Cyclist exposure to hand-arm vibration and pavement surface improvement in the City of Edinburgh

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1. Introduction

Cycle path maintenance is recognised as an important contributing factor to user comfort and safety. Comfort requires smooth rolling, low energy input and a good ride quality as measured by low transmitted vibrations (Hölzel *et al.*, 2012). Vibration from road pavement irregularities has been stated an important source of discomfort (Olieman *et al.*, 2012). Sustrans cycle friendly design guidance highlighted that a cycling route that is kept in good condition will be more popular than one allowed to deteriorate (Russell, 2014). Furthermore, they identified a need to prioritise maintenance of the 1.5 m to 2.0 m nearest to the kerb and in particular repair loose drain covers, potholes, surface damage, encroaching vegetation, defective lighting, sweep debris and repair damaged signs. In a study of enthusiastic cyclists, Ayachi *et al.* (2015) identified environmental factors that strongly contributed to comfort that included the road surface, the clothing worn, the road conditions and the vibration from the road surface.

Recent research has identified the many factors that influence cyclist's comfort. In a Chinese study of the physical environment and cyclists perception of comfort, the main factors influencing comfort included the width of the path, presence of slope (gradient), presence of bus stops, physical separation from pedestrians, surrounding land use and the bicycle flow rate (Li *et al.*, 2012). Recent research has compared vibration whilst cycling to the exposure limit values provided by the EU guidelines (Directive 2002/44/EC, 2002) for hand-arm vibration (Munera *et al.*,2014, Parkin and Eugenie-Sainte, 2014). The collated data will be examined with reference to the relevant EU Directive to provide an indication of the severity of the vibration experienced.

Micro-electro mechanical systems (MEMS) may generically be defined as miniaturised mechanical and electro-mechanical elements (devices and structures) that are manufactured using techniques of silicon-based microelectronics and micromachining technology. The functional elements of MEMS devices are micro-sensors or micro-actuators that can convert energy from one form to another and are controlled using integrated microelectronics. For example, a MEMS three-axis accelerometer can convert a vibration into an electrical signal. Batch fabrication techniques, similar to integrated circuit boards, means unparalleled levels of functionality and reliability can be incorporated onto the sensor at very low cost. It is this low cost element that provides extensive opportunities for the integration of such devices into instrumented probe bicycles (IPB) for obtaining data concerning the condition of cycle path pavements and road assets.

The aim of the research was to examine the relationship between pavement surface condition and hand-arm vibration generated by the direct contact of the bicycle tyre with the surfaces under scrutiny. The project seeks to establish the hand-arm vibration characteristics of a pavement surface from a cyclist's perspective. Furthermore, the research proposes how such data can be interpreted to assist monitoring of the condition of cycling routes and identify areas in need of maintenance or repair. The research aims to develop a reliable and inexpensive procedure to measure and record cyclist's hand-arm vibration exposure for incorporation into an assessment of cycle path or road pavement condition.

2. Previous research

Cycling contributes towards local and national policy objectives in relation to reduced emissions, tackling congestion, increased tourism and improvements to the physical and mental health of the nation (Bakr, 2011). There has been limited attention to the acquisition of asset condition data regarding cycling infrastructure and pavement quality (Pucher *et al.*, 2010). The road and rail sector have established equipment and procedures for the collection of asset condition assessment data. Roads have established methods to collect skid resistance, surface roughness and deflection data using a range of vehicle and trailer mounted equipment (Pearson, 2012). The Network Rail New Measurement Train (NMT) assesses the condition of track to allow engineers to determine where work is required. The train supplements walking the route to inspect the permanent way, but can do so at over 100 mph. Therefore, significantly increasing the efficiency of data collection for the network.

Traditionally, walkover surveys have been undertaken to assess cycle-path pavement condition and associated lighting, vegetation growth and flooding in the City of Edinburgh. These are time consuming and are limited in relation to the walking speed of the surveying engineer. Hölzel *et al.* (2012) highlighted that there is a demand for greater information about transmitted road vibrations in cycling. Cleland *et al.* (2005) concluded that the effects of surface texture and cycle path objects on bicycle stability are best measured with actual cyclists riding over the objects or surfaces to be evaluated. Rybarczyk and Wu (2010) applied a combination of global information system (GIS) and multi-criteria evaluation analysis to serve as an improved alternative to plan for optimal cycling infrastructure facilities.

Joo and Oh (2013) presented an IPB utilising a inertial measurement unit (IMU) and a global positioning system (GPS) receiver to examine manoeuvring data for identifying longitudinal, lateral and vertical movements which were prompted by environmental factors such as vehicle movements, surface conditions, gradients, crossings, speed humps and kerbs. In a global review of IPB research, Mohanty *et al.* (2014) highlighted the significant contributions of research examining the effects of dedicated infrastructure, bicycle-vehicle interactions, velocity, acceleration and angular velocity on perceived comfort and safety. Table 1 provides a summary of research undertaken using instrumented bicycles for a range of applications associated with vibration measurement including whole-body and hand-arm vibration.

Table 1: Instrumented bicycle platforms and applications.

Year	Author(s)	Objective	Instrumentation and locations
2015	Lepine *et al.*	Vibrtion induced on the cyclist at their hands and buttocks.	Strain gauges and accelerometers mounted on saddle and handle bars.
2014	Gomes *et al.*	Hand-arm vibration in leisure activity cycling in different pavement surfaces.	Accelerometer fixed to the bicycle handle bars.
2014	Parkin *et al.*	Study of comfort and health factors, nature of vibrations from riding a bicycle in different circumstances in London.	Accelerometerslocated at rear axle, seat post and saddle.
2014	Munera *et al.*	Summary of standards for evaluation of vibration and exposure limits - physiological and pathological disorders in athletes and performance.	A review of previously published research.
2012	Vanwalleghem *et al.*	Contact force and contact velocity measured.	Piezoelectric accelerometers with strain gauges.
2012	Giubilato et al.	Measuring and comparing the vibrational response of racing wheels caused by irregular road surfaces.	3-axis piezoelectric accelerometers. Uniaxial accelerometers mounted at (i) rear axle and (ii) positioned close to saddle on seat post.

The utilisation of an instrumented probe bicycle (IPB) is not a novel concept. Historical cycling research projects have extensively utilised IPB concepts for a range of performance and comfort related experiments. With the development of low cost sensor technology in combination with the availability of low cost microcontrollers and open hardware computers (e.g. Arduino, Raspberry Pi and Beaglebone), instrumentation possibilities and data collection options have improved substantially.

3. Equipment, location and methods

3.1. Equipment

An aluminium framed Trek 6000 bicycle (13.9 kg) was selected as a platform for the instrumented probe bicycle (IPB). Alternative styles of bicycle are available and are commonly used in the City of Edinburgh. The style of bicycle was selected based upon an observation of student bicycle types parked on the University campus. Other bicycle types may be considered in future research. The bicycle was ridden by an experienced commuter cyclist with the shock absorbers in the inactive (locked) position.

Vibration magnitude was measured using triple-axis accelerometers. The bicycle was mounted with a collection of hand grip adaptors and sensors. Figure 1 shows the mounting position of the handle bar accelerometers showing the three directions of an orthogonal coordinate system. Schwalbe 'Big Apple' 26x2.15 HS430 tyres were selected to minimise noise due to tyre tread pattern. Tyre pressure was maintained at 2.5 bar. Instrument specification facilitated mounting on the bicycle platform and mobile measurements. At an early stage, consideration was given to battery life, data transmission and storage.

Figure 1: Mounting position for accelerometers and tyre tread pattern.

Figure 2 depicts a block diagram showing the equipment and sensors utilized for the project. The system presented here is a working prototype and has been designed and constructed specifically for the measurement of bicycle hand arm vibration exposure. A Raspberry Pi 3 (Model B) was selected as a user interface and control device. A low cost and flexible platform for interfacing with MEMS devices. The touch screen allows the user to interact with the instrumentation, control data collection and observe the camera footage.

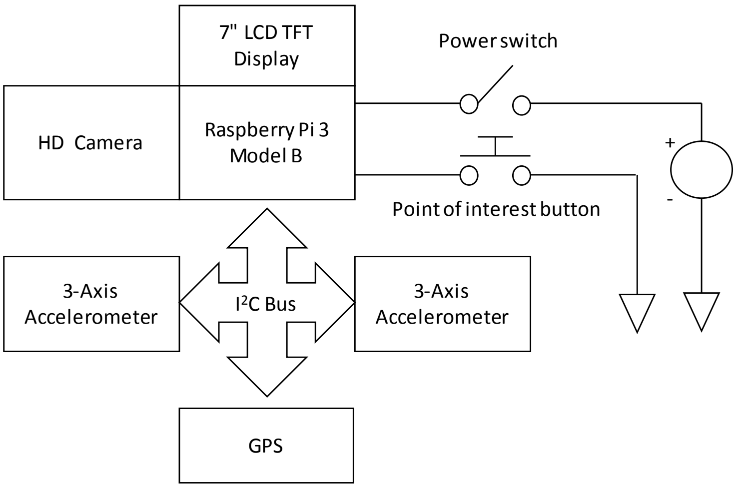

Figure 2: Instrumentation block diagram.

The hardware utilised for the instrumentation package included:

- Raspberry Pi 3 (Model B).
- 7” TFT LCD display.
- Raspberry Pi camera v 2.1.
- LIS3DH triple-axis accelerometers (±16g)
- MTK3339 GPS
- 2200 mAh DC 5V 1A cell
- Push button.

The I^2C (inter-integrated circuit) bus is used to allow the devices to communicate data to the Raspberry Pi in a high speed duplex mode. The I^2C bus is a bi-directional two wire serial bus that provides a communication link between integrated circuits. The accelerometers are factory calibrated for sensitivity and zero-g level. The trim values are stored inside the device in non-volatile memory. When the device is turned on, these values are downloaded into the registers to be used during active operation. No further calibration is required before using the device.

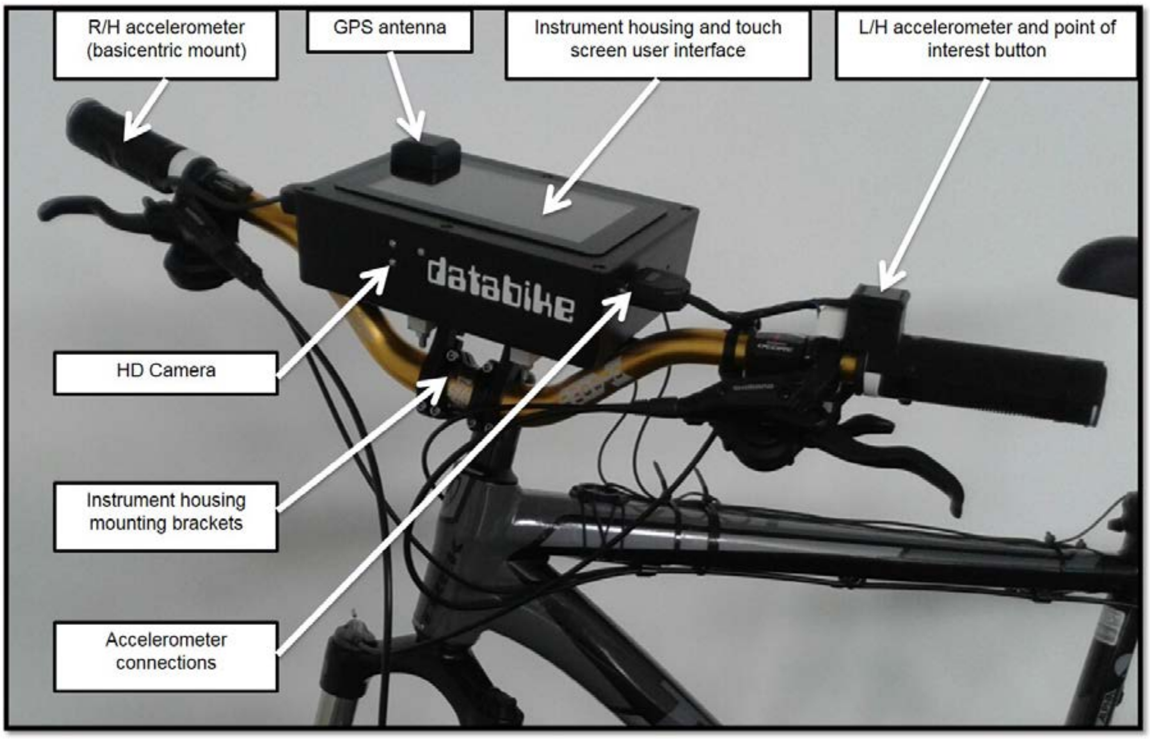

Figure 3: Instrumentation mounting locations.

Figure 3 shows the mounting positions and assembly of the instrumentation package. A general purpose acrylonitrile butadiene styrene (ABS) enclosure (220x140x60mm) was mounted on the handle using fabricated ABS bolted mounting brackets. Figure 4 shows the fabricated ABS handle bar grip adaptors fabricated to mount the accelerometers. The mass of both adaptors was 14.2g for the left adaptor and 12.4g for the right grip adaptor (including LIS3DH accelerometer). Both devices did not to exceed 15 g[1], as recommended for mounts for measuring at the palm of the hand (BSI, 2015b).

The hand grip adaptor was designed using Autodesk Inventor and constructed using a MakerBot Replicator+ 3D desktop printer. The right hand grip adaptor was mounted assuming the basicentric handgrip position coordinate system in accordance with EN ISO 5349-1 (BSI, 2001). The anatomical coordinate systems are defined relative to identifiable anatomical features. Basicentric coordinate systems are defined relative to surfaces which come into contact with the body and are more suited to the assessment of environmental vibration (Griffin, 1990). The left hand accelerometer mount was not mounted in accordance with the standard. The point of interest button was mounted on the left handle bar grip to allow marking of significant data points, e.g. major defects.

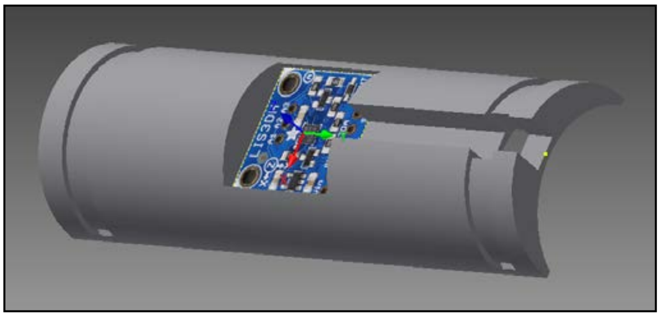

Figure 4: Handle bar grip adaptor showing accelerometer location.

[1] BS EN ISO 10819:2013 Clause 5.2.2.2

3.2. Location

Pavement locations were selected in accordance with their proximity to the university campus building. Local streets and cycle paths were considered as part of the pilot study to prove the conceptual design and undertake testing. Kocak and Noble (2010) identified the total length of cycle paths in the City of Edinburgh and provided an indication of the split between on-road and off-road cycle path infrastructure. In summary, the following infrastructure breakdown was provided:

- Total km cycle route: 224 km
- On-road bike lane: 82 km
- Off-road bike route: 142 km

For the present study, a sample has been considered to ensure off-road and shared space cycle path (adopted road) pavement surfaces are considered. General descriptions include the following:

- Canal tow path (aggregate with binder, cobbles).
- Shared space adopted road pavement (asphalt, cobbles or monoblock).

Figure 5 shows the pavement surfaces that have been considered for the present study. These do not represent an exhaustive list of the cycling pavement surfaces in the City of Edinburgh. They were specifically targeted as part of the pilot study. Future work will examine a broader range of pavement surfaces and improve the sample frame.

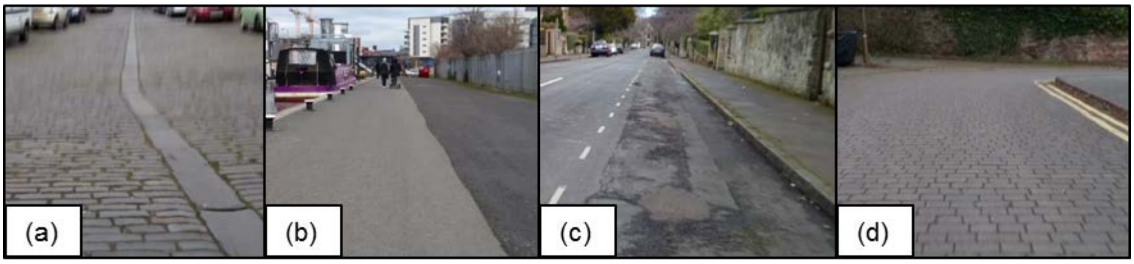

Figure 5: Pavement surfaces: (a) cobbles (Merchiston Mews, V0004); (b) bound gravel (Union Canal, V0002); (c) asphalt (Napier Road, V0007); (d) monoblock (Dorset Place,V0005).

Figure 6 shows the locations of the street and cycle paths surveyed during the pilot study (n=11). The present study surveyed 2.505 km of pavement surface. This represents a sample of 1.12% of the overall routes available. The total survey time elapsed was 520.63 seconds. The street locations were also considered due to their close proximity to the University campus buildings. The pilot study data collection was undertaken on the 18th February 2017. Exposure evaluations were conducted for the rider (1.78m, 98.42 kg) and ambient air temperature range was 8°C - 12°C.

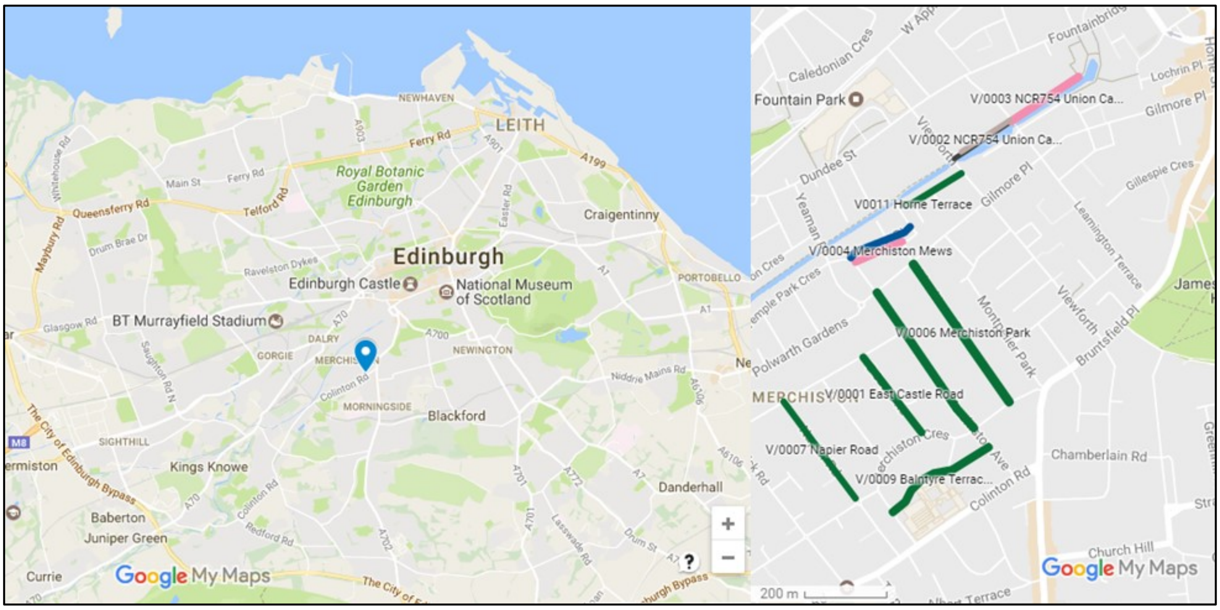

Figure 6: Pilot study street and cycle path locations.

Courtesy: Google Maps.

3.3. Method of vibration measurement

Vibration measurement focussed primarily upon exposure to hand-transmitted vibration, meaning vibration entering the body at the interface between the cyclists hand and the handle bar grip. The measure of vibration adopted for the study was the root-mean-square (ms^{-2} r.m.s) value. This is the square root of the average value of the square of the acceleration record and is the preferred method of quantifying the severity of human vibration exposure (Griffin, 1990).

The accelerometer sample rate was set at 5000 Hz to ensure that the Nyquist-Shannon frequency of at least two times the maximum frequency of 1250 Hz was captured (Griffin, 1990). Measurements were undertaken within the frequency range of 6 Hz to 1250 Hz (BSI, 2001). Short term measurement of intermittent cycling activity was achieved by cycling the route under examination. Typical data collection sample times range from 30s to 60s.

The assessment of hand-arm vibration was performed in accordance with International Standard EN ISO 5349-1 (BSI, 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, the vibration total value (a_{hv}) is defined as the root-sum-of-squares and the three component values as shown in Equation 1.

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

The vibration total value of the frequency weighted r.m.s acceleration may also be referred to as the vector sum or the frequency weighted acceleration sum. The SI units are metres per second squared (ms^{-2}). The r.m.s value of the time series data was calculated using Equation 2.

$$R = \left[\frac{1}{N}\sum x^2(i)\right]^{1/2} \qquad \text{Equation 2}$$

The measurement of frequency weighted acceleration requires the application of a frequency weighting and band limiting filter. The frequency weighting, W_h, reflects the assumed importance of different frequencies in causing injury to the hand (BSI, 2001).

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). Human response to vibration is a function of frequency, and the measured data should be weighted to give greater prominence to frequencies where humans are more sensitive (Rimell and Mansfield, 2007). Filtering was performed using a combination of a low-pass, high-pass and frequency weighting filter. Cascading the filters to produce an overall weighting filter W_h, where:

$$W_h = H_h(s).H_l(s).H_w(s) \qquad \text{Equation 3}$$

EN ISO 5349-1 combines the high-pass and low-pass filters to produce a band-limiting filter. The frequency weighting and band limiting filter characteristics (Equation 2) provided in EN ISO 5349-1 and are constructed using cascaded transfer functions and realised using Matlab 2016®. The construction and realisation of such digital filters is beyond the scope of this publication. However, the reference material provided contains further information and theory relating to this subject.

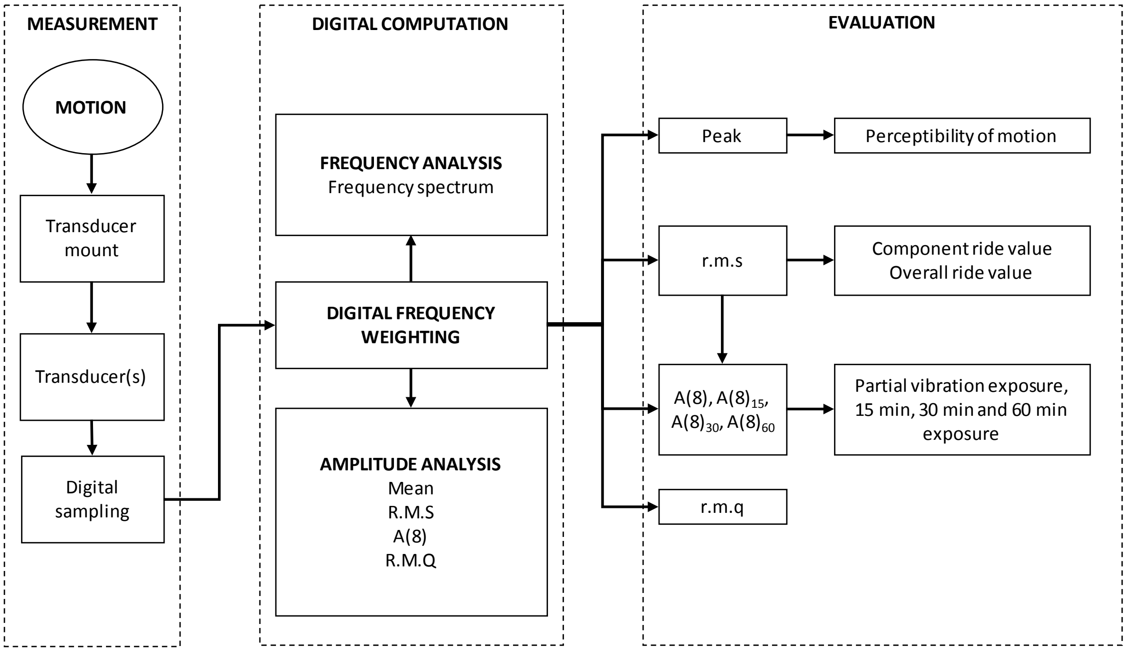

Figure 7: Illustration of measurement and evaluation of vibration data.

Source: adapted from Griffin (1990).

In order to provide a comparative measure of vibration exposure, the partial vibration exposures for the individual pavement surface measurement sample periods were calculated. Figure 7 provides a summary of the measurement and analysis procedure adopted during the research.

The daily vibration exposure is 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_{hvi}) as shown in Equation 4.

$$A(8) = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{hvi}^2 T_i}$$ Equation 4

Where T_i is the exposure time to that source, a_{hvi} vibration total value, n is the number of operations and T_0 is the reference duration of eight hours (28,800s).

In order to facilitate comparison between different operations and to evaluate the individual contribution of a particular operation to the daily vibration exposure A(8), BS EN ISO 5349-2 (BSI, 2015a) provides a means of calculating the partial vibration exposure, Ai(8), using Equation 5 below:

$$A_i(8) = a_{hvi}\sqrt{\frac{T}{T_0}}$$ Equation 5

Digital signal processing (DSP) was undertaken using Matlab 2016®. The frequency weighting and band limiting filter was constructed and then applied to the data obtained from the accelerometers. A Fast Fourier Transform (FFT) was utilised to convert the time domain data into the frequency domain. The frequency weighted r.m.s acceleration was then used in subsequent calculations to determine the partial vibration exposure ($A_i(8)$), fifteen minute vibration exposure ($A_{15}(8)$), thirty minute vibration exposure ($A_{30}(8)$) and one hour vibration exposure ($A_{60}(8)$).

4. Results

Table 2 shows the vibration measurement results for pavement surfaces surveyed (n=11). The unique identification number, location description, distance, surface classification, time (as sampled), root mean square (r.m.s) value, vibration dose value (VDV), partial vibration exposure (assuming time sampled) and the vibration exposure values calculated for 15 minute, 30 minute and 60 minute periods.

Table 2: Summary of vibration measurement results.

I.D.	Location	Distance	Surface	Time	R.M.S	Mean	S.Dev.	$A_i(8)$	$A_{15}(8)$	$A_{30}(8)$	$A_{60}(8)$
		(m)		(s)	(ms^{-2})	(ms-2)	(ms-2)	(ms^{-2})	(ms^{-2})	(ms^{-2})	(ms^{-2})
V0001	East Castle Road	230	Adopted road (HRA)	53.36	5.58	3.73	4.15	0.24	0.99	1.40	1.97
V0002	Union Canal*	160	Bound aggregate	38.58	3.21	2.54	1.96	0.12	0.57	0.80	1.14
V0003	Union Canal*	189	Cobble setts	60.06	12.73	6.01	8.78	0.58	2.25	3.18	4.50
V0004	Merchiston Mews	120	Cobble setts	32.90	11.92	8.90	7.92	0.40	2.11	2.98	4.21
V0005	Dorset Place	160	Monoblock	46.65	5.53	3.55	3.75	0.22	0.98	1.38	1.95
V0006	Merchiston Park	394	Adopted road (HRA)	54.50	7.37	5.40	5.01	0.32	1.30	1.84	2.61
V0007	Napier Road	283	Adopted road (HRA)	50.35	10.41	6.90	7.79	0.44	1.84	2.60	3.68
V0008	Merchiston Avenue	393	Adopted road (HRA)	61.98	7.16	4.68	5.41	0.33	1.27	1.79	2.53
V0009	Blantyre Terrace	282	Adopted road (HRA)	55.23	8.45	5.17	6.69	0.37	1.49	2.11	2.99
V0010	Union Canal*	138	Compacted fill material	34.95	5.35	3.91	3.66	0.19	0.95	1.34	1.89
V0011	Horne Terrace	156	Adopted road (HRA)	32.08	8.18	5.98	5.57	0.27	1.45	2.04	2.89

*Sustrans NR75 route

The highest vibration levels recorded were on pavement cobble setts with a frequency weighted acceleration sum of 12.73 ms^{-2} r.m.s, mean of 6.01 ms^{-2} and standard deviation of ± 8.78 ms^{-2}. Measurements on adopted roads recorded vibration levels ranging from 5.58 ms^{-2} r.m.s (mean = 3.73, SD = ± 4.15 ms^{-2}) to 10.41 ms^{-2} r.m.s (mean = 6.90, SD = ± 7.79 ms^{-2}). The lowest vibration measurements were obtained on a national cycle path (NR75) with a frequency weighted acceleration sum 3.21 ms^{-2} r.m.s , mean of 2.54 ms^{-2} and standard deviation of ± 1.96 ms^{-2}. If the sample period is considered as one complete journey, the A(8) vibration dose can be calculated. The journey A(8) value was 1.127 ms^{-2} r.m.s for a distance of 2.505 km and a journey (sample) time of 520.64s.

Figure 8 shows the frequency weighted acceleration time domain data for Napier Road (V0007) and the NR75 Union Canal tow path (V0002). The Union Canal tow path (V0002) measurement was conducted on a bound aggregate surface considered to be in good condition with minimal defects. Napier road (V0007) is an adopted road with considerable defects in the 1.5m to 2.0m edge gutter.

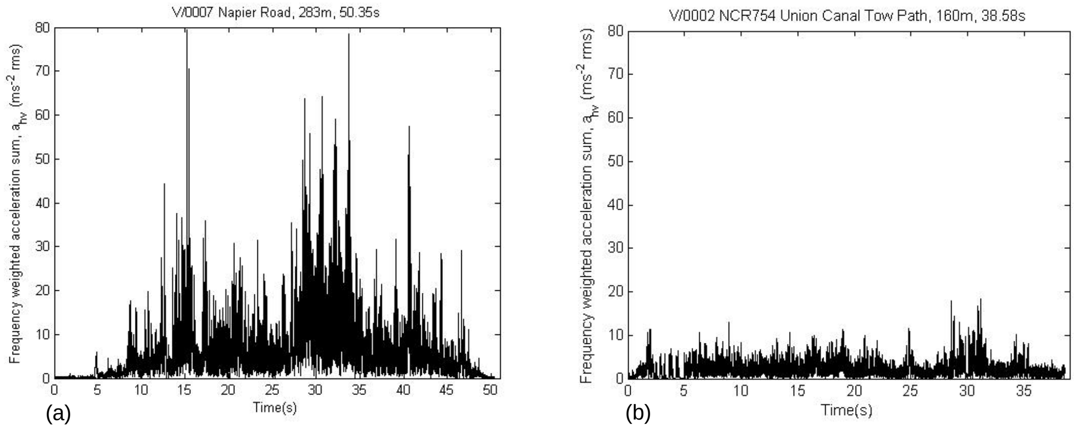

Figure 8: Time domain vibration data: (a) adopted road and (b) bound aggregate.

Figure 9 shows the frequency weighted acceleration time domain data for Merchiston Mews (V0004) Dorset Place (V0005). Dorset Place is an adopted road surfaced with monoblock paving. The two peaks (t = 15s and 22.5s) and are associated with mounting a series traffic calming speed humps. Merchiston Mews is an adopted road constructed from cobble setts. Figure 9(b) shows a change from cobble setts to monoblock at t = 26.5s. The transition between surfaces is clearly visible.

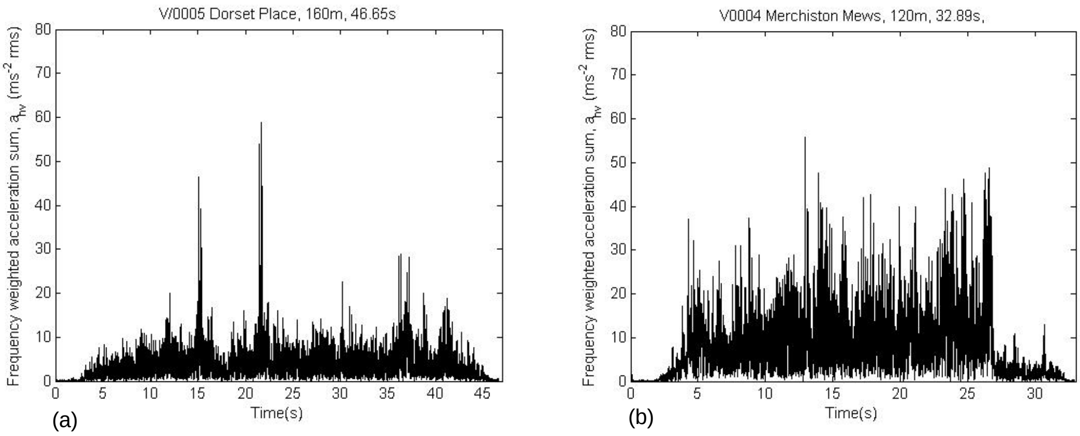

Figure 9: Example time domain vibration data (monoblock and cobbles).

It is important to remember that the most harmful vibration for a joint will be the one whose amplitude and especially the frequency is closest to the resonance frequency of this joint (Munera *et al.*, 2014). Figure 10 shows the spectral analysis for two path surfaces. Figure 10(a) shows that the peaks of vibration have greater magnitude for the defective adopted road compared to Figure 10(b) showing an off-road cycle-path considered to be in good repair. Figure 10(a) shows a number of high magnitude frequencies at 11Hz, 10.5 Hz and 8 Hz.

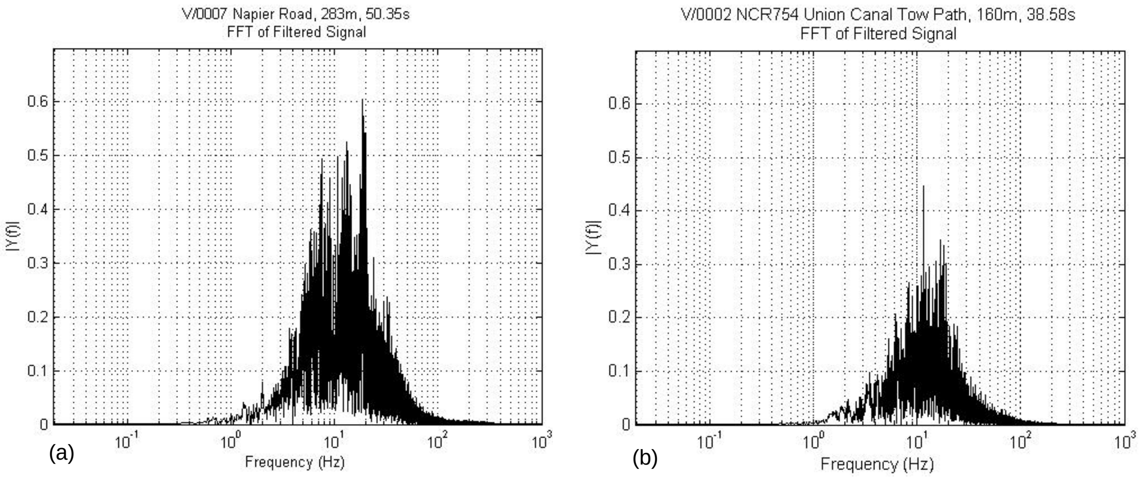

Figure 10: Frequency domain vibration data: (a) adopted road and (b) bound aggregate.

Directive 2002/44/EC of European Parliament Council (2002) provides details of the minimum health and safety requirements regarding exposure of workers to the risks arising from mechanical vibration. The Directive defines exposure limit values for hand-arm vibration based upon a standardized eight hour reference period (simulating a working day). The Directive defines the thresholds of hand-arm vibration exposure from which the employer has to control (Exposure Action Value, EAV = 2.5 ms^{-2} r.m.s) and threshold exposure limits to which workers must not be subjected (Exposure Limit Value, ELV = 5.0 ms^{-2} r.m.s). Figure 11 shows the partial, fifteen minute, thirty minute and sixty minute exposure values for the eleven pavement surfaces considered. Values for routes V/0003, V/0004 and V/0007 show concerning levels of vibration exposure for the fifteen to thirty minute exposure values. The thirty minute exposure values ($A_{30}(8)$) demonstrate that if a rider cycles on a pavement surface in this condition that they are likely to be exposed to levels above the EAV level.

When considering the adopted road pavements, a number of asphalt surface defects were recorded. These included:

- Potholes
- General loss of surface
- Exposed ironwork
- Edge cracking
- Edge deterioration
- Frost damage
- Patches or failed reinstatement

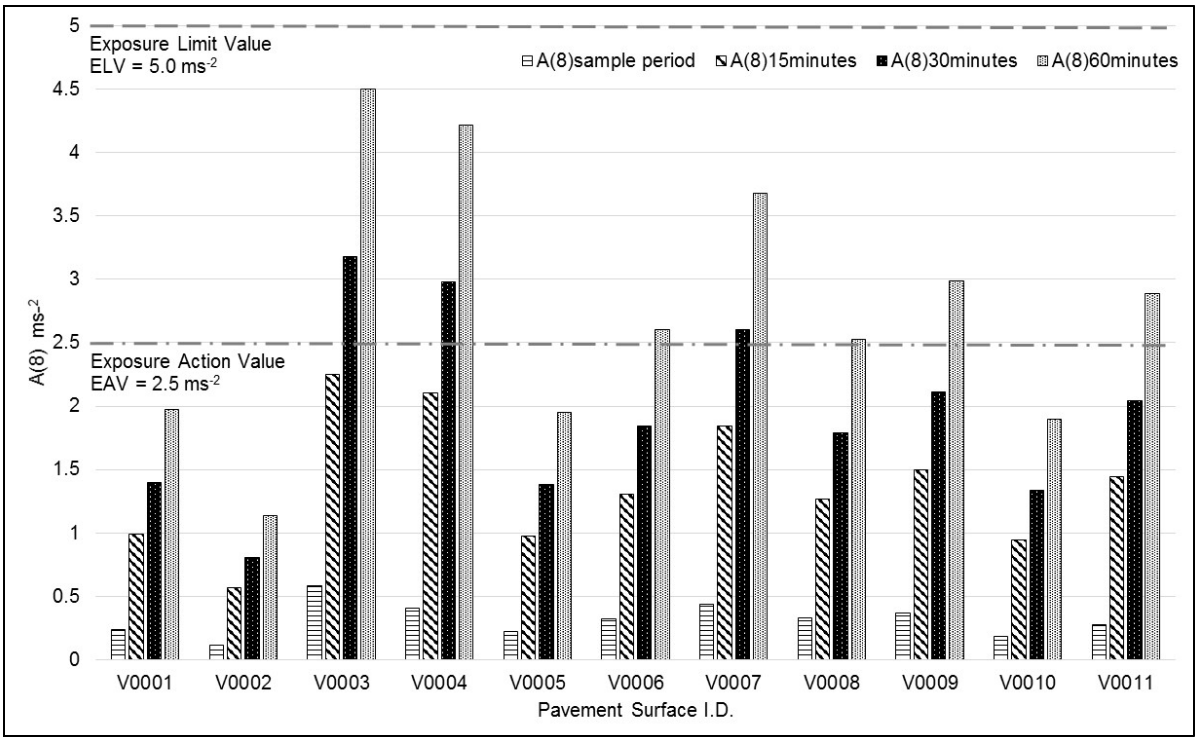

Figure 11: Partial and 15 min, 30 min and 60 min vibration exposure data summary (n=11).

5. Discussion

The results presented demonstrate that Edinburgh cyclists may be exposed to hand-arm vibration whilst cycling on the surface categories identified. Continued exposure to such vibration levels over commuter journeys may lead to discomfort and potential to cause harm. Of the sample pavements surfaces considered in the present study, it is clear that cobbles and defective asphalt surfaces are contributing to significant hand-arm vibration exposure. The present study compliments the findings of Parkin *et al.*(2014), Gomes *et al.* (2014) and Munera *et al.* (2014) in relation to the potential exposure of cyclists to hand-arm vibration through defective pavement surfaces. The medical implications of such exposure is beyond the scope of this paper. However, improvements to comfort whilst cycling can be considered a desirable outcome.

The results demonstrate the importance of a smooth, comfortable and defect free surface in relation to pavement surface design and maintenance. Furthermore, they demonstrate how hand-arm vibration measurement could be used as an indicative measure to rate pavement quality for cyclists. The use of MEMS sensors has significantly reduced the cost of developing instrumentation for cycling infrastructure asset data collection. The use of an IPB to collect cycling infrastructure asset condition data has been proposed as a novel approach that may provide a more efficient means of collecting objective asset condition data. The research presented has demonstrated the capabilities of an IPB and MEMS instrumentation to examine the comfort quality of alternative pavement surfaces.

6. Conclusions

In conclusion, although the current data set is small, the results suggest that evidence for the existence of exposure to hand-arm vibration in cycling on adopted and off-road cycle path pavement in the City of Edinburgh. The evaluation and control of pavement surface maintenance and design specification based upon objective vibration data may improve ride comfort.

Following further data collection to increase the pavement surface samples and assessment of commuter ride exposures, a greater understanding of rider comfort will be achieved. The presented research aims to contribute to local authority road management and cycling infrastructure maintenance using objective vibration measurement from a cyclists' perspective. Integrated within a global information system (GIS), such data may assist more efficient use of limited resources in relation to maintenance, repair, renewal and auditing of cycling infrastructure. Through the development of cycling specific vibration control limits, future research aims to contribute to the development of a safe, comfortable and accessible cycling pavement infrastructure throughout the City of Edinburgh and beyond.

7. Future work

Russell (2012) highlighted the importance of lighting provision on commuter routes, school routes and where usage is sustained throughout the longer periods of darkness associated with the winter months. Furthermore, the provision of street lighting at locations where nuisance issues or anti-social behaviour is frequently reported can help reduce these problems. Hence, future data collection may include the monitoring of luminescence (LUX) levels in association with geospatial data. The research method also includes the collection of data at night to assist in the provision of lighting safety audits as recommended by Transport Scotland, Cycling by Design (Bakr, 2010).

Mohanty *et al.* (2014) suggested that future research should consider improving the automation of steps between data collection and analysis. The authors' ongoing research aims to examine the provision cycling infrastructure quality monitoring utilising automated data acquisition, analysis and geospatial mapping. Proposals include assessing the impact of infrastructure maintenance and improvement programmes by providing comparative objective data showing the 'before and after' condition of cycling infrastructure. The authors welcome collaborative partners for potential trial data collection and infrastructure condition audits.

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