility workers.

## A REVIEW OF 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 (normalised to an eight-hour reference period) 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:

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

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). A manual codification of these publications revealed that they could be readily clustered into three thematic groupings of: i) *measurement studies* – that measure the vibration of tools or appendages on site and in a range of occupational settings (with frequency ($f$) = 31 publications (or 65.96% of the sample publications); ii) *health and well-being education* *studies* – that provide information and guidance to managers who seek to mitigate risks posed ($f$ = 11 or 23.40%); and iii) *medical studies* – that examine the impact of excessive vibration upon the human body ($f$ = 5 or 10.64%). There are two important findings arising from this synthesis of extant literature. First, although academic interest in this important area of employee health and well-being 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. Second, it is notable that none of the publications listed sort to measure exposure across a range of multiple tools used in practice and the probability that EAV values would be exceeded – thus compromising employer management strategies employed to mitigate the risks posed. Third, and regards specific sector researchers, 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, Edwards published one further paper in 2008 (Notini et al., 2008) and Edwards and Holt last published together in this area in 2010 (Edwards and Holt, 2010). Since then, construction and civil engineering academics have been surprisingly underrepresented in this area of health and well-being 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 Figure 1 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; Al-Saeed *et al.,* 2019; Al-Saeed *et al.,* 2020) was also undertaken to provide further depth and perspective on the emergent numerical findings. Within this overarching methodological design, a four~~three~~ stage ‘operational research process’ was implemented viz: *Stage one - research context and setting* provided key information about the company, tools used and industrial setting (i.e.

gas, electricity, water and reinstatement contracts). *Stage twoone – data mining and summary analysis* represented the first stage of quantitative data analysis and 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 threewo – probability modelling* represented the second stage of quantitative data analysis conducted and sought to determine the probability that operators would remain within a theoretical distribution of the ELV.; and Stage fourthree – discussion of data analysis results via *senior management interviews* were convened via telephone conference calls and sought to generate further qualitative debate and discussion on the findings presented. This latter stage gave the participating company and its employees an important opportunity to reflect upon the findings and practices employed within the organisation as well as stimulate discussion on how such practices could be modified and improved.

**STAGE ONE: 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 1).

<Insert Table 1 about here>

**STAGE TWO~~ONE~~ – DATA MINING AND SUMMARY ANALYSIS**

Data within Table 2 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 2 about here>

**STAGE THREE~~WO~~ - 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:

$$P\int_{\alpha}^{b} f(x)dx = P(\alpha \le X \le b)$$ [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:

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

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

$$F_n(x) = \frac{1}{n}.[Number\ of\ observations\ \le x]$$ [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:

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

The *Chi-squared test ($\chi^2$)* 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:

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

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:

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

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

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 $\alpha$ 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 3 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:

$k = 0.36096$; $\alpha = 2.1199$; $\beta = \ 3.2989$ 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 3 about here>

The PDF (Figure 2) and CDF (Figure 3) for the Burr 4P fitting are defined in equations 13 and 14 respectively as:

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

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

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

<Insert Figures 2 and 3 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 4). 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 4 about here>

**STAGE FOUR~~THREE~~ – DISCUSSION OF ANALYSIS RESULTS VIA 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 well-being 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~~subcontractor 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 well-being 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.

## LIMITATIONS AND FUTURE WORK

Despite the advancements to new knowledge presented in this paper, four main limitations are apparent and future research is required to address these weaknesses in future scholarly research viz: i) sample data size and validity; ii) use of high vibrating equipment; iii) international context; and iv) equipment and appendage degradation.

### Sample data size and validity

There are two issues with the sample data. First, the utilities industry utilises a far broader range of tools and equipment than those reported upon within this study and so a larger sample size is required to capture a more complete range of exposures. Such exposures could shed additional light onto industry practices and how these said practices could be reengineered to lower operator exposure (and thus risk) further. Moreover, a larger sample would facilitate sample stratification (for example, into tool types, types of workers (direct labour or subcontractors) and types of appendages used) and further cross comparative analysis between stratifications. Any observed differences could be used to further improve worker health and well-being. Second, some doubts were expressed about the reliability of data collected and perhaps an automated system of recording trigger time could be used in future studies to mitigate the risk of data falsification.

### Use of high vibrating equipment

The research revealed clear discrepancies within the business that led to the procurement of 'cheaper' high vibrating tools. Although improved management of procurement processes is an obvious solution, further work is required to develop persuasive cost-benefit analysis arguments. Such arguments must demonstrate that a cheap tool or appendage (to initially procure) may have a greater whole life cycle cost due to accelerated wear and deterioration rates. Simultaneously, such tools also often vibrate excessively but by presenting a strong cost argument, the temptation to procure with a lowest purchase cost mentality is removed (or as least dissuaded).

### International context

The present study was limited to the UK utilities industry and although the approach could be adopted elsewhere, the results may be very different for a variety of reasons (for example, local tool procurement practices and differences in international regulations). However, whilst it is not the intention to encourage direct replication of the work in different countries worldwide (as such offers little advancement of knowledge), it would be interesting to see how contractor risk mitigation practices differed internationally and whether there were any opportunities to share best practices or technological innovation.

### Tool and appendage ~~degredation~~degradation

The research presented relied upon OEM vibration emission data as a useful indicator of the risk posed but it is acknowledged that vibration measurement is extremely variable. To obtain more accurate and reliable readings will require the use of automated systems under the guise of an Industry 4.0 solution; where tri-axial sensors are an integral part of the tool and data is streamed via wireless connections to cloud-based servers. Such as a system could conduct real time (and highly accurate) monitoring of tool performance and when connected to computational intelligence algorithms, alert operators to their exposure level, predict tool replacement periods or similarly appendage replacement periods. However at this juncture, periodic calibration of sensors appears to be the major reason why such as system cannot yet be effectively implemented.

**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.

## ACKNOWLEDGEMENTS

The lead author wishes to thank the utility company's safety and plant services departments for supporting this research and also, workers within the company who participated in the study. Without your support, this work could not have been made possible. Thank you also to Professor Peter Love, Distinguished Professor, Curtin University who gave the lead author a harsh (but fair) reality check regards the lead author's own research and helped guide the use of this analysis technique – this jolt has spurred me on!

## REFERENCES


Al-Saeed, Y., Pärn, E.A., Edwards, D.J. and Scaysbrook, S. (2019) A conceptual framework for utilising BIM digital objects (BDO) in manufacturing design and production: a case study. *Journal of Engineering Design and Technology*, Vol. ahead-of-print No. ahead-of-print. DOI: https://doi.org/10.1108/JEDT-03-2019-0065

Al-Saeed, Y., Edwards, D. and Scaysbrook, S. (2020) Automating construction manufacturing procedures using BIM digital objects (BDOs): Case study of knowledge transfer partnership project in UK, *Construction Innovation*, DOI: https://doi.org/10.1108/CI-12-2019-0141

Black, C. (2008) Working for a healthier tomorrow, Information Policy Division, Norwich, UK: Crown Copyright. ISBN: 978-0-11-702513-4.

Bovenzi, M. (2008) A follow up study of vascular disorders in vibration-exposed forestry workers, *International Archives of Occupational and Environmental Health*, Vol. 81, No. 4, pp 401–408. DOI: https://doi.org/10.1007/s00420-007-0225-9

Brammer, A.J., Taylor, W. and Lundborg, G. (1987) Sensorineural stages of the hand-arm vibration syndrome, *Scandinavian Journal of Work, Environment and Health,* Vol. 13, No. 4, pp. 279-283. Stockholm Workshop 86: Symptomatology and diagnostic methods in the hand-arm vibration syndrome: Hässelby Castle, Stockholm, 21—23 May 1986.

CVWR (2005) The Control of Vibration at Work Regulations 2005, Statutory Instrument No. 2005 1093, London, UK: Crown Copyright. Available via: http://www.legislation.gov.uk/uksi/2005/1093/contents/made [Accessed: April, 2019].

Devine, R. (2016) Hand-arm vibration exposure in warm climates: promoting awareness of health effects and controls to employees, management and contractors, *Acoustics Australia*, Vol. 44, No. 1, pp. 107-1112. https://doi.org/10.1007/s40857-015-0033-4

Ebenso, B., Manzano, A., Uzochukwu, B., Etiaba, E., Huss, R., Ensor, T., Newell, J., Onwujekwe, O., Ezumah, N., Hicks, J. and Mirzoev, T. (2019) Dealing with context in logic model development: Reflections from a realist evaluation of a community health worker programme in Nigeria, *Evaluation and Program Planning,* Vol. 73, pp. 97-110. DOI: https://doi.org/10.1016/j.evalprogplan.2018.12.002

Edwards, D.J., Harris, F. and McCaffer, R. (2003) Management of Off-highway Plant and Equipment, London: Spon Press. ISBN-10: 0415251281

Edwards, D.J. and Holt, G.D. (2005) Exposure to hand-arm vibration: implications of new statutory requirements. *Building Research and Information*, Vol. 33, No. 3, pp. 257–66. DOI: https://doi.org/10.1080/09613210500082552

Edwards, D.J. (2006) Hand-arm vibration, OPERC health and safety study module OPERC-SM-009, Version 2. OPERC: Dudley, UK. Available via: https://www.operc.com/downloads/Bookshop/SM-009-HAV-a.pdf [Accessed: May, 2019].

Edwards, D.J. and Holt, G.D. (2006) Hand-arm vibration exposure from construction tools: results of a field study, *Construction Management and Economics*, Vol. 24, No. 2, pp. 209-217. DOI: http://dx.doi.org/10.1080/01446190500310643

Edwards, D. J. and Holt, G. D. (2007a) A guide to hand-arm vibration. 2nd edn. Dudley: Off-highway Plant and Equipment Research Centre. ISBN 978-0-947974-54-1

Edwards, D.J. and Holt, G.D. (2007b) Perceptions of workplace vibration hazards among a small sample of UK construction professionals, *Engineering, Construction and Architectural Management,* Vol. 14, No. 3, pp. 261-276. DOI: http://dx.doi.org/10.1108/09699980710744908

Edwards, D. and Holt, G.(2010) Cost-effective risk assessment of hand-arm vibration exposure, *Journal of Financial Management of Property and Construction*, Vol. 15 No. 2, pp. 158-175. DOI: https://doi.org/10.1108/13664381011063449

Edwards, D. J. and Love, P. E. D. (2016) A case study of machinery maintenance protocols and procedures within the UK utilities sector, *Accident Analysis and Prevention*, Vol. 93, pp. 319-329. DOI: http://dx.doi.org/10.1016/j.aap.2015.10.031

Edwards, D. J., Pärn, E. A., Love, P. E. D. and El-Gohary, H. (2017) Machinery, manumission and economic machinations. Journal of Business Research, 70, pp. 391-394. DOI:10.1016/j.jbusres.2016.08.012

Edwards, D. J., Pärn, E. A., Sing, C. P. and Thwala, W.D. (2019) Risk of excavators overturning: determining horizontal centrifugal force when slewing freely suspended loads. Engineering, Construction and Architectural Management. DOI: https://doi.org/10.1108/ECAM-03-2018-0125

Howell, K. H., Coffey, J. K., Fosco, G. M., Kracke, K., Nelson, S. K., Rothman, E. F. and Grych, J. H. (2016) Seven reasons to invest in well-being, *Psychology of Violence*, Vol. 6, No. 1, pp. 8-14. DOI: http://dx.doi.org/10.1037/vio0000019

HSE (2012) Hand-arm vibration at work: A brief guide, INDG175(rev3), London, UK: HSE Publications, Crown Copyright. Available via: http://www.hse.gov.uk/pubns/indg175.pdf [Accessed: May, 2019].

HSE (2014) Hand-arm vibration: A guide for employees, INDG296(rev2), London, UK: HSE Publications, Crown Copyright. ISBN: 978-0-7176-6547-1. Available via: http://www.hse.gov.uk/pubns/indg296.pdf [Accessed: May, 2019].

HSE (2018) Costs to Britain of workplace fatalities and self-reported injuries and ill health, 2016/17, London, UK: HSE Publications, Crown Copyright. Available via: http://www.hse.gov.uk/statistics/pdf/cost-to-britain.pdf [Accessed: April, 2019].

HSE (2019a) Hand arm vibration in Great Britain, London, UK: HSE Publications, Crown Copyright. Available via: http://www.hse.gov.uk/statistics/causdis/vibration/index.htm [Accessed: April, 2019].

HSE (2019b) Exposure points system and ready-reckoner, London, UK: HSE Publications, Crown Copyright. Available via: http://www.hse.gov.uk/vibration/hav/readyreckoner.htm [Accessed: May, 2019].

ISO (2001) International Standards Organisation ISO 5349-1: 2001. Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 1: General requirements, ISO Copyright Office, Geneva, Switzerland

ISO (2015) British Standard BS EN ISO ISO 5349-2:2001/Amd 1:2015. Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 2: Practical guidance for measurement at the workplace AMENDMENT 1, ISO Copyright Office, Geneva, Switzerland

Langdon, R. and Sawang, S. (2017) Construction workers' well-being: what leads to depression, anxiety, and stress? *Journal of Construction Engineering and Management,* Vol. 144, No. 2, pp. 1-15. DOI: http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0001406

Love, P. E. D., Edwards, D. J. and Irani, Z. (2010) Work stress, support, and mental health in construction, *Journal of Construction, Engineering and Management*, Vol. 136, No. 6, pp. 650-658. DOI: http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000165

Notini, L., Mansfield, N.J. and Edwards, D.J. (2008) The importance of powertool consumables on vibration exposure, In: Proceedings of the Ergonomics Society: Health and Well Being of Construction Workers Symposium, Nottingham, UK, 1-3 April 2008. pp. 191-196. ISDN:978-0-415-465755OECD (2016) Health workforce policies in OECD countries: right jobs, right skills, right places, The Organisation for Economic Co-operation and Development (OECD), OECD Health Policy Studies, Paris: OECD Publishing. DOI: https://doi.org/10.1787/9789264239517-en

Oja, P., Kelly, P., Pedisic, Z., Titze, S., Bauman, A.E., Foster, C., Hamer, M., Hillsdon, M. and Stamatakis, E. (2017) Associations of specific types of sports and exercise with all-cause and cardiovascular-disease mortality: a cohort study of 80 306 British adults, *British Journal of Sports Medicine*, Vol. 51, pp. 824-824. DOI: https://doi.org/10.1136/bjsports-2016-097343

ONS (2017) Sickness absence in the UK labour market, Office for National Statistics, London, UK: Crown Copyright. Available via: https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/datasets/sicknessabsenceinthelabourmarket [Accessed: April, 2019].

Palmer, K.T., Griffin, M.J., Syddall, H. Cooper, C. and Coggon, D. (2002) The clinical grading of Raynaud's phenomenon and vibration-induced white finger: relationship between finger blanching and difficulties in using the upper limb. International Archives of Occupational and Environmental Health, Vol. 75, pp. 29–36. DOI: https://doi.org/10.1007/s004200100275

Pärn, E. A., Edwards, D. J. and Sing, M. C. P. (2018) Origins and probabilities of MEP and structural design clashes within a federated BIM model. Automation in Construction, 85, pp. 209-219. DOI:10.1016/j.autcon.2017.09.010

Pretty, J., Barton, J., Bharucha, Z.P., Bragg, R., Pencheon, D., Wood, C. and Depledge, M.H. (2015) Improving health and well-being independently of GDP: dividends of greener and prosocial economies, *International Journal of Environmental Health Research*, Vol. 26, No. 1. pp. 11-36. DOI: https://doi.org/10.1080/09603123.2015.1007841

Rashid Z., Shafiq M., Cocca P., Marciano F. and Tayyab A. (2018) Hand arm vibration, grip strength assessment and the prevalence of health disorders among stone crushing workers. In: Goonetilleke R., Karwowski W. (eds) Advances in Physical

Ergonomics and Human Factors. AHFE 2017. Advances in Intelligent Systems and Computing, vol 602. Chambridge: Springer. DOI: https://doi.org/10.1007/978-3-319-60825-9_1

Rimell, A. N., Notini, L., Mansfield, N. J., and Edwards, D. J. (2008) Variation between manufacturers' declared vibration emission values and those measured under simulated workplace conditions for a range of hand-held power tools typically found in the construction industry, *International Journal of Industrial Ergonomics*, Vol. 38, No. 9-10, pp. 661-675. DOI: https://doi.org/10.1016/j.ergon.2007.10.023

Roberts, C. J., Pärn, E. A., Edwards, D. J. and Aigbavboa, C. (2018) Digitalising asset management: concomitant benefits and persistent challenges, *International Journal of Building Pathology and Adaptation*, Vol. 36, No. 2, pp. 152-173. DOI: https://doi.org/10.1108/IJBPA-09-2017-0036

Roe, J. and Aspinall, P. (2011) The restorative benefits of walking in urban and rural settings in adults with good and poor mental health, *Health and Place*, Vol 17, No. 1, pp. 103-113. DOI: https://doi.org/10.1016/j.healthplace.2010.09.003

Smyth, H, Roberts, A. Duryan, M. Sherratt, F, Jing, X. and Toli, A.M. (2019) Occupational Health, Safety and Wellbeing in Construction: Culture, Systems and Procedures in a Changing Environment - A research report on the UK findings, p10-11. UCL Bartlett School of Construction and Project Management: https://www.ucl.ac.uk/bartlett/construction/sites/bartlett/files/occupational_health_safety_and_wellbeing_in_construction_march_2019.pdf

Thornicroft, G., Mehta, N., Clement, S., Evans-Lacko, S., Doherty, M., Rose, D., Koschorke, M., Shidhaye, R., O'Reilly, C. and Henderson, C. (2016) Evidence for effective interventions to reduce mental-health-related stigma and discrimination, *The Lancet*, Vol. 387, No. 10023, pp. 1123-1132. DOI: https://doi.org/10.1016/S0140-6736(15)00298-6

TSO (2015), The Construction (Design and Management) Regulations 2015, Statutory Instruments 2015 No 51: The Stationery Office, http://www.legislation.gov.uk/uksi/2015/51/contents/made

Velardo, S. (2015) The nuances of health literacy, nutrition literacy, and food literacy, *Journal of Nutrition Education and Behavior*, Vol. 47, No. 4, pp. 385-389. DOI: https://doi.org/10.1016/j.jneb.2015.04.328

von Hippel, P.T. (2005) Mean, median, and skew: correcting a textbook rule, Journal of Statistics Education, Vol. 13, No. 2. DOI: https://doi.org/10.1080/10691898.2005.11910556

**Figure 1** – Publications per Annum 1998 to present.

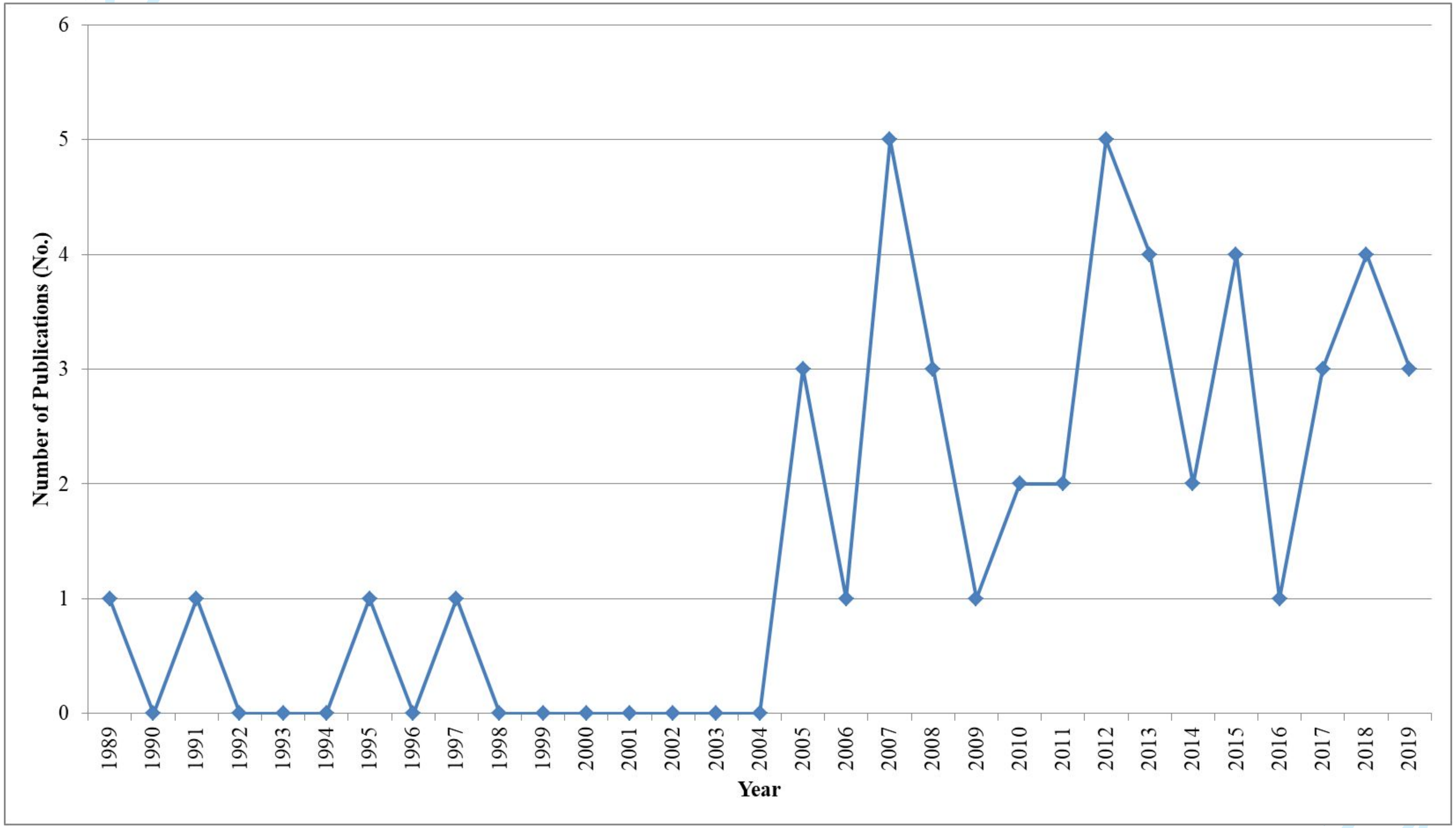

**Table 1** – Tools Used, Trigger Times and HSE Point

| **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 | 4.211 |
| 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 | 9.21 |
| Hand held disk cutter TS410 | 3.9 | 7 | 20 | 440 | 3.71 |
| Hand held disk cutter TS410 | 3.9 | 10 | 45 | 645 | 5.45 |
| Hand held disk cutter TS410 | 3.9 | 15 | 0 | 900 | 7.60 |
| 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 | 4.30 |
| Rammer BS50.2 | 5.4 | 60 | 0 | 3600 | 58.32 |
| Hand held disk cutter TS410 | 3.9 | 7 | 30 | 450 | 3.80 |
| Rammer BS50.2 | 5.4 | 15 | 48 | 948 | 15.35 |
| Hand held disk cutter TS410 | 3.9 | 4 | 50 | 290 | 2.45 |
| Hand held disk cutter TS410 | 3.9 | 10 | 19 | 619 | 5.23 |
| Compaction plate - VP112 | 2.5 | 25 | 39 | 1539 | 5.34 |
| Single drum vibrating roller - Terex MBR71 | 3.6 | 18 | 20 | 1080 | 7.77 |
| Floor Saw CS451 | 1.9 | 14 | 40 | 880 | 1.76 |
| Floor Saw CS451 | 1.9 | 7 | 45 | 465 | 0.93 |
| Hand held disk cutter TS410 | 3.9 | 5 | 55 | 355 | 2.99 |
| Floor Saw CS451 | 1.9 | 35 | 58 | 2158 | 4.32 |
| Rammer BS50.2 | 5.4 | 33 | 18 | 1998 | 32.36 |
| Floor Saw CS451 | 1.9 | 14 | 5 | 845 | 1.69 |
| Rammer BS50.2 | 5.4 | 18 | 38 | 1118 | 18.11 |
| Hand held disk cutter TS410 | 3.9 | 8 | 50 | 530 | 4.47 |
| Hand held disk cutter TS410 | 3.9 | 6 | 39 | 399 | 3.37 |
| Dewalt (Model: DCD785M1) | 15 | 4 | 0 | 240 | 30.00 |
| 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 | 16.76 |
| Non-specific oscillating tool | 16.1 | 7 | 31 | 451 | 64.94 |
| Hand held disk cutter TS420 | 3.9 | 61 | 0 | 3660 | 30.92 |
| Atlas Copco AY47 | 2.13 | 64 | 0 | 3840 | 9.67 |
| Non-specific vibrating poker | 4 | 12 | 8 | 728 | 6.47 |
| Non-specific vibrating poker | 4 | 15 | 46 | 946 | 8.40 |
| Hand held disk cutter TS400 | 3.9 | 41 | 50 | 2510 | 21.20 |

| | | | | | |
|---|---|---|---|---|---|
| Newson Wacker BS60-4 | 6.5 | 16 | 37 | 997 | 23.40 |
| Hand held disk cutter TS410 | 3.9 | 11 | 41 | 701 | 5.92 |
| Rammer BS50.2 | 5.4 | 2 | 26 | 146 | 2.36 |
| Compaction plate - VP112 | 2.5 | 3 | 26 | 206 | 1.00 |
| Single drum vibrating roller - Mecolae MBR71 | 3.6 | 5 | 39 | 339 | 2.44 |
| Makita 9557NBZ | 7.5 | *Error* | *Error* | *Error* | *Error* |
| Makita GA9020s | 5.5 | *Error* | *Error* | *Error* | *Error* |
| Makita 9557NBZ | 7.5 | 195 | 0 | 11700 | 365.62 |
| 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 | 337.50 |
| Makita 9557NBZ | 7.5 | 210 | 0 | 12600 | 393.75 |
| Non-specific 18v battery drill | 2.5 | 0 | 12 | 12 | 0.04 |
| Floor Saw CS451 | 1.9 | 10 | 20 | 620 | 1.24 |
| Hand held disk cutter TS400 | 3.9 | 13 | 7 | 787 | 6.65 |
| Petrol breaker - Wacker Neuson BH55RW | 4.5 | 9 | 58 | 598 | 6.72 |
| Hand held disk cutter TS400 | 3.9 | 12 | 24 | 744 | 6.28 |
| Husqvarna K760 | 2.5 | 18 | 10 | 1090 | 3.78 |
| Husqvarna K760 | 2.5 | 15 | 30 | 930 | 3.22 |
| Husqvarna K760 | 2.5 | 10 | 5 | 605 | 2.10 |
| Husqvarna K760 | 2.5 | 3 | 10 | 190 | 0.65 |

**Table 2** – Summary Statistics for the Trigger Time

| **Trigger Times (Seconds)** | | **HSE Points** | |
|---|---|---|---|
| *Statistic* | *Value* | *Statistic* | *Value* |
| Mean | 1968.13 | Mean | 41.26 |
| Standard Error | 403.95 | Standard Error | 13.07 |
| Median | 900.00 | Median | 6.56 |
| Mode | 900.00 | Mode | 14.58 |
| Standard Deviation | 3022.90 | Standard Deviation | 97.82 |
| Sample Variance | 9137907.00 | Sample Variance | 9569.82 |
| Kurtosis | 5.86 | Kurtosis | 7.04 |
| Skewness | 2.62 | Skewness | 2.91 |
| Range | 12588.00 | Range | 393.70 |
| Minimum | 12.00 | Minimum | 0.04 |
| Maximum | 12600.00 | Maximum | 393.75 |
| Sum | 110215.00 | Sum | 2310.67 |
| Count | 56 | Count | 56 |

**Figure 2** – Probability Density Function - Burr (4P)

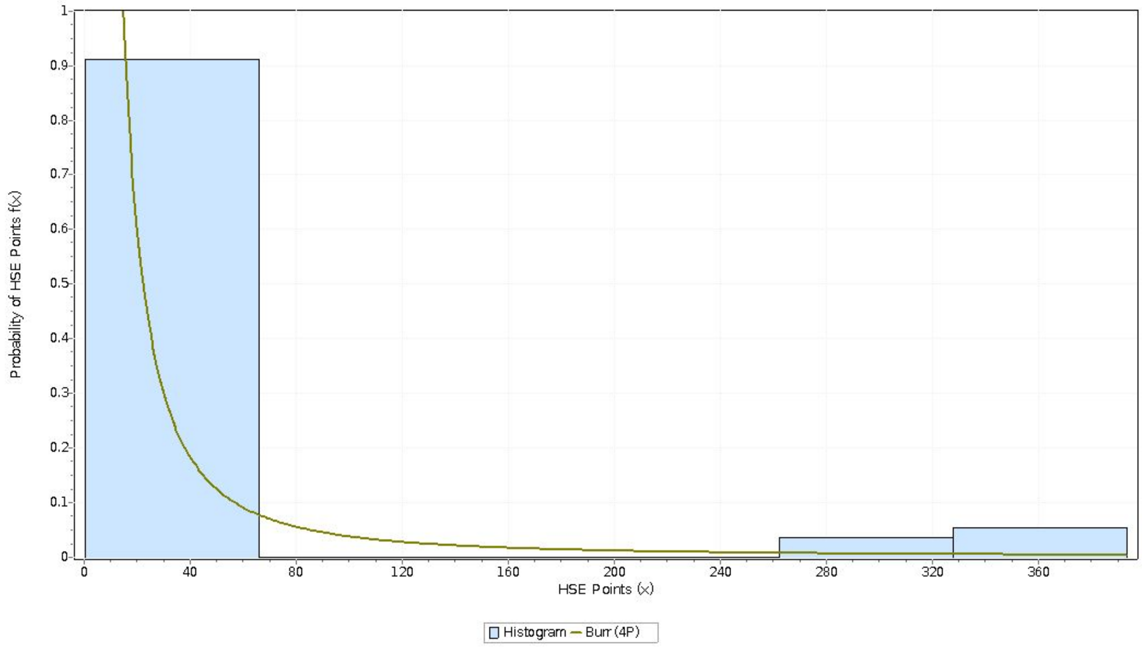

**Figure 3** – Cumulative Distribution Function – Burr (4P)

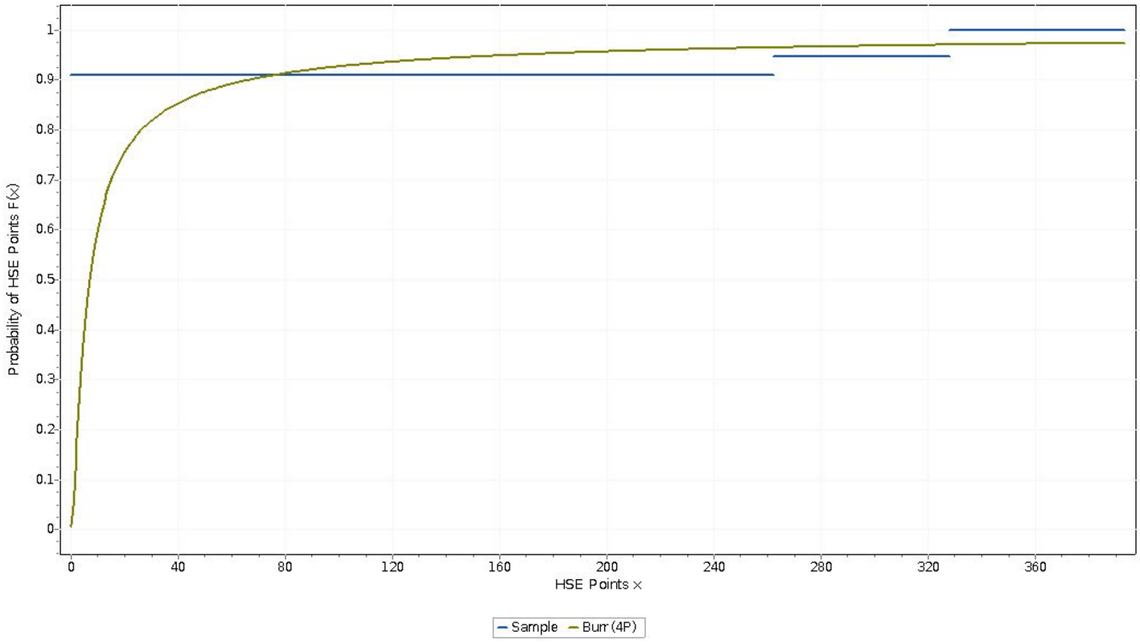

**Table 3** – Goodness of Fit Tests

| 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 | No |

**Table 4** – 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 |