Cycling pavement assessment using hand-arm vibration exposure

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Abstract

A defective pavement surface discourages cyclists from selecting certain routes and vibration exposure is a noticeable consequence of reduced path surface quality. Current asset management practice includes walk-over surveys and cyclists reporting defects direct to the local authority. The research proposes the use of an instrumented probe bicycle to collect data for the assessment of pavement condition and rider comfort. Furthermore, the collection of hand-arm vibration exposure data is proposed as a means of assessing pavement surface condition and suitability. Hand-arm vibration exposure has been measured in compliance with EN ISO 5349-1:2001. Root-mean-square vibration total values, vibration dose value and exposure values (15, 30 and 60 minutes) are provided for 13.682 km of pavement surface. The vibration exposure values are compared to the EU Directive 2002/44/EC11. Power spectral analysis is also provided to indicate power transferred to the cyclist hands and arms. The collated vibration data may be used as a means of assessing pavement surface condition. Such data may prove beneficial for local authority asset management associated with resurfacing or repair works.

Keywords: cycling, hand-arm vibration, pavement surface, asset management.

1. Introduction

The Scottish government continues to invest in active travel. Since 2007, 215 miles have been added to the National Cycle Network in Scotland. Since 2011, the Community Links Programme has contributed over 131 miles of new walking and cycling paths in and around our urban areas (Brown, 2015). The City of Edinburgh is experiencing growth in the number of journeys undertaken by bike. From less than

1% in 1981, cycle commuting has increased in the city each decade. In 2014, 11.8% of commuter journeys were undertaken by bicycle and 4.2% of all journeys in Edinburgh are by bicycle. Total cycling investment is estimated to be £40.052 million in 2015/2016 with the allocation of 1.9% of the total Scottish transportation budget of £2,108 million (Spokes, 2016).

In the City of Edinburgh, the management of existing cycling infrastructure assets is currently a labour intensive task and relies upon direct visual inspection of pavement surfaces for identifying defects. Reporting cycle path defects, road or pavement (footpath) defects to the local authority is encouraged through the use of an online reporting system and emergency phone number.

A poor pavement surface discourages cyclists from selecting certain paths or routes and vibration exposure is a prominent consequence of poor cycle track quality *(Bíl et al.*, 2015). Ayachi *et al.* (2015) conducted an online survey of experienced cyclists (>2000 km/year) and principal component analysis of the results identified that the road surface strongly contributes to rider comfort in conjunction with bicycle saddle and frame design.

Bicycle force transducers such as instrumented pedals, stems and seat posts have been used to measure loads at the contact interface between the cyclist and the bicycle. Instrumented handle bars and a seat post were used by Vanwalleghem *et al.* (2012) to measure absorbed power as a metric for cyclist comfort. Olieman *et al.* (2012) measured the effect of road surfaces, speed, wheel construction and tyre pressure on the vibrations induced to the frame and forks of a bicycle. They identified the benefits of micro electro-mechanical systems (MEMS) devices in relation to their physical size, cost and low power consumption as an ideal means of measuring movement in active sports.

The research proposes a low cost vibration measuring apparatus to record hand-arm vibration exposure for cyclists. The apparatus can be used to record objective pavement condition data for cycling infrastructure. The instrumented bicycle can be used as an asset management tool to provide reliable and repeatable condition measurements for cycling pavement surface condition.

2. Literature review

Previous research has been undertaken relating to the use of instrumented probe bicycles with accelerometers mounted at varying points on the frame and handle bars. A summary of the recent research examining vibration exposure during cycling is provided. The research is concerned with recreational, commuter and sports cycling scenarios. Objectives, rider characteristics, instrumentation, theory and standards applied are summarised.

Previous research has assessed the relative contribution of bicycle components on the vibration induced in the hands and buttocks of cyclists. Lépine *et al.* (2015) assessed the relative contribution of vibration through measurement in three different locations. These included the vertical force and acceleration transmitted via the saddle, force and acceleration transmitted through the handle bars and, finally, the force and acceleration transmitted to the hands on break hoods and the handle bars under the hands. Three measurements: (1) acceleration (2) force (3) absorbed power were undertaken. Accelerations were calculated using the root mean square (r.m.s.) values of the transducer signal filtered with the ISO 2631 standard vertical frequency weighting curves for whole body transmitted vibrations. Stem and brake acceleration and force were calculated using the r.m.s. value of the transducer signal filtered with the ISO 5349 standard frequency-weighting curves for hand transmitted vibrations.

The measurement and evaluation of human exposure to hand-arm vibration in relation to the pavement surface type has been examined in previous literature. Gomes and Savionek (2014) conducted hand-arm vibration exposure on three pavement surface types: asphalt, precast concrete and interlocking concrete blocks. Using a tri-axial piezoelectric accelerometer fixed to the handle bars, daily exposure to vibration (A(8)) for a daily duration of exposure of two hours (T=2 hrs) was considered to represent an average exposure time for leisure cycling purposes. A piezoelectric accelerometer Dytran model 3023 A2 S/N4147 (10 mV/g nominal sensitivity) was utilised. Analysis and storing of the acceleration measurements was undertaken using a Quest VI-400 Pro S/N 12430. The equipment conformed to ISO 8041. Exposure action values (EAV) of 2.5 ms^{-2} and exposure limit values (ELV) of 5.0 ms^{-2} were considered from directive 2002/44/EC corresponding to A(8) from ISO5349-1:2011. The r.m.s. acceleration weighted in frequency domain (weighted curve W_h) and passed through a narrow band filter, thereby producing a value defined as a weighted frequency r.m.s. acceleration a_{wh} in ms^{-2}. ANOVA analysis was then used to determine correlation between the opinions and measured accelerations.

Parkin and Eugenie Sainte (2014) provided a study of comfort and health factors including the nature of vibrations from riding in different circumstances in the city of London. Aluminium and steel framed bicycles were utilised. Apparatus employed included a Svan 958A (four channel sound and vibration analyser) and Dytran 3233A accelerometers. Accelerometers were located at the rear axle, seat post and on the edge of the saddle. Root-mean-quad (r.m.q.) and vibration dose value (VDV) in accordance with BS ISO 2631-1:1997 were recorded and calculated. VDV was considered a superior approach as it does not underestimate the peak values in using route-mean square (r.m.s.). Vertical axis (weighting W_k) was utilised when calculated whole body vibration exposure (WBV). European Directive 2002/44/EC11 was considered and $A_i(8)$ and $VDV_i(8)$ daily exposure to vibration with reference duration of eight hours was calculated. The research refered to the directive for daily Exposure Action Values (EAV) and daily Exposure Limit Values (ELV). Action and limit values for whole body vibration were considered and included: EAV A(8) = 0.5 ms^{-2} and VDV(8) = 9.1 $ms^{-1.75}$ and ELV A(8) = 1.15 ms^{-2} and VDV(8) = 21 $ms^{-1.75}$.

Munera *et al.* (2014) summarised the different standards and guidelines associated with the evaluation of vibration and exposure limits whilst cycling. They focussed upon physiological and pathological disorders in performance athletes. The research identified the application of the Directive 2002/44/EC11 in defining the limit of exposure and the limit triggering action for cyclists' vibration exposure. Furthermore, they identified ISO 5349-1 a suitable method for examining cyclists' vibration exposure.

Pelland-Leblanc *et al.* (2014) and Vanwalleghem *et al*. (2012) considered absorbed power a suitable metric for assessing rider comfort as it considers the energy exchange between the vibration structure and the human body. They stated that absorbed power is unaffected by the position of the rider due to absorbed power taking into account the force, acceleration, magnitude and phase. Contact force and velocity was measured utilising piezoelectric accelerometers with a 100 mV/g sensitivity and force with strain gauges mounted on the handle bars. Perception to vibrational comfort in whole-body was measured in accordance with ISO 2631-1:1997 and BS 6841. The higher the acceleration level, the less comfort the human encounters. Measured in terms of absorbed power, which is the energy being dissipated in the human body due to vibration. The human sensitivity to vibration depends upon (i) the frequency, (ii) the direction of vibration, both translational and rotational and (iii) the posture of the human. Frequency weighting curves take all these aspects into account. Drift in the velocity signal due to the integration process was removed with a 'high-pass' filter.

Giubilato and Petrone (2012) measured the vibration response of difference racing wheels to excitation caused by irregular road surfaces. Considering constant speeds (15,25 and 35 km/h) the utilised three-axis piezoelectric accelerometers SoMAt 1100 (+/- 50g, 0.3-15,000 Hz bandpass). The accelerometers were mounted at the rear axle and also positioned close to saddle on the seat post. Accelerometer channels sampled at 20kHz +/- 50g.

Hölzel *et al.* (2012) measured cyclists' exposure to vibration induced by four different cycle path pavement surfaces: asphalt, concrete paving slabs, cobblestones and self-binding gravel. They concluded that cycling pavement surfaces constructed from asphalt improve rider comfort and may encourage greater uptake of cycling. In a review of instrumented probe bicycle (IPB) research, Mohanty *et al.* (2014) summarised the development of comfort and safety prediction models highlighted the need to collect more accurate and continuous real-time data that represents the cycling experience.

Bíl *et al.* (2015) obtained vibration data using an accelerometer with a measurement frequency of 20 Hz. However, measuring at such a low sample rate does not comply with the Nyquist frequency and only allows vibration measurement of below 10 Hz. Although useful in providing a general indication of the surface quality, such low frequency measurement could not be utilised as a measure of human exposure to vibration in accordance with the relevant international standards (EN ISO 5349-1:2001).

3. Background

The City of Edinburgh has an established off-road (segregated) cycle path network with varied pavement materials and surface treatments. Cyclists are also encouraged to use on-road cycle path facilities with subsequent interaction with road pavement surfaces shared with vehicular traffic. The aim of the research was to measure and quantify pavement surface quality of on-road and off-road cycling facilities in the City of Edinburgh. This was to include the categorisation of pavement types and an assessment of the transmitted vibration to the hand-arm system. A typical Edinburgh commuter bicycle was selected and mounted with micro electro-mechanical systems (MEMS) including a micro controller, two tri-axial accelerometers, a global positioning system (GPS) and data storage device. The IPB was then used to measure hand-arm vibration exposure in accordance with EN ISO 5349-1 (2001) on different cycling pavement surfaces in the City of Edinburgh.

When assessing the suitability of a pavement surface for cycling, the physical condition, functionality and compliance may assist in forming a condition assessment. The data presented may be used as a means of objectively assessing the condition of a pavement surface through the measurement of hand-arm vibration exposure. The vibration data analysis was utilised to provide pavement surface condition assessment of the route under consideration. The resultant data set may contribute to improved asset maintenance decisions associated with resurfacing or repair works. Categorised surface condition assessment data may contribute to improving condition monitoring of cycling infrastructure and potentially reduce cost associated with data collection. Most importantly, all data collected will be from the perspective of the cyclist with data collection survey durations being significantly reduced.

4. Pavement materials and surfaces

The pavement surface is considered to be crucial in providing a comfortable riding experience for cyclists. Pavement surface quality also has an impact upon the perceived quality and attractiveness of the route. A cycle path pavement or highway surface utilised by cyclists should ideally have a flat and even profile and be free of major defects. Furthermore, the surface must be even skid resistant and provide adequate drainage.

Pavement surface types and categories considered in the present study include:

- Hot rolled asphalt (HRA).
- Asphaltic concrete (AC).
- Concrete (C).
- Monoblock (M).
- Concrete pavers (CP).
- Compacted fill material (CF).
- Cobble setts (CS).
- Unbound compacted aggregate (UCA).

Figures 1, 2 and 3 show typical off-road and road pavement surface materials considered in the present study. Although not exhaustive, they represent the common pavement surface materials used on cycle paths and cycle lanes in the City of Edinburgh.

Figure 1: Off-road pavement surface materials: from left to right CP, AC and HRA.

Figure 2: Off-road surface materials: from left to right C, UCA and CF.

Figure 3: Road pavement surface materials: from left to right CB, CS and HRA.

National cycle network routes were considered for vibration exposure assessment. In conjunction with dedicated cycle path routes, adopted roads were also surveyed to provide a comparison with dedicated off-road cycle path pavement surfaces. Data concerning cyclists' exposure to hand-arm vibration associated with riding on the shoulder area (1.5m to 2.0m from kerb) on adopted roads was considered. The verge area is predominantly utilised by buses and passenger vehicles. Bus lanes are predominantly utilised in the City of Edinburgh as shared space with bicycle traffic.

Kocak and Noble (2010) identified the total length of all cycle paths in the City of Edinburgh as 224 km. They also provided an indication of the split between on-road and off-road cycle path infrastructure as 82 km and 142 km respectively. The present study surveyed 13.682 km of off-road and on-road pavement surfaces, representing

6.1% of the cycle paths identified in 2010. Table 1 gives the breakdown of various surfaces.

Pavement material	**Road (m)**	**Off-road (m)**	**Total (m)**
Hot rolled asphalt	3408	4290	7698
Asphaltic concrete	0	2392	2392
Cobble setts	1472	189	1661
Compacted fill material	0	1099	1099
Monoblock	160	257	417
Concrete pavers	0	316	316
Concrete	0	99	99
Total survey distance	5040	8642	13682
Total Edinburgh network	82000	142000	224000
% of network surveyed	6.15%	6.09%	6.11%

Table 1: Summary of surveyed cycle path classification and pavement material.

5. Human exposure to vibration whilst cycling

Munera *et al.* (2014) reviewed human exposure to vibration whilst cycling and provided a detailed summary of the associated physiological and pathological disorders. Studies examining different pavement surfaces and their influence upon comfort were highlighted. Chiementin *et al.* (2012) studied cyclists' exposure to vibration transmitted from the road surface identifying the harmful potential of the road profile to athletes with detrimental effects upon competitive performance. In a study of cycling vibration exposure in the city of London, Parkin and Sainte Cluque (2014) identified that workplace Exposure Action Values (EAV) and Exposure Limit Values (ELV) in accordance with European Directive 2002/44/EC11 were exceeded, concluding that pavement surface quality was a significant contributory factor in the cyclists' exposure to significant hand-arm vibration.

Mirbod *et al.* (1997) defined the term hand-arm vibration syndrome (HAVS) used to describe the collection of peripheral neurological, vascular, and musculoskeletal symptoms that are recognised to affect the upper extremities of workers exposed to vibration. In a study of HAVS associated with police motorcyclists, data demonstrated that the motorcycle itself, the riding period and the surrounding environment contributed significantly to vibration exposure levels. Ergonomic posture was highlighted as an important factor as sensitivity of the human body depends to some extent on posture and on the way in which vibration is imparted to the body (Bishop, 1979).

As a means of collecting objective data on the condition of a pavement surface from a cyclists' perspective, hand-arm vibration exposure is considered as an appropriate measurement for the present study.

5.1. Hand-arm vibration measurements

The assessment of hand-arm vibration was performed in accordance with International Standard EN ISO 5349-1(2001). Munera *et al.* (2014) identified this standard as an appropriate measurement of vibration exposure applied to cycling. The vibration entering the hand contains contributions from the three basicentric axis directions. The vibration exposure is calculated using a combination of the three measurement axes. As defined by EN ISO 5349-1 (2001), the vibration total value (a_{hv}) is defined as the root-sum-of-squares and the three component values as shown in Equation 1.

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \qquad \text{Equation 1}$$

Filters are required to remove elements of the measured signal that are not of interest. The weighting of the acceleration data is required as the risk of damage is not equal from all frequencies and a frequency weighting is used to represent the probability of damage due to a specific frequency range (Chiementin *et al.*, 2012).

Rimell and Mansfield (2007) demonstrated the practical application of the weighting filters as digital infinite response filters (IRR). Filtering was performed using a combination of a low-pass, high-pass and frequency weighting filter. EN ISO 5349-1 (2001) combines a high-pass and low-pass filters to produce a band-limiting filter. The frequency weighting and band limiting filter characteristics provided in Table 2 are constructed using cascaded transfer functions.

The band-limiting filter defined by the transfer function of the filter, $H_b(s)$:

$$H_b(s) = \frac{s^2 4\pi^2 f_2^2}{\left(s^2 + \frac{2\pi f_1 s}{Q_1} + 4\pi^2 f_1^2\right)\left(s^2 + \frac{2\pi f_2 s}{Q_1} + 4\pi^2 f_2^2\right)} \qquad \text{Equation 2}$$

Where $s = j2\pi f$ is the variable of the Laplace transform.

The frequency weighting filter defined by the transfer function of the filter, $H_w(s)$:

$$H_w(s) = \frac{(s + 2\pi f_3) 2\pi \mathrm{K} f_4^2}{\left(s^2 + \frac{2\pi f_4 s}{Q_2} + 4\pi^2 f_4^2\right) f_3} \qquad \text{Equation 3}$$

Where $s = j2\pi f$ is the variable of the Laplace transform. Both the band-limiting and frequency weighting filters were realised by a two-pole filter. The total frequency-weighting function is:

$$H(s) = H_b(s).H_w(s) \qquad \text{Equation 4}$$

Figure 4 shows frequency response plot constructed using the band limiting and frequency weighting transfer functions provided in Equations 2, 3 and combined as the total frequency weighting function in Equation 4.

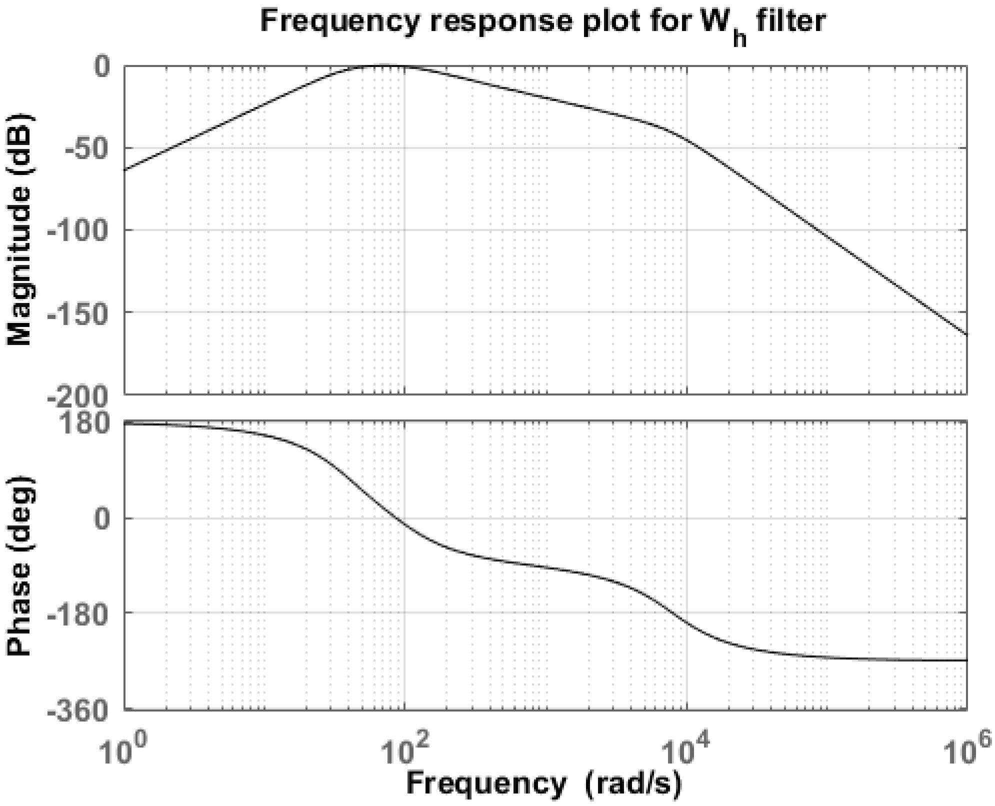

Figure 4: Band limiting and frequency-weighting filter frequency response plot.

Band limiting filter		Frequency weighting filter	
f_1	6.3	f_3	15.915
f_2	1258.9	f_4	15.915
Q_1	0.71	Q_2	0.64
		K	1

Table 2: Frequency weighting filter characteristics.
Source: EN ISO 5349-1:2001, Annex A, Table A.1.

5.2. Vibration exposure

The daily vibration exposure was calculated in accordance with EN ISO 5349-1 (2001). Comparisons between daily vibration exposure of different durations is facilitated by expressing daily exposure in terms of the eight hour energy equivalent frequency weighted vibration total value ($a_{hv(eq,8h)}$) as shown in Equation 5.

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \qquad \text{Equation 5}$$

Where T is the total daily duration of exposure to the vibration (a_{hv}) and T_0 is the reference duration of eight hours. For the present study four durations were considered for assessing the vibration exposure: (1) the sample time ($A(8)_t$); (2) the fifteen minute exposure duration ($A(8)_{15min}$); (3) the thirty minute exposure duration ($A(8)_{30min}$) and; (4) the sixty minute exposure duration ($A(8)_{60min}$). Finally, as a potential indicator of the condition of the surface, the time elapsed until the European Directive

2002/44/EC11 exposure action value (EAV) and exposure limit value (ELV) is reached is also calculated.

The fourth power relationship is mostly used as a dose that increases with duration, rather than as an average (root mean quad, r.m.q.). Vibration dose value (VDV) is calculated from the r.m.q without dividing by the exposure duration:

$$VDV = \left[\int_{t=0}^{t=T} a_w^4(t)dt\right]^{1/4} \qquad \text{Equation 6}$$

Where $a_w(t)$ is the frequency-weighted acceleration and T is the period during which a person is exposed to vibration. The VDV provides a robust and easy-to-use measure with a time dependency that is plausible for periods from seconds up to a full day and gives relative weight to occasional higher vibration magnitudes (Griffin, 2007).

6. Data collection method

It is essential that human vibration exposure is quantified by the vibration conditions at the interface between the environment and the human body: not by the vibration at any other arbitrary position on the body or in the vibration environment (Griffin, 1990). An accelerometer is a sensor that measures the physical acceleration experienced by an object due to inertial forces or mechanical excitation.

The transducer is a device that converts energy from one form to another. Converting a mechanical signal to an electrical signal is a typical example. The MEMS accelerometer type was considered to be a suitable device for measuring HAV exposure from bicycle handle bars.

An aluminium framed Trek 6000 (m=13.9 kg) was selected as the bicycle platform for the instrumented probe. The bicycle was selected as a typical commuting, sports and recreational bicycle type witnessed in the Edinburgh. There are many variables associated with the power supplied by a cyclist to provide the locomotive force. These include the mechanical efficiency of the bicycle, the mass of the rider, the mass of the bicycle, the coefficient of rolling resistance, the gradient of the surface, aerodynamic drag, frontal area of the rider and the headwind velocity. Furthermore, parameters associated with the tyre tread pattern, tyre pressure and the movement of shock absorbers can significantly vary the repeatability of the data collected. Table 3 provides a technical summary of the bicycle, frame, rider characteristics, drive chain and components on the bicycle. When collecting data, it is imperative that these details are considered and any change or variation recorded.

Manufacturer/model	Trek 6000
Year manufactured	2012
Frame size	495mm (19.5")
Frame material	Aluminium
Mass of bicycle	13.9 kg
Mass of rider	95.2 kg
Wheels	Shimano M435 hubs, Bontrager AT-850 32-hole rims
Tyre type	Schwalbe Big Apple Plus 660 x 54.61mm (26 x 2.15")
Tyre pressure	60 psi
Drive train	Crank: Shimano M552 42/32/24
	Cassette: Shimano HG62-10 11-36, 10 speed
	Pedals: Wellgo alloy platform
	Front derailleur: Shimano Deore
	Rear derailleur: Shimano Deore XT M780 Shadow
	Shifters: Shimano Deore M591, 10 speed
Components	Handle bars: Tactic AI-6061 aluminium, 730mm, 31.8mm dia., 76.2mm rise.
	Saddle: Selle Royal Avenue comfort saddle, width 161mm, length 273mm
	Stem: Truvativ 60mm +7°
	Headset: 1-1/8" threadless, semi-integrated, semi-cartridge bearings
	Brakeset: Shimano M446 hydraulic disc brakes
	Shock absorbers: SR Suntour lockout equipped XCRRL

Table 3: Bicycle and rider characteristics.

The development of MEMS sensors are providing alternatives to traditional accelerometer types. Production methods are similar to the batch fabrication techniques adopted in the manufacturing of integrated circuits. Therefore, such production techniques have greatly reduced the cost of such components. The IPB mounted instrumentation was designed as a lightweight, low cost and compact device as not to hinder the cyclists hand movements associated with breaking, changing gear and steering. Therefore, such a system could be economically mounted to bicycles to facilitate data collection to support asset data collection.

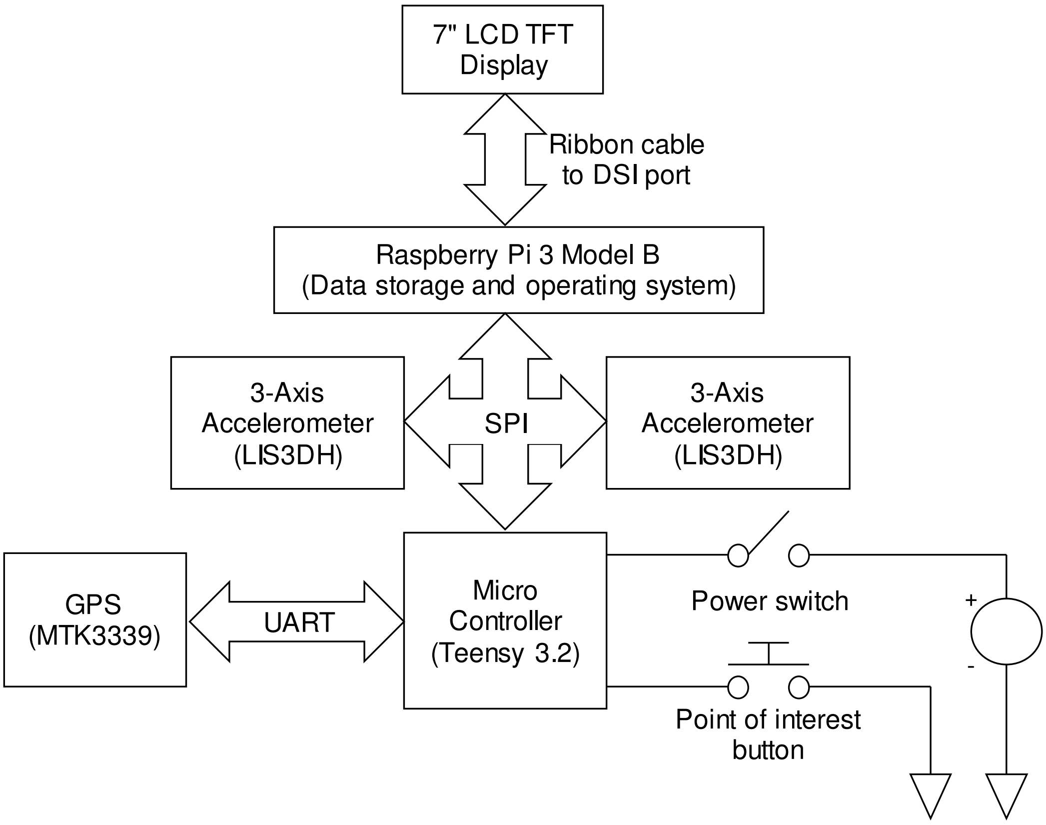

Figure 5: Sensor system block diagram schematic.

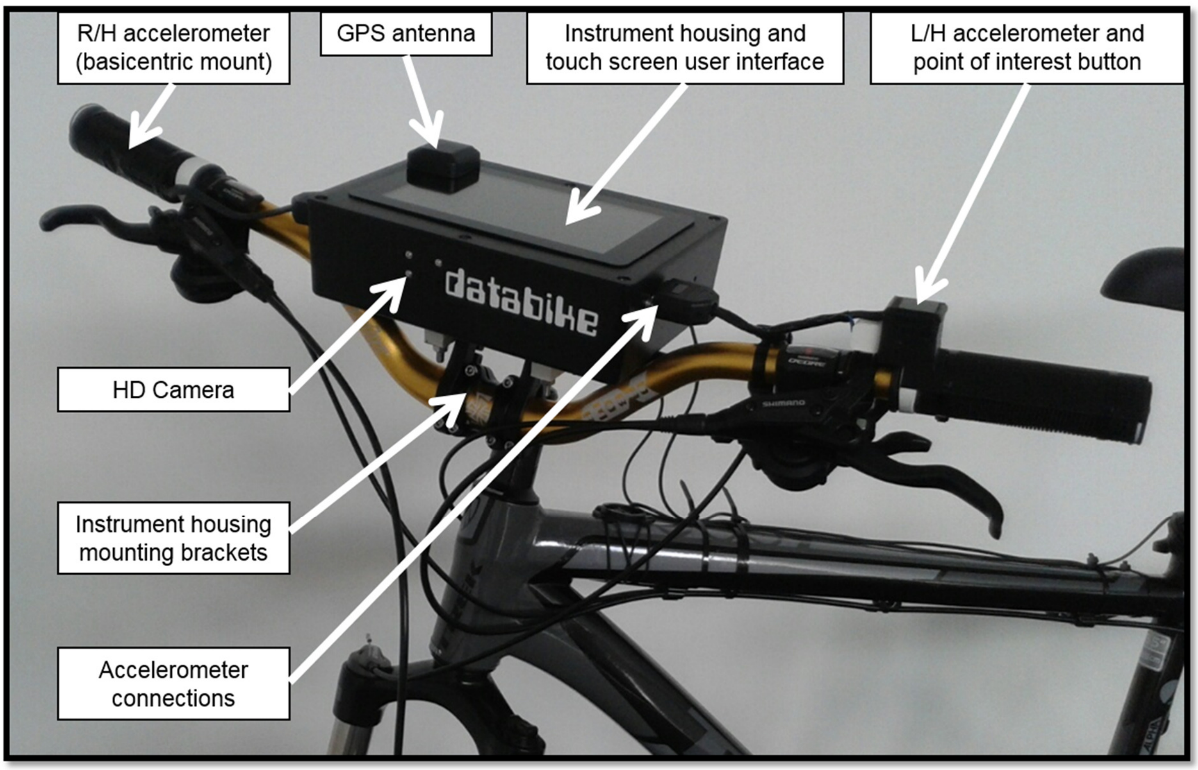

Figure 6: Instrument and sensor mounting position.

The vibration measurement system was constructed using an Arduino-compatible microcontroller (Teensy 3.2, 32 bit, MK20DK256), two accelerometers, real-time clock and GPS device. The micro controller was utilised as a dedicated central processing and control unit. A Raspberry Pi 3 (Model B, Raspian operating system) with a 7 inch (180mm) LCD touch screen was then used as an operating interface and data storage device. Figure 6 shows the apparatus mounted on the bicycle handle bars.

Two three axes digital output motion accelerometers (Adafruit LIS3DH) with digital serial interface standard outputs were utilised. The accelerometer break-out board has user selectable scales of sensitivity of ±2g, ±4g, ±8g and ±16g and is capable of measuring accelerations with output data ranges from 1Hz to 5kHz. The accelerometer sensitivity was set to ±16g sampling at 5kHz for the present study. The GPS device utilised was an Adafruit Ultimate GPS breakout board containing an MTK3339 chipset.

A high definition (HD) camera module (Raspberry Pi camera, Rev 13) was mounted on the instrumentation housing facing the direction of travel. This provided the surveyor with a means of visually inspecting surface defects in relation to points of interest relating to high vibration levels. The camera clock was synchronised with the micro controller real-time clock to facilitate data location during data processing, analysis and inspection of defects.

The accelerometers are connected over a serial peripheral interface (SPI) bus and initialised to run in 'first in first out' (FIFO) mode to limit central processing unit interaction time and bus traffic. This was implemented to allow for writing to a secure digital (SD) card in between sensor readings. The sample rate was set at 5 kHz to ensure that the Nyquist frequency of at least two times the maximum frequency of 1.25 kHz was captured. Only the right hand grip accelerometer data was utilised for the present study.

Once the FIFO buffer is full, the LIS3DH module sets its interrupt pin high to signal the microcontroller that it is ready to be read. The microcontroller then responds to only one of the interrupt pins and uses that signal to synchronise the readings from both accelerometers (right and left grip mounts). The X, Y and Z axis data is formatted into comma separated variable (CSV) files with data parsed from the GPS sentences. The Raspberry Pi has a shell script that configures the USB serial port to raw so that it does not drop any data when redirecting to a data log file. It also starts an HD video recording simultaneously with the data log file. The CSV file output format is: X1, Y1, Z1, X2, Y2, Z2, time, longitude, latitude and point of interest markers. Geospatial data and point of interest markers were used to confirm locations and identify points of interest.

7. Method of mounting the accelerometers

Griffin (2007) highlighted that vibration should be measured at the interfaces between the body and the vibrating environment (e.g. at the supporting seat surface, the feet and the hands. Munera *et al.* (2014) also recommended that the origin of the coordinate system must be at the point where the vibration enters the body. Furthermore, Griffin (2007) and Chiementin *et al.* (2012) stated that measurements of vibration on the body and at locations other than the machine-hand interfaces with the vibrating environment are not useful when predicting vibration discomfort.

A handle bar grip adaptor was designed and constructed to mount the accelerometer on the bicycle as shown in Figure 7. Subsequently, this avoided the mounting of the accelerometers directly onto the curved rubber surface of the handle bar grip. The device was used to hold the accelerometer between the hand and the grip. The grip mount was then secured using cable ties. The right hand grip mount was designed to allow positing in accordance with EN ISO 5349-1:2001 and the basicentric coordinate system for mounting on a cylindrical bar (Figure 8). The mount was designed using AutoDesk Inventor 2016. The mount was constructed from a stereolithographic file using a 3-D printer (Makerbot Replicator 2) and acrylonitrile butadiene styrene (ABS) thermoplastic polymer material. Figure 9 provides a dimensioned drawing of the grip adaptor. Figure 10 shows a rendered image of the grip adaptor showing the accelerometer mounted and the orientation of the measurement axes.

The mass the right hand adaptor was 12.4 grams including the accelerometer. Neither devices exceeded 15 grams, as recommended for mounts for measuring at the palm of the hand[1]. The grip adaptor was manufactured from ABS and was considered to be a rigid material suitable for its purpose[2] (BSI, 2015).

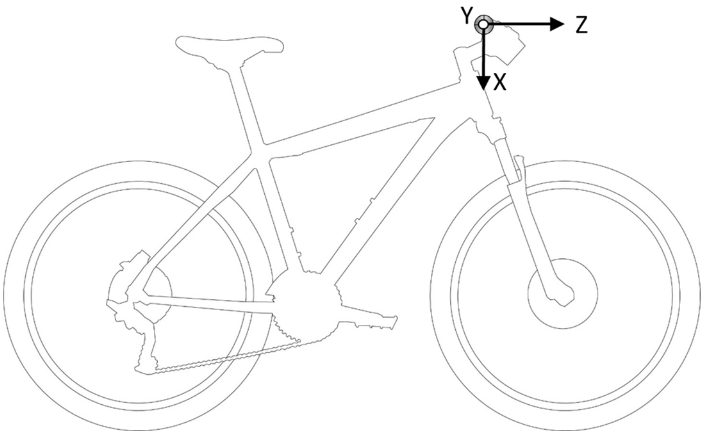

Figure 7: Accelerometer mounting position on bicycle.

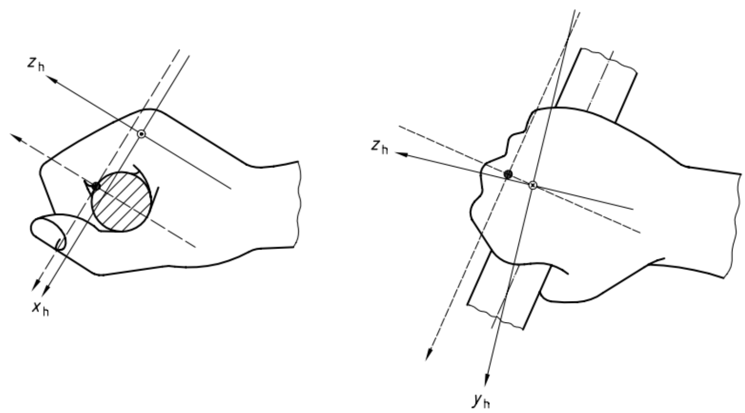

Figure 8: Basicentric coordinate system for the handle bar grip.
Source: BS EN ISO 5349-1:2001, Figure 1.

[1] BS EN ISO 10819:2013 Clause 5.2.2.2
[2] As recommended by BS EN ISO 10819:2013 Incorporating corrigendum August 2015.

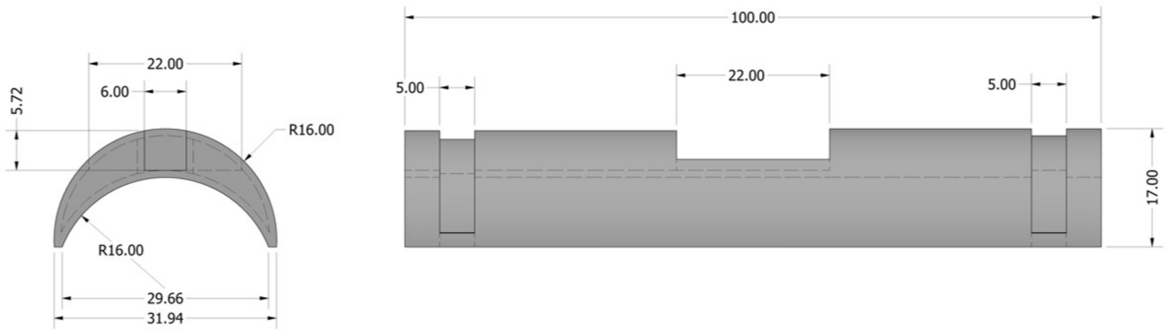

Figure 9: Handle bar grip adaptor accelerometer mount (dimensions in mm).

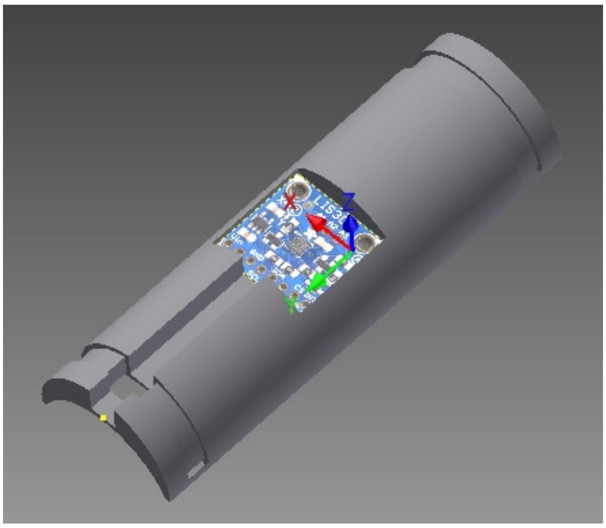

Figure 10: Handle bar grip adaptor mount showing accelerometer location.

8. Analysis of results

All digital signal processing was undertaken using Matlab 2017a. Toolbox add-ons included the Control System Toolbox (Version 10.2), Digital Signal Toolbox (Version 9.4) and Signal Processing Toolbox (Version 7.4). Digital filters were constructed using continuous time transfer functions. Figure 11 shows a flow chart describing the measurement (data collection), analysis (digital computation) and the evaluation (analysis) of the results.

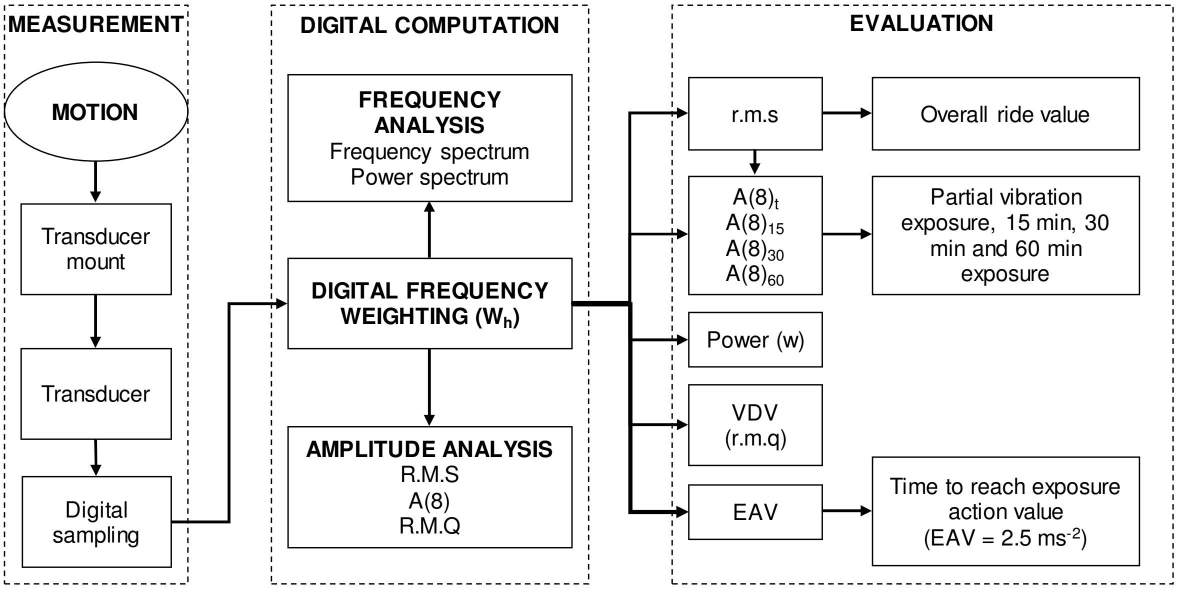

Figure 11: Illustration of measurement and evaluation of vibration data.
Source: adapted from Griffin,1990.

Frequency and power spectral analysis were used to examine the power transferred to the hand arm system. The results show the vibration exposure measurements including overall r.m.s, A(8) and VDV. To show the power being transferred to the hand-arm system, power spectral analysis data provides the power transferred with and without the application of the W_h filter. Furthermore, the results also show the power in the frequency range 6.3 Hz to 1250 Hz and 6.3 Hz to 870 Hz.

Table 4 presents the measured data for the 13.682 km of pavement surface surveyed. The data includes the r.m.s. vibration being the vibration total sum (a_{hv}). Exposure values ($A(8)_t$) are provided for the sample time (the distance travelled on the pavement surface), fifteen minute exposure ($A(8)_{15min}$), thirty minute exposure ($A(8)_{30min}$) and sixty minute exposure ($A(8)_{60min}$) times. Typically, hot rolled asphalt surfaces produced the lowest vibration total sum values. The lowest value being Stenhouse Drive off-road path (V20, a_{hv} = 2.15 ms^{-2} r.m.s) with subsequent low vibration dose value and exposure values (VDV = 10.89 ms$^{-1.75}$ and $A(8)_{60min}$ = 0.76 ms^{-2}). Typically off-road (no vehicular traffic) hot rolled asphalt surfaces provided the lowest vibration exposure results. These were closely followed by concrete pavers and asphaltic concrete.

Asphaltic concrete on non-vehicular pavement surfaces also provided a low vibration response. Hot rolled asphalt surfaces on adopted roads with surface defects provided substantially higher vibration exposure. For example, Napier Road contained several surface defects and had a subsequent higher vibration exposure value (V07, a_{hv} = 10.41 ms^{-2} r.m.s). Pavement surface defects on adopted roads experiencing vehicular traffic provide significant vibration exposure to cyclists.

Figure 12 identifies the pavement surfaces that exceed the exposure action value of 2.5 ms^{-2} after the selected durations of travel (15 min, 30 min and 60 min). The surfaces which exceed this value typically include adopted roads and cobble setts.

Compacted fill material also provided considerable vibration exposure. Such material is common in rural locations and is typically specified for paths which experience limited cyclists or equestrian use. Cobble setts pose considerable vibration exposure to the rider. The greatest exposure measured is on the High Street (V16) with a vibration exposure of a_{hv} = 13.66 ms^{-2} r.m.s.

Table 5 shows the time taken to reach the EAV and ELV for the data collected. The time to reach the EAV value of 2.5 ms^{-2} varies considerably. However, cobble setts, hot rolled asphalt (adopted roads) and compacted fill material have short exposure durations to meet the EAV limit. The High Street (V16) has the shortest duration to the EAV limit. A total of 16 minutes cycling on the current surface would take exposure to the EAV limit. In comparison, cycling on the hot rolled asphalt surface of North Meadow Walk (V14) or Middle Meadow Walk (V15) would require rider exposure in excess of 4 hours 26 minutes and 4 hours 48 minutes, respectively, to reach the EAV limit.

The frequency domain spectra of the pavement surfaces varied in magnitude and frequency content associated with the condition of the surface and the material utilised. Power spectral analysis results are provided in Table 6. Power spectral analysis results are presented showing the total power without the W_h filter applied, with the W_h filter applied. Furthermore, the results show the power in the frequency range of 6.3 Hz to 1250 Hz and to examine the low frequency power element from 6.3 Hz to 80 Hz.

Code	Location Identification	Distance	Road/ Off-road	Surface classification	Average speed	Sample time	R.M.S	VDV	$A(8)_t$	$A(8)_{15min}$	$A(8)_{30min}$	$A(8)_{60min}$
		(m)			(kph)	(s)	(ms^{-2})	($ms^{-1.75}$)	(ms^{-2})	(ms^{-2})	(ms^{-2})	(ms^{-2})
V01	East Castle Road	230	Road	Hot rolled asphalt	15.52	53.36	5.58	26.29	0.24	0.99	1.40	1.97
V02	NCR754 Union Canal (Viewforth to Leamington Road)	160	Off-road	Asphaltic concrete	14.93	38.58	3.21	11.48	0.12	0.57	0.80	1.14
V03	NCR754 Union Canal (Leamington Road to Edinburgh Quay)	189	Off-road	Cobble setts	11.33	60.06	12.73	50.24	0.58	2.25	3.18	4.50
V04	Merchiston Mews	120	Road	Cobble setts	13.13	32.90	11.92	39.98	0.40	2.11	2.98	4.21
V05	Dorset Place	160	Road	Monoblock	12.35	46.65	5.53	25.86	0.22	0.98	1.38	1.95
V06	Merchiston Park	394	Road	Hot rolled asphalt	26.03	54.50	7.37	32.99	0.32	1.30	1.84	2.61
V07	Napier Road	283	Road	Hot rolled asphalt	20.23	50.35	10.41	47.03	0.44	1.84	2.60	3.68
V08	Merchiston Avenue	393	Road	Hot rolled asphalt	22.83	61.98	7.16	39.54	0.33	1.27	1.79	2.53
V09	Blantyre Terrace to Mardale Crescent	282	Road	Hot rolled asphalt	18.38	55.23	8.45	47.62	0.37	1.49	2.11	2.99
V10	Gilmore Place to Viewforth (NCR754)	138	Off-road	Compacted fill material	14.22	34.95	5.35	20.34	0.19	0.95	1.34	1.89
V11	Horne Terrace	156	Road	Hot rolled asphalt	17.51	32.08	8.18	32.18	0.27	1.45	2.04	2.89
V12	Forrest Road to George IV Bridge/High Street junction	354	Road	Hot rolled asphalt	22.15	57.52	4.51	18.21	0.20	0.80	1.13	1.59
V13	Lawnmarket	102	Road	Cobble setts	13.11	28.00	9.03	36.44	0.28	1.60	2.26	3.19
V14	North Meadow Walk	571	Off-road	Hot rolled asphalt	26.26	78.28	3.36	15.09	0.18	0.59	0.84	1.19
V15	Middle Meadow Walk	301	Off-road	Hot rolled asphalt	18.86	57.47	3.23	15.15	0.14	0.57	0.81	1.14
V16	High Street, George IV Bridge junction to City Chambers	252	Road	Cobble setts	21.50	42.20	13.66	46.95	0.52	2.42	3.42	4.83
V17	High Street, Parliament Square to North Bridge junction.	159	Road	Cobble setts	19.73	29.02	12.85	44.25	0.41	2.27	3.21	4.54
V18	Lawnmarket to Johnston Terrace to Spittal Street	839	Road	Cobble setts	30.99	97.46	10.11	53.48	0.59	1.79	2.53	3.57
V19	Balgreen/Carrick Knowe	1110	Off-road	Hot rolled asphalt	23.00	173.75	2.81	17.68	0.22	0.50	0.70	0.99
V20	Stenhouse Drive	442	Off-road	Hot rolled asphalt	22.90	69.48	2.15	10.89	0.11	0.38	0.54	0.76
V21	Bankhead Drive	408	Off-road	Hot rolled asphalt	17.38	84.51	3.68	23.15	0.20	0.65	0.92	1.30
V22	Bankhead Drive to Cultins Road	780	Off-road	Hot rolled asphalt	19.46	144.27	3.14	17.74	0.22	0.55	0.78	1.11
V23	Station Park (Edinburgh Park)	316	Off-road	Concrete pavers	17.20	66.16	2.50	13.14	0.12	0.44	0.62	0.88
V24	Station Park (Edinburgh Park)	257	Off-road	Monoblock	15.27	60.59	3.88	30.04	0.18	0.69	0.97	1.37
V25	A720 Culvert	99	Off-road	Concrete	10.14	35.13	3.77	14.17	0.13	0.67	0.94	1.33
V26	A720 Culvert to Railway Bridge	165	Off-road	Compacted fill material	11.78	50.44	6.31	24.57	0.26	1.11	1.58	2.23
V27	Railway Bridge to Gogar Station Road access to A720 Culvert	182	Off-road	Compacted fill material	12.22	53.61	6.64	26.90	0.29	1.17	1.66	2.35
V28	Research Avenue North	678	Off-road	Hot rolled asphalt	18.42	132.49	3.95	29.63	0.27	0.70	0.99	1.40
V29	Research Avenue North to Forth Gait	695	Road	Hot rolled asphalt	23.33	107.23	2.77	13.07	0.17	0.49	0.69	0.98
V30	Muir Wood Road	621	Road	Hot rolled asphalt	25.19	88.75	3.38	20.47	0.19	0.60	0.84	1.19
V31	Donkey Lane	614	Off-road	Compacted fill material	18.31	120.75	9.71	55.42	0.63	1.72	2.43	3.43
V32	NCR754 Union Canal (Westburn Middlefield to Wester Hailes Rd.)	517	Off-road	Asphaltic concrete	23.05	80.74	3.72	16.53	0.20	0.66	0.93	1.31
V33	NCR754 Union Canal (Hailes Quarry Park to railway bridge)	621	Off-road	Asphaltic concrete	21.09	105.98	4.65	28.32	0.28	0.82	1.16	1.64
V34	NCR754 Union Canal (Kilncroft Side to Slateford Aquaduct)	484	Off-road	Asphaltic concrete	18.26	95.40	3.37	20.98	0.19	0.60	0.84	1.19
V35	NCR754 Union Canal (Colinton Rd railway tunnel to Harrison Park)	610	Off-road	Asphaltic concrete	17.73	123.84	4.13	25.73	0.27	0.73	1.03	1.46

Table 4: Pavement surface location, description, distance, classification and vibration data (n = 35).

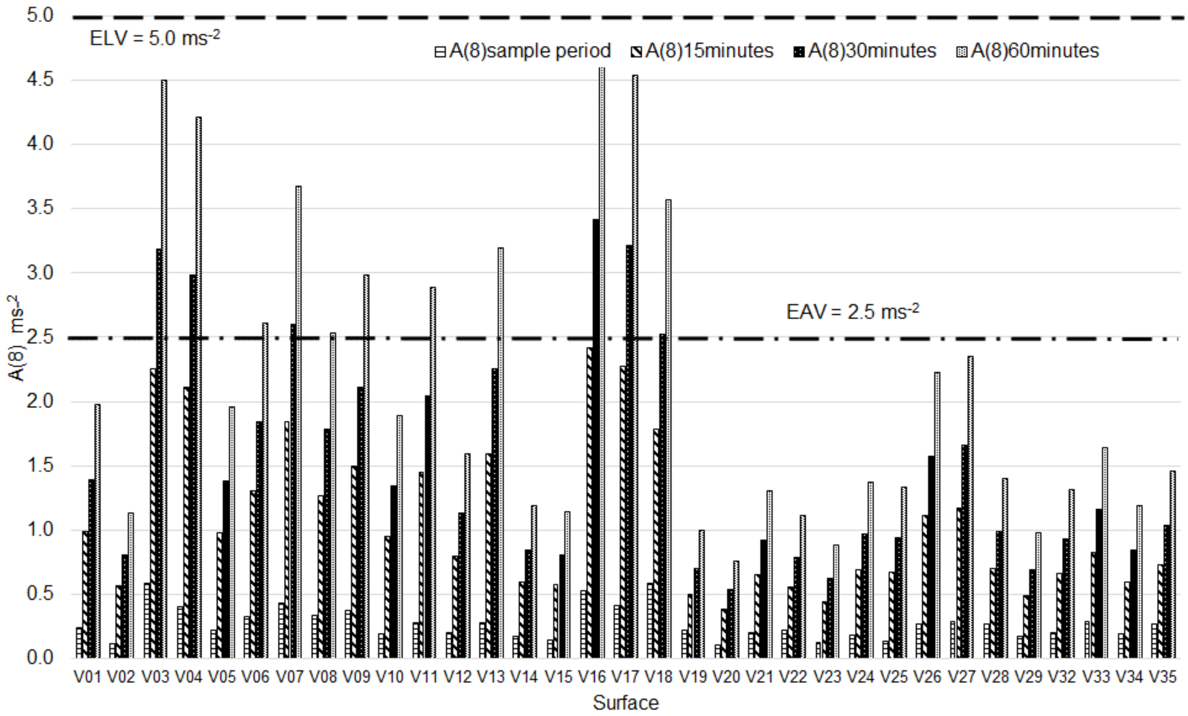

Figure 12: Vibration exposure summary, EAV and ELV limits.

Code	**Road/ Off-road**	**Surface classification**	**R.M.S (ms^{-2})**	**Time to reach EAV = 2.5 ms^{-2} A(8)$_t$**		**Time to reach ELV = 5.0 ms^{-2} A(8)$_t$**	
				Hours	**Minutes**	**Hours**	**Minutes**
V01	Road	Hot rolled asphalt	5.58	1	36	6	25
V02	Off-road	Asphaltic concrete	3.21	4	51	19	23
V03	Off-road	Cobble setts	12.73	0	19	1	14
V04	Road	Cobble setts	11.92	0	21	1	24
V05	Road	Monoblock	5.53	1	38	6	33
V06	Road	Hot rolled asphalt	7.37	0	55	3	41
V07	Road	Hot rolled asphalt	10.41	0	28	1	51
V08	Road	Hot rolled asphalt	7.16	0	59	3	54
V09	Road	Hot rolled asphalt	8.45	0	42	2	48
V10	Off-road	Compacted fill material	5.35	1	45	6	59
V11	Road	Hot rolled asphalt	8.18	0	45	2	59
V12	Road	Hot rolled asphalt	4.51	2	28	9	50
V13	Road	Cobble setts	9.03	0	37	2	27
V14	Off-road	Hot rolled asphalt	3.36	4	26	17	43
V15	Off-road	Hot rolled asphalt	3.23	4	48	19	11
V16	Road	Cobble setts	13.66	0	16	1	4
V17	Road	Cobble setts	12.85	0	18	1	13
V18	Road	Cobble setts	10.11	0	29	1	57
V19	Off-road	Hot rolled asphalt	2.81	6	20	>24	-
V20	Off-road	Hot rolled asphalt	2.15	10	49	>24	-
V21	Off-road	Hot rolled asphalt	3.68	3	41	14	45
V22	Off-road	Hot rolled asphalt	3.14	5	5	20	20
V23	Off-road	Concrete pavers	2.50	8	1	>24	-
V24	Off-road	Monoblock	3.88	3	19	13	18
V25	Off-road	Concrete	3.77	3	31	14	5
V26	Off-road	Compacted fill material	6.31	1	15	5	2
V27	Off-road	Compacted fill material	6.64	1	8	4	32
V28	Off-road	Hot rolled asphalt	3.95	3	12	12	48
V29	Road	Hot rolled asphalt	2.77	6	32	>24	-
V30	Road	Hot rolled asphalt	3.38	4	23	17	33
V31	Off-road	Compacted fill material	9.71	0	32	2	7
V32	Off-road	Asphaltic concrete	3.72	3	37	14	29
V33	Off-road	Asphaltic concrete	4.65	2	19	9	15
V34	Off-road	Asphaltic concrete	3.37	4	23	17	34
V35	Off-road	Asphaltic concrete	4.13	2	56	11	42

Table 5: Hand-arm vibration exposure durations to reach EAV and ELV limits.

Figure 13 shows time-domain data for two surfaces considered. Napier Road (V07) is an adopted road with no cycle facility and V02 is an off-road (no vehicular traffic) canal tow path which constitutes part of the national cycle route network (NCR754). The figure provides a comparison of the frequency weighted acceleration sum (a_{hv}) for the two surfaces.

Figure 14 shows frequency-domain data having been converted from time-domain data using a fast Fourier transform. The figure demonstrates the high magnitude frequency component of surface paved with cobble setts (V03) as compared to a hot rolled asphalt surface (V19) on a segregated cycle path not exposed to vehicular traffic.

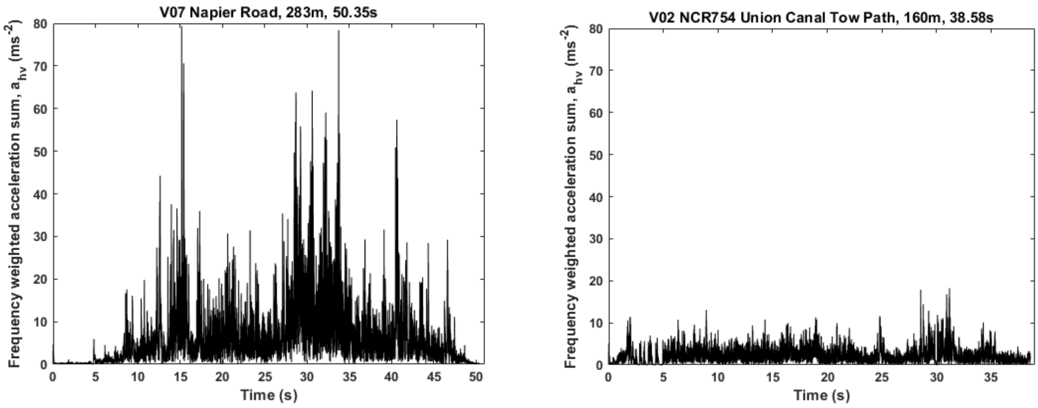

Figure 13: Example time-domain data (V07 vs. V02).

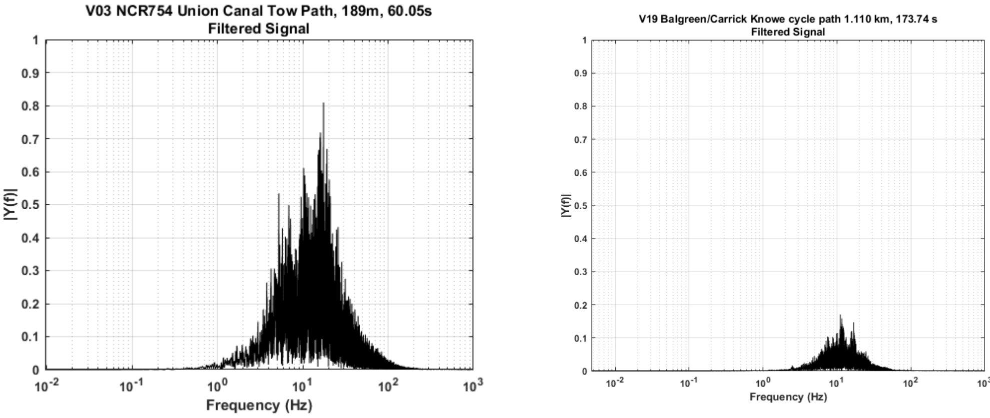

Figure 14: Example frequency-domain data (V03 vs V19).

Code	Total power (W)		Power 6.3-1250 Hz (dBW)		Power 6.3-80 Hz (dBW)		Frequency Resolution (Hz)
	No Filter	Filter	No Filter	Filter	No Filter	Filter	
V01	168.0235	31.1573	16.3008	9.8225	15.7025	9.7050	0.0187
V02	108.9384	10.3140	11.1674	2.7180	10.4453	2.5878	0.0259
V03	453.1075	162.0963	21.1865	15.3014	20.5026	15.1702	0.0167
V04	411.4883	142.0967	21.2049	15.2666	20.5196	15.1234	0.0304
V05	155.6005	30.5390	14.5500	8.5805	14.0698	8.5102	0.0214
V06	216.5994	54.3285	18.1528	11.5552	17.2887	11.4660	0.0184
V07	286.5068	108.2665	18.9925	14.6774	18.3870	14.6281	0.0199
V08	186.5066	51.2113	15.0404	9.3278	14.5439	9.2644	0.0161
V09	220.4605	71.4278	17.5501	12.5135	16.8031	12.4352	0.0181
V10	150.3752	28.6733	12.5542	5.9153	12.0848	5.8241	0.0286
V11	251.4155	66.8558	18.1558	12.0725	17.3389	11.9142	0.0312
V12	148.0662	20.3296	11.5598	3.6313	9.3913	3.3298	0.0174
V13	274.3049	81.5285	20.0641	13.1300	19.0820	13.0097	0.0357
V14	117.6695	11.2895	8.9249	2.2330	8.3155	2.1700	0.0128
V15	116.4312	10.4243	9.3913	3.2370	8.7824	3.1735	0.0174
V16	548.0017	186.6325	22.0309	15.3879	20.9360	15.2102	0.0237
V17	518.8959	165.2419	23.6726	16.3855	22.3714	16.2393	0.0345
V18	369.1286	102.2170	19.0434	12.2684	16.8696	12.0799	0.0103
V19	90.8855	7.8851	7.2494	1.5574	6.6978	1.5124	0.0058
V20	85.2929	4.6213	6.3259	0.0273	5.3807	-0.0536	0.0144
V21	102.4111	13.5604	10.5390	5.0126	9.9745	4.9582	0.0118
V22	94.0893	9.8364	8.6147	2.2250	8.0877	2.1839	0.0069
V23	110.0975	6.2365	7.9758	2.1062	7.4086	2.0393	0.0151
V24	104.8518	15.0393	10.9472	6.4830	10.3177	6.4201	0.0165
V25	106.8942	14.1990	12.0186	6.3781	11.1281	6.2927	0.0285
V26	163.0794	39.7592	14.8852	9.9177	14.1791	9.8323	0.0198
V27	170.5381	44.1450	15.2679	10.0321	14.6605	9.9543	0.0187
V28	105.4345	15.6306	11.0917	5.6276	10.6317	5.5812	0.0075
V29	101.7208	7.6500	9.0033	1.1510	6.8753	0.8415	0.0093
V30	127.7889	11.3925	10.0016	3.0537	9.4657	3.0061	0.0113
V31	268.1269	94.2189	17.6949	12.8438	16.7696	12.7581	0.0083
V32	140.0728	13.8105	11.8206	4.7630	10.7035	4.6267	0.0124
V33	152.9037	21.6029	11.9477	5.3128	11.0580	5.1978	0.0094
V34	136.0165	11.3904	9.8518	1.9215	8.3053	1.7067	0.0105
V35	146.9420	17.0846	13.2290	5.9735	12.0001	5.8134	0.0081

Table 6: Power spectral analysis summary.

The discussion of results so far has been concerned with the magnitude of accelerations such as frequency weighted sum (a_{hv}, r.m.s) and exposure values (A(8)). The frequency content of the data is of particular interest, that is, at what specific frequency does vibration occur. This is of particular importance when describing rider comfort and assessing the power transferred to the riders' hands and arms. To analyse the surveyed pavement surfaces, power spectral density was used to identify the dominant frequencies of the bicycle vibration motion at the handle bar hand grip interface.

Constant bandwidth analysis of the data was undertaken. Power spectral densities (PSD) provided a measure of the power content versus the frequency. They can be used to demonstrate which frequencies contain the signal's power, the frequency resolution being the reciprocal of the total sampling time. Periodograms were used to create non-parametric PSD estimates of the random signals.

Computing the fast Fourier transform (FFT) and normalising the output allows the PSD to be obtained for each vibration measurement. From the measured (recorded) power spectrum, the power at specific frequencies has been calculated. The power spectrum density shows how the power of the vibration signal is distributed with frequency using units of watts (W).

Referring to Table 6, considerable low-frequency power is present. The low frequency range relative to the total range was considered. A comparison of the total power available over the range; (1) 6.3 Hz to 1250 Hz and (2) 6.3 Hz to 80 Hz is provided in Table 6. The data demonstrate that a significant amount of the power transmitted to the rider's hands is present in the lower frequency range.

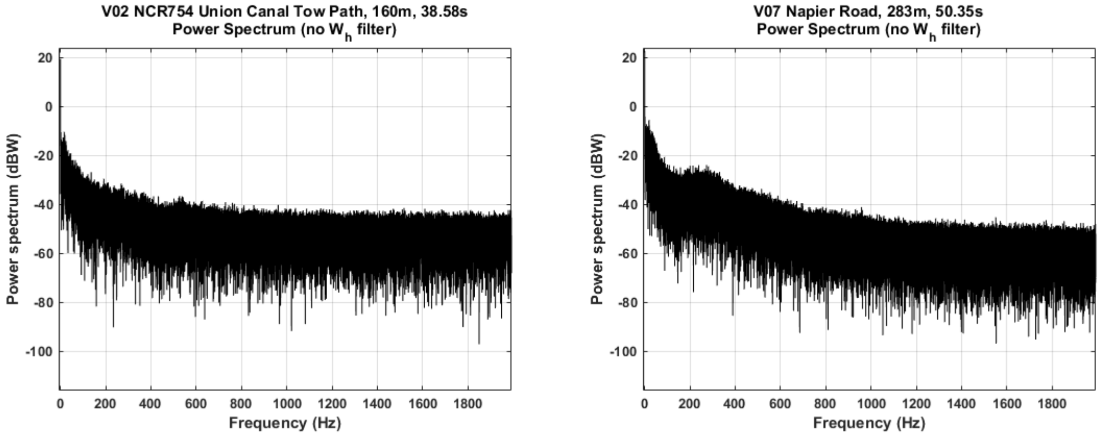

Figure 15: Power spectral analysis, V02 0.0259Hz resolution and V07 0.0199Hz resolution. W_h band limiting and frequency weighting filter not applied.

Of the surface categories considered, the power transferred to the hands over certain surfaces is significantly greater. Of the categories considered, hot rolled asphalt pavements on off-road cycle paths in the City of Edinburgh provide the most suitable surface for cycling in relation to vibration exposure and comfort.

9. Discussion

The present study investigated the measurement of hand-arm vibration exposure while cycling. The research demonstrated that a low cost instrumentation package can be constructed to allow vibration exposure to be assessed in a reliable and repeatable manner. In particular, the research involved the design and development of a device for assessing pavement surface quality by hand-arm vibration exposure while cycling.

The main finding of this study is that cobble setts and defective adopted road surfaces (hot rolled asphalt and asphaltic concrete) are causing considerable exposure to hand-arm vibration over sustained periods of cycling. In the City of Edinburgh, certain pavement surfaces are generating exposure ratings in excess of the EAV in a period of less than sixteen minutes. The City of Edinburgh does have a range of off-road (non-vehicular) paths which provide a low vibration alternative to adopted road surfaces or cobble setts.

These findings concur with other studies that demonstrate the suitability of vibration exposure as a means of assessing rider comfort. However, the present study complies with the technical requirement of measuring hand-arm vibration exposure, i.e. basicentric mounting or accelerometers, utilising the correct frequency range and ensuring the application of the correct frequency weighting and band pass filtering. Furthermore, power spectral analysis provides a suitable means for future assessment of clinical damage associated with absorbed power.

The research describes the process of using low cost inertial sensors to measure cyclists' exposure to hand-arm vibration. Furthermore, the resulting data could be used by local authorities in relation to asset management decisions associated with re-surfacing or general maintenance of pavement surfaces and adopted road verges used for cycling.

The present study has a number of limitations relating to bicycle dynamics, mechanical performance of the bicycle, the tyre interaction with the surface and the variability of the rider (riding position and mass). Future work intends to examine the variables associated with the mass of the rider, the use of different frame materials, locked out suspension or rigid forks, changes to saddle riding position, grip force applied to handle bars, tyre pressure and tyre tread pattern.

Although this study focussed upon the City of Edinburgh, the method described could be used as a model for assessing pavement surface quality throughout the United Kingdom. These findings may contribute to the development of a rating system associated with the cyclist hand-arm vibration exposure results. Asset managers and local authority cycling departments may consider the use of such an IPB to collate cycling infrastructure condition data for decision making purposes. The presented research demonstrates that a more objective approach to data collection may improve the quality of data available for refurbishment or route improvement decision making.

10. Conclusions and further research

Research has successfully demonstrated the development of a low cost method for the assessment of cycle path surface quality, the vibration exposure over different surface types in the City of Edinburgh and the surface materials and maintenance issues that may cause excessive cyclist vibration exposure.

There is a demand for further studies associated with the clinical impact of surface quality on hand-arm vibration exposure in the City of Edinburgh. Future studies must consider the variables associated with a bicycle including rider age, body mass index, weight, ability, physical fitness, tyre type, tread pattern, tyre pressure, suspension, frame material and health history questionnaires. The development of a standard test associated with cyclist exposure to vibration as a means of pavement condition assessment may contribute to improved consistency in measurement.

Future studies in other Scottish local authority areas would be of particular interest. Considering clinical hand-arm vibration exposure studies across a range of riders of different abilities would provide greater understanding of the potential of defective pavement surfaces to cause actual harm to riders.

The collection of objective data for cyclists' vibration exposure as a result of pavement surface interaction may contribute to improved pavement specification and asset management practice, and may reduce the requirement for local authorities to conduct direct visual inspection walkover surveys. Potentially, data capture and appropriate analysis will remove the reliance on subjective assessment.

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References

AYACHI, F. S., DOREY, J. & GUASTAVINO, C. 2015. Identifying factors of bicycle comfort: An online survey with enthusiast cyclists. *Applied Ergonomics,* 46, Part A**,** 124-136.

BÍL, M., ANDRÁŠIK, R. & KUBEČEK, J. 2015. How comfortable are your cycling tracks? A new method for objective bicycle vibration measurement. *Transportation Research Part C: Emerging Technologies,* 56**,** 415-425.

BISHOP, R. E. D. 1979. *Vibration,* Cambridge, United Kingdom, Cambridge University Press.

BSI 2001. BS EN ISO 5349-1:2001 Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 1: General requirements. British Standards Institution.

BSI 2015. BS EN ISO 10819:2013 Mechanical vibration and shock - Hand-arm vibration - Measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. BSI Standards Ltd.

CHIEMENTIN, X., RIGAUT, M., CREQUY, S., BOLAERS, F. & BERTUCCI, W. 2012. Hand-arm vibration in cycling. *Journal of Vibration and Control,* 19**,** 2551-2560.

GIUBILATO, F. & PETRONE, N. 2012. A method for evaluating the vibrational response of racing bicycles wheels under road roughness excitation. *Procedia Engineering,* 34**,** 409-414.

GOMES, H. M. & SAVIONEK, D. 2014. Measurement and evaluation of human exposure to vibration transmitted to hand-arm system during leisure cyclist activity. *Revista Brasileira de Engenharia Biomedica (BRazilian Journal of Biomedical Engineering),* 30**,** 291-300.

GRIFFIN, M. J. 1990. *Handbook of human vibration,* London, United Kingdom, Academic Press Ltd.

GRIFFIN, M. J. 2007. Discomfort from feeling vehicle vibration. *Vehicle System Dynamics,* 45**,** 679-698.

HÖLZEL, C., HÖCHTL, F. & SENNER, V. 2012. Cycling comfort on different road surfaces. *Procedia Engineering,* 34**,** 479-484.

KOCAK, N. & NOBLE, P. 2010. Edinburgh Active Travel Action Plan - Making Edburgh a Cycling City. *European Transport Conference.* Glasgow, United Kingdom.

LÉPINE, J., CHAMPOUX, Y. & DROUET, J.-M. 2015. The relative contribution of road bicycle components on vibration induced to the cyclist. *Sports Engineering,* 18**,** 79-91.

MIRBOD, S. M., YOSHIDA, H., JAMALI, M., MASAMURA, K., INABA, R. & IWATA, H. 1997. Assessment of hand-arm vibration exposure among traffic police motorcyclists. *International Archives of Occupational and Environmental Health,* 70**,** 22-28.

MOHANTY, S., LEE, A., CARVALHO, T., DIAS, L. & LOVEGROVE, G. 2014. A Global Review of Current Instrumented Probe Bicycle (IPB) Technology and Research. *International Cycling Safety Conference.* Gothenburg, Sweden.

MUNERA, M., CHIEMENTIN, X., CREQUY, S. & BERTUCCI, W. 2014. Physical risk associated with vibration at cycling. *Mechanics & Industry,* 15**,** 535-540.

OLIEMAN, M., MARIN-PERIANU, R. & MARIN-PERIANU, M. 2012. Measurement of dynamic comfort in cycling using wireless acceleration sensors. *Procedia Engineering,* 34**,** 568-573.

PARKIN, J. & EUGENIE SAINTE, C. The impact of vibration on comfort and bodily stress while cycling. 46th Annual Universities Transport Research Group Conference, 6th-8th January 2014 2014 Newcastle University.

PELLAND-LEBLANC, J.-P., LÉPINE, J., CHAMPOUX, Y. & DROUET, J.-M. 2014. Using Power as a Metric to Quantify Vibration Transmitted to the Cyclist. *Procedia Engineering,* 72**,** 392-397.

RIMELL, A. N. & MANSFIELD, N. J. 2007. Design of digital filters for frequency weightings required for risk assessments of workers exposed to vibration. *Industrial Health,* 45**,** 512-519.

SPOKES 2016. Spokes Bulletin 123.

VANWALLEGHEM, J., MORTIER, F., DE BAERE, I., LOCCUFIER, M. & VAN PAEPEGEM, W. 2012. Design of an instrumented bicycle for the evaluation of bicycle dynamics and its relation with the cyclist's comfort. *Procedia Engineering,* 34**,** 485-490.