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RESEARCH ARTICLE

Vibration characterisation of strollers and cargo bicycles for transporting infants over different road surfaces

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ABSTRACT
The objective of this study was to comprehensively evaluate vibrations with dummies representing infants aged 0, 3, and 9 months lying or sitting in five strollers and two cargo bicycles with dedicated baby seats on six common road surfaces using the ISO standard for whole-body vibration. Strollers induced on average $0.4\,\mathrm{ms^{-2}}$ on tarmac and up to $5.0\,\mathrm{ms^{-2}}$ on cobblestones at a mean walking speed of $5.3\,\mathrm{km\ h^{-1}}$. Cargo bicycles induced on average $0.6\,\mathrm{ms^{-2}}$ on tarmac and up to $10.7\,\mathrm{ms^{-2}}$ at $25\,\mathrm{km\ h^{-1}}$ on paver bricks. The standard suggests the highest accelerations for strollers and cargo bicycles are extremely uncomfortable and continuous exposure should be limited to less than 10 min. Vintage strollers have reduced vibrations compared to modern strollers, indicating benefits of compliant suspensions. We recommend that designers systematically consider vibration, users avoid prolonged exposure to surfaces rougher than tarmac, and researchers pursue scientifically founded test procedures and standards for infant vibration.

Practitioner Summary: Strollers pushed over cobblestones and cargo bicycles travelling over paver bricks at typical speeds induce infant seat pan accelerations up to 5 and $11\,\mathrm{m\ s^{-2}}$, respectively. The adult whole-body vibration standard suggests these accelerations are extremely uncomfortable and continuous exposure should be limited to less than 10 min.

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KEYWORDS
Whole-body vibration; infant; bicycle; stroller; ISO 2631

1. Introduction

All means of infant transport cause vibration, which is transferred to the sitting or lying child. Unlike early-century perambulator design considerations (Behrend 1931), vibration is seemingly not a subject of attention in the present design of infant transportation products. Modern strollers do not have much suspension, and cargo bicycles are increasingly used for infants with seats that offer marginal suspension or padding. We thoroughly reviewed the literature (Daams et al. 2025) but found very little about the maximal vibration load that babies and older children can receive during transport without discomfort or harm, and vibrations generated by infant transport are only sparsely investigated. Furthermore, only a few studies focus on vibrations experienced by infants younger than 12 months. To establish the amount of vibration to which infants are subjected in transportation products, we measured seat pan vibrations while transporting infant dummies in strollers and cargo bicycles with a focus on potential health risks and discomfort. In the absence of infant-specific safety and comfort standards, this paper provides a measurement framework to target the future development of specific ISO standards.

The comfort experienced by riders and passengers (e.g. infants/children in cargo bicycles), is a multifaceted (Ayachi, Dorey, and Guastavino 2015) challenge to wide acceptance of bicycling. The comfort of bicycles (Too 1990) is mainly affected by physical comfort and the impact of environmental factors (weather, route geometry, and road roughness). Physical comfort is related to mechanical (bicycle and component design), biomechanical (whole-body vibrations, human body dynamics, and kinematics), and physiological factors (individual characteristics, e.g. sex, body size, weight). Although there is relevant literature exploring the impact of environmental factors (i.e. irregular road surface quality, weather conditions) on cyclist comfort (Ayachi, Dorey, and Guastavino 2015; Stinson and Bhat 2003; Hagemeister and Schmidt 2003; Verhoeven et al. 2017; Teixeira et al. 2020), there is only limited work on understanding the biomechanical and physiological

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factors of comfort of bicycle passengers (infants/children in bicycle seats, cargo bicycles, or trailers). A particular concern is the transport of infants under one year of age, who cannot well express any experience of discomfort or pain. Similar concerns are raised about strollers, where infants are also exposed to road-induced vibrations.

Biomechanical comfort is mainly related to vibrations induced by road irregularities and transmitted through the vehicle to the human body (Too 1990). Road irregularities are a driving factor, as vibrations induced in children are not efficiently isolated due to the lack of adequate suspension systems in most bicycle models (Vasudevan and Patel 2017) and strollers. The bicycle or stroller design and the seating configuration affect posture and vibration transmission (Brand et al. 2020; Verma et al. 2016). Children/infants can be transported sitting or lying in a different location than the cyclist (e.g. above a wheel when in a bicycle seat) and in/on a different 'seat' (a car seat, bicycle seat, stroller seat, or cot). Vibrations generally increase with travel speed, for example, when running with a stroller or due to the increased power offered by electric bicycles (with and without trailers). For the latter, the average speed using electric bicycles and speed pedelecs is 19% higher (21.0 km h^{-1} and up to 63% higher (28.1 km h^{-1}), respectively, than conventional bicycling (SWOV 2022). The intensity of these vibrations could become even more critical with the change of load, which is related to the age and size of the infant/children transported. However, there is limited literature exploring whole-body vibrations of infants and children transported by bicycle trailers, cargo bicycles, and strollers (Ota, Nishiyama, and Shinohara 2012; Ota, Nishiyama, and Shinohara 2014; Margaret Kanya-Forstner 2020; Driessche 2018; Schwanitz, Stuff, and Odenwald 2020; Rothhämel 2023). Most literature focuses on comfort rather than health risks.

One of the research fields closely related to the vibrations that act on infants during transportation is that of inflicted head injury by shaking trauma (IHI-ST). However, there is a lack of reliable, applicable, and validated injury thresholds to assess IHI-ST risks (Hutchinson et al. 2024). Similarly, even if there are indications that vibration affects comfort in bicycles or strollers, there are no standard vibration assessment methods or guidelines available with respect to their design. ISO 2631 (Gao et al. 2018), the international standard for assessing whole-body vibrations, was derived using data sets on motion platforms, with adults as participants and sitting postures adopted in passenger vehicles rather than on bicycles. Gao et al. (2018) show this discrepancy with vibration comfort limits for adults riding bicycles, based on their subjective feedback, tolerating more than the vibration limits suggested by ISO 2631-1. Furthermore, in ISO 2631-1 the exposure time to vibrations is not considered a factor in the determination of comfort, despite having a clear impact on health risks according to the European Directive (2002/44/EC, 2002) (EU Directive and GE Provisions 2002).

Despite the lack of knowledge and test methods with regard to comfort or inflicted head injury by shaking trauma for children/infants on bicycles, there are clear indications in the literature that these should be considered. About 36% of males and 42% of females in a total sample of 900 cyclists had various discomfort complaints (Groenendijk 1992). Discomfort occurred even during short bicycle trips (3 km to 10 km). However, the results of research on the comfort of active adult cyclists cannot be applied directly to infants or children sitting or lying in transportation systems.

Schwanitz, Stuff, and Odenwald (2020) tested a child bicycle trailer on smooth tarmac, gravel, and cobblestones using child-shaped sandbag dummies (baby and toddler sizes) using ISO 2631-1 weightings. Tyre pressure and number of passengers had no significant effect on vibration magnitude, but the road surface and travel speed did. The infant dummy (5 kg) experienced a 20% higher vibration than the toddler dummy (10 kg), while the measured values generally exceeded the ISO 2631-1 limit for vibrational comfort of adults. Rothhämel (2023) tested a trailer seat and a tadpole configuration three-wheel cargo bicycle on smooth tarmac and cobblestones for speeds from 10 km h^{-1} to 20 km h^{-1} using ISO 2631-1 assessment. They found a large increase in vibration amplitude on cobblestones compared to tarmac in the same speed range. The child trailer exhibited larger accelerations than the cargo bicycle with the child seat between the front wheels. Child seats in trailers and cargo bicycles generally had vibrations of higher magnitude than those experienced in a car seat travelling at 30 km h^{-1} on a rough road (Gromadowski and Wieckowski 2013). Rothhämel and Liu (2023) also conducted laboratory measurements with a 6.5 kg mass representing an infant in a bicycle trailer with various tyre pressures. All their values fell into the 'extremely uncomfortable' zone for ISO 2631-1.

In addition to studies with dummies or lumped masses representing infants, Margaret Kanya-Forstner (2020) measured acceleration in bicycle child trailers with human subjects aged 12 months to 6 years over tarmac and gravel terrain (average speed of 12 km h^{-1} over a 20 min ride). According to the health assessment using ISO 2631-1, the vibrations are similar to those experienced in child seats in cars and illustrate moderate or low health risk for a 2 h duration. She points out the importance of correcting for duration, otherwise the values point to moderate and high risks. The type of road surface had the greatest influence on the levels of vibration exposure, followed by the type of trailer, while the gel cushions as support did not significantly influence the vibration measured at the seat/pan interface.

In the context of infant transportation with stroller seats, Kok Siong (2018) carried out an indoor and an outdoor experiment to capture the vibrations at the seat and backrest of a baby stroller, using weights from 4 kg to 14 kg, and a child subject of 10.30 kg as well as a dummy weighing 10.30 kg. Comfort levels (ISO 2631-1) for indoor testing were 'Fairly uncomfortable' to 'A little uncomfortable', where outdoor testing resulted in 'Extremely uncomfortable' and 'Fairly uncomfortable' values. The child and dummy provided similar results. Sierzputowski et al. (2021) tested a modern and an older stroller on tarmac road, concrete paving blocks, concrete plates, dirt road, lawn, and damaged concrete. Several conditions resulted in the highest discomfort levels ($>2\,\mathrm{m\ s^{-2}}$ according to ISO 2631-1). Okajima, Ota, and Ota (2020) tested seven children, sitting upright in a stroller, riding over a protrusion (13×60 mm) with either one wheel or two wheels. The children were 3 to 6 years old, boys and girls, weighing 15.94 kg to 19.96 kg with a length of 98.0 cm to 112.4 cm. The heads and chests of the children exhibited strong vibrations at 1 Hz along all three axes (x, y, and z), and at 2 Hz along the y-direction, with limited vibration above 8 Hz.

The above studies provide experimental evidence of potentially worrying vibrations in real children, dummies, or simple masses transported in cargo bicycles, bike trailers, and strollers. Most studies use ISO 2631-1 frequency weighting and report very or extremely uncomfortable conditions with higher speeds and rough surfaces, while only one study evaluated health effects. Only a few studies focus on vibrations experienced by infants under 12 months of age.

This paper provides measurements of vibration exerted on infant dummies in strollers and cargo bicycles, which may be used as risk indicators for discomfort or health effects. We equipped five strollers and two cargo bicycles with inertial measurement units (IMU) and carried out 67 experiments on different road surfaces and with different travel speeds, using dummies representing 0, 3, and 9-month-old infants. We derived results using ISO 2631-1 frequency weightings and procedures to enable comparison with previous studies. However, given that ISO 2631-1 is neither validated for children nor for lying postures, we also report unweighted results to assess the power spectrum and bandwidth. We investigated the influence of vehicle, seat, body size, speed, and road surface and provided recommendations to users, designers, and for future research. Furthermore, as an example of how such measurements could be used for assessing discomfort and health effects, we discuss these in the light of thresholds suggested by ISO 2631-1 and Gao et al. (2018) to benchmark against these limited, but established, references.

2. Materials and methods

2.1. Test equipment

Vibration measurements were conducted using five different strollers and two cargo bicycles with two baby seats, chosen for their popularity and/or distinctive features. The strollers included three modern strollers: Bugaboo Fox 5 (Bugaboo, Amsterdam, the Netherlands), Maxi-Cosi Street Plus (Dorel Juvenile, Foxborough, USA), and Stokke BABYZEN YOYO 0+ (Stokke, Ålesund, Norway) and two vintage strollers from unknown manufacturers 'Green Machine' cot-style and 'Old Rusty' seat-style. The cargo bicycles were a delta configuration tricycle Keiler (Keiler Bakfiets, the Netherlands) and a two-wheel Urban Arrow (Pon Bicycle Holding B.V., Amsterdam, the Netherlands). Each was tested with both seats: Maxi-Cosi X Joolz Pebble Pro i-Size (Dorel Juvenile, Foxborough, USA) and Melia Baby Shell (Melia, Rotterdam, the Netherlands). The underlined words for each product designate an abbreviated name used in figures and tables in the paper and Figure 1 shows the tested products.[1]

We tested three baby dummies with sizes and weights representative of infants 0, 3, and 9 months. Newborns ('0 months') are the youngest (smallest, lightest) children transported in strollers with a cot or in rear-facing car seats (such as the Pebble used in this study). At nine months, on average, infants can sit up straight by themselves and thus can be transported sitting in a stroller with a seat or on the bench of a cargo bicycle. Testing with real infants would be unethical for the most severe conditions and create challenges in terms of reproducibility. Hence, we bought and adapted commercially available 'Reborn' dummies (Atelier Wiesje, De Bilt, the Netherlands) shown in Figure 1[2]. Although newborns are less frequently transported in strollers and cargo bicycles compared to older infants, these transport means are still used in daily routines for newborns. For example, in the Netherlands parents transport newborns by bicycle.

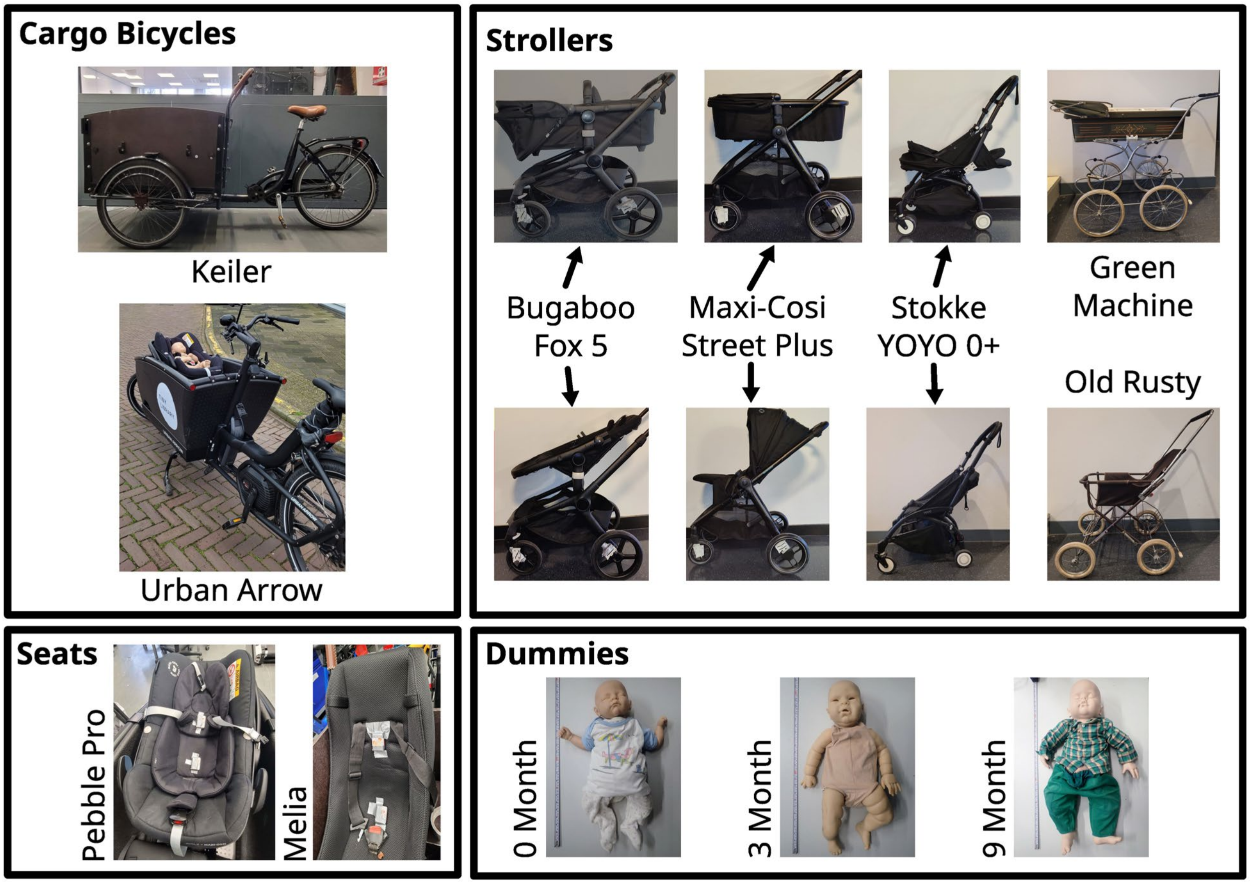

Figure 1. Tested products: cargo bicycles with baby seats, strollers, and dummies.

Including newborns in the test matrix is therefore a conservative approach and allows us to consider the worst-case scenario: newborns have the least developed musculoskeletal system, have the lowest mass, and are potentially the most vulnerable group. The weight and body height of the dummies were made to match the average measures for children of 0, 3 and 9 months old: 3.48 kg|50 cm 5.90 kg|62.5 cm, and 8.90 kg|70 cm, respectively. We used Dutch infant growth charts to determine the average weight and body height at age 0 months (Groei-onderzoek 1997) and French growth charts for 3 and 9 months (Courbes de croissance des garçons et des filles 2018) as requested by the funder; with French children being the smallest in Europe, while the Dutch are the tallest. The dummies were filled with a mixture of cat litter, sand, and water to reproduce the mass and mass distribution according to the body segment information reported in Snyder et al. (1977).

2.2. Measurement equipment

Linear accelerations and angular velocities were measured tri-axially using Consensys Shimmer3 IMUs with a Consensys Base 6U.01 dock (Shimmer Sensing, Dublin, Ireland). The IMUs were updated to firmware version LogAndStream v0.11.0 and managed via the software ConsensysBASIC v1.6.0-64bit on a Dell 7310 laptop with Microsoft Windows 10. We 3D printed supports (material: PLA) for the sensors to firmly fix the sensors on the tested bicycle/stroller (small white and orange boxes visible in Figure 2). Each vehicle was equipped with five IMUs. The IMUs under the head and buttocks contacting the dummy were placed according to the recommended practice in vibration testing standard ISO-2631-1.[3] This generates acceleration data representative of the mechanical load transferred from the seat to the human body taking into account the compliance of the seat foams and the inertia and compliance of the dummy.

The sampling frequency was set to 910.22 Hz for all IMUs. The full-scale range was set to the sensors' maximum: ±16 g for the accelerometer and $\pm 2000^\circ\,\mathrm{s}^{-1}$ for the gyroscope. All tests were recorded with two GoPro Hero7 cameras: one directly mounted on the strollers/bicycles to capture the dummy-seat relative motion, while the other was held by an experimenter who was walking or riding along with the vehicle to have a complete overview of the experiment.

(a) IMU on Urban Arrow rear hub. (b) IMUs on the Pebble seat. (c) Stokke, dummy, and camera.

Figure 2. Example equipment set up. (a) An IMU was placed on the wheel hub (cargo bicycles) or clamped to the wheel (strollers) for measuring travel speed. The travel (longitudinal) speed was derived according to the wheel radius and the IMU's angular speed about the wheel axis. In (b) the IMUs were taped into the baby seat at the interface between the dummy's buttocks or head and the baby seat. In (c) the camera is mounted to the stroller handlebar and IMUs are on the wheels.

2.3. Postures

All tested equipment provided full support for the back and head, allowing usage in lying or reclined postures. Nine-month-old infants are generally able to sit erect, but will often rest their heads or be asleep. Although sitting upright is the best posture for children who can sit upright, a more reclined posture was tested because this allowed measurement of vibration at the head-seat interface while the head was always supported by the headrest. We tested all systems with horizontal or reclined postures. The angle of inclination with respect to the ground is listed in Table 1 for each condition tested.

Table 1. Inclination angles of the IMUs 'Seat Head' and 'Seat Pan', per each tested configuration (without rider and dummy).

				Inclination angle [deg]	
Vehicle type	Model	Dummy	Baby seat (facing direction)	Head	Seat Pan
Stroller	Bugaboo	0 mo	Baby cot (RF)	0	0
		9 mo	Baby seat (FF)	49	24
	Green Machine	0 mo	Baby cot (RF)	0	0
	Maxi-Cosi	0 mo	Baby cot (RF)	0	0
		9 mo	Baby seat (FF)	40	10
	Old Rusty	9 mo	Baby seat (FF)	48	5
	Stokke	0 mo	Baby cot (RF)	12	12
		9 mo	Baby seat (FF)	45	4
Cargo bicycle	Keiler	0 mo	Pebble (RF)	41	2
		3 mo	Pebble (RF)	41	2
		3 mo	Melia (FF)	64	2
	Urban Arrow	0 mo	Pebble (RF)	41	2
		3 mo	Pebble (RF)	41	2
		3 mo	Melia (FF)	64	2

For the head, positive angles represent forward head rotation with 0° indicating a fully supine posture (lying horizontally) and 90° fully erect. For the seat pan, 0° is horizontal and positive angles indicate elevated legs, see Figures in Supplementary Materials 'Experimental Equipment' for details. RF indicates rearward-facing, and FF indicates forward-facing.

2.4. Experimental protocol

All tests were conducted in Delft, the Netherlands, on public roads near Delft University of Technology[4]. After mounting the sensors and reaching the location of the experiment, we turned on the sensors to start the experimental 'session', where a session is a continuous data collection period from a single vehicle that may include different road surfaces or speeds. Before each trial, we pushed the vehicle back and forth on level ground to mark the beginning of the session as an extra time-synchronization measure. For the cargo bicycle, a single rider conducted all trials to be consistent across different sessions (rider mass: 59 kg; rider height: 1.70 m). We tested cargo bicycles on tarmac and paver bricks road surfaces at target speeds of 12 km h^{-1}, 20 km h^{-1}, and 25 km h^{-1}. The stroller tests were conducted on tarmac, paver bricks, sidewalk pavers, cobblestones, and sidewalk slabs (concrete blocks with gaps in between) road surfaces[5]. Figure 3 shows

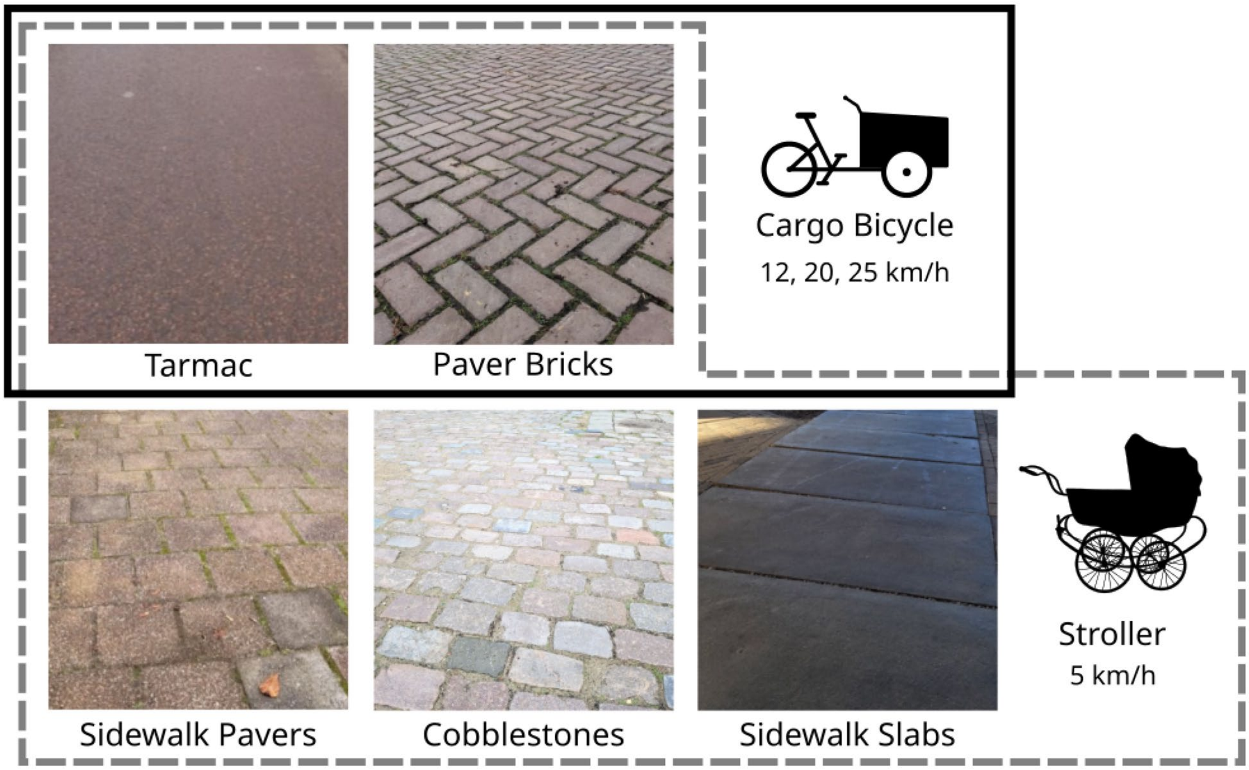

Figure 3. Road surfaces tested: tarmac and paver bricks (cargo bicycles and strollers), sidewalk pavers, cobblestones, sidewalk slabs (strollers).

the road surfaces used for each vehicle type. In all tests, the speed was manually controlled by the pusher or cyclist by observing a speedometer mounted on the handlebar of the stroller or cargo bicycle. We selected convenient road surfaces representative of commonly occurring urban conditions in Delft. Although these surfaces cover only part of the full range of worldwide possibilities, we tested at various locations to capture local variation in surface quality.

2.5. Data processing

We analysed the raw data with a custom data processing pipeline. The open source MIT licenced code is hosted at github.com/mechmotum/baby-vibration and implemented in Python 3.13.1 using the following libraries: DynamicistToolKit 0.6.1, Matplotlib 3.9.3, NumPy 2.2.0, Pandas 2.2.3, pyyaml 6.0.2, SciPy 1.14.1, and Seaborn 0.13.2. The pipeline generates a website at mechmotum.github.io/baby-vibration with an exhaustive collection of figures to examine the quality of the data and general results for all trials, including the selected tables and figures in this paper.

Each session was segmented into 'trials' corresponding to a different road surface or activity and each trial was divided into subsequent back-to-back 'repetitions'. We divided longer trials into repetitions to expose the variation of road surface features within a trial. The raw data consists of a single comma-separated value (CSV) file per session per IMU, along with metadata for the sessions and vehicles. The CSV file contains the time series data from each IMU: linear acceleration along and angular speed about each of the body-fixed orthogonal axes of the IMU alongside Epoch Unix timestamps. We segmented the sessions into trials representing a motion state of the vehicle: either static on level ground or being propelled over one of the surfaces of interest at a constant speed. Figure 4 gives an example of segmenting a session in different trials.

The data were processed per session as follows:

1. Calculate the vehicle travel speed during the session from the angular rate of the rear wheel and the vehicle's wheel radius.
2. Extract segments representing a single trial from each session time history, based on the manually labelled segment 'start', and 'end' times.
3. Split the trials with durations longer than 40 s into repetitions of 20 s to 39 s. Trials less than 20 s are not split.
4. Rotate the accelerometer data for each sensor from body-fixed sensor coordinates to body-fixed vehicle coordinates. This is achieved by

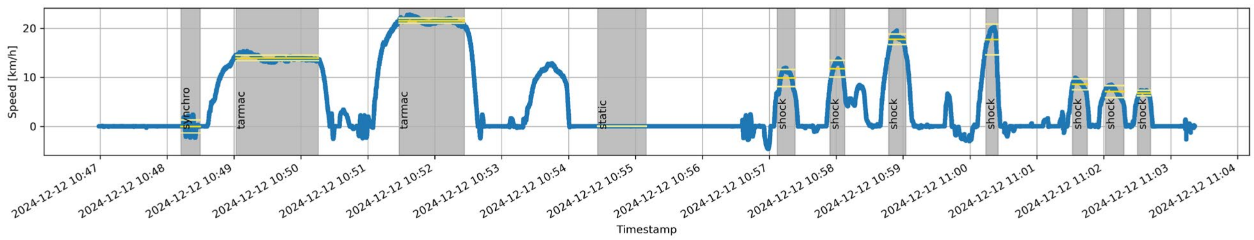

Figure 4. Vehicle speed versus time derived from the wheel hub IMU for an entire session (015) showing the trials in the shaded grey areas. Gold horizontal lines depict the mean speed during trials bounded by its standard deviation.

Table 2. Number of repetitions performed on each road surface and speed along with the mean duration and its standard deviation.

			Repetitions		
		Target Speed	Count	Mean Duration	STD Duration
Vehicle type	Road Surface	[km h^{-1}]		[s]	[s]
Bicycle	Paver Bricks	12	13	25.1	7.0
		20	8	28.8	7.6
		25	3	33.4	4.3
	Tarmac	12	14	25.0	7.0
		20	6	25.2	7.2
		25	6	22.0	2.5
Stroller	Cobblestones	5	26	22.8	5.6
	Paver Bricks	5	20	25.0	7.6
	Sidewalk Pavers	5	19	25.2	8.2
	Sidewalk Slabs	5	23	22.8	3.4
	Tarmac	5	16	28.9	9.6
		Count Sum	154		

Tables 3 and 4 provide metrics for repetition sets.

rotating the coordinate axes about the sensor's body-fixed axis, which was manually aligned with the vehicle's pitch axis. We subtracted the mean measured acceleration due to gravity (standard gravity) giving the linear acceleration of each sensor projected into the vehicle's SAE body-fixed axes (Society of Automotive Engineers 2008), named: longitudinal *x*, lateral *y*, and vertical *z*.

5. Extract each motion trial segment and select the vehicle body-fixed longitudinal, lateral, and vertical component of the seat pan accelerometer.

This resulted in acceleration versus time recordings of 154 total repetitions. The repetitions have durations in the range of 20 s to 40 s (mean: 25 s), see Table 2.

2.6. Data analysis

Figure 5 shows an example time history of the vertical (*z*) acceleration of the seat pan during a single repetition. To perform the ISO 2631-1 recommended health and comfort analysis, we first downsampled the time history from the hardware-set variable sampling frequency of approximately 910.22 Hz to a constant sample rate of 400 Hz using linear interpolation, giving sufficient samples for the bandwidth of interest based on the Nyquist frequency. We set any acceleration values outside of the sensor manufacturer's reported operating range of ±16 g to that maximum or minimum, respectively, given that values outside the range may be unreliable. Values that exceeded the range are rare, and only present in nine of the cargo bicycle paver brick repetitions. Following the ISO 2631-1 recommendation, we low-pass filtered the signal at $1.5 \times 80\,Hz = 120\,Hz$ using a zero-lag 2$^{\text{nd}}$ order Butterworth filter, given that the standard only applies to frequencies up to 80 Hz.

ISO 2631-1 provides weighting filters that highlight frequencies that adults are most sensitive to. To apply them, we calculated the amplitude spectra of the acceleration time histories of each trial using the Fast Fourier Transform (FFT). Figure 6 gives an example of a raw amplitude spectrum along with smoothed versions of the raw and ISO 2631-1 weighted signals. In almost all repetitions, there is a single dominant peak frequency in the ISO weighted and smoothed spectra. A handful of trials had two or more peaks at adjacent frequencies of approximately the same amplitude. We selected the maximum amplitude peak in those cases. Before ISO weighting, the area under the spectrum curve was calculated and the frequency below which 80% of the amplitude content falls was marked as an indicator of bandwidth.

We calculated the root mean square (RMS) over *N* samples of the downsampled, low-pass filtered, and ISO 2631-1 weighted vertical component of acceleration $a_{w,z}$ at the seat pan for each repetition using Equation (1) to use for the health assessment and the RMS of the magnitude of the 3D acceleration vector at the seat pan $\text{RMS}_{a_{w,xyz}}$ using Equation (2) for the comfort assessment, as per ISO 2631-1 guidelines. We set the ISO 2631-1 adjustment factors k_x, k_y, k_z equal to 1 for all acceleration components. RMS gives an indication of the average vertical acceleration experienced at the infant's buttocks-seat

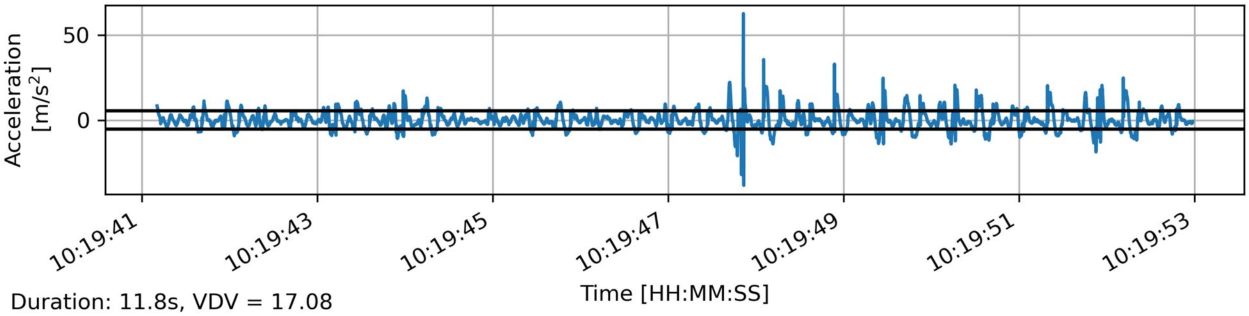

Figure 5. Raw seat pan vertical acceleration versus time from session 001: Maxi-Cosi stroller over the Sidewalk Slabs. Black horizontal lines indicate the ±root mean square (RMS) about the mean. The vibration dose value (VDV) for the first 10 s of the printed duration is shown in the bottom left.

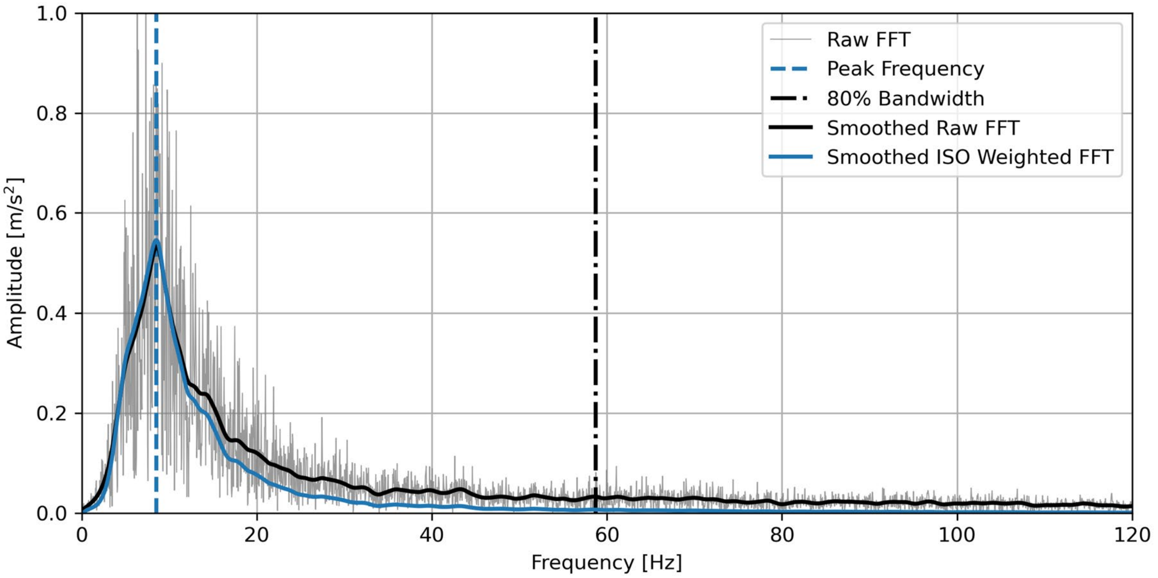

Figure 6. Seat pan vertical acceleration amplitude spectrum from session 004: Maxi-Cosi stroller over cobblestones. The grey curve shows the result of the FFT, the black line is a smoothened version of the FFT (zero-lag Butterworth low pass), and the blue line is the smoothed ISO weighted FFT. The blue dashed vertical line indicates the frequency at the maximum amplitude of the smoothed curve. The black dashed-dotted vertical line indicates the bandwidth threshold for 80% of the area under the black curve.

interface for the duration of the trial and is indicated in Figure 5 with black horizontal lines. It is the primary metric recommended by ISO-2631-1 for evaluation of health and comfort in adult whole-body vibration. We also calculated the vibration dose value VDV_{a_z} of the raw data vertical acceleration a_z using M samples corresponding to the first 10 s of the repetition with Equation (3), indicated in Figure 5. Lastly, we computed the crest factor CF_{a_z} of the downsampled and low pass filtered vertical acceleration[6] with Equation (4). All of these per-repetition metrics are reported as mean values over the repetitions corresponding to a scenario in Tables 3 and 4. The following equations describe the metrics:

$$\mathrm{RMS}_{a_{w,z}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} k_z^2 a_{w,z}^2(t_n)} \quad (1)$$

$$\mathrm{RMS}_{a_{w,xyz}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} k_x^2 a_{w,x}^2(t_n) + k_y^2 a_{w,y}^2(t_n) + k_z^2 a_{w,z}^2(t_n)} \quad (2)$$

$$\mathrm{VDV}_{a_z} = \left[\sum_{m=2}^{M} \frac{1}{2}(a_{z,m}^4 - a_{z,m-1}^4)(t_m - t_{m-1})\right]^{1/4} \quad (3)$$

$$\mathrm{CF}_{a_z} = \frac{\max|a_z(t_m)|}{\sqrt{\frac{1}{M}\sum_{m=1}^{M} a_z^2(t_m)}} \quad (4)$$

3. Results

Results for all 67 combinations of vehicle setup, road surface, and target speed are shown in Table 3 for strollers and Table 4 for cargo bicycles. These tables

Table 3. Mean computed metrics of the strollers for all 40 scenarios using seat pan acceleration.

Vehicle	Seat, Baby	Road Surface	Target Speed [$\mathrm{kmh^{-1}}$]	Rep. Count	RMS Acc [$\mathrm{ms^{-2}}$]	ISO Weighted RMS Acc [$\mathrm{ms^{-2}}$]	ISO Weighted RMS Mag [$\mathrm{ms^{-2}}$]	10 s VDV Acc [$\mathrm{ms^{-1.75}}$]	Crest Factor	Peak Freq [Hz]	Band-width [Hz]	Dur-ation [s]
Bugaboo	cot, 0 mo	Cobblestones	5	4	4.4	4.3	4.5	11.5	6.2	6.5	20.5	20.4
		Paver Bricks	5	3	2.6	2.4	2.5	6.1	4.1	9.5	23.4	23.3
		Sidewalk Pavers	5	2	2.9	2.7	2.9	15.6	13.5	6.1	49.8	25.4
		Sidewalk Slabs	5	3	4.8	4.7	4.8	12.5	6.4	5.8	30.6	20.2
		Tarmac	5	2	0.7	0.6	0.7	1.7	3.3	10.1	33.3	23.1
	seat, 9 mo	Cobblestones	5	4	2.5	2.3	2.5	6.2	4.7	6.6	37.9	22.5
		Paver Bricks	5	3	2.3	1.8	1.8	5.2	3.8	9.4	43.2	22.6
		Sidewalk Pavers	5	3	1.7	1.4	1.6	4.5	5.5	7.7	39.5	24.7
		Sidewalk Slabs	5	3	2.4	2.2	2.3	5.9	5.3	6.0	36.6	24.5
		Tarmac	5	2	0.6	0.4	0.5	1.6	6.5	8.4	51.2	34.6
Green Machine	cot, 0 mo	Cobblestones	5	3	3.2	2.9	3.4	7.2	5.3	4.1	38.1	23.7
		Paver Bricks	5	2	1.6	1.3	1.6	3.2	4.5	4.2	47.4	29.6
		Sidewalk Pavers	5	2	2.7	2.5	2.9	7.4	6.5	4.1	41.3	28.2
		Sidewalk Slabs	5	3	3.5	3.2	3.4	7.6	6.7	3.9	36.0	23.9
		Tarmac	5	2	0.5	0.4	0.7	1.1	4.1	4.2	52.5	22.1
Maxi-Cosi	cot, 0 mo	Cobblestones	5	4	4.6	4.4	4.5	11.3	4.9	8.1	51.2	20.7
		Paver Bricks	5	2	3.2	2.8	2.9	7.5	3.9	10.4	53.6	27.2
		Sidewalk Pavers	5	3	3.0	2.9	3.0	8.3	5.5	7.6	40.1	21.4
		Sidewalk Slabs	5	3	5.0	4.6	4.7	13.8	8.2	5.1	70.3	16.3
		Tarmac	5	2	0.9	0.8	0.8	2.1	8.0	9.6	43.4	34.3
	seat, 9 mo	Cobblestones	5	3	4.1	3.7	3.8	10.4	5.8	8.0	46.9	25.9
		Paver Bricks	5	2	3.0	2.4	2.4	6.9	3.4	9.7	57.4	27.8
		Sidewalk Pavers	5	2	2.6	2.3	2.5	7.2	5.5	7.3	47.2	27.8
		Sidewalk Slabs	5	3	3.1	2.9	3.0	7.8	5.4	6.9	51.4	25.6
		Tarmac	5	2	1.0	0.7	0.8	2.6	5.8	10.2	55.5	36.1
Old Rusty	seat, 9 mo	Cobblestones	5	2	4.7	2.0	2.3	13.0	6.0	5.1	105.1	29.9
		Paver Bricks	5	3	3.4	1.2	1.4	8.7	6.1	5.2	106.1	21.9
		Sidewalk Pavers	5	2	3.3	1.4	1.7	9.7	9.7	5.4	104.2	27.3
		Sidewalk Slabs	5	3	3.2	1.6	1.7	10.5	11.6	5.3	103.9	23.8
		Tarmac	5	2	1.1	0.5	0.6	2.7	5.7	7.0	105.5	22.6
Stokke	cot, 0 mo	Cobblestones	5	3	4.1	4.0	4.1	10.5	4.8	6.4	66.3	21.3
		Paver Bricks	5	2	3.0	2.1	2.2	6.9	4.1	9.4	97.7	29.5
		Sidewalk Pavers	5	3	2.8	2.6	2.7	7.0	5.5	6.7	69.9	22.2
		Sidewalk Slabs	5	2	4.0	3.8	3.9	11.6	6.4	5.2	79.1	25.7
		Tarmac	5	2	0.9	0.6	0.6	2.8	7.4	7.7	89.3	19.5
	seat, 9 mo	Cobblestones	5	3	5.2	4.9	5.0	12.4	4.4	7.7	69.1	21.5
		Paver Bricks	5	3	3.6	3.0	3.0	8.2	3.8	10.4	93.4	22.5
		Sidewalk Pavers	5	2	3.1	2.7	2.8	11.9	9.9	8.3	78.3	28.5
		Sidewalk Slabs	5	3	4.0	3.7	3.8	9.7	6.2	5.3	69.7	23.3
		Tarmac	5	2	0.7	0.4	0.5	1.9	6.3	11.1	95.6	39.1

show the mean values over scenario repetitions. They report the unweighted and ISO 2631-1 weighted seat pan vertical RMS acceleration, weighted seat pan magnitude RMS acceleration, unweighted seat pan vertical VDV for the first 10 seconds of the repetition, crest factor, peak frequency, bandwidth, and duration for all combinations of vehicle setup, road surface, and target speed.

The magnitude (combining *x*,*y*,*z*) ISO weighted RMS is only a bit higher (<4% in modern strollers and cargo bicycles) than the vertical (*z*) ISO weighted RMS, indicating that vertical vibration is dominant. This also holds for the Keiler tricycle, which will roll due to differing road unevenness at left and right wheels, resulting in lateral seat motion, but this seems hardly relevant in the current data. An exception is the Green Machine, where the magnitude is up to 24% higher, indicating relevant contributions of horizontal seat pan motion that may be due to the lack of a rigid horizontal constraint on the cot. As expected, in all cases the vertical ISO weighted RMS acceleration is below the vertical unweighted RMS, and this reduction is on average 10% for modern strollers, 13% for the vintage Green Machine, and even 56% for the vintage Old Rusty which sees the highest bandwidth (105 Hz). For cargo bicycles, ISO weighting leads to an average reduction of 16%. The Keiler with Melia on paver bricks at 20 km $\mathrm{h^{-1}}$ sees a 29% reduction with a bandwidth of 83 Hz. These strong effects of ISO frequency weighting in some vehicle and speed combinations are addressed further in the discussion. Below we present ISO weighted results for which guidelines have been published using acceleration magnitude for discomfort and vertical acceleration for health.

Table 4. Mean computed metrics of the cargo bicycles for all 27 scenarios, using seat pan acceleration.

Vehicle	Seat, Baby	Road Surface	Target Speed [kmh^{-1}]	Rep. Count	RMS Acc [ms^{-2}]	ISO Weighted RMS Acc [ms^{-2}]	ISO Weighted RMS Mag [ms^{-2}]	10 s VDV Acc [ms$^{-1.75}$]	Crest Factor	Peak Freq [Hz]	Band-width [Hz]	Dur-ation [s]
Keiler	Meila, 3 mo	Paver Bricks	12	2	5.4	4.9	5.0	12.9	8.1	7.9	62.5	26.3
			20	2	9.5	6.7	6.9	31.9	10.2	6.8	82.6	23.0
		Tarmac	12	2	1.2	1.2	1.3	2.7	8.2	7.8	41.6	25.4
			20	2	1.6	1.5	1.6	3.6	3.8	8.3	28.9	22.6
	Pebble, 0 mo	Paver Bricks	12	2	7.0	6.9	7.1	15.7	7.2	7.6	36.6	23.8
			20	1	12.6	10.7	10.9	26.6	9.9	6.8	74.8	34.0
		Tarmac	12	3	1.8	1.8	1.9	6.4	8.3	8.1	18.7	24.6
			20	2	2.8	2.8	2.8	6.7	5.1	7.8	16.7	29.2
	Pebble, 3 mo	Paver Bricks	12	2	6.3	5.7	5.9	14.7	11.0	8.0	47.5	28.9
			20	2	9.8	7.8	8.0	28.7	14.4	7.2	68.3	21.4
		Tarmac	12	2	1.5	1.5	1.6	4.9	8.1	7.6	18.5	27.8
			20	2	2.1	2.1	2.2	5.1	3.9	6.4	16.0	23.8
Urban Arrow	Melia, 3 mo	Paver Bricks	12	2	4.5	4.1	4.1	12.0	8.3	7.5	31.9	24.1
			20	1	6.9	6.2	6.3	15.2	8.6	7.9	40.1	36.8
			25	1	7.6	6.8	6.8	15.1	7.2	9.2	47.7	31.7
		Tarmac	12	3	0.9	0.9	0.9	3.6	9.3	9.4	33.2	20.4
			25	2	1.4	1.3	1.3	3.4	5.8	9.4	27.8	23.0
	Pebble, 0 mo	Paver Bricks	12	3	6.5	5.7	5.7	26.1	9.6	7.6	58.5	20.8
			20	1	9.2	8.5	8.6	15.5	9.9	8.0	53.1	39.1
			25	1	11.6	8.2	8.3	31.8	13.7	6.9	85.0	38.3
		Tarmac	12	2	1.3	1.2	1.2	4.8	8.3	9.3	24.8	29.0
			25	2	2.1	1.9	1.9	4.7	5.2	9.7	24.6	21.5
	Pebble, 3 mo	Paver Bricks	12	2	4.5	3.9	3.9	11.5	13.5	5.8	46.0	29.1
			20	1	10.8	7.4	7.5	15.2	14.7	5.0	71.9	32.1
			25	1	10.6	7.7	7.8	36.3	14.7	6.3	71.0	30.3
		Tarmac	12	2	1.1	1.0	1.0	3.8	9.6	8.8	28.3	25.3
			25	2	1.6	1.5	1.5	3.8	4.9	9.5	25.4	21.6

3.1. Effect of speed and model

Figure 7 compares the two cargo bicycle models both fitted with the same set of two baby seats (Melia and Pebble). Keiler sees higher accelerations compared to the two-wheeled Urban Arrow, with a pronounced increase on tarmac and a modest increase on paver bricks. Both vehicles show increasing accelerations with speed.

Regarding strollers, Figure 8 shows the vertical RMS accelerations for each road surface for each of the five strollers, lumping seat configurations and dummy sizes. The Maxi-Cosi and Stokke strollers have similar mean values. The Bugaboo has a slightly lower mean for cobblestones, paver bricks, and sidewalk pavers. The Green Machine performs better than the modern strollers on paver bricks, but similarly otherwise. The Old Rusty performs better than the modern strollers on all surfaces except tarmac. All strollers seem to experience similar accelerations on tarmac. All road surfaces compared to tarmac at least double the RMS acceleration.

3.2. Dominant frequency and bandwidth

Figure 9 shows frequency spectra averaged over body size and posture for all strollers on sidewalk pavers (left) and cargo bicycles on paver bricks. These surfaces are highly relevant as they are common in the Netherlands. Apparently, the two vintage strollers show a lower peak frequency, which is 4.1 Hz for Green Machine and 5.6 Hz for Old Rusty whereas modern systems peak around 7 Hz to 9 Hz. This can be explained by the more compliant suspension of the vintage strollers. The Old Rusty shows the lowest acceleration peak, and the lowest RMS weighted acceleration, but above 30 Hz it shows the highest power of all strollers. The Keiler sees much higher peak values as compared to the Urban Arrow. In both cargo bicycles, the peak frequencies range from 6 Hz to 10 Hz and hardly depend on vehicle and speed. Figure 10 shows the distributions of the dominant (peak) frequency across road surface types for each of the target speeds. Peak frequencies range from about 4 Hz to 11 Hz across all trials. For strollers (5 km h^{-1}), the median frequency increases from sidewalk slabs to cobblestones and sidewalk pavers and then to tarmac and paver bricks. For cargo bicycles, the difference in peak frequency between the two road surfaces is not as apparent or consistent.

Figure 11 gives a general indication of the bandwidth (80% of the amplitude spectrum content) for each of the target speed groups. On average, the bandwidth is 56 Hz for modern strollers, 46 Hz for Green Machine, 105 Hz for Old Rusty, and 44 Hz for cargo bicycles.

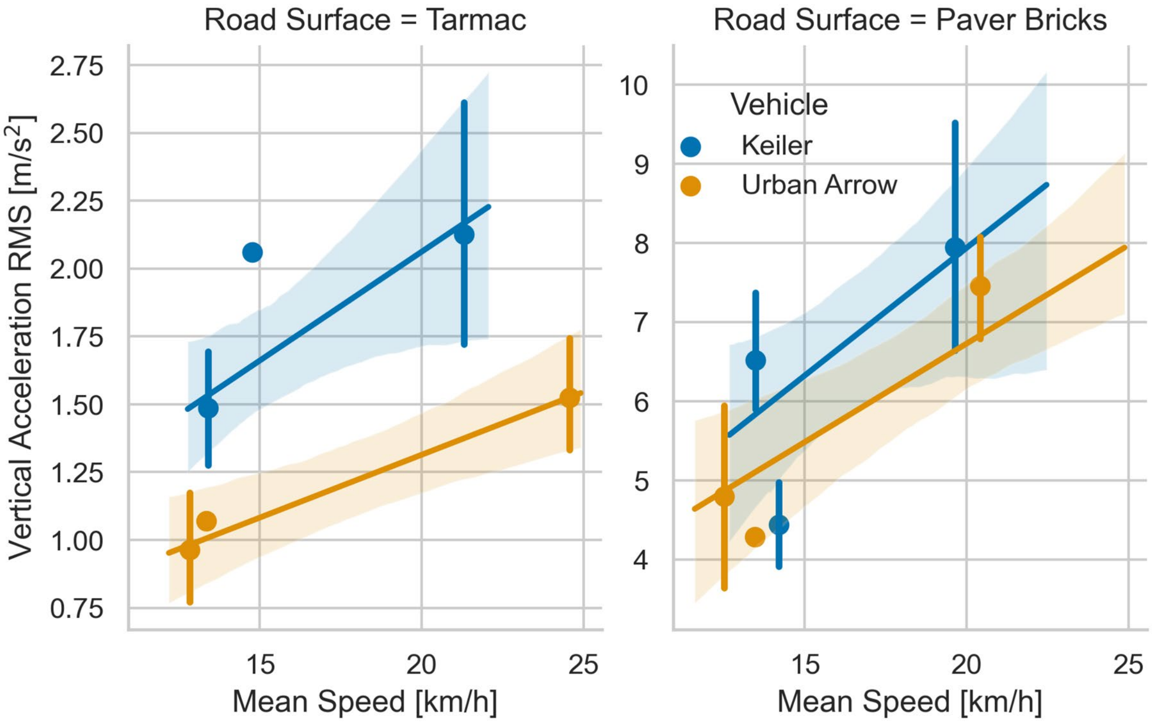

Figure 7. Seat pan ISO 2631-1 weighted vertical RMS acceleration versus speed grouped by road surface and cargo bicycle model. Slanted lines indicate a linear regression, vertical lines are the standard deviation at those speeds, and shaded regions show the 95% confidence intervals for the regression.

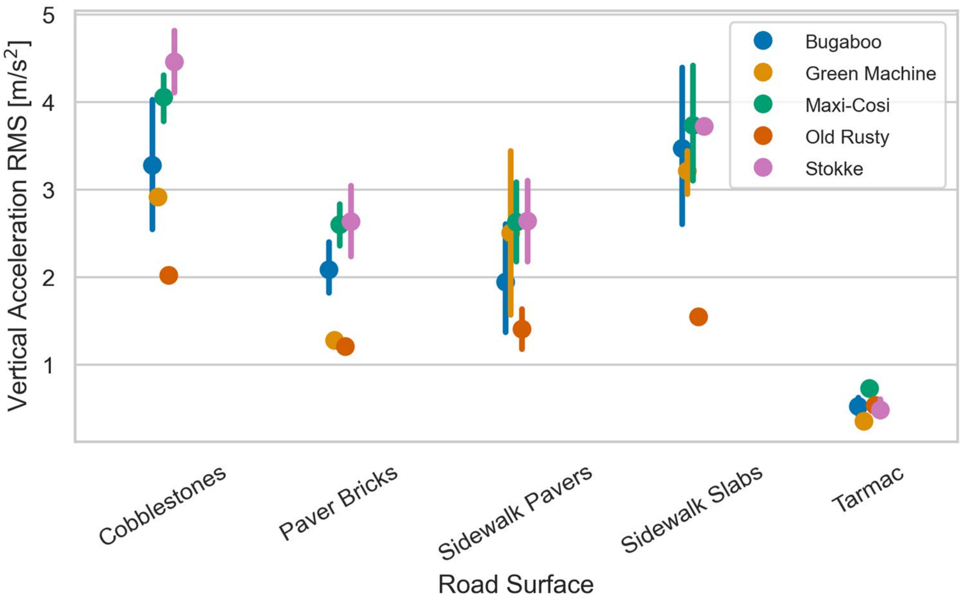

Figure 8. Seat pan ISO 2631-1 weighted vertical RMS acceleration per road surface for each stroller. Vertical lines indicate the standard deviation for categories that have more than one repetition.

3.3. Health assessment

Figures 12 and 13 show the ISO 2631-1 weighted vertical acceleration at the seat pan for all repetitions of the stroller and cargo bicycles, respectively. The horizontal lines in the figure correspond to the boundaries of the 'health caution' and 'health risk' zones in the standard, which depend on the duration of exposure. If acceleration values are above the health caution zone, ISO 2631-1 states that 'health risks are likely' for adults in erect seating postures for a continuous daily dose. It must be emphasised that ISO 2631-1 is based on adults and may not result in a representative risk for infants or older children. We use it for comparative

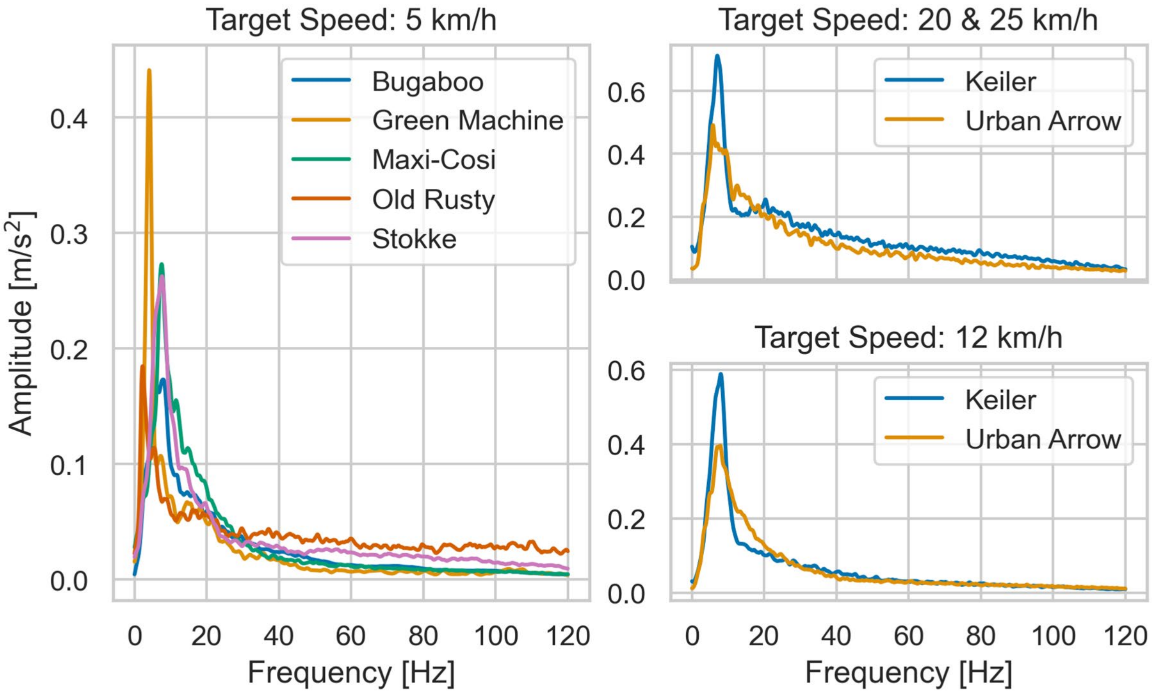

Figure 9. Mean vertical seat pan amplitude spectra of each vehicle for strollers on sidewalk pavers (left) and cargo bicycles on paver bricks (right).

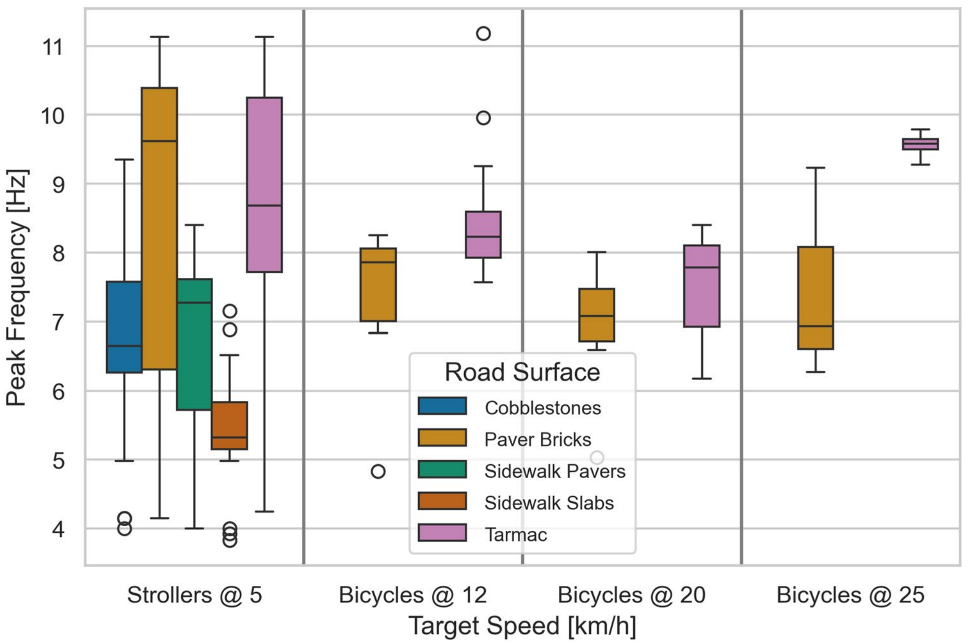

Figure 10. Seat pan vertical peak frequency distributions comparisons among road surfaces for each target speed group for all repetitions. The boxes bound the quartiles and indicate the median. The whiskers indicate the 95th percentile and circles are outliers.

and reference purposes and are aware of the limitations that we explain later in the discussion and conclusion.

For the strollers, all vibration measurements were below the health caution zone boundary if the long-term daily continuous exposure is under 10 min. Additionally, all strollers pushed over tarmac were below the zone for long-term daily continuous exposure under 4 h. Pushing the Bugaboo and Maxi-Cosi with a 0-month-old infant or the Stokke with a 9-month-old infant over cobblestones and sidewalk slabs may have health risks for long-term daily continuous

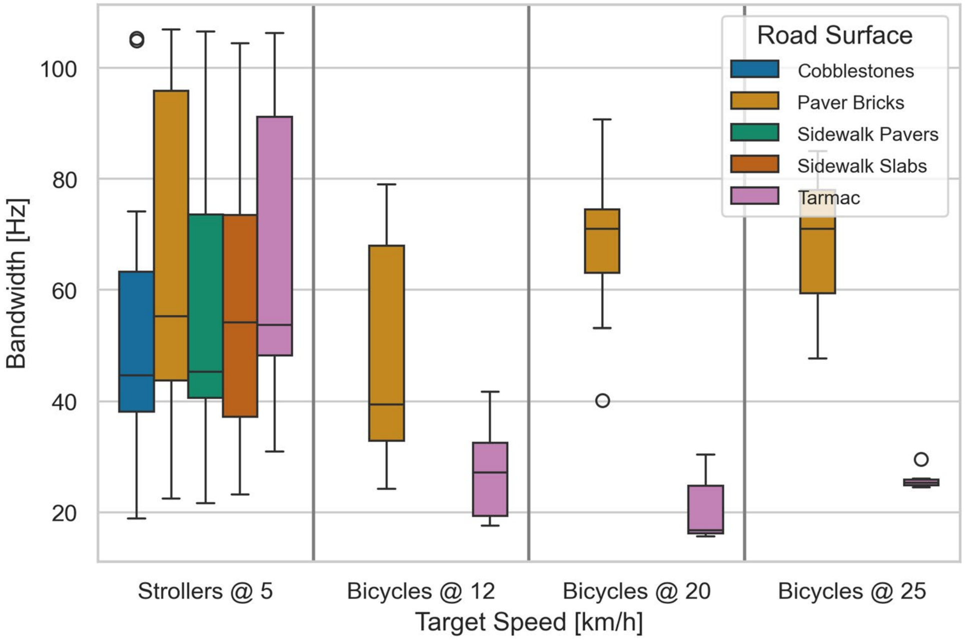

Figure 11. Bandwidth (based on 80% of the area under the unfiltered seat pan vertical amplitude spectrum) for each target speed group for all repetitions. The boxes bound the quartiles and indicate the median. The whiskers indicate the 95th percentile and circles are outliers.

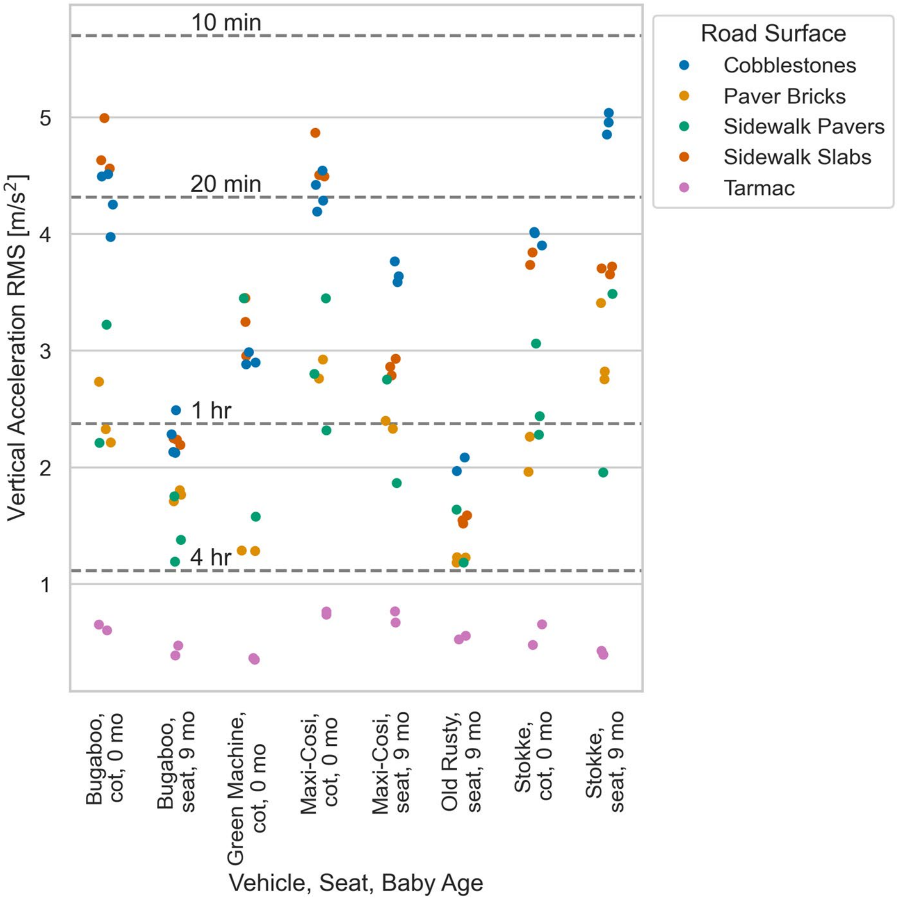

Figure 12. ISO 2631-1 weighted seat pan vertical RMS acceleration of all stroller repetitions with colour representing road surface. The horizontal dashed grey lines with time duration indicators are the upper bounds of the ISO 2631-1 ‘health caution zones’ for long-term exposure of adults seated erectly, daily experiencing these vibrations with continuous duration.

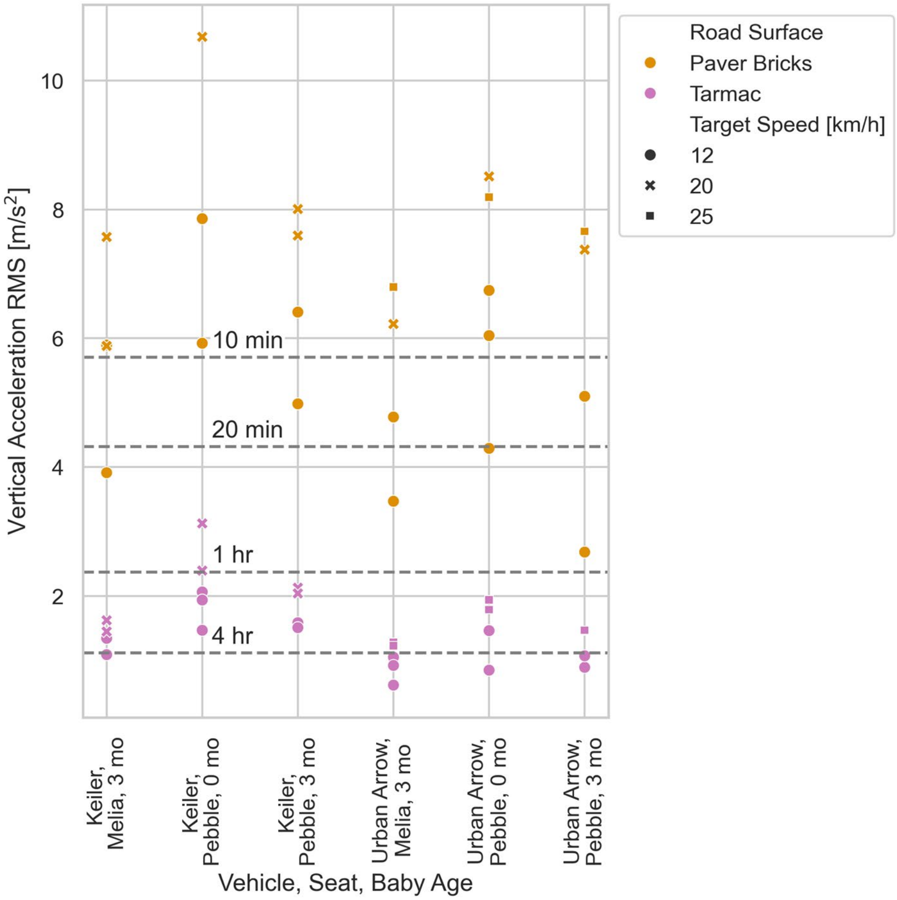

Figure 13. ISO 2631-1 weighted seat pan vertical RMS acceleration of all cargo bicycle trials with colour representing road surface and marker style indicating the target speed. The horizontal dashed grey lines with time duration indicators are the upper bounds of the ISO 2631-1 'health caution zones' for long-term exposure of adults seated erectly, daily experiencing these vibrations with continuous duration.

exposures exceeding 20 min. For almost all strollers, pushing over any surface except tarmac exceeded the 1 h risk boundary. Notably the Bugaboo and Old Rusty with a 9-month-old infant fell at or under the 1 h threshold for all surfaces. The 0-month dummy experienced worse accelerations than the 9-month dummy in the Bugaboo and Maxi-Cosi, but that was opposite for the Stokke. Old Rusty showed the lowest overall acceleration magnitudes.

For both cargo bicycles, accelerations exceeded the 10 min health risk threshold when ridden above 20 km h^{-1} on paver bricks and exceeded the health risk threshold when ridden more than 1 h above 12 km h^{-1} on paver bricks. All but the Keiler with the Pebble and the 0-month dummy were below the 1 h threshold for riding on tarmac at any target speed. Only the Urban Arrow with the 3-month dummy was (mostly) under the 4 h threshold when ridden at either speed over tarmac. The accelerations were lower for the Melia versus the Pebble.

3.4. Comfort assessment

ISO 2631-1 recommends using the magnitude of the weighted seat pan acceleration 3D vector for comfort assessment. Figures 14 and 15 plot RMS of the acceleration magnitude along with the comfort indicators provided in the standard that are based on adults seated in public transit for an unspecified duration. As already mentioned above, the ISO 2631-1 comfort assessment was compiled for adults, with many warnings and limitations, and may not be applicable for other contexts or populations, like infants or older children. We also include a line representing cyclists' discomfort threshold reported by Gao et al. (2018). It is important to recognise that cyclists perched on a bicycle seat seem to tolerate higher vibration amplitudes than the public transit riders who were surveyed for the ISO ratings. This points to possible weakness in or contradiction to the ISO recommendations or to other factors affecting cycling discomfort (e.g. the

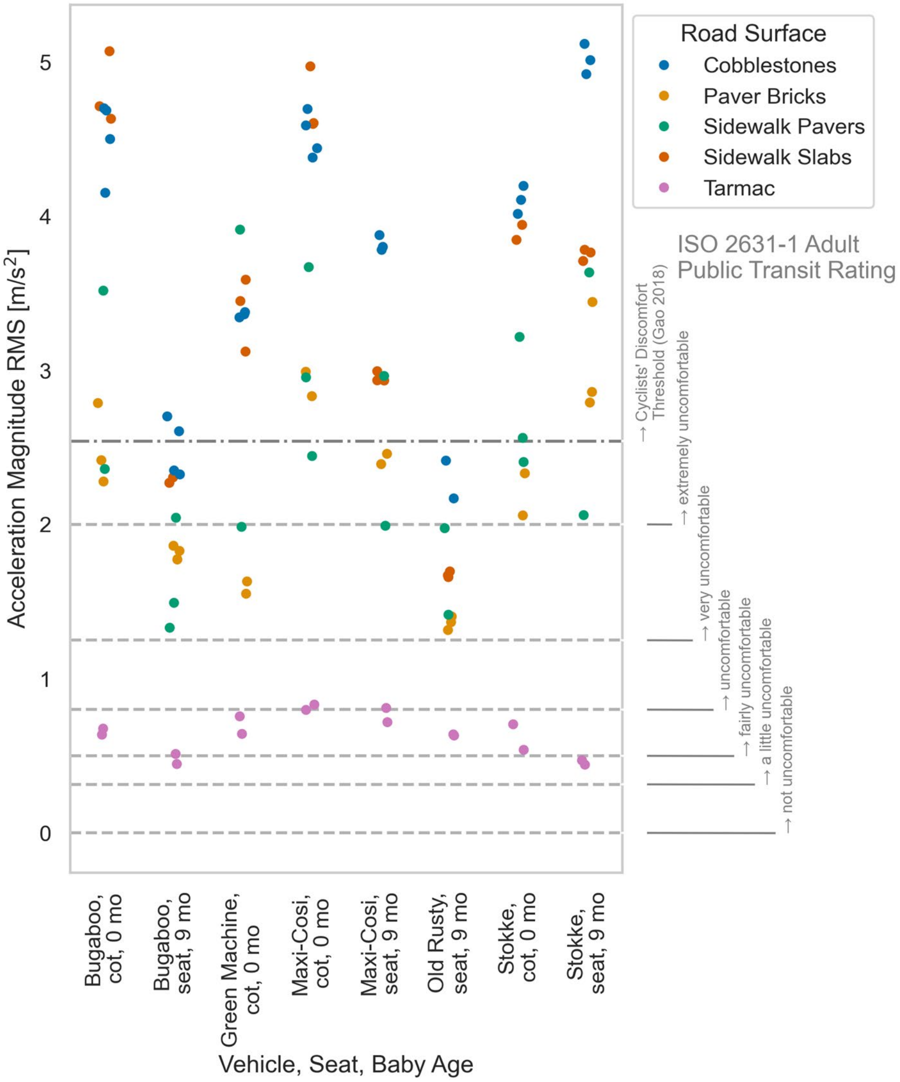

Figure 14. ISO 2631-1 weighted seat pan magnitude RMS acceleration of all stroller repetitions with colour representing the road surface. The horizontal dashed lines are the lower bound of the ISO 2631-1 'comfort zones' for adults seated erectly experiencing vibrations in public transit. The horizontal dashed dotted line is the cyclists' vibration discomfort threshold as reported by Gao et. al (Gao et al. 2018).

ability to stand on the pedals to lower vibration to the body and the head).

When following the threshold definitions from the ISO 2631-1 guidelines for the strollers, all are at least 'a little uncomfortable' on all surfaces. All strollers but the Stokke are 'fairly uncomfortable' on tarmac. All other road surfaces are at least 'very uncomfortable'. The 'Bugaboo, seat, 9 mo' and 'Green Machine, cot, 0 mo' over paver bricks and 'Old Rusty, seat, 9 mo' over paver bricks, sidewalk pavers, and sidewalk slabs are 'very uncomfortable', but all other strollers and surfaces are 'extremely uncomfortable'. The Old Rusty generally shows the lowest discomfort levels.

Both cargo bicycles ridden at any tested speed over paver bricks, as well as the Keiler with Pebble ridden over tarmac at high speed fall into the category 'extremely uncomfortable'. Those are also above the cyclist discomfort threshold. The other vehicle setups fall between 'fairly uncomfortable' and 'very uncomfortable' over tarmac for all tested speeds. The Urban Arrow with Melia performs, on average, the best on paver bricks and tarmac at all tested speeds.

4. Discussion

We have presented a comprehensive set of acceleration measurements from experiments that simulate vibrations experienced by infants in the 0–9-month age and mass range during transportation in strollers and cargo bicycles. We compared the average magnitude of vertical and total acceleration at the seat pan across a variety of road surfaces and seats at typical

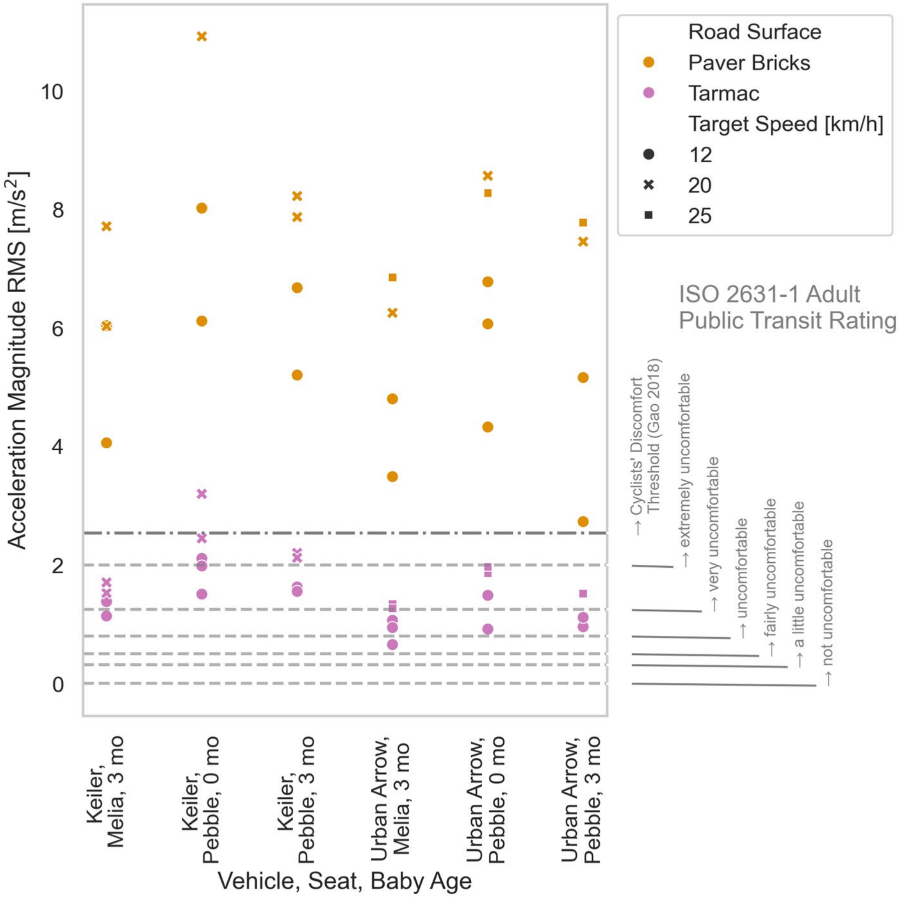

Figure 15. ISO 2631-1 weighted seat pan magnitude RMS acceleration of all cargo bicycle repetitions with colour representing road surface and marker style representing the target speed. The horizontal dashed lines with the upper bound of the ISO 2631-1 'comfort zones' for adults seated erectly experiencing vibrations in public transit. The horizontal dashed-dotted line is the cyclists' vibration discomfort threshold as reported by Gao et. al (Gao et al. 2018).

travel speeds. ISO 2631-1 weighted average acceleration ranged from 0.4 m s^{-2} to 10.7 ms^{-2} across all tested scenarios. Strollers induced 0.4 ms^{-2} to 5.0 m s^{-2} for a mean walking speed of 5.3 km h^{-1}. Cargo bicycles induced 0.6 m s^{-2} to 10.7 m s^{-2} over a speed range of 12 km h^{-1} to 25 km h^{-1}.

4.1. Surface and speed

Travelling over a tarmac surface showed the least vibration in all types of vehicles at any speed with a range of 0.4 m s^{-2} to 1.2 m s^{-2}. For strollers, the roughest surfaces being cobblestones and sidewalk slabs with large gaps caused 5× the acceleration experienced on tarmac, reaching 5.0 m s^{-2}. More common surfaces, sidewalk pavers and paver bricks, reach values up to 3 m s^{-2}.

For cargo bicycles, travelling over paver bricks at the same speeds can quadruple average acceleration relative to tarmac. Travelling at the maximum allowed speed of an electric cargo bicycle (25 km h^{-1}) over paver bricks caused average accelerations that exceeded 8 m s^{-2}. Additionally, the effect of speed on vibration was apparent for paver bricks but not so much for tarmac. Rothhämel and Liu (2023) contrarily found a larger effect of speed on tarmac.

Whereas speed strongly affected the acceleration amplitude, it had less effect on the peak frequency and the bandwidth. Peak frequency at the highest speed was 1.25× higher for tarmac than paver bricks and bandwidth approximately doubled for paver bricks relative to tarmac at high speeds. This suggests that oscillations induced by the systems tested may have strong influence relative to dominant frequencies resulting from the road surface.

4.2. Baby mass

The size of the dummy (mass and build) had no obvious systematic effect on the average acceleration at the seat pan, but this may simply be because we did not isolate dummy mass as an independent variable.

The absence of an effect is contrary to Schwanitz, Stuff, and Odenwald (2020)'s findings, where they tested dummies of 5 and 10 kg in a bicycle trailer. Seat pan vibrations are transmitted to the infant's body and the mechanical properties (mass, stiffness, and damping) of the infant's body determine whether this excitation is amplified or not and the degree to which each body segment is affected. Tests with more realistic dummies or real infants along with comparisons of equivalent vehicle setups are necessary to investigate how the infant itself moves when excited by this level of vibration. This information is not readily available in the literature and may be difficult to acquire due to ethical limitations and the absence of validated infant dummies. Due to a lack of dummies validated for vibration conditions, we tested with dummies of representative mass and body size. As is common for adult vibration, accelerations were measured at the dummy-seat interface rather than on the body. This limits influence of infant body motion to the measurements. The only effect that stood out for mass was that, counter-intuitively, the lighter dummy had less acceleration than the heavier dummy for the Stokke stroller, but this may well be explained by the different stroller configurations tested for the two body sizes.

4.3. Health

Vertical RMS acceleration on uneven surfaces can be relatively large compared to the smoothest experience on tarmac. When we compare the vibration measured for infants in strollers and cargo bicycles with the ISO 2631-1 standard vibration 'health risk zone' as defined for long-term exposure of adults seated erectly, we see that:

- only strollers pushed over tarmac at 5 km h^{-1} had average acceleration below the 'health risk zone' for 4 h daily duration,
- walking with an infant in a stroller on cobblestones and sidewalk slabs can exceed the 'health risk zone' within 20 min to 1 h, depending on the stroller model and the age of the child,
- cargo bicycles ridden at 12 km h^{-1} to 25 km h^{-1} over tarmac delivered accelerations below the 1 h 'health risk zone' for all but the Keiler with the newborn,
- cycling with an infant in a cargo bicycle on tarmac at 12 km h^{-1} can be maintained for approximately two hours before exceeding the 'health risk zone',
- cargo bicycles ridden at 12 km h^{-1} over paver bricks delivered accelerations exceed the 10 min 'health risk zone' for three of the 6 vehicle setups and range between 1 h to 20 min otherwise, and
- cycling with an infant in a cargo bicycle on paver bricks at 20 km h^{-1} to 25 km h^{-1} for 10 min gives the infant a vibration load that equals or exceeds the 'health risk zone'.

When utilising the ISO 2631-1 standard, we can conclude that strollers can be pushed over paver bricks and sidewalk pavers continuously for no more than half an hour. On extreme surfaces like cobblestones and sidewalk slabs, strollers should be pushed slower than 5 km h^{-1} with a duration of maximal 10 min. For tarmac, the vibration is relatively lower and longer durations are possible. But for long durations, the parent/caregiver would need to consider appropriate breaks to allow the infant to move. Cargo bicycles carrying infants over paver bricks should slow down to 12 km h^{-1} or preferably less, and the duration should be kept under 10 min. When riding a cargo bicycle over tarmac at 20 km h^{-1}, the duration should be kept under 1 h. At 12 km h^{-1}, cargo bicycles can ride over tarmac for maximal 2 h.

The largest unweighted RMS vertical acceleration we recorded at the seat pan was 12.6 m s^{-2}. Tsujiuchi, Koizumi, and Hara (2014) studied inflicted head injury by shaking trauma and give evidence based on finite element modelling that shaking an infant at the chest with an unsupported head at 14 m s^{-2} for 2 s could rupture brain bridging veins. This is a largely different scenario with an unsupported head and accelerations acting in different directions than in our experiments, yet it is worrisome that the acceleration magnitudes are of the same order of magnitude.

4.4. Comfort

When considering comfort, the ISO 2631-1 guidelines estimate that adults would report the vibrations experienced in strollers and bicycles as uncomfortable. For strollers, the vibrations over tarmac would be rated 'fairly uncomfortable' and all other road surfaces would be 'very' or 'extremely uncomfortable'. Similar results were reported by Kok Siong (2018). When riding a cargo bicycle over paver bricks, the vibrations would be rated as 'extremely uncomfortable' and over tarmac spans 'fairly' to 'extremely'. The ISO 2631-1 comfort rating scale is derived from adult subjective ratings of vibrations felt when riding public transit for an unspecified duration, so we question whether the scale is appropriate for typical strolling and cycling durations. Furthermore, the standard extensively emphasises that comfort perception depends on many interacting factors. Gao et al. (2018) report that cyclists do not rate vibrations as extremely uncomfortable on normal road surfaces, indicating a possible contradiction, especially given a bicycle saddle is generally perceived less comfortable than a chair-style seat used in the standard development. Lastly, it is not readily possible to assess subjective comfort directly from infants so we can only extrapolate from children and adult experience.

4.5. Vehicle and seat design

Different combinations of vehicle, seat, and baby mass cause different average vertical accelerations at the seat pan. We are only able to compare vehicle setups, other than comparing the same two different baby seats in both cargo bicycles. A striking discovery is that the two tested 1970s strollers significantly outperformed many of the modern stroller setups on most road surfaces. The vintage strollers had more sophisticated suspension systems that used springs, straps, and larger wheels. Stroller manufacturers may have reduced suspension as a side effect of decreasing the size and weight of strollers and introducing swivelling front wheels, which makes steering easier but limits suspension design options. As an example, the 'Old Rusty' stroller was the only one that did not exceed the 1 h health risk line for any road surface.

Both the Bugaboo and Maxi-Cosi strollers showed lower accelerations for the heavier baby, as expected, but the Stokke stroller showed the opposite trend for cobblestones and paver bricks. This points to design choices in the seated configuration that may excite resonance on certain surface profiles. The 'Bugaboo, Seat, 9 mo' configuration performed better than the other modern strollers for all non-tarmac road surfaces. The Urban Arrow performed better than Keiler on tarmac but there was no difference on paver bricks. Additionally, there was no difference between different seats for the 3-month-old infant. The performance of a vehicle setup was not necessarily constant with respect to cot or seat configuration; contrarily, performance was often significantly different when converting for different baby ages. This may be due to designs being optimised for one configuration.

4.6. ISO frequency weighting and bandwidth

We report RMS accelerations as well as the ISO 2631-1 weighted accelerations for comparison. Vibrations at frequencies between 4 Hz to 11 Hz showed the largest unweighted magnitude, but there are substantial accelerations at higher frequencies, as shown by the unweighted 80% bandwidth. Our results show substantial differences between RMS and VDV, highlighting the importance of reviewing their meaning. These differences emerge from the high bandwidth of the accelerations now measured, which greatly exceed the bandwidth of accelerations measured with adults seated in cars (see e.g. Figure 2 in (Griffin and Newman 2004)). Adult experiments investigating discomfort as a function of frequency, show that significant discomfort can be measured across all tested frequencies, being up to 80 Hz (Morioka and Griffin 2010) or even up to 315 Hz (Morioka and Griffin 2006) albeit with reduced sensitivity.

The ISO frequency weightings are defined for adults in more or less erect postures with the head being unsupported, whereas we now studied dummies representing infants from 0 to 9 months lying with the head directly supported. The ISO 2631-1 weightings represent a reduced sensitivity above 8 Hz, which is associated with the vertical dynamics of erect seated subjects, and filter out such high frequencies (Toward and Griffin 2011; Mirakhorlo et al. 2022). However, adult experiments show greater discomfort for frequencies above 8 Hz when lying with head supported with 30° to 90° back inclination compared to sitting erect without head support (Basri and Griffin 2013). Higher frequencies have also been associated with effects on the central nervous system. For instance, experiments on rats showed brain injury visible in behaviour through functional impairment and in visual changes of brain structures in post-mortem dissection after exposure to prolonged whole-body vibration at 30 Hz and 5 m s^{-2} (Yan et al. 2015). In some conditions, the RMS exceeds the ISO Weighted RMS substantially, warranting further research on the effects of higher frequencies, in particular for conditions where the head is supported and for children. Meanwhile, a conservative approach is to (also) consider the unweighted RMS in the design and evaluation of transport means for very young children.

5. Conclusion

5.1. Summary

The results herein raise concerns about transporting infants in strollers and cargo bicycles. If the user's behaviour is not adjusted to avoid rough surfaces or to travel slowly over them when transporting an infant, there are potential health risks and discomfort from daily and repeated exposure to large vibrations over a longer time. However, there is no direct evidence that connects whole-body vibration as measured in this study to infant harm or negative health effects and discomfort, thus we can only extrapolate from the limited guidelines on adults in occupational settings. We did measure vibrations that would not be permitted for adults to maintain long-term occupational health and it is reasonable to believe we should not subject our infants to the same. The preceding statement should certainly not be interpreted to mean that vibration lower than these limits is deemed acceptable for infants. The relative vulnerability of infants points more towards infant limits being lower than those of adults. Further research to establish direct evidence to infant health and comfort would possibly permit more or less caution than we conclude below in our recommendations.

It is well known that whole-body vibration can be attenuated with good suspension design. We see this in the drastic historical evolution of suspensions in automobiles, buses, trucks, and trains. We do not see this same kind of attention to suspension in strollers, cargo bicycles, and baby seats for these vehicles. Both walking and cycling are well known to offer great societal and personal benefits over travelling by car, so it behoves us all to optimise transport for infants in these two modes of transportation.

5.2. Recommendations

Our conclusions result primarily from the recommended application of ISO 2631-1. It is of utmost importance to recognise that this standard cautions against extending the use of the standard to situations for which its supporting data were not derived. The standard is based primarily on pre-1997 studies of adult whole-body vibration in occupational durations (4 h to 8 h daily dose) or during public transport.

The recommendations in standard ISO 2631-1 have not been based on or validated for infants, children, or young adults, nor for recumbent or reclined seating postures with the head supported. Additionally, the admissible durations for health are not validated for daily short durations or shorter lifetime accumulation that dominate stroller and cargo bicycle travel with infants. So, our recommendations must be taken with caution, at least until more research is done to improve the standard guidance.

Nevertheless, the following list provides recommendations for users, researchers, designers, and manufacturers based only on the findings of this paper, independent of other factors one must take into consideration. We believe these recommendations stand in spite of the standard's limitations.

1. Manufacturers of strollers, cargo bicycles, and seats should test for vibrations for all expected surface types and ranges of relevant body sizes and postures to ensure that their designs isolate vibrations well for all use conditions. Testing across relevant body sizes is especially important for strollers, due to the high mass of the infant relative to the mass of the stroller.
2. Manufacturers should collaborate in testing and report their results publicly, similar to the safety ratings of the automobile industry. For the combined use of cargo bicycles and baby seats, manufacturers should collaborate in this effort.
3. Manufacturers and scientists should collaborate to develop metrics and testing procedures for the long-term goal of a new standard.
4. Designers should ensure that adequate vibration isolation occurs for vehicles that have multiple configurations (e.g. recumbent vs. erect seating).
5. Designers and manufacturers should incorporate better suspension systems, as currently occurring vibrations can be drastically reduced. Useful information may be derived from past designs with better suspension.
6. To reduce road-induced vibration, new cycling roads and sidewalks should have a tarmac-like smoothness. Cobblestones should be avoided.
7. Users should consider limiting their speed when walking with strollers or riding over surfaces rougher than tarmac, as bumpier surfaces aggravate accelerations.
8. Users are suggested to limit the duration of transport over surfaces rougher than tarmac to periods that do not exceed 10–30 continuous minutes depending on the system (quality of suspension, larger tyres or wheels) and other countermeasures like adequate non-vibration breaks in between.
9. Users should preferably ride any cargo bicycle at a speed of maximally 12 km h^{-1} over surfaces rougher than tarmac. E-cargo bicycles can easily reach the maximum speed of 25 km h^{-1}. Infants should only be transported for short durations when riding over non-tarmac surfaces at these speeds.
10. Standard ISO 2631-1 is not validated to characterise health and comfort effects of vibration for infants or children, for short travel durations, for vibration accumulation over only a small

number of years, or for non-erect seating. However, this is the only available standard in the literature assessing health and comfort levels on vibrations, and should be used as a benchmark. More research should be done to enable the design of a standard on vibration that is applicable for infant transportation.

Notes

1. Supplementary Material "Experimental Equipment" provides more detailed figures and technical descriptions of all tested strollers and cargo bicycles.
2. Supplementary Materials "Experimental Equipment" provides full details of the dummies.
3. Only two sensors were used in this study and descriptions of the remaining three sensors and detailed drawings showing the vehicles and the sensors' location are in Supplementary Materials "Experimental Equipment".
4. Details of all test locations and surfaces are shown in Supplementary Materials "Location and Pictures of the Experiment Areas".
5. We also performed shock experiments but do not include the results here due to an abundance of sensor saturation. See the Supplementary Materials "Shock Tests" for that information.
6. Some scenarios have crest factors larger than 9, but we do not report metrics other than RMS as ISO 2631-1 recommends for this study.

Authors' contributions

CRediT: **Gabriele Dell'Orto**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; **Brecht Daams**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing; **Riender Happee**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing; **Georgios Papaioannou**: Conceptualization, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing; **Arjo J. Loeve**: Conceptualization, Funding acquisition, Writing – review & editing; **Jesper Meijerink**: Data curation, Investigation, Methodology, Writing – review & editing; **Thomas Valk**: Data curation, Investigation, Methodology, Writing – review & editing; **Jason K. Moore**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Data availability statement

The data are made available in the public repository at the following link: 10.5281/zenodo.17723466.

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