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Vibration Characterisation of Strollers and Cargo Bicycles for Transporting Infants

Including Recommendations for Users, Designers, Manufacturers, and Researchers

Gabriele Dell'Orto   Brecht Daams   Riender Happee   Georgios Papaioannou
Arjo J. Loeve   Jesper Meijerink   Thomas Valk   Jason K. Moore*

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Notice

This paper has been submitted for peer review and is subject to change with revisions.

Abstract

We evaluated 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 $\mathrm{m\,s^{-2}}$ on tarmac and up to 5.0 $\mathrm{m\,s^{-2}}$ on cobblestones at a mean walking speed of 5.3 $\mathrm{km\,h^{-1}}$. Cargo bicycles induced on average 0.6 $\mathrm{m\,s^{-2}}$ on tarmac and up to 10.7 $\mathrm{m\,s^{-2}}$ 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. Two vintage strollers significantly reduced vibrations compared to three modern strollers, indicating benefits of compliant suspensions. We recommend designers systematically consider vibration, users avoid prolonged exposure to surfaces rougher than tarmac, and researchers to pursue scientifically founded test procedures and standards for infant vibration.

Keywords

whole-body vibration, infant, bicycle, stroller, ISO

*corresponding author: j.k.moore@tudelft.nl, +31 (0)15 278 3556

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1 Introduction

When a baby is born, it is not able to walk and must be carried by others or transported in a suitable wheeled transport. Until about a century ago, babies were mainly kept at home, which is still customary in some non-western cultures. More than a century ago, perambulators were introduced to transport infants outdoors. However, mothers were advised that a playpen in the garden is healthier than the use of perambulators, in part because vibrations generated by a perambulator were deemed not comfortable and even harmful to babies [4], even though in those days perambulators had ample suspension. Since about 1970, cars became ubiquitous and the heavy and sizeable perambulators became strollers: lighter and smaller products foldable for easy transportation in cars. Over the years, new means of transportation came into use for infants: child safety seats to use in cars, bicycles with child seats, and cargo bicycles with child seats or baby shells.

All means of transport cause vibration, which is transferred to the sitting or lying infant. Unlike the advice in the 1930's, vibration is seemingly not a subject of attention in the present design of these products. On the contrary; modern strollers do not have much suspension, and (electric) cargo bicycles are increasingly used for infants with seats that offer marginal suspension or padding. We thoroughly reviewed the literature, 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. 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.

Research on vibration comfort during cycling is a logical starting point for investigating similar road-induced vibrations for infants. Cycling is beneficial for health [20] and greatly contributes to reducing CO_2 emissions, congestion, and air pollution [19]. As a result, bicycles are increasingly being used to deliver goods, for daily commuting and for leisure. Among all journeys in the EU, 20-40% are by bicycle or on foot, with bicycle trips most frequent in the Netherlands, Denmark, and Sweden and least frequent in, for example, Finland. Various countries and employers offer incentives to increase bicycle use. However, the comfort experienced by riders and passengers (e.g. infants/children in cargo bicycles), is a multifaceted [2] challenge to wide acceptance of bicycling.

The comfort of bicycles [35] 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 [31, 11, 2, 40, 33], there is only limited work on understanding the biomechanical and physiological 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 [35]. 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 [39] and strollers. The bicycle or stroller design and the seating configuration affect posture and vibration transmission [5, 41]. 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 $\mathrm{km\,h^{-1}}$ and up to 63% higher (28.1 $\mathrm{km\,h^{-1}}$), respectively, than conventional bicycling [32]. The intensity of these vibrations could become even more critical with the change of load, which is related with 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 [22, 23, 14, 38, 27, 25]. Most literature focusses 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 [12]. 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 [13], 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. [7] show this discrepancy with vibration comfort limits for adults riding bicycles, based on their subjective feedback, tolerating more than the 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) [6].

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 [9]. 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 et al. [27] 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 et al. [25] tested a trailer seat and a tadpole configuration three-wheel cargo bicycle on smooth tarmac and cobblestones for speeds from $10\,\mathrm{km\,h^{-1}}$ to $20\,\mathrm{km\,h^{-1}}$ 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 $30\,\mathrm{km\,h^{-1}}$ on a rough road [10]. Rothhämel and Liu [24] 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, Kanya-Forstner [14] measured acceleration in bicycle child trailers with human subjects aged 12 months to 6 years over tarmac and gravel terrain (average speed of $12\,\mathrm{km\,h^{-1}}$ 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. Hence, there is a need to refocus on the impact of vibrations on infants and children's health and comfort [26] to ensure safe, comfortable and widespread use of bicycles.

In the context of infant transportation with stroller seats, Kok Siong [15] 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. [28] 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 et al. [21] 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), vibration along the y-direction at 2 Hz, 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 addresses both comfort and potential health effects for infants. 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 assessed the data and derived results using ISO 2631-1 frequency weightings and procedures. Given

Figure 1: Tested products: cargo bicycles with baby seats, strollers, and dummies. Images are reproduced from manufacturer's websites except for the vintage strollers and dummies.

that ISO-2631-1 is neither validated for children nor for lying postures, we also report unweighted results to assess 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.

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]

The tests involved three baby dummies with sizes and weights representative of infants 0, 3 and 9 months of age. Newborns ('0 months') are the youngest (smallest, lightest) children that are transported in strollers with a cot. 3-month-old infants are the youngest (smallest, lightest) children that are transported in cargo bicycles, fixed in a baby car seat or baby shell. At nine months on average, infants can sit up straight by themselves and thus can be transported sitting up straight, 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

[1] Appendix E provides more detailed figures and technical descriptions of all tested strollers and cargo bicycles.

(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.

and create challenges in terms of reproducibility. Hence we bought and adapted commercially available "Reborn" dummies (Atelier Wiesje), see Figure 1 where Appendix E provides full details.

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 [34] and French growth charts for 3 and 9 months [1] 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 [29].

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. [2] 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.

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

[2] 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 Appendix E.

Table 1: Inclination angles of the IMUs "Seat Head" and "Seat Pan", per each tested configuration (without rider and dummy). 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 Appendix E. RF indicates rearward facing and FF indicates forward-facing.

				Inclination angle [deg]	
Vehicle Type	Model	Dummy	Baby seat (facing direction)	Head	Seat Pan
Stroller	Bugaboo	0 mo	Baby cot (RF)	0	0
	Bugaboo	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
	Maxi-Cosi	9 mo	Baby seat (FF)	40	10
	Old Rusty	9 mo	Baby seat (FF)	48	5
	Stokke	0 mo	Baby cot (RF)	12	12
	Stokke	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

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.

2.4 Experimental Protocol

All tests were conducted in Delft, The Netherlands, on public roads near Delft University of Technology [3]. 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 $\mathrm{km\,h^{-1}}$, 20 $\mathrm{km\,h^{-1}}$, and 25 $\mathrm{km\,h^{-1}}$. The stroller tests were conducted on tarmac, paver bricks, sidewalk pavers, cobblestones, and sidewalk slabs (concrete blocks with gaps in between) road surfaces. Figure 3 shows 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.

2.5 Data Processing

We analysed the raw data with a custom data processing pipeline. The open source MIT licensed 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, Seaborn 0.13.2, and statsmodels 0.14.4. 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 into repetitions to capture 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

[3]Details of all test locations and surfaces are shown in Appendix F.

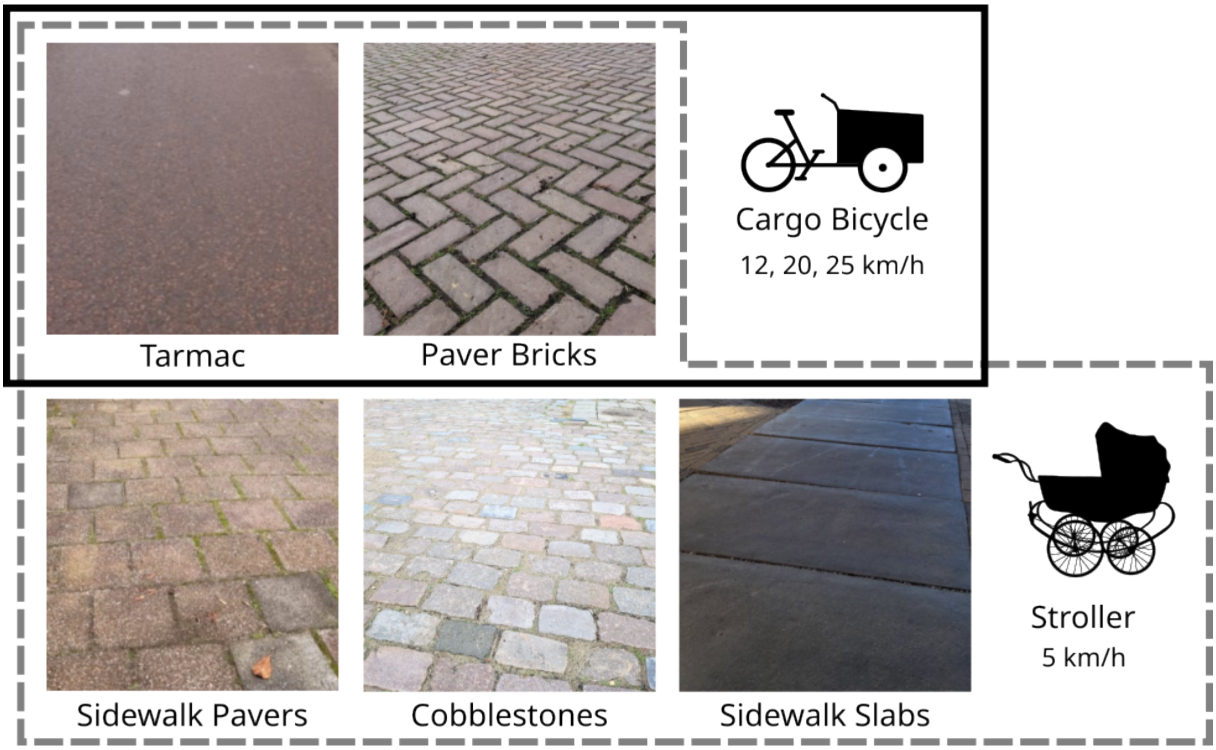

Figure 3: Road surfaces tested: tarmac and paver bricks (cargo bicycles and strollers), sidewalk pavers, cobblestones, sidewalk slabs (strollers).

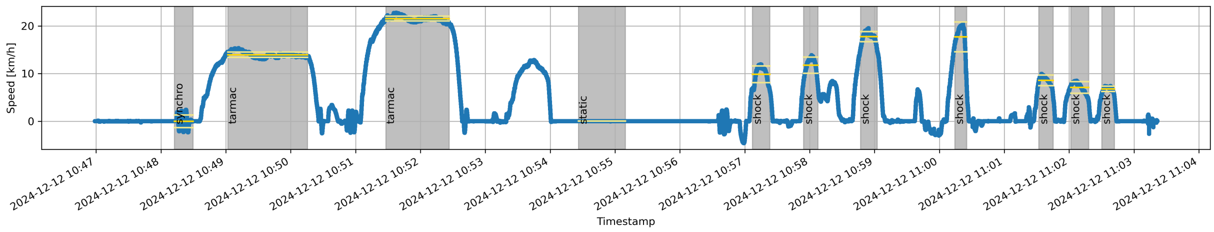

Figure 4: Vehicle speed versus time derived from the wheel hub IMU for an entire session (015) showing the trials in the shaded grey areas. Gold horizontal lines depict the mean speed during trials bounded by its standard deviation.

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 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 linear acceleration of each sensor projected into the vehicle's SAE body-fixed axes [30], 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.

Table 2: Number of repetitions performed on each road surface and speed along with the mean duration and its standard deviation. Tables 3 and 4 provide metrics for repetition sets.

			Repetitions		
Vehicle Type	Road Surface	Target Speed [$km\,h^{-1}$]	Count	Mean Duration [s]	STD Duration [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**		

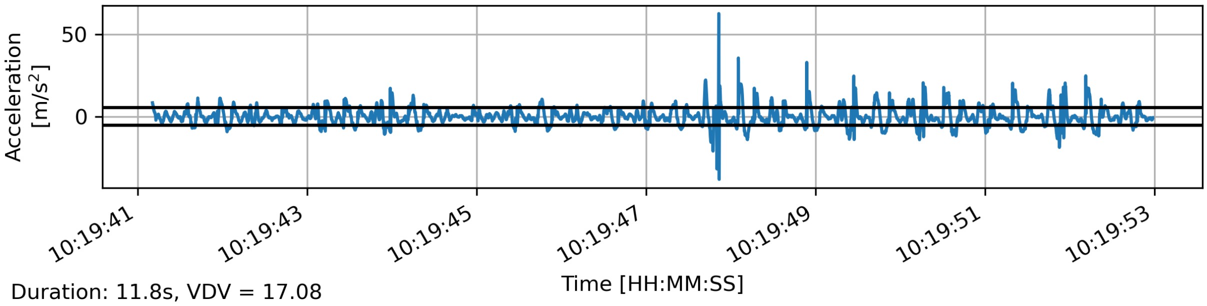

Figure 5: Raw seat pan vertical acceleration versus time from session 001: Maxi-Cosi stroller over the Sidewalk Slabs. Black horizontal lines indicate the ±root mean square (RMS) about the mean. The vibration dose value (VDV) for the first 10 s of the printed duration is shown in the bottom left.

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 only present rarely in nine of the cargo bicycle paver brick repetitions. Following the ISO 2631-1 recommendation, we low-pass filtered the signal at 1.5×80 Hz = 120 Hz using a zero-lag 2^{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 marked as an indicator of bandwidth.

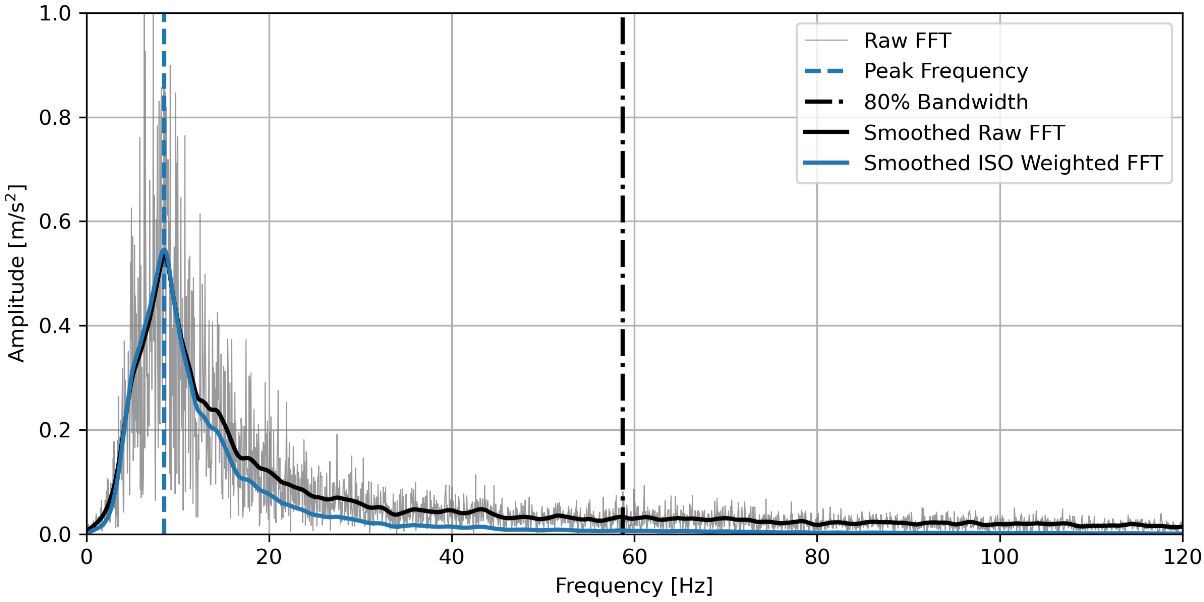

Figure 6: Seat pan vertical acceleration amplitude spectrum from session 004: Maxi-Cosi stroller over cobblestones. The gray curve shows the result of the FFT, the black line is a smoothened version of the FFT (zero-lag Butterworth low pass), and the blue line is the smoothed ISO weighted FFT. The blue 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.

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 $\mathrm{RMS}_{a_{w,xyz}}$ 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 interface for the duration of the trial and can be seen in Figure 5. 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 M raw data vertical acceleration a_z samples corresponding to the first 10 s of the repetition with Equation 3, seen in Figure 5. Lastly, we computed the crest factor CF_{a_z} of the downsampled and low pass filtered vertical acceleration[4] with Equations 4, respectively. All of these per-repetition metrics are reported as mean values over the repetitions corresponding to a scenario in Table 3 and Table 4. The following equations describe the metrics:

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

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

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

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

[4]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.

2.7 Statistical Modelling

To determine how road surface and stroller setup predict ISO 2631-1 weighted vertical RMS acceleration, we fitted an ordinary linear least squares model to the data using:

$$\mathrm{RMS}_{a_{w,z}} = \beta_0 + \beta_1 x_{\text{Road Surface}} + \beta_2 x_{\text{Stroller}} + \epsilon \tag{5}$$

Both $x_{\text{Road Surface}}$ and x_{Stroller} are categorical variables, and we selected tarmac and the Green Machine as reference values when coding the categorical variables, respectively. We did not consider the interaction of road surface and stroller given no expectation of such an effect.

To determine how speed, road surface, and cargo bicycle setup predict ISO 2631-1 weighted vertical RMS acceleration, we fit an ordinary linear least squares model to the data using:

$$\mathrm{RMS}_{a_{w,z}} = \kappa_0 + \kappa_1 x_{\text{Road Surface}} + \kappa_2 x_{\text{Cargo Bicycle}} + \kappa_3 x_{\text{Speed}} + \kappa_4 x_{\text{Road Surface}} \times x_{\text{Speed}} + \epsilon \tag{6}$$

Both $x_{\text{Road Surface}}$ and $x_{\text{Cargo Bicycle}}$ are categorical variables and x_{Speed} is a continuous variable. We selected tarmac and the 'Keiler, Pebble, 0 mo' setup as the reference values when coding the categorical variables, respectively. We did not consider the interaction of road surface and cargo bicycle setup given no expectation of such an effect but we did consider the interaction of speed with road surface. For both strollers and cargo bicycles, each tested combination of vehicle, seat, and dummy size was considered as a different vehicle type. We use $p < 0.05$ to indicate significant differences for both models. Following fitting of the two statistical models, we applied Tukey's Range Test to compare vehicle setups among each other for the different road surfaces and speed ranges with $p = 0.05$ for the adjusted limit for significance.

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 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, which may be due to the lack of 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 $\mathrm{km\,h^{-1}}$ 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 magnitude for discomfort and vertical for health.

3.1 Effect of Speed and model with Cargo Bicycles

Figure 7 compares the two cargo bicycle models which were 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.

3.2 Effect of Stroller Model

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

Table 3: Mean computed metrics of the strollers for all 40 non-shock scenarios, using seat pan acceleration.

Vehicle	Seat, Baby	Road Surface	Target Speed [$km\,h^{-1}$]	. Rep. Count	RMS Acc [$m\,s^{-2}$]	ISO Weighted RMS Acc [$m\,s^{-2}$]	ISO Weighted RMS Mag [$m\,s^{-2}$]	10 s VDV Acc [$m\,s^{-1.75}$]	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
greenmachine	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
maxicosi	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
oldrusty	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

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.

3.3 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.

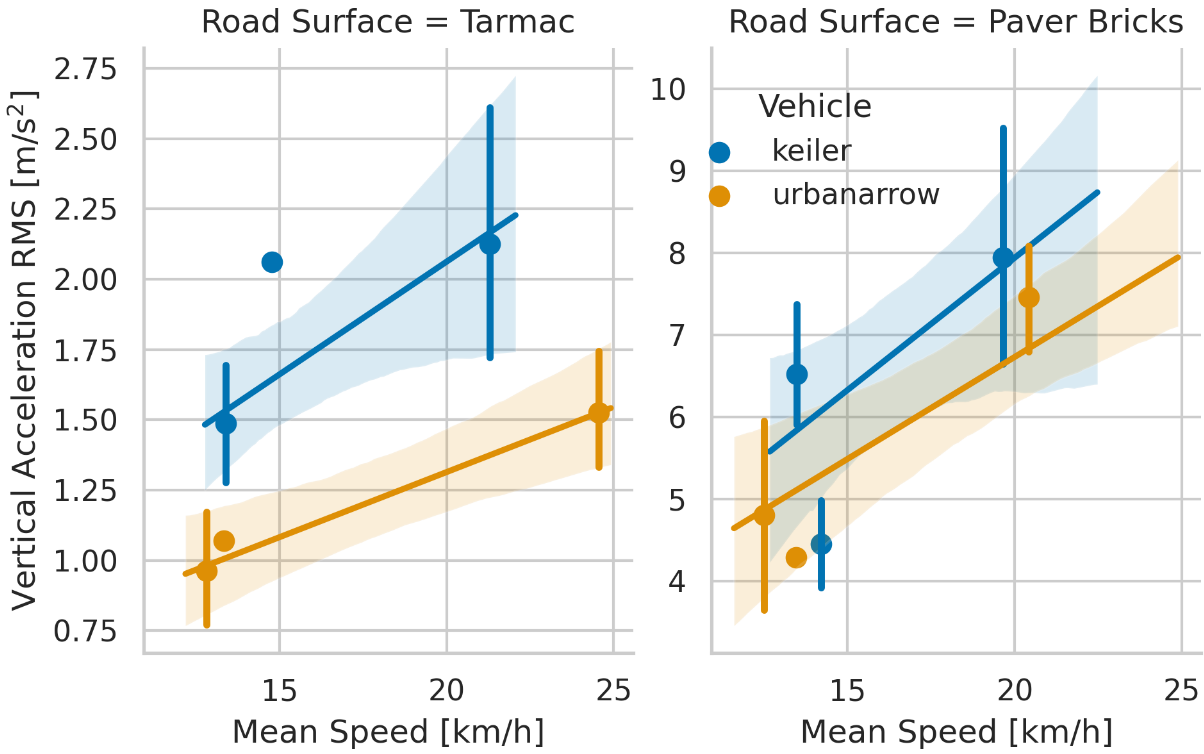

Figure 7: Seat pan ISO 2631-1 weighted vertical RMS acceleration versus speed grouped by road surface and cargo bicycle model. Slanted lines indicate a linear regression, vertical lines are the standard deviation at those speeds, and shaded regions show the 95% confidence intervals for the regression.

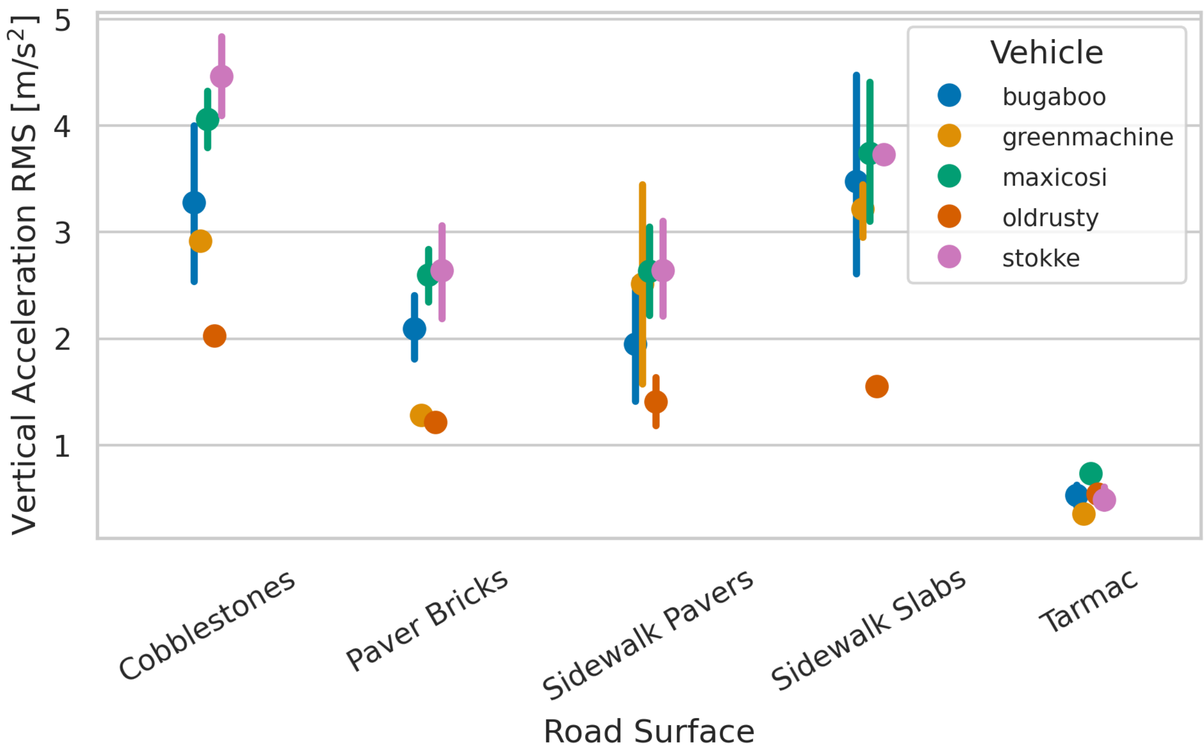

Figure 8: Seat pan ISO 2631-1 weighted vertical RMS acceleration per road surface for each stroller. Vertical lines indicate the standard deviation for categories that have more than one repetition.

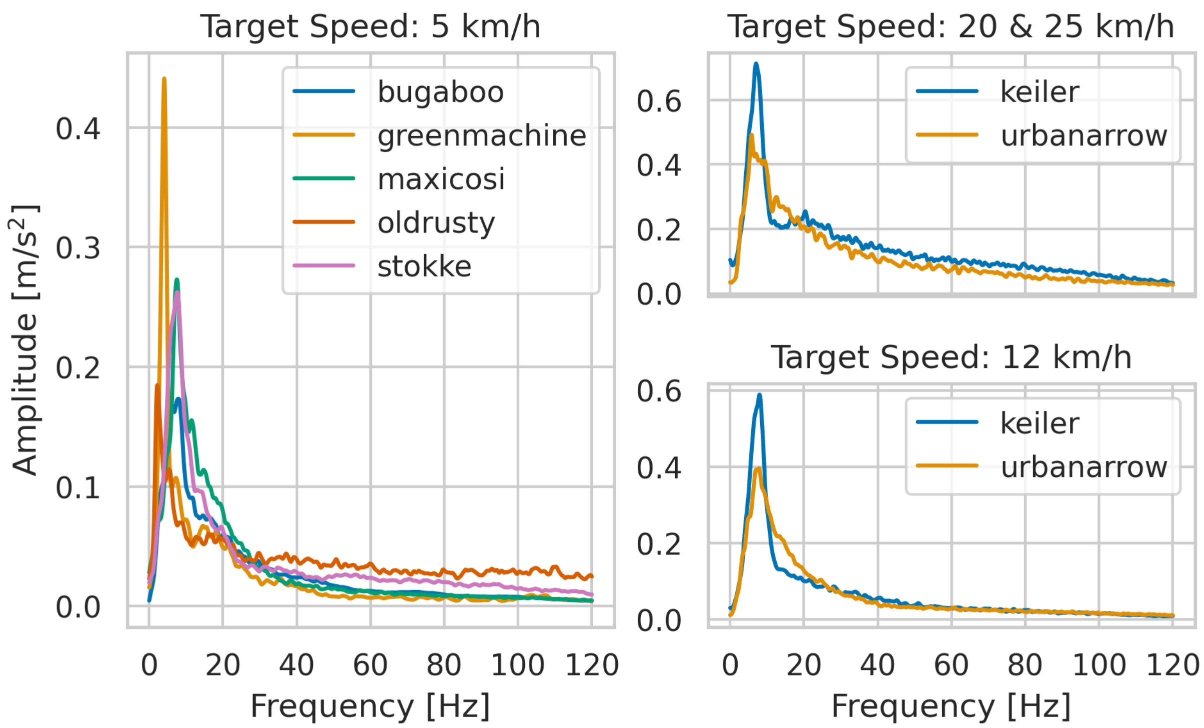

Figure 9: Mean vertical seat pan amplitude spectra of each vehicle for strollers on sidewalk pavers (left) and cargo bicycles on paver bricks (right).

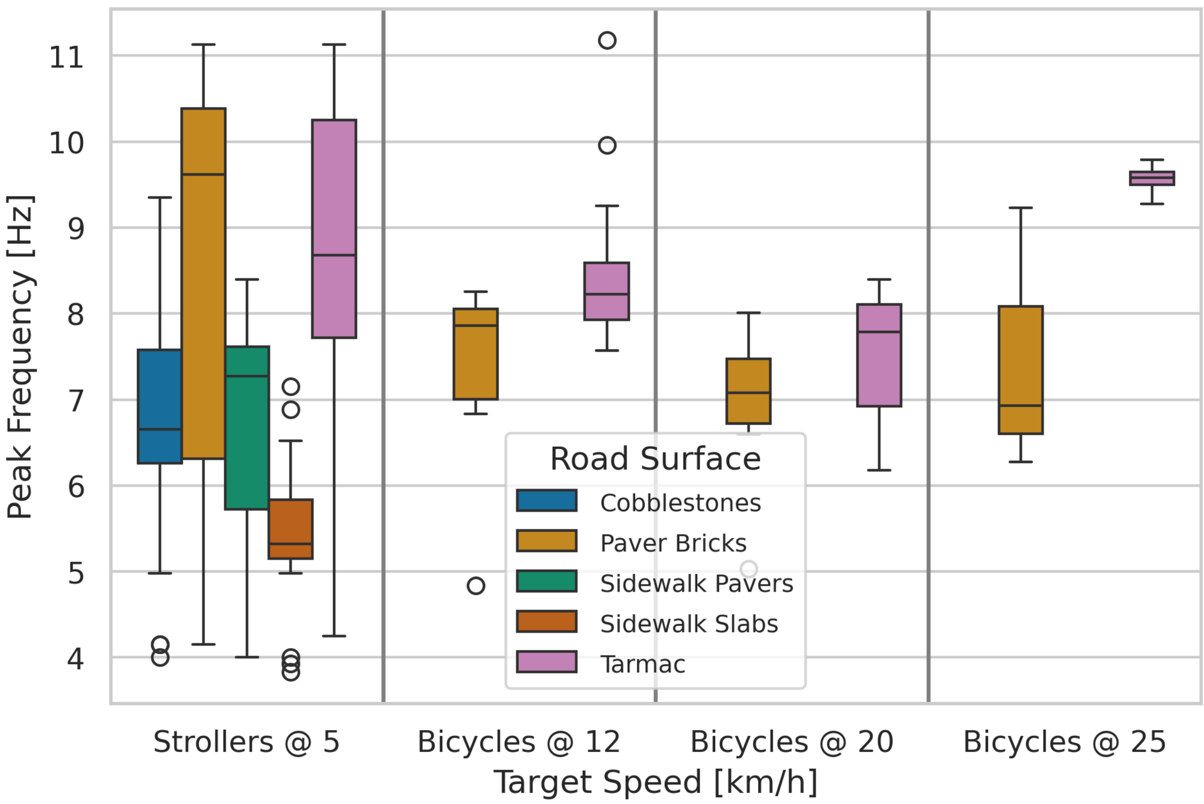

Figure 10: Seat pan vertical peak frequency distributions comparisons among road surfaces for each target speed group for non-shock repetitions. The boxes bound the quartiles and indicate the median. The whiskers indicate the 95$^{\text{th}}$ percentile and circles are outliers.

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

Vehicle	Seat, Baby	Road Surface	Target Speed [$km\,h^{-1}$]	Rep. Count	RMS Acc [$m\,s^{-2}$]	ISO Weighted RMS Acc [$m\,s^{-2}$]	ISO Weighted RMS Mag [$m\,s^{-2}$]	10 s VDV Acc [$m\,s^{-1.75}$]	Crest Factor	Peak Freq [Hz]	Band-width [Hz]	Dur-ation [s]
keiler	melia, 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
urbanarrow	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

3.4 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.

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 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, which is statistically confirmed in Section 3.6.

3.5 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. It must be emphasised that 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 [7]. It is important to recognise that cyclists perched on a bicycle seat seem to tolerate higher vibration amplitudes than the

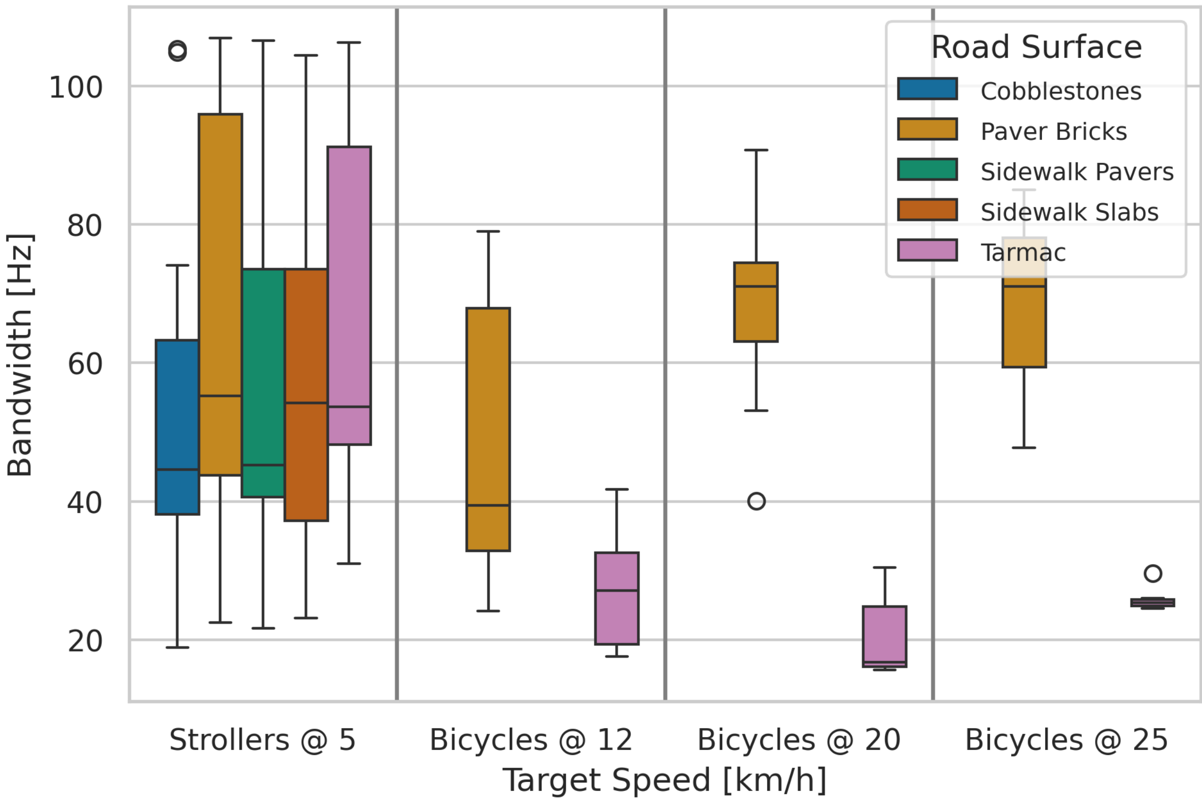

Figure 11: Bandwidth (based on 80% of the area under the unfiltered seat pan vertical amplitude spectrum) for each target speed group for non-shock repetitions. The boxes bound the quartiles and indicate the median. The whiskers indicate the 95$^{\text{th}}$ percentile and circles are outliers.

public transit riders who were surveyed for the ISO ratings. This points to possible weakness in the ISO recommendations or to other factors affecting cycling discomfort (e.g., the 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.

3.6 Statistical Results

For strollers, Table 5 shows the results of the 11 degrees of freedom statistical model for the 104 repetitions ($R^2 = 0.867, F = 54.69$). Both categorical variables have significant effects. The intercept gives the mean acceleration of the Green Machine pushed over tarmac, which is not significant. All road surfaces cause significantly higher acceleration than tarmac, with cobblestones having the largest relative effect (3.0 $\mathrm{m\,s^{-2}}$ larger), followed by sidewalk slabs (2.7 $\mathrm{m\,s^{-2}}$ larger), sidewalk pavers (1.8 $\mathrm{m\,s^{-2}}$ larger), and paver bricks (1.6 $\mathrm{m\,s^{-2}}$ larger). The 'Bugaboo, Seat, 9 mo' and 'Maxi-Cosi, Seat, 9 mo' are not significantly different from the 'Green Machine, Cot, 0 mo' but the other strollers are. The 'Old Rusty, Seat, 9 mo' and 'Bugaboo, Cot, 0 mo' showed significantly lower RMS acceleration than 'Green Machine, Cot, 0 mo' by 0.8 and 0.5 $\mathrm{m\,s^{-2}}$, respectively. The remaining strollers have higher accelerations than the 'Green Machine, Cot, 0 Mo' on tarmac: 'Maxi-Cosi, Cot, 0 mo' (1.1 $\mathrm{m\,s^{-2}}$), 'Bugaboo, Cot, 0 mo' (1.0 $\mathrm{m\,s^{-2}}$), 'Stokke, Seat, 9 mo' (1.0 $\mathrm{m\,s^{-2}}$), and 'Stokke, Seat, 0 mo' (0.6 $\mathrm{m\,s^{-2}}$).

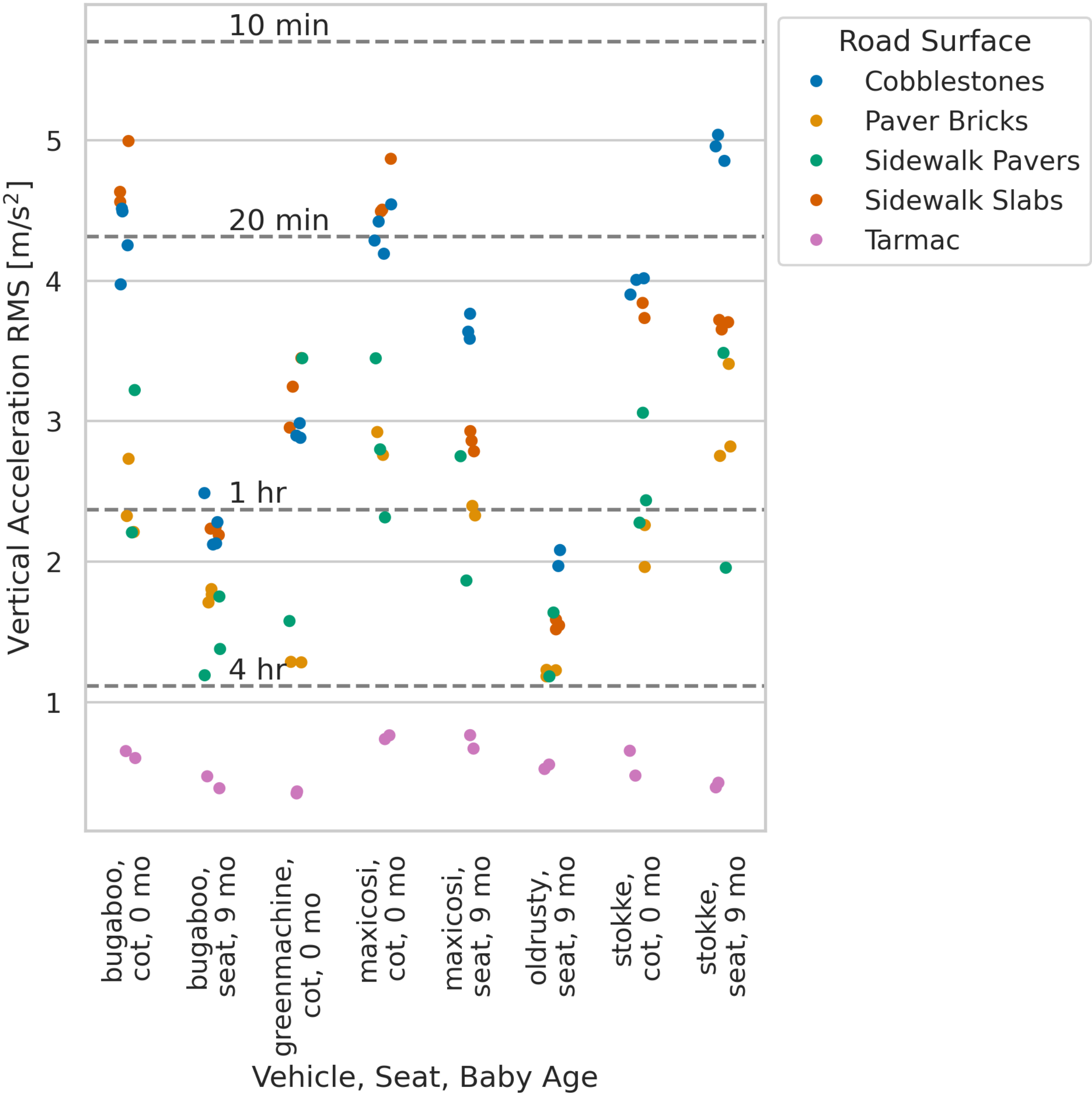

Figure 12: ISO 2631-1 weighted seat pan vertical RMS acceleration of all stroller repetitions with colour representing road surface. The horizontal dashed grey lines with time duration indicators are the upper bounds of the ISO 2631-1 "health caution zones" for long-term exposure of adults seated erectly,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

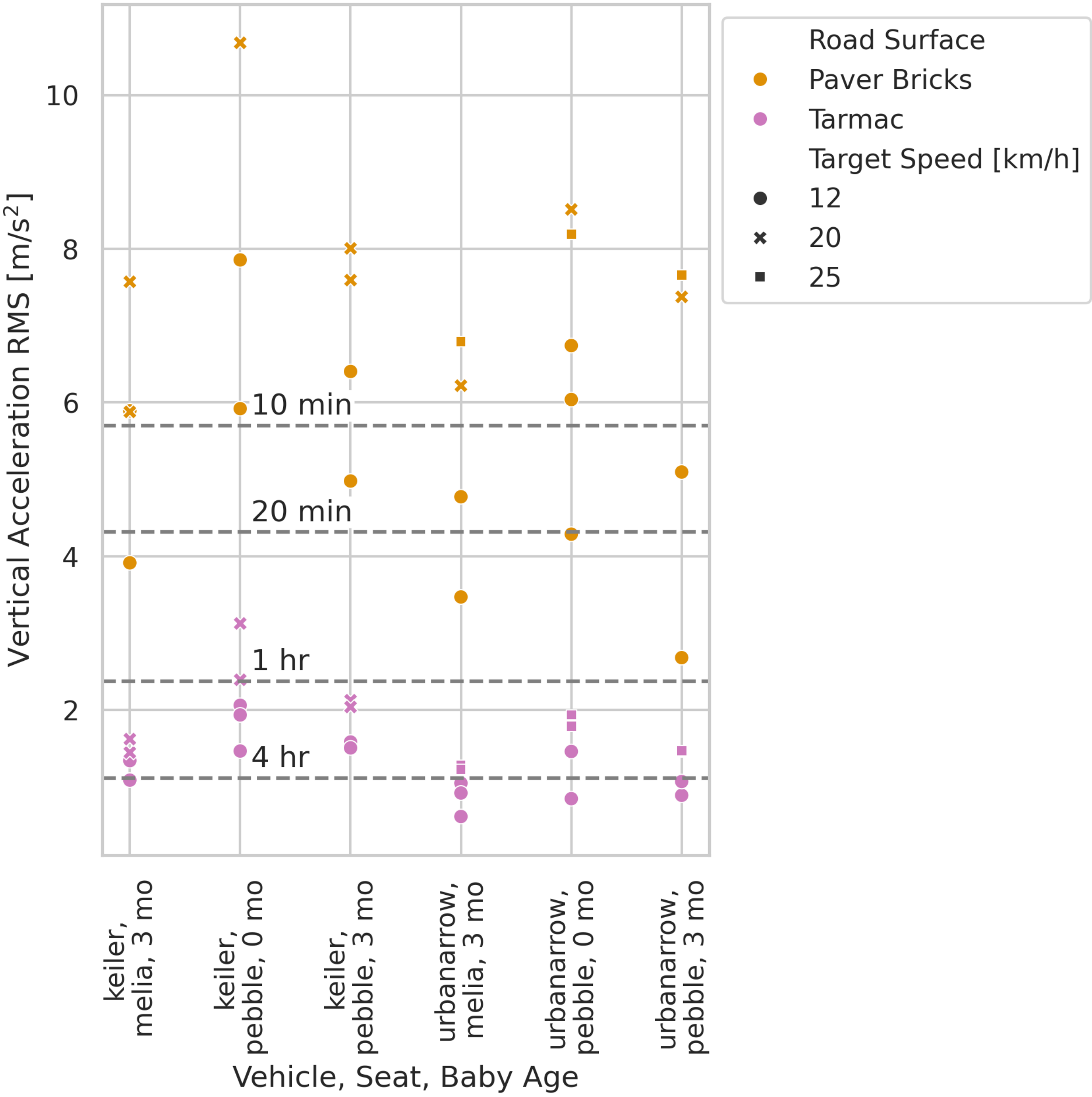

Figure 13: ISO 2631-1 weighted seat pan vertical RMS acceleration of all cargo bicycle trials with colour representing road surface and marker style indicating the target speed. The horizontal dashed grey lines with time duration indicators are the upper bounds of the ISO 2631-1 “health caution zones”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

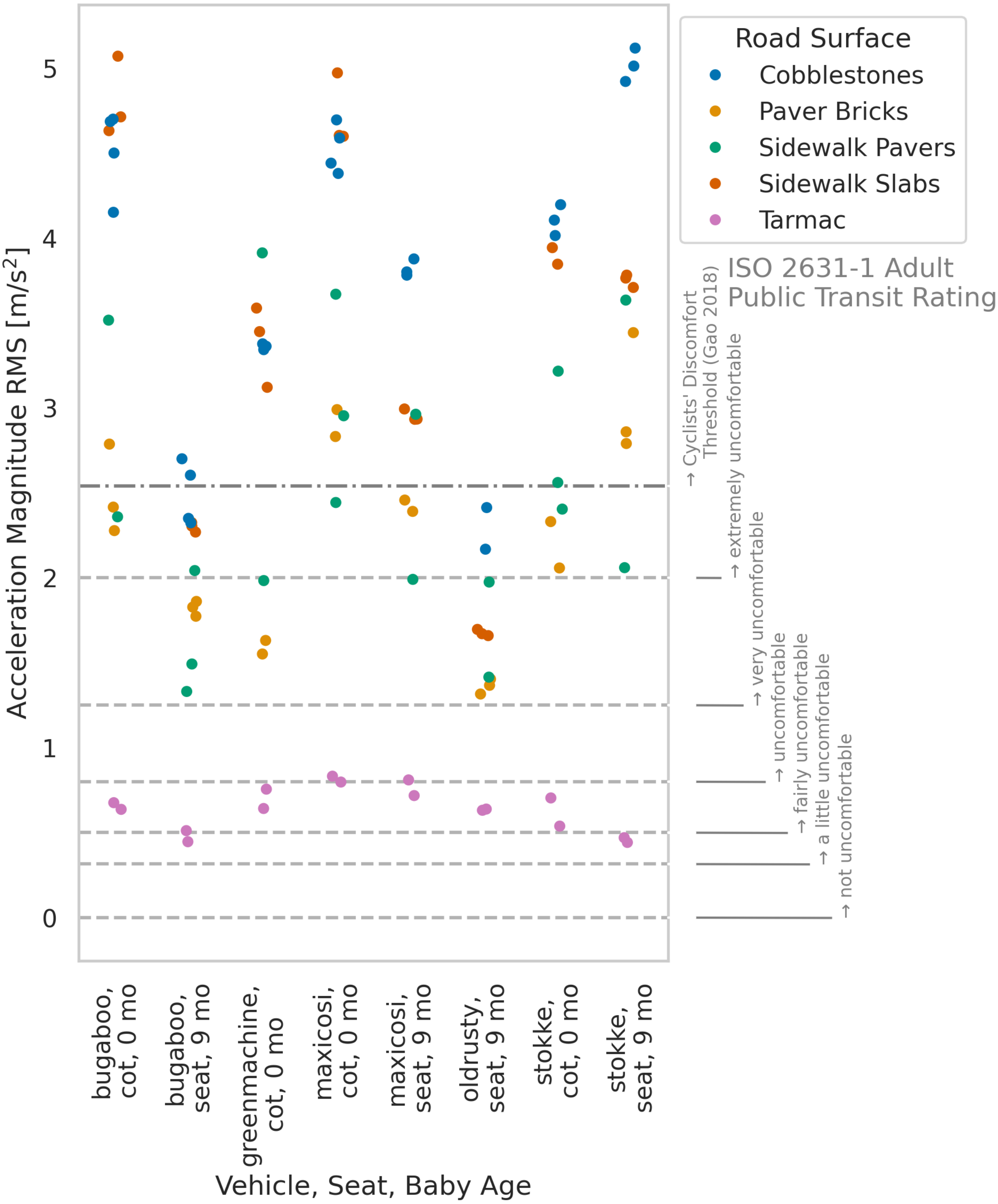

Figure 14: ISO 2631-1 weighted seat pan magnitude RMS acceleration of all stroller repetitions with colour representing the road surface. The horizontal dashed lines are the lower bound of the ISO 2631-1 "comfort zones" for adults seated erectly experiencing vibrations in public transit. The horizontal dashed dotted line is the cyclists' vibration discomfort threshold as reported by Gao et. al [7].

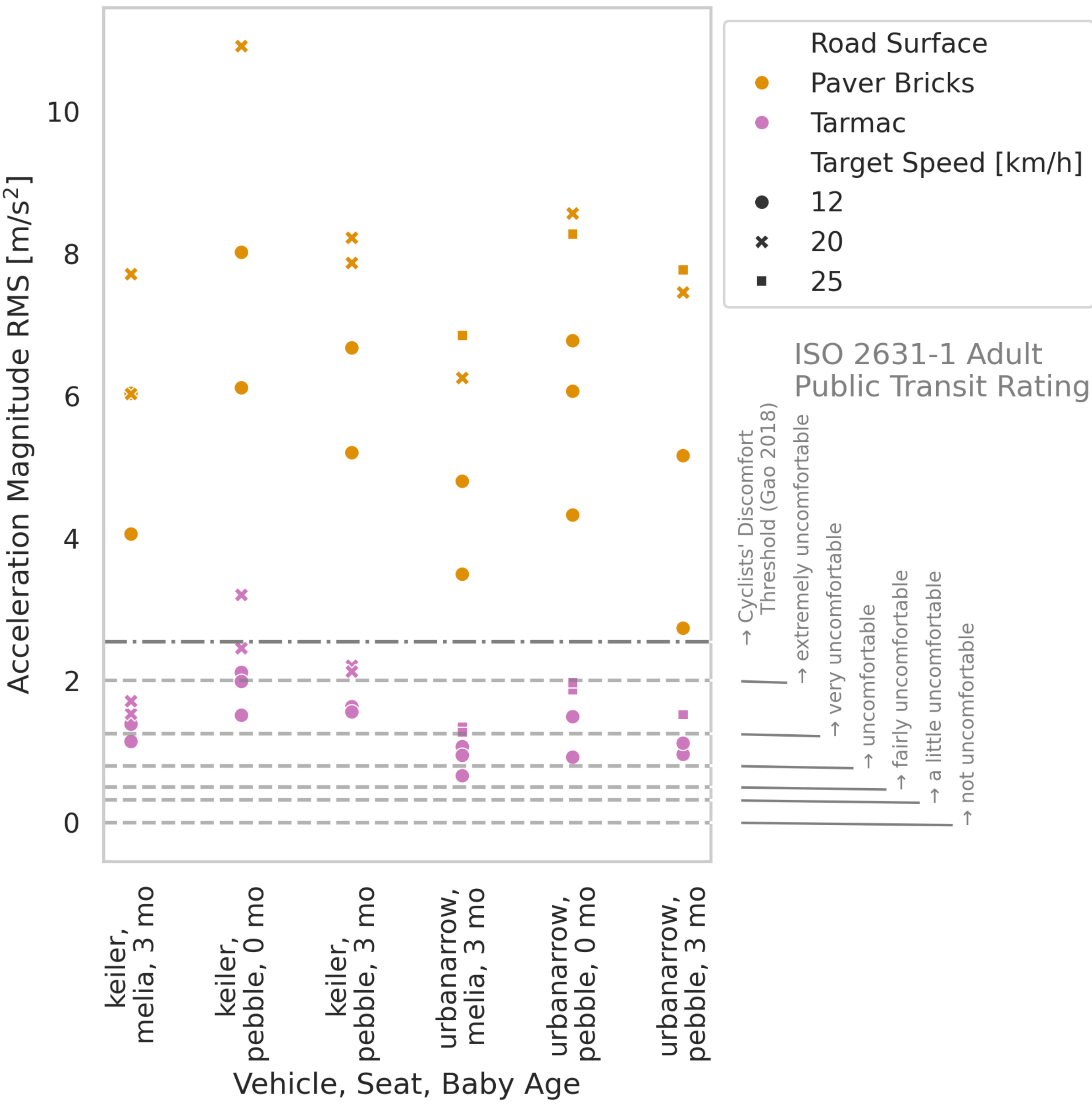

Figure 15: ISO 2631-1 weighted seat pan magnitude RMS acceleration of all cargo bicycle repetitions with colour representing road surface and marker style representing the target speed. The horizontal dashed lines with the upper bound of the ISO 2631-1 "comfort zones" for adults seated erectly experiencing vibrations in public transit. The horizontal dashed-dotted line is the cyclists' vibration discomfort threshold as reported by Gao et. al [7].

Table 5: Ordinary Linear Regression Results for Strollers. Tarmac and Green Machine (with Cot 0 month) are the references for the categorical Road Surface and Stroller variables, respectively. The columns give the effect β, standard error, T-statistic, p-value, and the 95% confidence interval.

	coef	**std err**	**t**	**P> |t|**	**[0.025**	**0.975]**
Intercept	0.2212	0.188	1.177	0.242	-0.152	0.595
Cobblestones	3.0117	0.163	18.473	0.000	2.688	3.336
Paver Bricks	1.6000	0.172	9.299	0.000	1.258	1.942
Sidewalk Pavers	1.7566	0.174	10.092	0.000	1.411	2.102
Sidewalk Slabs	2.7754	0.167	16.637	0.000	2.444	3.107
Bugaboo, cot, 0 mo	0.9706	0.202	4.813	0.000	0.570	1.371
Bugaboo, seat, 9 mo	-0.5065	0.199	-2.551	0.012	-0.901	-0.112
Maxi-Cosi, cot, 0 mo	1.0795	0.202	5.353	0.000	0.679	1.480
Maxi-Cosi, seat, 9 mo	0.3012	0.209	1.441	0.153	-0.114	0.716
Old Rusty, seat, 9 mo	-0.7551	0.209	-3.605	0.001	-1.171	-0.339
Stokke, cot, 0 mo	0.5766	0.209	2.753	0.007	0.161	0.993
Stokke, seat, 9 mo	0.9706	0.205	4.731	0.000	0.563	1.378

Table 6: Ordinary Linear Regression Results for Cargo Bicycles. Tarmac and 'Keiler, Pebble, 3 mo' are the references for the categorical Road Surface and Cargo Bicycle variables, respectively. The columns give the effect κ, standard error, T-statistic, p-value, and the 95% confidence interval.

	coef	**std err**	**t**	**P> |t|**	**[0.025**	**0.975]**
Intercept	0.8067	0.643	1.255	0.216	-0.491	2.104
Paver Bricks	1.2956	0.889	1.457	0.153	-0.500	3.091
Keiler, Pebble, 0 mo	0.8664	0.415	2.085	0.043	0.027	1.705
Keiler, Melia, 3 mo	-0.5060	0.415	-1.219	0.230	-1.344	0.332
Urban Arrow, Pebble, 0 mo	-0.0512	0.404	-0.127	0.900	-0.867	0.764
Urban Arrow, Pebble, 3 mo	-0.8895	0.415	-2.141	0.038	-1.728	-0.051
Urban Arrow, Melia, 3 mo	-1.1357	0.403	-2.819	0.007	-1.949	-0.322
Mean Speed [m/s]	0.2034	0.116	1.747	0.088	-0.032	0.439
Mean Speed×Road Surface	0.7803	0.180	4.338	0.000	0.417	1.144

For cargo bicycles, Table 6 shows the results of the 8 degree of freedom statistical model for the 50 repetitions ($R^2 = 0.925, F = 63.17$). The categorical variable for vehicle setup has significant effects, the categorical variable for road surface alone does not, but the interaction of speed with road surface does have significant effects. The intercept should be zero because there is no vertical vibration when the speed is zero which aligns with the intercept not being significantly different than zero. Speed is not a significant predictor on tarmac, but the interaction variable shows that 0.8 $\mathrm{m\,s^{-2}}$ is gained in acceleration for each 1 $\mathrm{km\,h^{-1}}$ increase on paver bricks. The Urban Arrow with the 3 mo infant in either seat has significant difference to the 'Keiler, Pebble, 3 mo', both showing reduction in relative acceleration. If the 0 mo dummy is used in the Keiler with the Pebble there is significantly higher vibration.

Given that the vehicle setup (x_{Stroller} and $x_{\text{Cargo Bicycle}}$) has a significant effect, we performed a post-hoc analysis to compare vehicles on each road surface. Table 7, derived from Figure 19 in Appendix B, shows the groupings of non-significant comparisons for a Tukey Range Test among the strollers. Old Rusty and 'Bugaboo, Seat, 9 mo' and the Green Machine perform generally better (significantly) than the other vehicles, shown by the "overall" ranking. For cobblestones, this is also true as well as: 1) the 'Stokke, Seat, 9 mo' is the worst stroller tested and, interestingly, the heavier dummy performs worse than the lighter one; 2) the 9-month dummy experiences lower acceleration in the Bugaboo and Maxi-Cosi. For paver bricks: 1) Old Rusty, 'Bugaboo, Seat, 9 mo', and Green Machine are again the best and 2) 'Stokke, Seat, 9 mo' sees higher acceleration than the 0-month configuration. For sidewalk pavers, there was no significant difference among all the strollers. For sidewalk slabs: 1) Old Rusty is the best and Bugaboo the second best; 2) the 0-month in the Bugaboo and Maxi-Cosi see more than the 9-month in the same vehicle, respectively; and 3) no difference in Stokke when comparing dummy sizes. For tarmac: 1) the Green Machine, 'Bugaboo, Seat, 9 mo', and 'Stokke, Seat, 9 mo' are better than Maxi-Cosi with either dummy size; and 2) the Green Machine is better than the 'Bugaboo, Cot, 0 mo'.

Table 7: Stroller Significance Ranking Groups (based on Figure 19). The numbers indicate the group where there is no significant difference with 1 being the best (lower acceleration) and 8 being the worst (higher acceleration). The "Overall" column gives an overall ranking based on the mean ranking of the other columns.

Vehicle Setup	Overall	Cobblestones	Paver Bricks	Sidewalk Pavers	Sidewalk Slabs	Tarmac
Bugaboo, cot, 0 mo	7	5-7	4-8	1-8	7-8	2-8
Bugaboo, seat, 9 mo	2	1-2	1-5	1-8	2	1-6
Green Machine, cot, 0 mo	3	3	1-3	1-8	3-4	1-5
Maxi-Cosi, seat, 0 mo	8	5-7	5-8	1-8	7-8	4-8
Maxi-Cosi, seat, 9 mo	4	4-5	3-8	1-8	3-4	4-8
Old Rusty, seat, 9 mo	1	1-2	1-3	1-8	1	1-8
Stokke, cot, 0 mo	5	4-7	3-6	1-8	5-6	1-8
Stokke, seat, 9 mo	6	8	6-8	1-8	5-6	1-6

Table 8: Cargo Bicycle Significance Ranking Groups (based on Figure 20). The numbers indicate the group where there is no significant difference with 1 being the best (lower acceleration) and 6 being the worst (higher acceleration). The "Overall" column gives an overall ranking based on the mean ranking of the other columns. Note that the mean ranking is very close for all cargo bicycles.

Vehicle Setup	Overall	Paver Bricks Low Speed	Tarmac Low Speed	Paver Bricks High Speed	Tarmac High Speed
Keiler, Melia, 3 mo	2	1-6	1-6	1-5	1-5
Keiler, Pebble, 0 mo	6	1-6	2-6	3-6	5-6
Keiler, Pebble, 3 mo	5	1-6	1-6	1-6	1-6
Urban Arrow, Melia, 3 mo	1	1-6	1-5	1-5	1-5
Urban Arrow, Pebble, 0 mo	4	1-6	1-6	1-6	1-5
Urban Arrow, Pebble, 3 mo	2	1-6	1-6	1-5	1-5

When comparing cargo bicycles (Table 8), most vehicle setups deliver similar acceleration to the seat pan when ridden over the same surface at the same target speed. For low speed on tarmac, the Urban Arrow with Melia and a 3-month dummy has significantly less acceleration than the Keiler with Pebble and 0-month dummy. There is no significant difference in any vehicle setups at low speed on paver bricks. At higher speeds, the Urban Arrow and Keiler with Melia and the 3-month dummy are significantly better than the Keiler with Pebble and the 0-month dummy on paver bricks and on tarmac. It is important to point out that there is no significant difference when simply swapping the seat for the 3-month dummy, which does not support the hypothesis in Section 3.4.

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

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 $0.4\,\mathrm{m\,s^{-2}}$ to $1.2\,\mathrm{m\,s^{-2}}$. For strollers, the roughest surfaces being cobblestones and sidewalk slabs with large gaps caused 5× the acceleration experienced on tarmac, reaching $5.0\ \mathrm{m\,s^{-2}}$. More common surfaces, sidewalk pavers and paver bricks, reach values up to $3\ \mathrm{m\,s^{-2}}$.

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 significant for paver bricks but not for tarmac.

Whereas speed strongly affected the acceleration amplitude, it had lesser 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. These vibrations are transmitted to infant's body, and the physical properties (mass, stiffness, and damping) of the infant's body determine whether this excitation is amplified or not and which body segment is more 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. 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 utilizing the ISO 2631-1 guidance, 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. A stroller can be walked continuously for four hours only on tarmac, and only if the infant is lying in the cot. If the infant is sitting, 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 $m\,s^{-2}$. Tsuijuchi et al. [37] 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". 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. [7] 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 lighter but which made manufacturers drop suspension solutions like these in the vintages products). 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 to have 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 [8]). 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 [18] or even up to 315 Hz [17] 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 0-9 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 [36, 16]. 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 [3]. 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 postmortem dissection after exposure to prolonged whole-body vibration at 30 Hz and 5 $\mathrm{m\,s^{-2}}$ [42]. 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. Further research to establish direct evidence to infant health and comfort would possibly permit less conservative caution than we conclude below.

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 on the findings of this paper that we believe 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. 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. When transporting over tarmac, continuous durations should not exceed 4 hours, and need to include regular breaks, if only to allow the infant to move free from the seat harness.

9. Users should preferably ride any cargo bicycle at a speed of maximal 12 $\mathrm{km\,h^{-1}}$ over surfaces rougher than tarmac. E-cargo bicycles can easily reach the maximum speed of 25 $\mathrm{km\,h^{-1}}$. 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.

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5.4 Declaration of Interest Statement

The authors report there are no competing interests to declare.

5.5 Data Availability Statement

The data will be made publicly available alongside publication.

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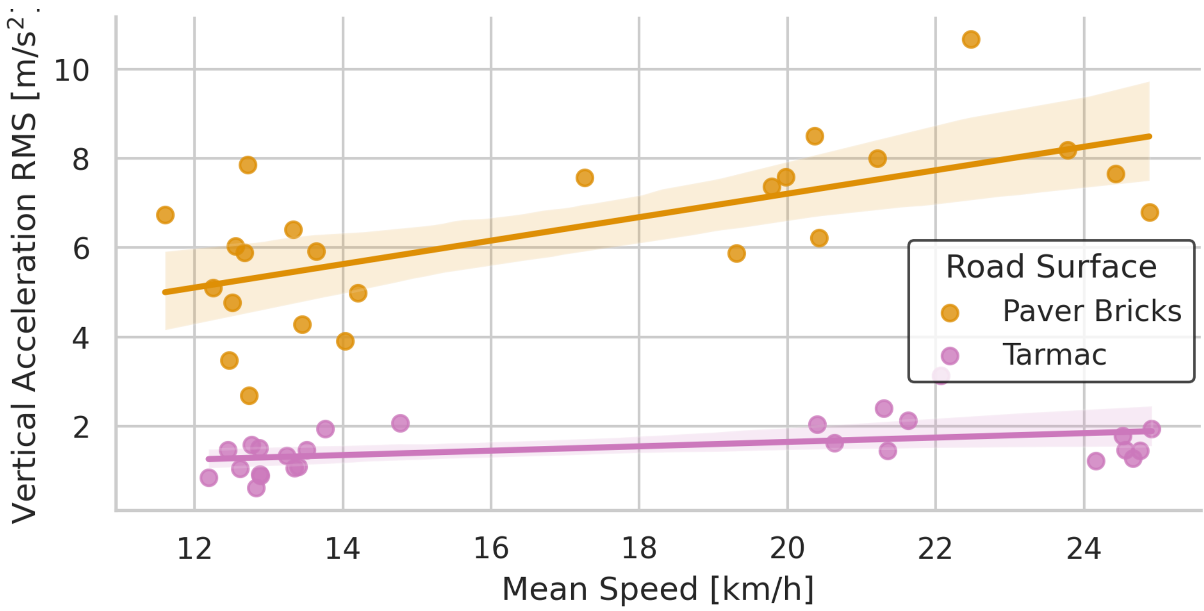


Figure 16: Seat pan ISO 2631-1 weighted vertical acceleration RMS versus speed for all cargo bicycle repetitions. Shaded regions represent the 95% confidence intervals from a simple linear regression that ignores $x_{\text{Cargo Bicycle}}$.

A Additional Exploratory Statistics

A.1 Effect of Speed

Figure 16 shows the variation in ISO 2631-1 weighted vertical RMS acceleration across the tested speeds. On paver bricks, the RMS acceleration increased by approximately 1.6× when increasing the speed from 12 km h^{-1} to 25 km h^{-1}.The effect of speed while cycling on tarmac was less drastic, but still showed a slight increase.

A.2 Effect of Dummy Size

Figure 17 shows the ISO 2631-1 weighted vertical RMS acceleration for each repetition for all vehicles, and compares the dummy sizes. Substantial variation has been shown to relate significantly to the surface and within cargo bicycles, as well as to speed (see tables 7,8). When comparing the vertical RMS acceleration values between cargo bicycles and strollers, there are no obvious differences due to baby size, i.e. each dummy size experienced a similar range of acceleration magnitudes when the vehicle type and the road surface are ignored. For bicycles, the lightest dummy sometimes experienced a higher acceleration than the heavier dummy, but high and low accelerations were observed across the tested speed range.

A.3 Effect of Road Surface

Figure 18 shows ISO 2631-1 weighted vertical RMS acceleration from repetitions grouped into the various road surfaces tested. All vehicles were tested on paver bricks and tarmac, but only strollers were tested on cobblestones, sidewalk pavers, and sidewalk slabs, i.e. light colour dots (strollers are present in each column). It is notable that tarmac almost always induced lower RMS acceleration than other road types regardless of speed and vehicle type. The sidewalk slabs and cobblestones have very similar acceleration ranges for all strollers. Paver bricks and sidewalk pavers appear to have a similar range of RMS acceleration for the same 5 km h^{-1} walking speeds. Paver bricks cause relatively large accelerations at high travel speeds in cargo bicycles. Paver bricks result in approximately 4-5× higher accelerations compared to tarmac.

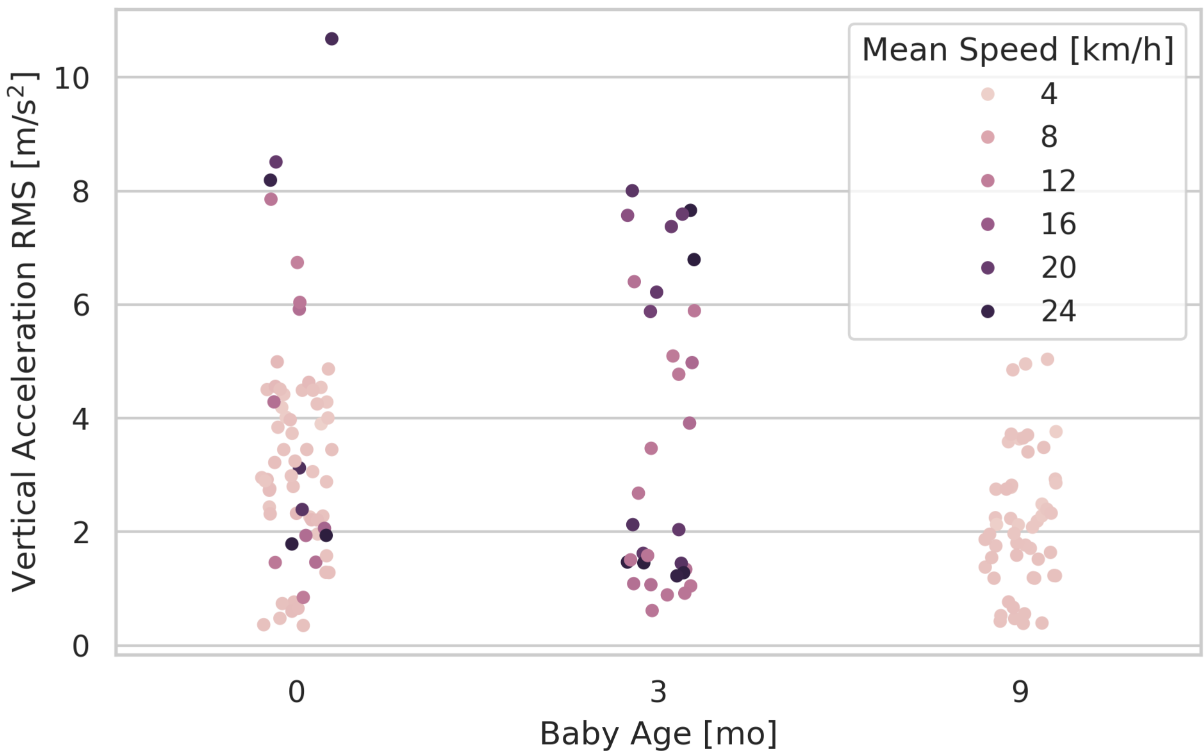


Figure 17: Seat pan ISO 2631-1 weighted vertical RMS acceleration grouped by baby age (and thus size & mass) for all repetitions with colour indicating the mean speed of the trial. The lightest colour dots are strollers (4 km/h) and the remaining are cargo bicycles (8-24 km/h).

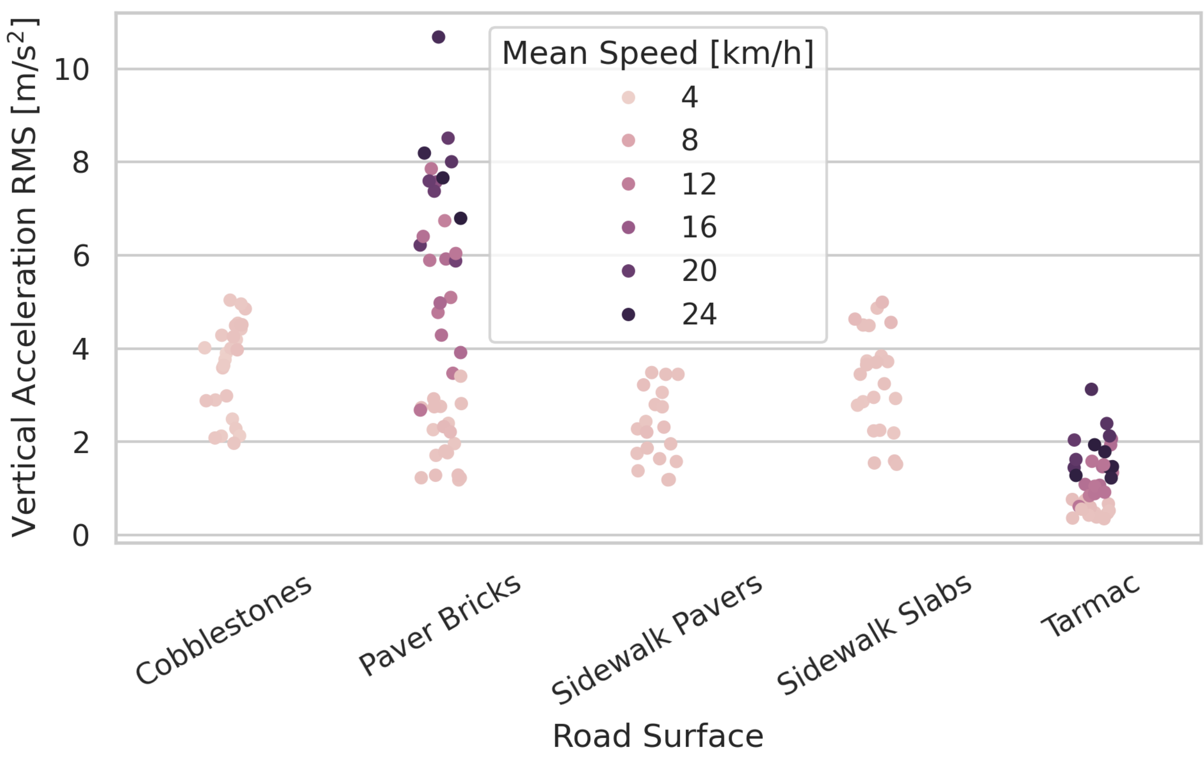
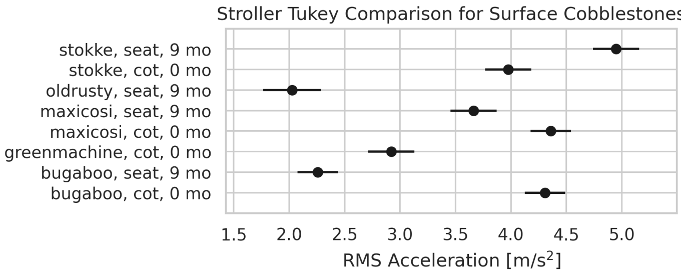


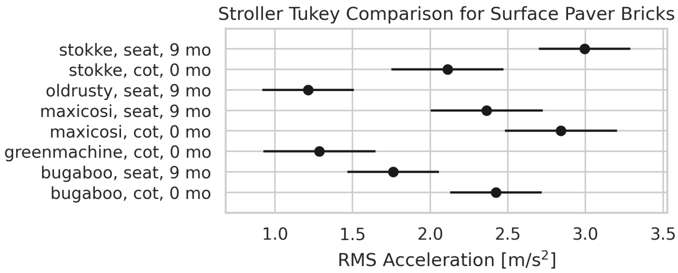
Figure 18: Seat pan ISO 2631-1 weighted vertical RMS acceleration grouped by road surface with colour indicating the mean speed of the repetition. The lightest colour dots are strollers (4 km/h), and the rest are cargo bicycles (8-24 km/h).

B Vehicle Statistical Comparisons

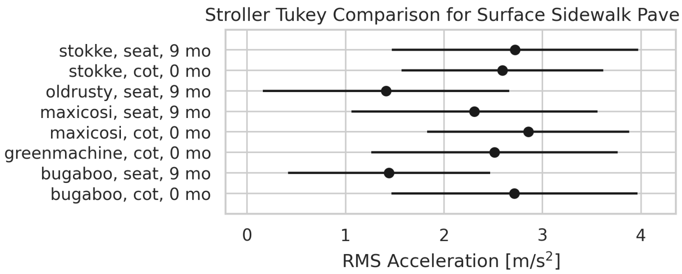
Tukey Range Test multiple comparison plots. Horizontal lines indicate 95% confidence intervals. Non-overlapping confidence intervals indicate a significant difference.



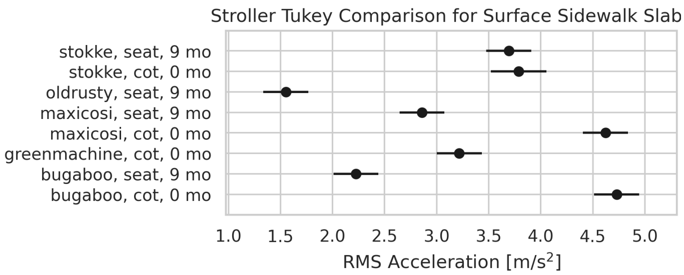
(a)



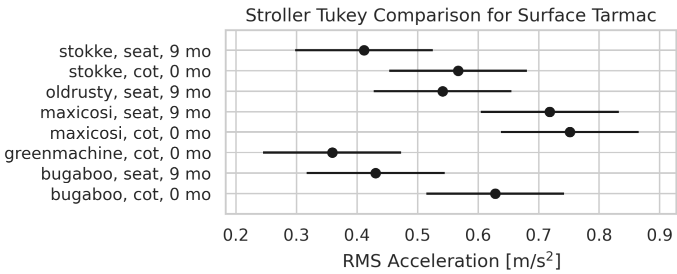
(b)



(c)

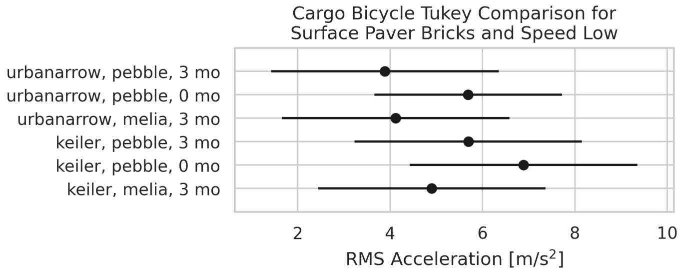


(d)

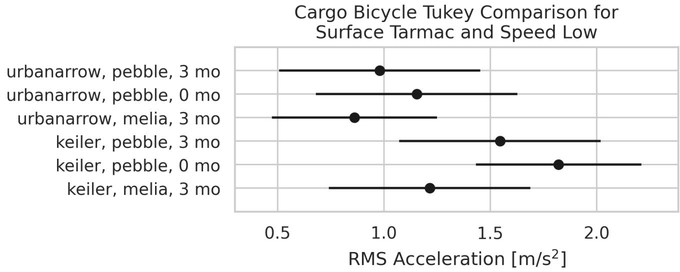


(e)

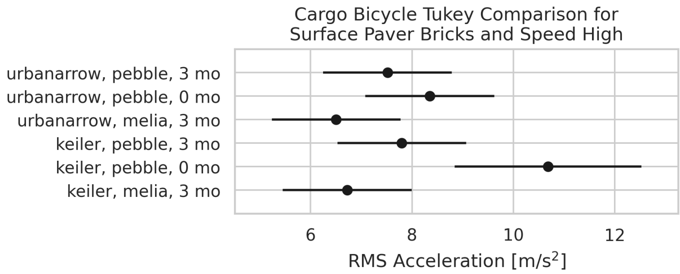
Figure 19: Tukey Comparison Plots for the Strollers



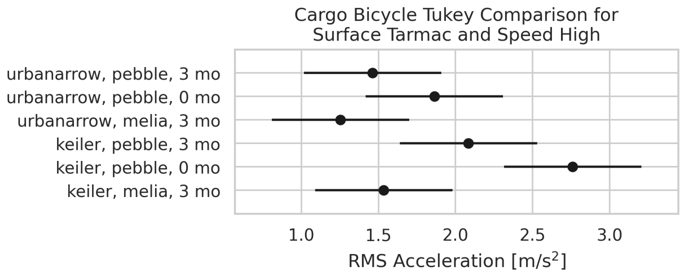
(a)



(b)



(c)



(d)

Figure 20: Tukey Comparison Plots for the Cargo Bicycles

C Shock tests

We identified the maximum peak acceleration values for each trial (Equation 7), then averaged them across repetitions to obtain the results listed in Table 9 for different vehicles and configurations. There is a significant variation between tests, with the peaks for the bicycles sometimes reaching the full scale of the accelerometer (± 16 g). The seat pan accelerations for strollers are generally lower than those experienced with bicycles, but in strollers the configuration (0 or 9 months) may play a large role. Among bicycles, the Melia seems to transmit lower accelerations compared to Pebble, 3 months, for both the Keiler and the Urban Arrow. Strollers with the baby seat configuration for 9 months show much lower acceleration compared to the baby cot for 0 months (Bugaboo and Maxi-Cosi). Surprisingly, the vintage strollers (Old Rusty and Green Machine) performed very well during the shock test, resulting in the lowest seat pan acceleration among all the vehicles tested. Figure 21 shows the peaks of the vertical acceleration recorded at the seat pan, grouped by different vehicles, for the shock test. As noted in Table 9, the vintage strollers Old Rusty and Green Machine show lower acceleration values. We do not clearly distinguish any trend with speed for the bicycles (Keiler and Urban Arrow). During tests involving Keiler and strollers, we

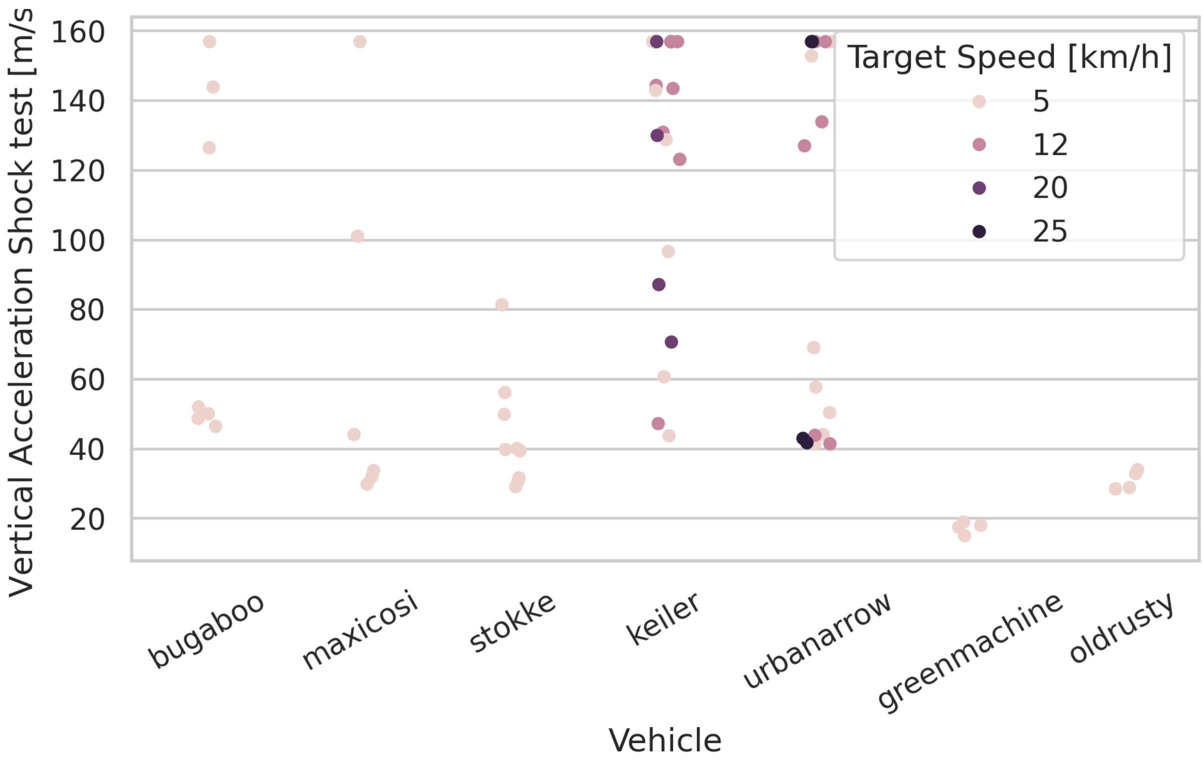


Figure 21: Vertical acceleration recorded at the seat pan during the shock test per each trial, grouped by vehicles. The colour indicates the mean speed of the trial. The lighter the colour the lower the speed.

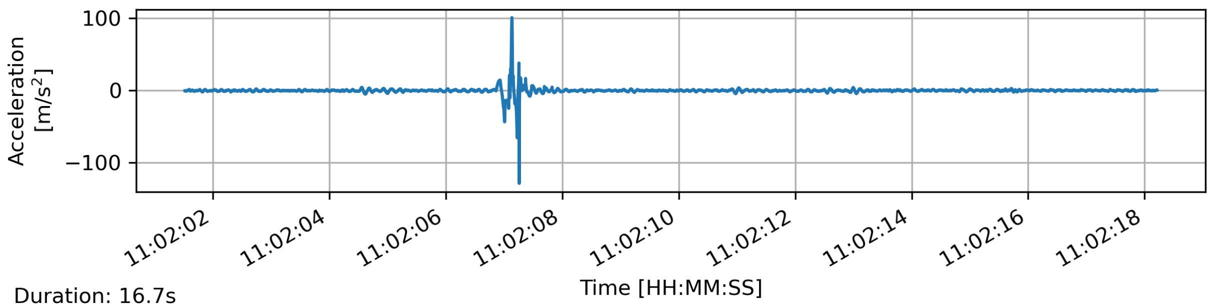


Figure 22: Raw seat pan vertical acceleration versus time from session 015: Keiler tricycle during the shock test.

cannot exclude that the front wheels (left and right) hit the bump at slightly different time instants.

Regarding the shock test, the analysis presented in Appendix C was conducted on unfiltered data (not downsampled). We selected the maximum (absolute) peak from the time history of the vertical acceleration of the seat pan starting from the events' time histories (Figure 22), limiting it to 16 g when the peak exceeded that maximum.

$$\mathrm{MAX}_{a_z} = \max |a_z(t_n)| \tag{7}$$

D Future Work

There are four possible directions for future work: more in-depth analysis of the present measurements, more research on the vibrations transmitted by infant transport systems, more research on the effects of vibration on infants, and development of a benchmark.

Table 9: Mean of the maximum seat pan acceleration across trials in $\mathrm{m\,s^{-2}}$ recorded for shock test, for different vehicles and baby masses.

Vehicle Type	Model	Seat, Baby	Target Speed [km/h]	Trial Count	Max Acceleration [m/s²]
Strollers	Bugaboo	Cot, 0 mo	5	3	146
		Seat, 9 mo	5	4	49
	Green Machine	Cot, 0 mo	5	4	17
	Maxi-Cosi	Cot, 0 mo	5	2	131
		Seat, 9 mo	5	4	35
	Old Rusty	Seat, 9 mo	5	4	31
	Stokke	Cot, 0 mo	5	4	35
		Seat, 9 mo	5	4	51
Bicycles	Keiler	Melia, 3 mo	5	2	52
		Melia, 3 mo	12	2	85
		Melia, 3 mo	20	2	124
		Pebble, 0 mo	5	2	113
		Pebble, 0 mo	12	2	140
		Pebble, 0 mo	20	2	115
		Pebble, 3 mo	5	2	151
		Pebble, 3 mo	12	2	160
		Pebble, 3 mo	20	2	145
	Urban Arrow	Melia, 3 mo	5	2	43
		Melia, 3 mo	12	2	43
		Melia, 3 mo	25	2	42
		Pebble, 0 mo	5	1	50
		Pebble, 0 mo	12	2	63
		Pebble, 0 mo	25	2	130
		Pebble, 3 mo	5	2	156
		Pebble, 3 mo	12	2	160
		Pebble, 3 mo	25	2	160

Concerning further analysis of the present measurements: We acquired data from four other sensors on the vehicles, each with three accelerometer and three gyroscope time histories, for a total of 30 time histories of possible interest. This paper provides a look into the experiments via four metrics: ISO weighted vertical RMS acceleration, maximum acceleration, peak frequency, and bandwidth of the seat pan sensor. The collected data can also be used to investigate the transmissibility from sensor to sensor, as well as rotational vibration effects. Investigating these further can give a more complete picture of the connections to health and comfort. This work also gives a benchmark against which new designs can be tested to show reduction in vibration.

Concerning more research on vibrations generated by infant transport systems: Some products, scenarios, and variables have not yet been investigated for their effect on vibration. For example, running with an infant in a jogging stroller is a subject of interest as vibrations are likely to exceed health limits. Furthermore, recumbent postures in jogging strollers are estimated to increase the vibration load on the head of the infant. It is important to establish the actual vibration load on the head in practice.

Concerning more research on the effects of vibration on infants: The frequency weighting of the ISO 2631-1 standard is not designed or validated to characterise health and comfort for infants or children, for short durations, and for non-erect seating. Research is urgently needed to develop a new standard with a more appropriate frequency weighting to improve assessment of the comfort and health effects of whole-body vibration of infants and children, also for short durations and for non-erect seating. Furthermore, tests with more realistic dummies and/or real infants are necessary to investigate how the infant itself moves when excited by various vibrations in different postures. The results will contribute to the assessment of the transmissibility of vibration in children, which is needed to deduce the vibrations transmitted to the head.

Concerning the development of a benchmark: At this moment, no requirements exist for the vibrational properties of child transport systems in the standards for strollers, cargo bicycles, bicycle seats, bicycle trailers, and car seats. Due to the magnitude of vibrations that can occur during child transport, it is imperative to include requirements for the vibrational properties in the standards for these products. At this moment, it is difficult to develop new requirements because there is not enough information. With the information resulting from more research on infant vibration, a benchmark for the vibration properties of infant transportation products needs to be developed. Tests as performed in this study mark a first milestone. Road surfaces, speeds, dummies, posture, and metrics could be standardised. Over the years, these could be refined building upon scientific research. Acceptance thresholds could be set to accept current products that perform well. This will enable the inclusion of (minimal) requirements for vibration properties in the standards, which would greatly increase the health and comfort of infants who must use these products.

E Experimental Equipment

We considered the use of "crash test dummies" (also known as anthropomorphic test devices or ATDs), which are designed and commonly used to test child seats in car crash tests. However, the closest available body sizes for crash test dummies do not meet the body sizes desired for this investigation. Furthermore, crash test dummies are of a fundamentally different design, based on scaling of adult biomechanical data rather than child data and with dynamic properties designed for crash conditions, not for vibration testing. Therefore, crash test dummies were not used for the envisaged vibration tests. The following lists the dummies used:

Dummy 0 months weight 3.48 kg, size 50 cm. Dollkit 20", "Andi Asleep" (product code AW380008). (Webpage)

Dummy 3 months weight 5.90 kg, size 62.5 cm. Dollkit 25", "Asia - Limited Edition" (product code 300287). (Webpage)

Dummy 9 months weight 8.90 kg, size 70 cm. Dollkit 28", "Hailey" (product code 304137). (Webpage)

The strollers and bicycles used for the experiments are shown below, along with their wheelbase, wheel diameter, sensor location, and orientation for all the tested vehicles.

Strollers A selection of vintage and modern strollers for carrying infants. The modern strollers are configurable as cots for newborns and as seats for older infants.

- **Bugaboo Fox 5** Featuring large wheels and a suspension system that makes it an all-terrain stroller, according to the manufacturer. It has large puncture-resistant tyres and an air-permeable mattress. (Bugaboo website)
- **Green Machine** An unknown brand vintage perambulator with a cot, dating approximately from the 1970s that includes a leather strap suspended cot in a metal frame. The wheels are relatively large compared to modern strollers.
- **Maxi-Cosi Street Plus** This stroller comes with a cot configuration (0-6 months) and an infant seat option. It has large wheels with only a marginal suspension system. (Maxi-Cosi website)
- **Old Rusty** An unknown brand vintage seat-style stroller dating approximately from the 1970s that includes a metal spring suspension system and wheels that are slightly larger than those on modern strollers.
- **Stokke BABYZEN YOYO 0+** Among the smallest foldable strollers on the market. It has only a marginal suspension system and smaller wheels compared to other strollers available on the market. (Model rented for the experiment)

Cargo Bicycles Two modern Dutch "bakfietsen" in which different baby seats can be mounted.

- **Keiler Tricycle** A tadpole (two wheels in the front, one in the rear) cargo tricycle without electric assist. This vehicle will not roll into curves. However, differing road surface unevenness at the left and right front wheels will induce lateral roll and lateral acceleration in infants. We added masses in specific locations to simulate the presence of an electric motor and battery package, in order to compare the results with those of the Urban Arrow. The tricycle was equipped with tyres CST XPEDIUM Safe 47-559 (Cheng Shin Tire, Yuanlin, Taiwan) on the rear, and Schwalbe Green Comfort Road Cruiser K-Guard 3 47-507 (Ralf Bohle GmbH, Reichshof-Wehnrath, Germany) on the front. We set both tyres to an inflation pressure of 300 kPa. (Product Webpage)

(a) IMU on the front fork (b) IMU under the cargo bay

Figure 23: IMU locations on the Urban Arrow. The white 3D printed sensor supports are visible in (a) and (c). The last figure (d) shows how the sensors were taped to the seat pan and backrest.

Urban Arrow Cargo Bicycle An electric cargo bicycle that is popular in the Netherlands. This vehicle has two inline wheels, which makes it roll into curves like a regular bicycle. It is featured by a long frame that can carry loads (e.g., a child in a car seat or a baby shell) placed in between the rider and the front wheel. We used the "Family Performance Plus" model, with an electric drivetrain from Bosch Performance Line (65 Nm, 250 W). It was equipped with tyres Schwalbe Big Ben Plus 55-559 on the rear, and Schwalbe Big Ben Plus 55-406 on the front (Ralf Bohle GmbH, Reichshof-Wehnrath, Germany). We set both tyres to an inflation pressure of 300 kPa, according to the range recommended by the manufacturer. (Urban Arrow website)

Baby Seats These two baby seats were mounted in the cargo bays of the two cargo bicycles.

Melia Baby Shell Baby seat specifically designed for cargo bicycles meant for babies from 2 to 9 months old. Mounted to the seat platform in both cargo bicycles. (Melia Webpage)

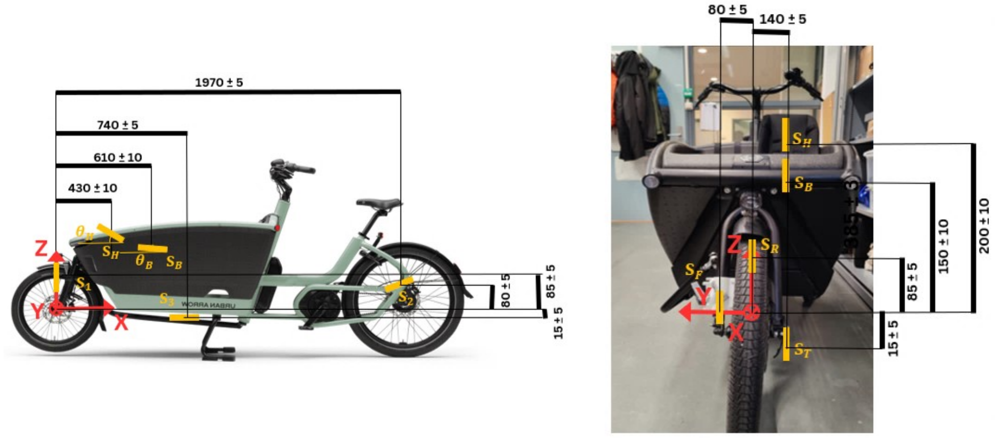
Maxi-Cosi X Joolz Pebble Pro i-Size Car Seat Can be adapted to be mounted on cargo bicycles with a fitting fixing system (e.g. "Urban Arrow Baby Car Seat Adapter"). Comes with an integrated suspension system. The same adapter was used in both cargo bicycles. (Maxi-Cosi Webpage)

Additional sensor locations are as follows.

1. **Front Wheel** This IMU was mounted on the front wheel fork (the caster wheel for the stroller). This was the non-rotating measurement point closest to the ground. The purpose of this sensor was to measure the road roughness filtered out only by the tyres.

2. **Frame** On the cargo bicycle, an IMU was placed below the frontal cargo bay and clamped to the frame. This was to provide an understanding of the damping characteristics of the bicycle frame, together with an estimation of the effect of the suspension system. On the stroller, the IMU was taped under the baby seat.

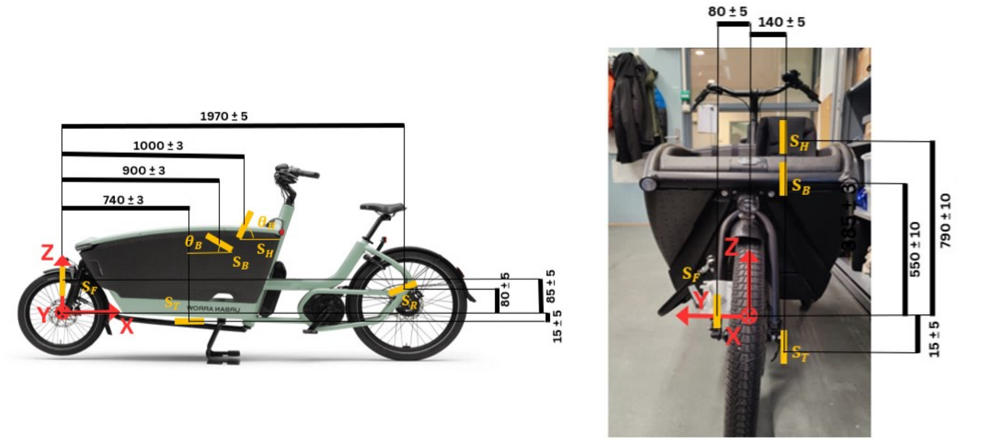
3. **Seat Head** IMU taped into the baby seat (on the soft mattress), directly in contact with the dummy's head. This IMU measured the vibration transmitted to the head contact point.



s_F	Front Wheel
s_R	Rear Wheel
s_T	Bottom Trike
s_B	Seat Bottom
s_H	Seat Head
θ_B	2 deg
θ_H	41 deg
Front wheel diameter	520 ± 5 mm
Back wheel diameter	670 ± 5 mm
Weight	58 kg

(a) Lateral view (b) Front view

Figure 24: IMU locations on the Urban Arrow, equipped with Pebble.



s_F	Front Wheel
s_R	Rear Wheel
s_T	Bottom Frame
s_B	Seat Bottom
s_H	Seat Head
θ_B	2 deg
θ_H	64 deg
Front wheel diameter	520 ± 5 mm
Back wheel diameter	670 ± 5 mm
Weight	54 kg

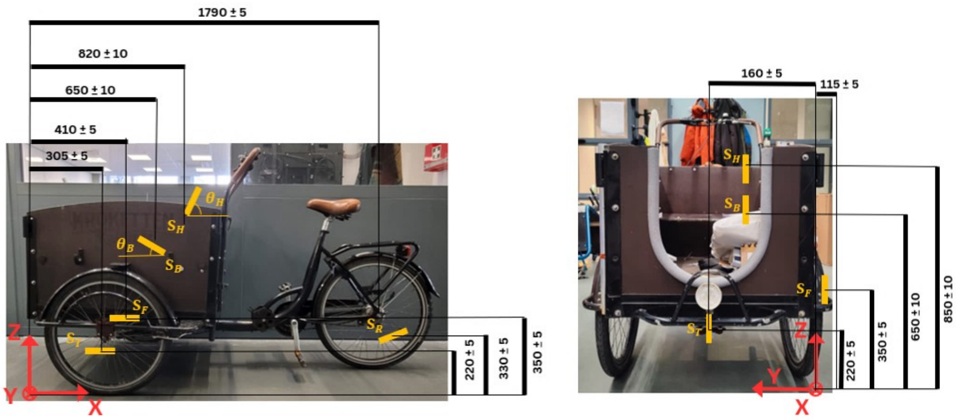
(a) Lateral view (b) Front view

Figure 25: IMU locations on the Urban Arrow, equipped with Melia.

S_F	Front Wheel
S_R	Rear Wheel
S_T	Bottom Trike
S_B	Seat Bottom
S_H	Seat Head
θ_B	2 deg
θ_H	41 deg
Front wheel diameter	500 ± 5 mm
Back wheel diameter	650 ± 5 mm
Weight	81 kg

(a) Lateral view (b) Front view

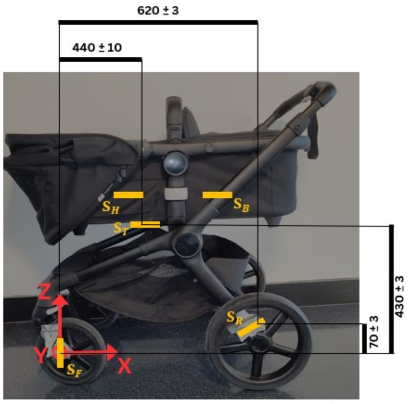
Figure 26: IMU locations on the Keiler, equipped with Pebble.



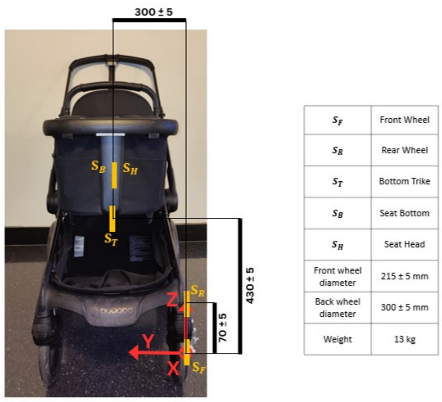
S_F	Front Wheel
S_R	Rear Wheel
S_T	Bottom Trike
S_B	Seat Bottom
S_H	Seat Head
θ_B	2 deg
θ_H	64 deg
Front wheel diameter	500 ± 5 mm
Back wheel diameter	650 ± 5 mm
Weight	77 kg

(a) Lateral view (b) Front view

Figure 27: IMU locations on the Keiler, equipped with Melia.

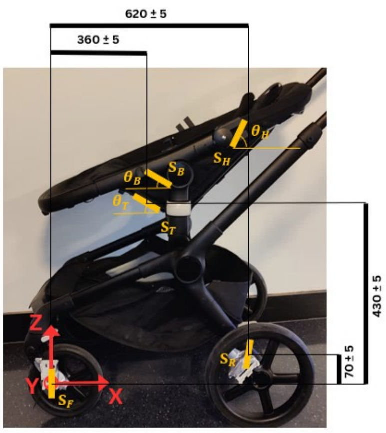


(a) Lateral view

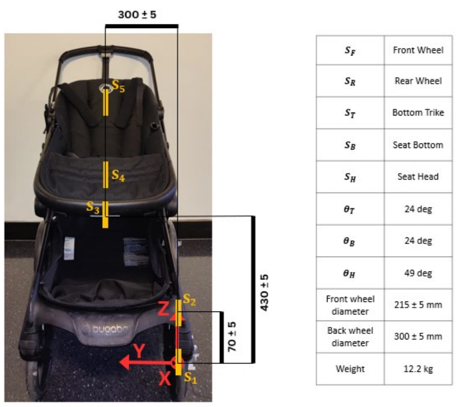


(b) Front view

Figure 28: IMU locations on the Bugaboo, configured for a 0-month-old baby.

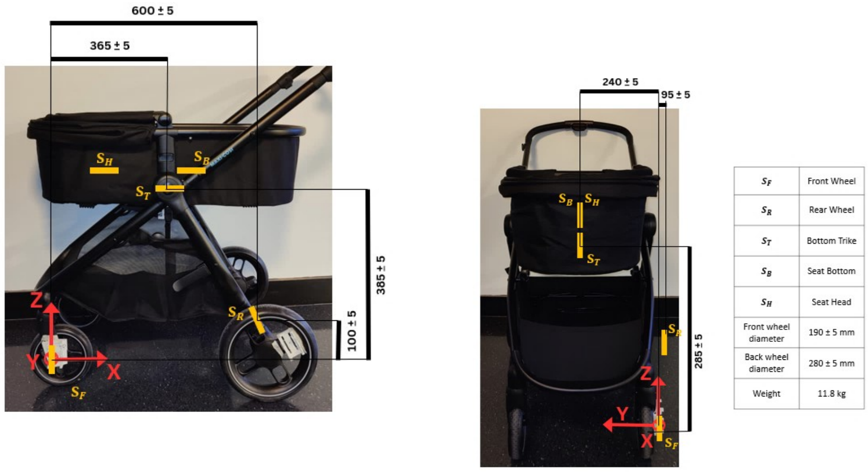


(a) Lateral view



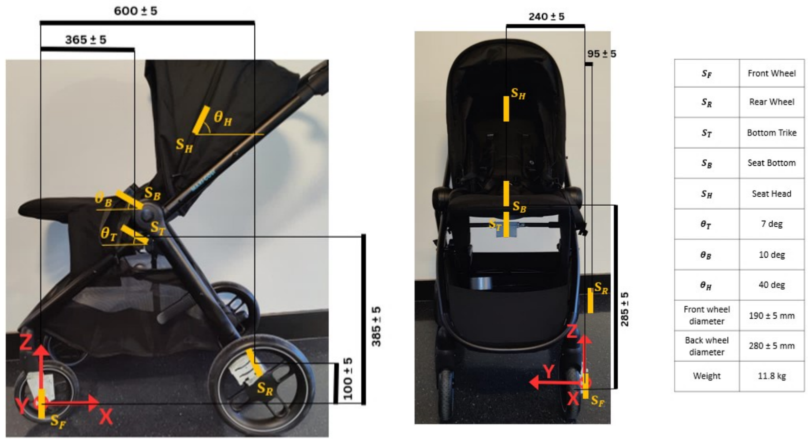
(b) Front view

Figure 29: IMU locations on the Bugaboo, configured for a 9-month-old baby.



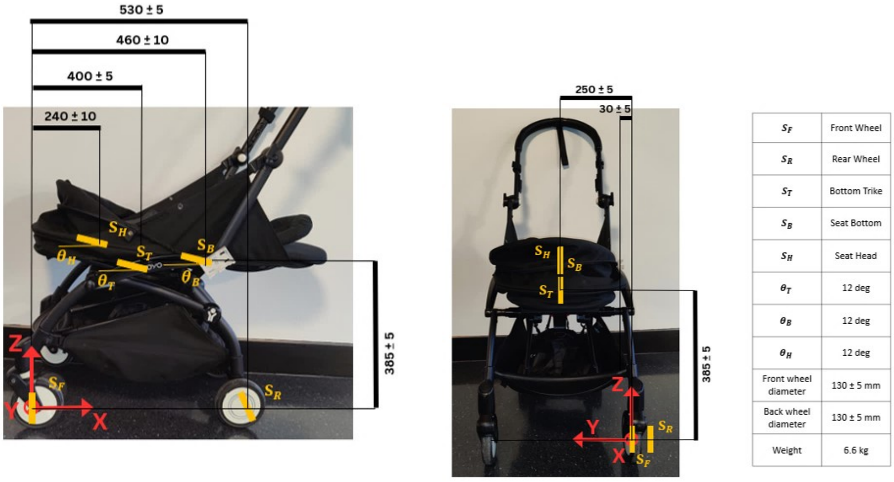
(a) Lateral view (b) Front view

Figure 30: IMU locations on the Maxi-Cosi, configured for a 0-month-old baby.



(a) Lateral view (b) Front view

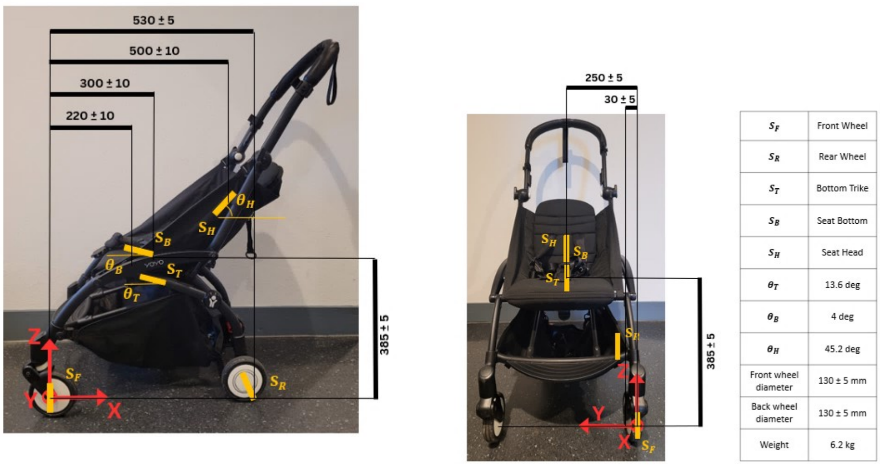
Figure 31: IMU locations on the Maxi-Cosi, configured for a 9-month-old baby.



S_F	Front Wheel
S_R	Rear Wheel
S_T	Bottom Trike
S_B	Seat Bottom
S_H	Seat Head
θ_T	12 deg
θ_B	12 deg
θ_H	12 deg
Front wheel diameter	130 ± 5 mm
Back wheel diameter	130 ± 5 mm
Weight	6.6 kg

(a) Lateral view (b) Front view

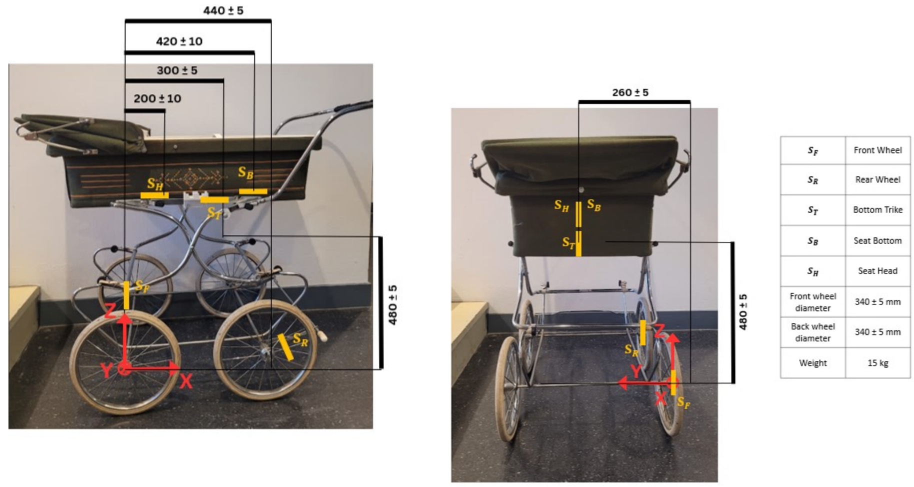
Figure 32: IMU locations on the Stokke, configured for a 0-month-old baby.



S_F	Front Wheel
S_R	Rear Wheel
S_T	Bottom Trike
S_B	Seat Bottom
S_H	Seat Head
θ_T	13.6 deg
θ_B	4 deg
θ_H	45.2 deg
Front wheel diameter	130 ± 5 mm
Back wheel diameter	130 ± 5 mm
Weight	6.2 kg

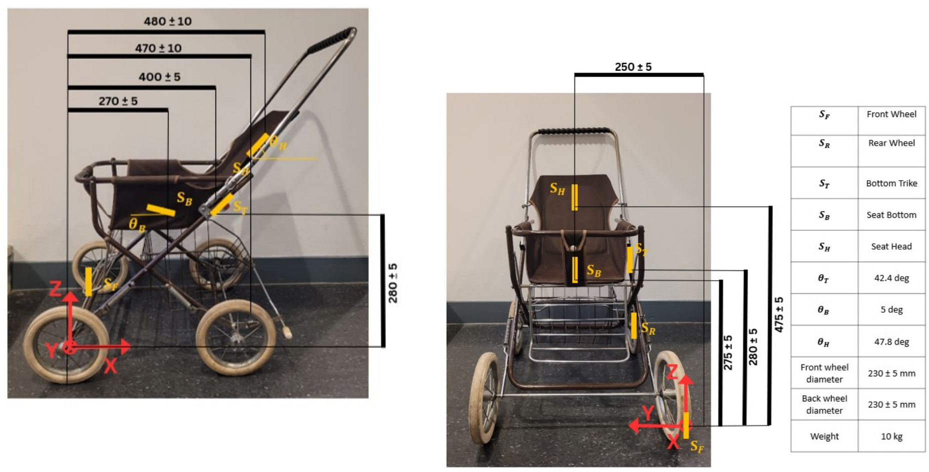
(a) Lateral view (b) Front view

Figure 33: IMU locations on the Stokke, configured for a 9-month-old baby.



(a) Lateral view (b) Front view

Figure 34: IMU locations on the Green Machine, configured for a 0-month-old baby.



(a) Lateral view (b) Front view

Figure 35: IMU locations on the Old Rusty, configured for a 9-month-old baby.

F Location and pictures of the experiment areas

- **Strollers** were tested with dummies of 0 months and 9 months at 5 $\mathrm{km\,h^{-1}}$ at:
  - Tarmac
  - Paver bricks
  - Sidewalk pavers
  - Cobblestones
  - Sidewalk slabs (concrete blocks with gaps in between)
  - Shock bump: A 30x30 mm square section aluminium bar
- **Cargo bicycles** were tested with dummies of 0 months and 3 months. Tests were performed at 12 $\mathrm{km\,h^{-1}}$ for both vehicles. The Urban Arrow was also tested at 25 $\mathrm{km\,h^{-1}}$ whereas the Keiler was tested at 20 $\mathrm{km\,h^{-1}}$ for safety reasons (due to wobbling). The test surfaces are:
  - Tarmac
  - Paver bricks
  - Shock bump: A 30 mm x 30 mm square section aluminium bar (also tested at 5 $\mathrm{km\,h^{-1}}$)
- **Baby seats** Both the Pebble and the Melia was tested on each cargo bicycle using the same mounting systems.

F.1 For Bicycles

- Tarmac

Figure 36: Tarmac surface where we tested bicycles.

The bicycle experiment on the tarmac was conducted along Leeghwaterstraat, 2628 CA Delft, The Netherlands (GPS coordinates: 52.001053, 4.369071).

- Paver bricks

  The bicycle experiment on the paver bricks was conducted along Hertog Govertkade and Kanaalweg, 2611 DD Delft, The Netherlands (GPS coordinates: 52.006264, 4.363013).
  Details of paver brick: rectangular shape, dimensions 195x95 mm (gap in between: 7±2 mm).

Figure 37: Paver bricks surface where we tested bicycles.

- Shock

Figure 38: We performed a shock test with bicycles riding over a 30x30 mm square section bar.

The bicycle shock experiment was conducted along Leeghwaterstraat, 2628 CA Delft, The Netherlands (same location of the experiment on the tarmac, GPS coordinates: 52.001053, 4.369071). Details of the shock experiment: we rode over a square-sectioned aluminium bar 30x30 mm.

F.2 For Strollers

- Tarmac

Figure 39: Tarmac test area.

The bicycle experiment on the tarmac was conducted along Julianalaan, 2628 BG Delft, The Netherlands (GPS coordinates: 52.002727, 4.366845).

- Cobblestone

Figure 40: Cobblestone surface where we tested strollers.

The bicycle experiment on the cobblestone was conducted along Julianalaan, 2628 BG Delft, The Netherlands (GPS coordinates: 52.002727, 4.366845). Details of cobblestone: rectangular shape, dimensions 180x125 mm (gap in between: 20±4 mm).

- Sidewalk pavers

Figure 41: Sidewalk pavers test area for strollers.

The experiment was conducted along Prins Bernhardlaan, 2628 CN Delft, The Netherlands (same location as Paver bricks test, GPS coordinates: 52.003147, 4.369530).
Details of sidewalk bricks: rectangular shape, dimensions 290x290 mm (gap in between: 12±2 mm).

- Sidewalk slabs

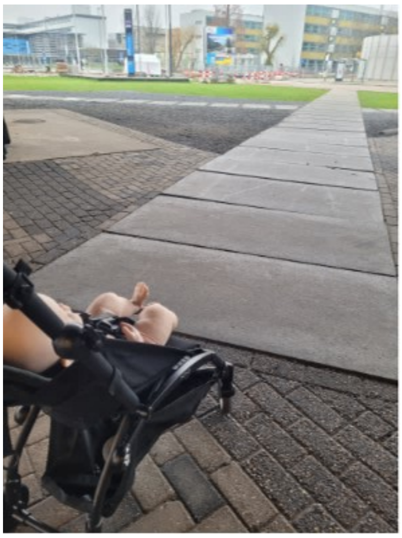


Figure 42: Sidewalk slab test area where we conducted the test with strollers.

The experiment was conducted in front of TU Delft Aula Conference Centre (Building 20), Mekelweg 5, 2628 CC Delft, The Netherlands (GPS coordinates: 52.002250, 4.372665).
Details of sidewalk slab: made of concrete, rectangular shape, dimensions 2000x990 mm (gap in between: 160±3 mm).

- Paver bricks

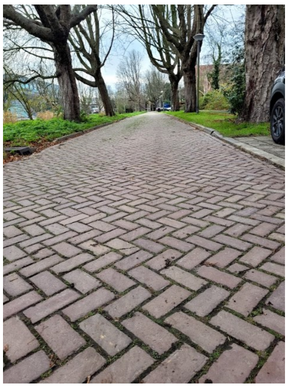


Figure 43: Details of the paver bricks test area.

The experiment was conducted along Prins Bernhardlaan, 2628 CN Delft, The Netherlands (same location as Sidewalk paver test, GPS coordinates: 52.003147, 4.369530).
Details of paver brick: rectangular shape, dimensions 195x95 mm (gap in between: 7±2 mm).

- Shock

Figure 44: Area where we tested strollers during the shock experiment.

The experiment was conducted inside TU Delft Mechanical Engineering faculty (Building 34 - Ground floor, aisle in front of Gezelschap Leeghwater office), Mekelweg 2, 2628 CD Delft, The Netherlands (GPS coordinates: 52.000587, 4.372224).
Details of the shock experiment: we pushed the stroller over a square section aluminium bar 30x30 mm.