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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This draft report is not yet peer reviewed and is subject to change with revisions. These results are preliminary, so we do not recommend relying on them until a supporting peer reviewed paper is published.

### Abstract

Infants are transported in strollers and in baby seats mounted in cargo bicycles. The infants experience whole-body vibration during the associated walking and cycling trips, but there is little existing knowledge about associated comfort and health effects. To improve this, we measure the seat pan acceleration of five strollers and two styles of cargo bicycles with dummy infants representing ages 0 to 9 months over six different road surfaces of varying road roughness at typical travel speeds. The five strollers included three modern systems and two vintage systems with some level of suspension. One cargo bicycle had electric support enabling speeds up to  $25 \text{ km h}^{-1}$ . We report average seat pan acceleration for 78 different scenarios and investigate the effects of road surface, vehicle, seat type, and travel speed. Using the whole-body vibration ISO standards, we show that rough road surfaces, amplified by travel speed, may have health risks for travel durations as low as 10 min to 30 min. Stroller designs from 50 years ago significantly reduce vibrations, relative to most modern strollers we tested, indicating the need for return of suspension elements. Cargo bicycles ridden at the maximum electric bicycle speed over paver bricks can cause accelerations that should likely be avoided except for only the shortest of durations until more direct evidence of risks to infants is studied. Standards are needed for infant transport testing and evaluation, designers need to incorporate better suspension for infants, and research is needed to develop clear and direct connections to health and comfort effects.

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

# Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>Methods</b>	<b>5</b>
2.1	Test Equipment . . . . .	5
2.2	Measurement Equipment . . . . .	7
2.3	Experimental Protocol . . . . .	7
2.4	Postures . . . . .	9
2.5	Data Processing . . . . .	9
2.6	Trial Analyses . . . . .	10
2.7	Statistical Modelling . . . . .	13
<b>3</b>	<b>Results</b>	<b>14</b>
3.1	Effect of Speed with Cargo Bicycles . . . . .	14
3.2	Effect of Dummy Size . . . . .	14
3.3	Effect of Road Surface . . . . .	14
3.4	Effect of Vehicle Model . . . . .	15
3.5	Dominant Frequency and Bandwidth . . . . .	15
3.6	Health Assessment . . . . .	17
3.7	Comfort Assessment . . . . .	18
3.8	Shock . . . . .	19
3.9	Statistical Results . . . . .	19
<b>4</b>	<b>Discussion</b>	<b>26</b>
4.1	Surface and Speed . . . . .	26
4.2	Baby Mass . . . . .	27
4.3	Health . . . . .	27
4.4	Comfort . . . . .	28
4.5	Vehicle and Seat Design . . . . .	28
4.6	ISO Filters and Bandwidth . . . . .	28
<b>5</b>	<b>Conclusion</b>	<b>29</b>
5.1	Summary . . . . .	29
5.2	Recommendations . . . . .	29
5.3	Future Work . . . . .	30
5.4	Acknowledgement . . . . .	31
<b>A</b>	<b>Experimental Equipment</b>	<b>34</b>
A.1	Location and pictures of the experiment areas . . . . .	40
A.1.1	For Bicycles . . . . .	40
A.1.2	For Strollers . . . . .	41
<b>B</b>	<b>Table of Repetition Metrics</b>	<b>45</b>
<b>C</b>	<b>Vehicle Statistical Comparisons</b>	<b>46</b>

## 1 Introduction

When a baby is born, it is not able to walk. To move around or travel, it must be either carried by adults or transported in a suitable means of wheeled transport. Until about a century ago, babies mainly stayed at home. This still is customary in some non-Western cultures. A century ago, perambulators were used to transport infants outdoors. However, mothers were advised that a playpen in the garden is healthier than the use of a perambulator, partly because the vibrations generated by a perambulator were deemed not comfortable and even harmful for the baby [2], 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 to enable easy transportation in a car. Over the years, new means of transportation came into use for infants: cars with a child car seat, bicycles with a bicycle seat and cargo bicycles with either a car seat or a baby shell.

All means of transport cause vibration, which is transferred to the infant sitting or lying in it. Unlike the advice in the 1930s, 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 cargo bicycles which generate more vibration are increasingly used for infants. Interestingly, in the literature we could find 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 also only sparsely investigated. Therefore the effect of transport on infant comfort and health can not easily be assessed. To establish the amount of vibration that infants are subjected to in transportation products, we investigated the vibration that infants receive during transport in strollers and cargo bicycles.

Cycling, one of the active transportation modes, is advantageous for health [18] and greatly contributes to reducing CO<sub>2</sub> emissions, congestion, and air pollution [17]. As a result, bicycles are increasingly used as a means to deliver goods to consumers, and also for daily commuting to work and personal matters (shopping, commuting with children/infants, and others). 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 less frequent in Finland. Various countries and employers provide incentives to increase the use of bicycles. However, some challenges need to be overcome to secure the wide acceptance and use of active transportation modes. One of these challenges is the comfort levels experienced by riders and passengers (i.e., infants/children in cargo bicycles), which is a multifaceted aspect [1] and critical for the wide acceptance and use of bicycles as a daily means of transport. Meanwhile, this is a topic that is of great interest and requires attention when it comes to infants' transportation with strollers or bicycles.

The research on cyclist comfort is a natural starting point for investigations of similar road-induced vibrations for infants. Comfort on bicycles [33] is mainly affected by physical comfort and the impact of environmental factors (weather, geometry of the route, 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 and others). While there is extensive literature exploring the impact of environmental factors (i.e., irregular road surface quality, weather conditions) on cyclists' comfort [30, 9, 1, 37, 32], there is limited work on understanding the biomechanical and physiological factors of comfort while being carried by bicycle (infants/children in bicycle seats, on cargo bicycles, or in trailers). A particular concern is the transport of infants under one year, who cannot well express any experience of discomfort or pain. Similar concerns are raised when it comes to strollers, where infants are also exposed to vibrations induced by roads. In this paper, we will explore biomechanical comfort by assessing the whole-body vibrations that could be experienced by transported infants both in cargo bicycles and strollers, and evaluating potential health risks and discomfort that might arise.

Biomechanical comfort is mostly related to the vibrations induced by road irregularities and transmitted via the vehicle to the human body and head while being driven [33]. According to the literature, road irregularities are a critical factor for the amplitude of the resulting vibrations experienced by the bicyclists and passengers, as the vibrations induced on the body and head are not efficiently isolated due to the lack of or inadequate suspension systems in most of the bicycle models [36] or strollers. The bicycle or stroller design and its specific configuration can affect the sitting posture, and eventually the transmissibility of the vibrations [3, 38]. The sitting posture can also vary in case of children/infants who may be transported sitting or lying down in a different posture and 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). These all influence the level of whole-body vibrations and the transmission of the vibrations from the seat to the body and head. Furthermore, the amplitude of the vibrations experienced by bicyclists/passengers/transported infants while biking or being transported in a stroller may increase because

of increased travelling speed either due to running with a stroller or due to the increased power offered by electric bicycles (with and without trailers). For the latter, the average speed of electric bicycles and speed pedelecs is 19% higher ( $21.0 \text{ km h}^{-1}$  and up to 63% higher ( $28.1 \text{ km h}^{-1}$ ), respectively, than the average speed of conventional bicycling [31]. The intensity of these vibrations could become even more critical with the change of load, which could be related with age and size of the infant/children transported. However, there is limited literature exploring the whole-body vibrations of infants and children being transported by bicycles with trailers, cargo bicycles, stroller seats and others [20, 21, 12, 35, 25, 23]. At the same time, the available literature is mostly focusing on comfort rather than health risks.

One of the research fields closely related to vibrations acting on infants during transportation is that of inflicted head injury by shaking trauma (IHI-ST). However, there is a lack of reliable, applicable, validated injury thresholds for assessing IHI-ST risks [10]. Similarly, even if there are significant indications that the vibration amplitude affects comfort in bicycles or strollers, there are no standard assessment methods or guidelines available with regards to their design. ISO 2631 [11], the international standard for assessing whole-body vibrations, was derived using datasets on motion platforms, adults as human participants and sitting postures which are adopted in passenger vehicles rather than on bicycles. This inconsistency was captured by Gao et al. [5], who derived different limits of comfort for adults riding on bicycles based on their subjective feedback, compared to the vibration limits suggested by ISO 2631-1. In addition, the exposure time to the vibrations is not considered as a factor of comfort by the ISO 2631-1, despite having a clear impact on health risks according to the European Directive (2002/44/EC, 2002) [4].

Despite the lack of clarity with regards to comfort assessment or inflicted head injury by shaking trauma for children/infants on bicycles, there are clear indications in the literature that these should be explored and considered. About 36% of males and 42% of females in a total sample of 900 people had various complaints about comfort [7]. Discomfort for both men and women occurred even during short bicycle trips (3 km to 10 km). However, results from research into comfort of adult cyclists can not be applied directly to infants or children sitting or lying in transportation systems.

Schwanitz et al. [25] assessed accelerations in a child bicycle trailer riding over smooth asphalt, gravel, and cobblestones using ISO 2631-1 weighted RMS vertical accelerations. Anthropomorphic children shaped sandbag dummies (baby and toddler sizes) were used as lumped masses. According to the results, tyre pressure and the number of passengers had no significant effect on vibration magnitude, but road surface and travel speed did. The baby sized dummy (5 kg) experienced 20% higher vibration than the toddler sized dummy (10 kg), while the measured values generally exceeded the ISO 2631-1 vibrational comfort of adults. Rothhämel et al. [23] conducted measurements using a trailer seat and a tadpole configuration three-wheel cargo bicycle on smooth asphalt and cobblestones for speeds between  $10 \text{ km h}^{-1}$  to  $20 \text{ km h}^{-1}$ . After weighting the accelerations using ISO 2631-1 methods, they found a large increase of the vibration amplitude on cobblestones compared to asphalt on the same speed range. The child trailer exhibited larger weighted RMS accelerations than the cargo bicycle with the child seat between the front wheels. Both the trailer and cargo bicycle child seats had generally larger magnitude vibrations than experienced in an automobile seat travelling at  $30 \text{ km h}^{-1}$  on a rough road [8]. Rothhämel and Liu [22] conducted measurements with a 6.5 kg mass representing an infant with various tyre pressures. All their values fell into the “extremely uncomfortable” zone for the ISO 2631-1.

In addition to the studies with dummies or lumped masses representing infants, Kanya-Forstner [12] measured acceleration in bicycle child trailers with human subjects aged 12 months to 6 years over asphalt and gravel terrain (averaged speed of  $12 \text{ km h}^{-1}$  over the 20 min ride). According to the health assessment using ISO 2631-1, the vibrations are similar to the ones experienced in car seats in vehicles and illustrated moderate or low health risk for a 2 h duration. On the other hand, if not corrected for duration, the values point to moderate and high risks. The terrain type had the greatest influence on vibration exposure levels followed by trailer type, while gel cushions as support did not significantly influence vibration measured at the seat/pan interface. Hence, there is a need to re-focus on the impact of vibrations on infants and children’s health and comfort [24] to ensure the safe, comfortable and wide use of bicycles.

In the context of infants transportation with stroller seats, Kok Siong [13] carried out an indoor and an outdoor experiment to capture the vibrations transmitted onto the seat and backrest of a baby stroller, using weights from 4 kg to 14.14 kg, and a child subject of 10.30 kg as well as a dummy weighing 10.30 kg. The comfort levels for the indoor testing were labelled as ‘Fairly uncomfortable’ to ‘A little uncomfortable’, but the outdoor testing resulted in ‘Extremely uncomfortable’ and ‘Fairly uncomfortable’ values. They used both a child and dummy for the experiments, identifying similar patterns. However, the results still consider ISO 2631-1 standard, which is designed for adults and specific postures. In a similar research, Sierzputowski et al. [26] investigated vibrations induced in a modern and an older

stroller, when moving on different surfaces: asphalt road, concrete paving blocks, concrete plates, dirt road, lawn and damaged concrete. The obtained weighted RMS acceleration values based on ISO 2631-1 were several times in the range of the highest discomfort ( $>2 \text{ m s}^{-2}$ ). Another research which included also children as test subjects was conducted by Okajima et al. [19] measuring vibrations that seven children received, sitting upright in a stroller, when riding over a protrusion (13x60 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 and measuring 98.0 cm to 112.4 cm in length. Based on the results, the infant’s head and chest exhibit strong vibrations at 1 Hz along all three axes (x,y and z), vibrate easily along the y-direction at 2 Hz, and are less likely to vibrate at more than 8 Hz. This result is critical as this range of frequencies is very common in bicycles and strollers. However, they did not assess the comfort and the health risk when the children were exposed to these vibrations. Despite significant research on the effect of whole-body vibrations on children’s comfort, there is limited research on infants.

This paper reports on the vibration induced on infants of different ages when transported in strollers and cargo bicycles. Vibration can be related to discomfort and might lead to negative health consequences. However, the topic is poorly addressed in scientific literature, and only a few studies focus on the effect of vibration on babies as reviewed above. To measure the actual vibration transmitted to infants, we equipped five strollers and two cargo bicycles with inertial measurement units (IMU) and conducted 78 experiments on different road surfaces and travel speeds, using dummies representing the size and mass of 0, 3, and 9 months old infants. We present results in the time and frequency domains, which allows comparing vertical accelerations at the baby-seat interface, as recommended by ISO 2631-1 standards for vibration discomfort. We investigated the influence of different variables on vibration, such as type of vehicle, baby seat, travelling speed, dummy size and mass, and road surfaces and provide recommendations to users, designers, and future researchers based on the findings.

## 2 Methods

### 2.1 Test Equipment

Vibration measurements were conducted at approximate constant speed using five different strollers, two cargo bicycles, and two baby seats <sup>1</sup>, chosen for their popularity and/or distinctive features:

**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.

**Maxi-Cosi Street Plus** This stroller comes with a cot configuration (0-3 months) and an infant seat option. It has large wheels, with only a marginal suspension system. ([Maxi-cosi website](#))

**Stokke BABYZEN YOYO 0+** The smallest foldable stroller on the market. It has only a marginal suspension system and smaller wheels compared to those of other strollers available on the market. ([Model rented for the experiment](#))

**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-proof tyres and an air-permeable mattress. ([Bugaboo website](#))

**Green Machine** An unknown brand vintage perambulator, dating approximately from the 1970’s that includes a leather strap suspended cot in a metal frame. The wheels are relatively large in diameter compared to the modern strollers.

**Old Rusty** An unknown brand vintage seat-style stroller from approximately the 1970’s that includes a metal spring suspension system and wheels that are slightly larger than the modern strollers.

**Cargo Bicycles** Two modern Dutch “bakfietsen” in which different baby seats can be mounted.

**Urban Arrow Bicycle** A popular electric cargo bicycle 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 baby shell) placed in between the rider and the front wheel. ([Urban Arrow website](#))

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<sup>1</sup>Appendix A provides figures and technical descriptions of all the strollers and cargo bicycles.

**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 wheel 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. ([Product Webpage](#))

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

**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](#))

**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](#))

The tests involved three baby dummies with sizes and weights representative of newborns and 3 and 9 month old infants. Newborns (‘0 months’) are the youngest (smallest, lightest) children that are transported in strollers with a cot. Three month old infants are the youngest (smallest, lightest) children that are transported in cargo bicycles, fixated in a baby car seat or baby shell. Nine month old infants are the youngest (smallest, lightest) that 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.

We considered the use of “crash test dummies” (also known as anthropomorphic test devices or ATD’s) which are designed and commonly used to test child seats in car crash tests. However, the nearest available body sizes for crash test dummies were a 6-weeks Q0-dummy, a 6-months Crabi dummy, and a 12-months Q-dummy (Humanetics, Farmington Hills, USA). These 3 dummies are of a fundamentally different design, hampering comparison, and did not match the desired body sizes. Moreover, these child dummies have dynamic properties designed for crash conditions, and they were designed based on scaling of adult biomechanical data rather than child data, so in that respect there is no benefit over other dummies.

Testing with real infants would be unethical, and would create challenges in terms of reproducibility. Hence we bought and adapted “reborn” dummies available in a wide range of postures from a webshop specialising in dolls and dummies ([Atelier Wiesje](#)). The dummies were filled with a mixture of cat litter sand and water to reproduce the exact weights needed for testing. Cat litter sand features smooth and round-shaped grains, which do not damage the dummies’ materials (fabric and plastic). The weight and body height of the dummies were made to match the average measures for children of 0, 3 and 9 months old.

We wanted to use the measurements from Steenbekkers [29]. However, this research provided the results only per three-month group, which did not fit our age categories. We decided to use the growth charts used by clinicians to assess infant growth to determine the average weight and body height at the right ages. The average weight at 0 months and the average body height at all three ages are derived from Dutch growth charts. We used measurements of Dutch children because they are the target group of the project funder, VeiligheidNL. Dutch children are also the tallest in Europe. We derived the average weight of 3 and 9 months old children from French growth charts. French children are the smallest in Europe. At 3 months, average Dutch children weigh 113 gram more than average French children and at 9 months, the difference is 85 gram. 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](#))

To achieve a realistic mass distribution in the body of the dummies, each limb was filled with a proper amount of wet sand (for the 0-month dummy, water was added to achieve the correct weight). To do this, we simplified the geometry of each body segment according to the defined basic geometric shapes: a sphere for the head, and cylinders for the torso, upper arms, upper legs and lower legs, according to what was stated in [27]. We also assumed an equal density for each limb, and we rescaled the measurements of the limb segments reported in [27] to match the dimensions of our dummies. In doing so, we were able

to calculate the volume of each segment, thus the mass of each limb of the dummies (assuming a density of  $1000 \text{ kg m}^{-3}$ ).

## 2.2 Measurement Equipment

Linear accelerations and angular velocities were measured tri-axially using Consensys Shimmer3 IMUs with a Consensys Base 6U.01 dock (Shimmen 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 ensure a firm clamp between the sensor and the bicycle/stroller tested (Small white and orange boxes visible in Figure 1). Each vehicle was equipped with five IMUs, as listed below. All the drawings showing the vehicles and the sensors’ location are reported in Appendix A.

1. **Rear Wheel** This IMU was placed on the wheel hub (cargo bicycles) or clamped to the wheel (strollers) for measuring the travel speed. The travelling (longitudinal) speed was derived according to:

$$v = \omega \cdot r \quad (1)$$

where  $\omega$  is the angular speed of the wheel (obtained from the IMU’s gyroscope aligned with the wheel’s axis) and  $r$  is the radius of the wheel.

2. **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.
3. **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.
4. **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.
5. **Seat Pan** This IMU was taped into the baby seat, at the interface between the dummy’s buttock and the baby seat. It measured the vibration transmitted to the dummy’s buttock.

The IMUs for the seat head and seat buttock positions contacting the dummy were placed according to the recommended practice in vibration testing standard ISO-2631-1. 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 target sampling frequency was 910.22 Hz for all IMUs. The full-scale range was set to  $\pm 16 \text{ g}$  for the accelerometer (“WR: wide range” configuration on Consensys Shimmer software), and  $\pm 2000 \text{ }^\circ \text{ s}^{-1}$  for the gyroscope. All tests were recorded with two GoPro Hero7 cameras: one directly mounted on the strollers/bicycles to record the dummy-seat relative motion, while the other was held by an experimenter walking or riding alongside the vehicle to have a complete overview of the experiment.

## 2.3 Experimental Protocol

All tests were conducted in Delft, The Netherlands, on public roads near the Delft University of Technology, Faculty of Mechanical Engineering. Latitude and longitude of each location along with local photographs of each site are provided in Appendix A.1. After mounting the sensors and reaching the location of the experiment, we turned on the sensors to start the experimental session. Before each trial, we pushed the vehicle back and forth on level ground to mark the beginning of the trial as an extra time-synchronization measure. For the cargo bicycle test, a single rider conducted all trials to be consistent across different sessions (rider mass: 59 kg; rider height: 1.70 m). We tested three types of road surfaces with the cargo bicycles and repeated those at different speeds. The stroller tests were conducted on six different surfaces with the pusher manually keeping a consistent walking speed of approximately  $5 \text{ km h}^{-1}$ . In all tests, speed was controlled by the pusher or cyclist using a speedometer mounted on the stroller handle bar or the steer of the cargo bicycle. We gathered data from multiple trials within the same session. The test combinations, “scenarios”, are listed below.



(a) IMU on the front fork

(b) IMU on the rear wheel hub



(c) IMU under the cargo bay

(d) IMUs on the baby seat surface

Figure 1: IMU locations on the Urban Arrow cargo bicycle. 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.

- **Strollers** The stroller tests were done with the dummies of 0 months and 9 months old. All the test surfaces listed below are shown in Appendix A.1.
  - Tarmac
  - Paver bricks
  - Sidewalk pavers
  - Cobblestones
  - Sidewalk slabs (concrete blocks with gaps in between)
  - Shock bump: A 30x30 mm square section aluminium bar was taped to the ground (smooth surface)
- **Cargo bicycles** The cargo bicycle tests were conducted using the dummies of 0 months and 3 months. With the Keiler tricycle, the speed was limited to  $20 \text{ km h}^{-1}$  for safety reasons (due to wobbling), and difficulties to safely keep a constant speed over  $22 \text{ km h}^{-1}$ . The test surfaces are listed below:
  - Tarmac
  - Paver bricks
  - Shock bump: As mentioned before, we conducted shock test riding over a 30x30 mm square section aluminium bar, at three speeds:
    - \* Low speed:  $5 \text{ km h}^{-1}$
    - \* Medium speed:  $12 \text{ km h}^{-1}$
    - \* High speed:  $20 \text{ km h}^{-1}$  for the Keiler tricycle,  $25 \text{ km h}^{-1}$  for the Urban Arrow cargo bicycle
- **Baby seats** Both the Maxi-Cosi X Joolz Pebble Pro i-Size and the Melia baby shell were tested on each cargo bicycle using the same mounting systems.

## 2.4 Postures

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

## 2.5 Data Processing

We analysed the raw data with a custom data processing pipeline. The pipeline’s open source code (MIT license) is hosted at [github.com/mechmotum/baby-vibration](https://github.com/mechmotum/baby-vibration) implemented in Python 3.13.1 using the following software packages: 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](https://mechmotum.github.io/baby-vibration) with an exhaustive collection of figures for examining the quality of the data and general results for all trials including the selected tables and figures presented and discussed in the results section of this paper.

We define a “session” as a continuous data collection period from a single vehicle. Each session is segmented into “trials” corresponding to a different road surface or activity and each trial is divided into subsequent, back-to-back “repetitions”. 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 segment the sessions into trials representing a motion state of the vehicle: either static on level ground or being propelled over one of the surfaces of interest at a constant speed. Figure 2 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.

Table 1: Inclination angles of the IMUs “Seat Head” and “Seat Pan”, per each tested configuration. For the head 0 ° means erect posture, and positive angles represent rearward head rotation with 90 ° indicating a fully supine posture (lying horizontally). For the seat pan I STILL DONT UNDERSTAND especially the -28 for Melia.

Vehicle Type	Model	Dummy	Baby seat (facing direction)	Inclination angle [deg]	
				Seat Head	Seat Pan
Cargo Bicycle	Urban Arrow	0 mo	Maxi-Cosi X Joolz (RF)	41	2
		3 mo	Maxi-Cosi X Joolz (RF)	41	2
		3 mo	Melia (FF)	64	2
	Keiler	0 mo	Maxi-Cosi X Joolz (RF)	41	2
		3 mo	Maxi-Cosi X Joolz (RF)	49	-43
		3 mo	Melia (FF)	64	2
Stroller	Maxi-Cosi Street Plus	0 mo	Baby cot (RF)	0	0
	Maxi-Cosi Street Plus	9 mo	Baby seat (FF)	40	10
	Babyzen YOYO 0+	0 mo	Baby cot (RF)	12	12
	Babyzen YOYO 6+	9 mo	Baby seat (FF)	45	4
	Bugaboo Fox 5	0 mo	Baby cot (RF)	0	0
	Bugaboo Fox 5	9 mo	Baby seat (FF)	49	24

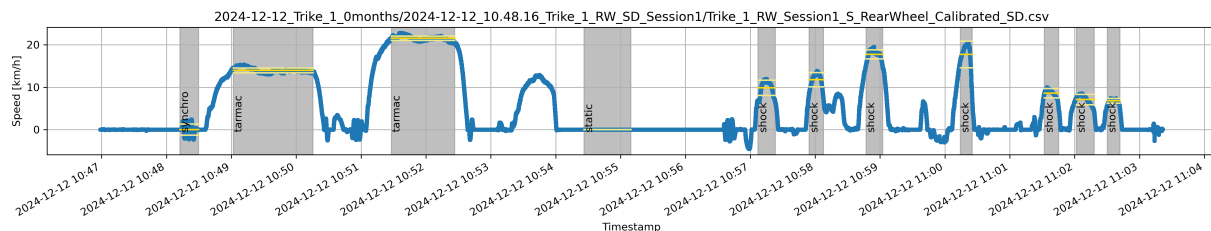


Figure 2: Vehicle speed versus time for an entire session (015) showing the trials in the shaded grey areas. Gold horizontal lines depict the mean speed during the trial bounded by the standard deviation of the speed.

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.
4. Rotate the accelerometer data for each sensor from body-fixed sensor coordinates to body-fixed vehicle coordinates and subtract the constant standard gravity component. 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 giving linear acceleration of each sensor projected into the vehicle’s SAE body-fixed axes [28], named: longitudinal  $x$ , lateral  $y$ , and vertical  $z$ .
5. Extract each motion trial segment and select the vehicle body-fixed longitudinal, lateral, and vertical component of the seat pan accelerometer.

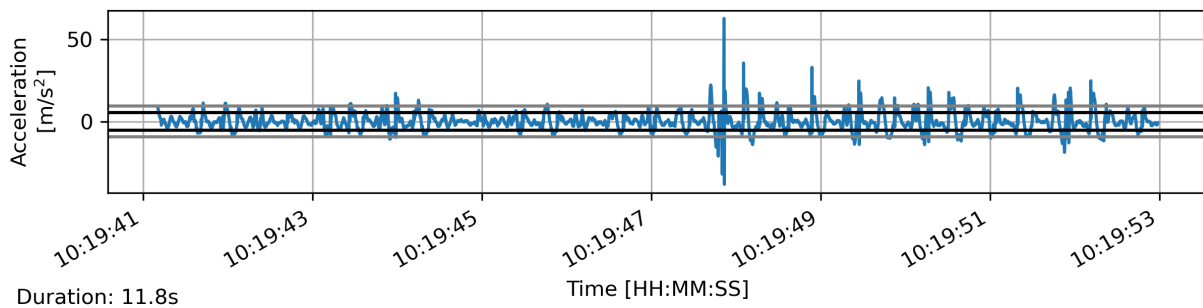
This resulted in acceleration-time recordings of 220 total repetitions. The non-shock repetitions have durations in the range of 10s to 40s (mean: 25 s), see Table 2 for a breakdown of the non-shock repetitions.

## 2.6 Trial Analyses

Figure 3 shows an example time history of the vertical 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  $\pm 16$  g to that maximum or minimum, respectively, given that values outside

Table 2: Number of repetitions performed on each road surface, excluding shock, and speed along with the mean duration in seconds and its standard deviation.

Vehicle Type	Road Surface	Target Speed [km h <sup>-1</sup> ]	Repetitions		
			Count	Mean Duration [s]	STD Duration [s]
Cargo 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
<b>Count Sum</b>			<b>154</b>		

Figure 3: Raw seat pan vertical acceleration versus time from session 001: Maxi-Cosi Street Plus Stroller over the Sidewalk Slabs. Black horizontal lines indicate the  $\pm$ root mean square (RMS) about the mean and grey horizontal lines indicate the  $\pm$ vibration dose value (VDV) about the mean.

the range may be unreliable. Values that exceed the range are rare and only present in some of the cargo bicycle paver brick trials, but are common in the shock tests. Following the ISO 2631-1 recommendation, we low-pass filtered the signal at  $1.5 \times 80 \text{ Hz} = 120 \text{ Hz}$  using a zero-lag 2<sup>nd</sup> order Butterworth filter, given that the standard only applies to frequencies up to 80 Hz.

ISO 2631-1 provides weighting filters that highlight those frequencies 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 4 gives an example of a raw amplitude spectrum along with smoothed versions of the raw and ISO 2631-1 weighted signals. In almost all trials, there is a single dominant peak frequency in the ISO weighted and smoothed spectra. For the few trials that had two or more peaks at approximately the same amplitude, the second peak was sometimes selected. After 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.

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 trial using Equation 2 to use for the health assessment and the RMS of the magnitude of the acceleration vector at the seat pan using Equation 3 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 3. 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) of the  $M$  raw data vertical acceleration  $a_z$  samples with Equation 4, seen in Figure 3. Lastly, we compute the crest factor and absolute maximum of the downsampled and low pass filtered vertical

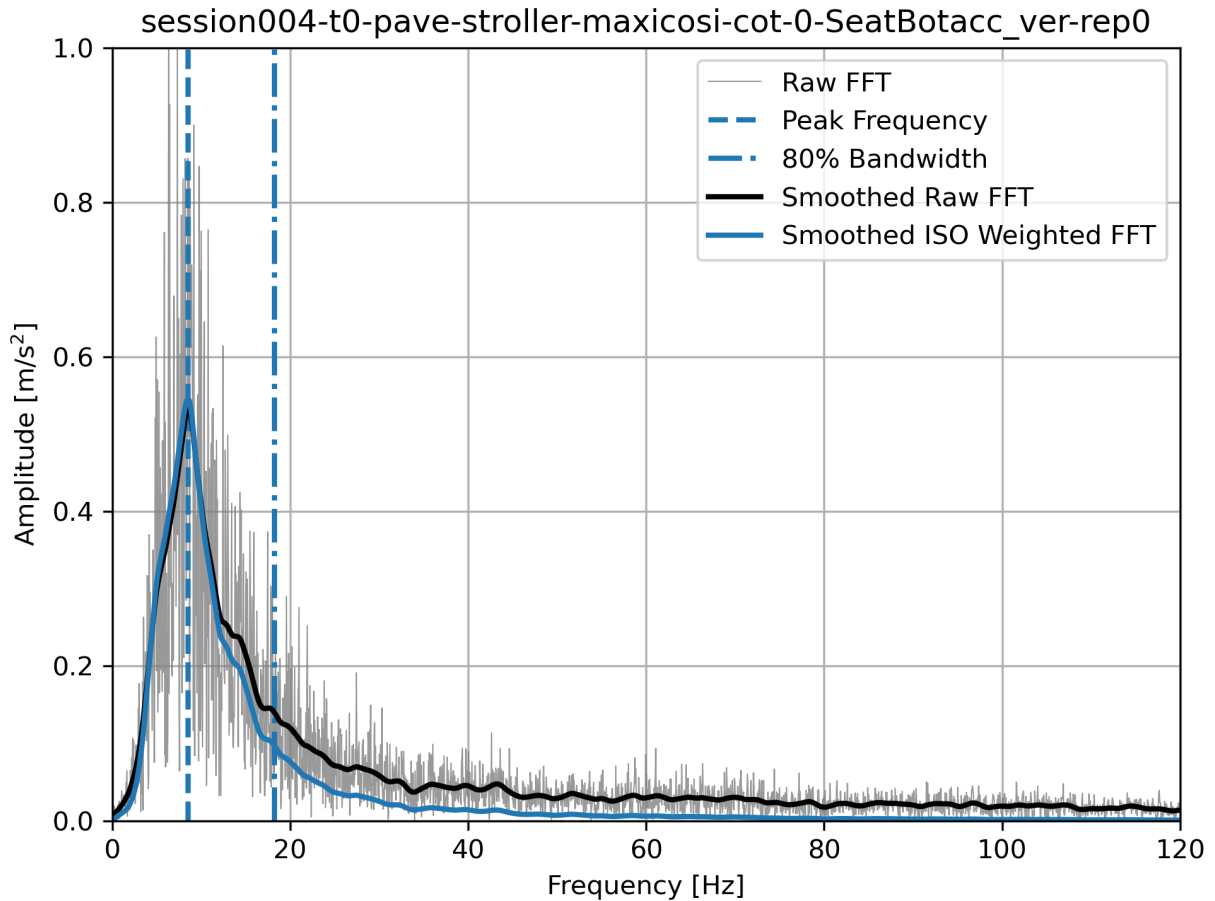


Figure 4: Seat pan vertical acceleration amplitude spectrum from session 004: Maxi-Cosi Street Plus over cobblestones. The gray curve shows the result of the FFT, the black line is a smoothed version of the FFT (zero-lag Butterworth low pass), and the blue line is the smoothed ISO weighted FFT. The blue dashed vertical line indicates the frequency at the maximum amplitude of the smoothed curve. The blue dashed-dotted vertical line indicates the bandwidth threshold for 80% of the area under the blue curve.

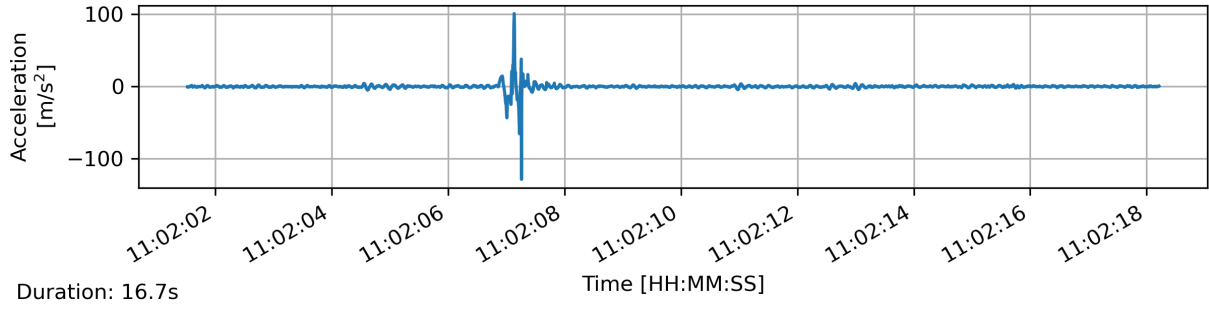


Figure 5: Raw seat pan vertical acceleration versus time from session 015: Keiler tricycle during the shock test.

acceleration<sup>2</sup> with Equations 5 and 6, respectively. All of these per-repetition metrics are reported as mean values over the repetitions corresponding to a scenario in Table 8 in Appendix B. Regarding the shock test, the analysis 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 5), limiting it to 16 g when the peak exceeded that maximum. The following equations give the details of the metrics calculations:

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

$$\text{RMS}_{a_{w,xyz}} = \sqrt{\frac{1}{N} \sum_{n=1}^N k_x^2 a_{w,x}^2(t_n) + k_y^2 a_{w,y}^2(t_n) + k_z^2 a_{w,z}^2(t_n)} \quad (3)$$

$$\text{VDV}_{a_z} = \left( \frac{1}{M} \sum_{m=1}^M a_z^4(t_m) \right)^{1/4} \quad (4)$$

$$\text{Crest Factor}_{a_z} = \frac{\max |a_z(t_m)|}{\sqrt{\frac{1}{M} \sum_{m=1}^M a_z^2(t_m)}} \quad (5)$$

$$\text{MAX}_{a_z} = \max |a_z(t_n)| \quad (6)$$

## 2.7 Statistical Modelling

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

$$\text{RMS}_{a_{w,z}} = \beta_0 + \beta_1 x_{\text{Road Surface}} + \beta_2 x_{\text{Stroller}} + \epsilon \quad (7)$$

Both  $x_{\text{Road Surface}}$  and  $x_{\text{Stroller}}$  are categorical variables and we select tarmac and the Green Machine as the reference values when coding the categorical variables, respectively. We do not consider the interaction of road surface and stroller.

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:

$$\text{RMS}_{a_{w,z}} = \kappa_0 + \kappa_1 x_{\text{Road Surface}} + \kappa_2 x_{\text{Cargo Bicycle}} + \kappa_3 x_{\text{Speed}} + \kappa_4 x_{\text{Road Surface}} \times x_{\text{Speed}} + \epsilon \quad (8)$$

<sup>2</sup>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.

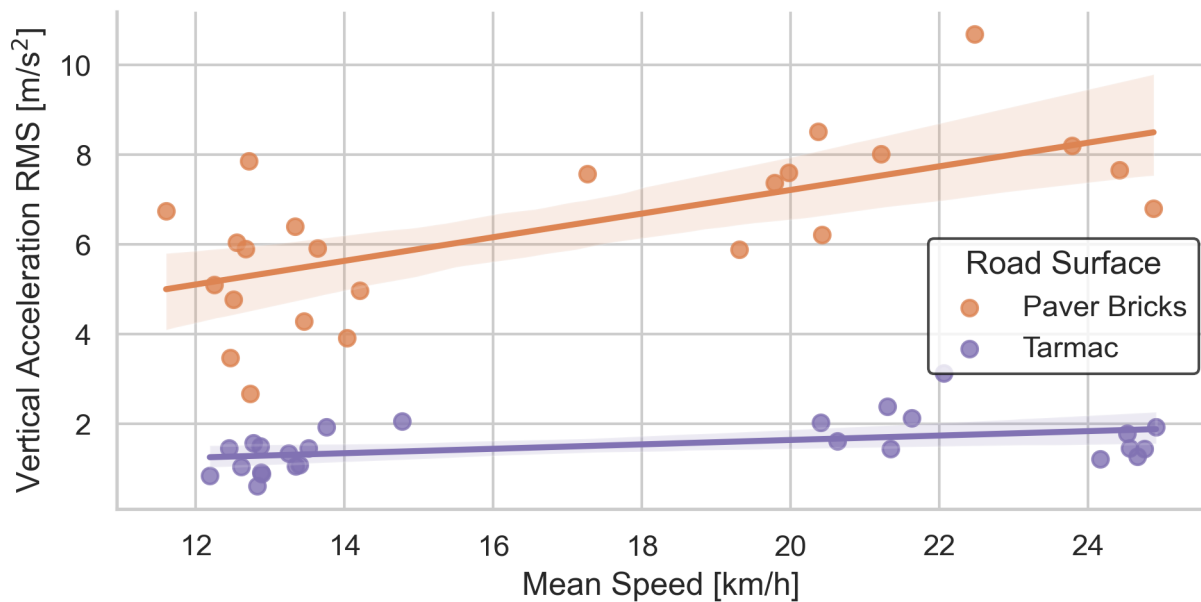


Figure 6: Seat pan ISO 2631-1 weighted vertical acceleration RMS versus speed for all cargo bicycle repetitions. Shaded regions represent the 95% confidence intervals from a simple linear regression that ignores  $x_{\text{Cargo Bicycle}}$ .

Both  $x_{\text{Road Surface}}$  and  $x_{\text{Cargo Bicycle}}$  are categorical variables and  $x_{\text{Speed}}$  is a continuous variable. We select tarmac and the ‘Keiler, Maxi-Cosi seat, 0 mo’ setup as the reference values when coding the categorical variables, respectively. We do not consider the interaction of road surface and cargo bicycle setup, but we do consider the interaction of speed with road surface. We use  $p < 0.05$  to indicate significant differences for both models. Following fitting the two statistical models, we apply 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

#### 3.1 Effect of Speed with Cargo Bicycles

Figure 6 shows the variation in ISO 2631-1 weighted vertical RMS acceleration across the tested speeds. Accelerations experienced when riding over the paver bricks were always larger than for tarmac at the same speed, with the paver bricks showing about a  $4\text{--}5\times$  higher acceleration magnitude than tarmac. Over paver bricks, the RMS acceleration increased by about  $1.6\times$  when increasing the speed from  $12\text{ km h}^{-1}$  to  $25\text{ km h}^{-1}$ . The effect of speed while cycling over tarmac was less drastic but also may show a slight increase of accelerations over the speed range.

#### 3.2 Effect of Dummy Size

Figure 7 shows the ISO 2631-1 weighted vertical RMS acceleration for each repetition for all vehicles, comparing among dummy sizes. There were larger accelerations in the bicycle (high speeds) versus the stroller (low speeds), likely mostly attributed to the different testing speeds. 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 vehicle type and road surface are ignored. For the bicycles, the lightest dummy sometimes experienced higher acceleration than the heavier dummy, but high and low accelerations are seen across the speed range tested.

#### 3.3 Effect of Road Surface

Figure 8 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 and sidewalk pavers and sidewalk slabs, i.e. light colour dots (strollers are present in each

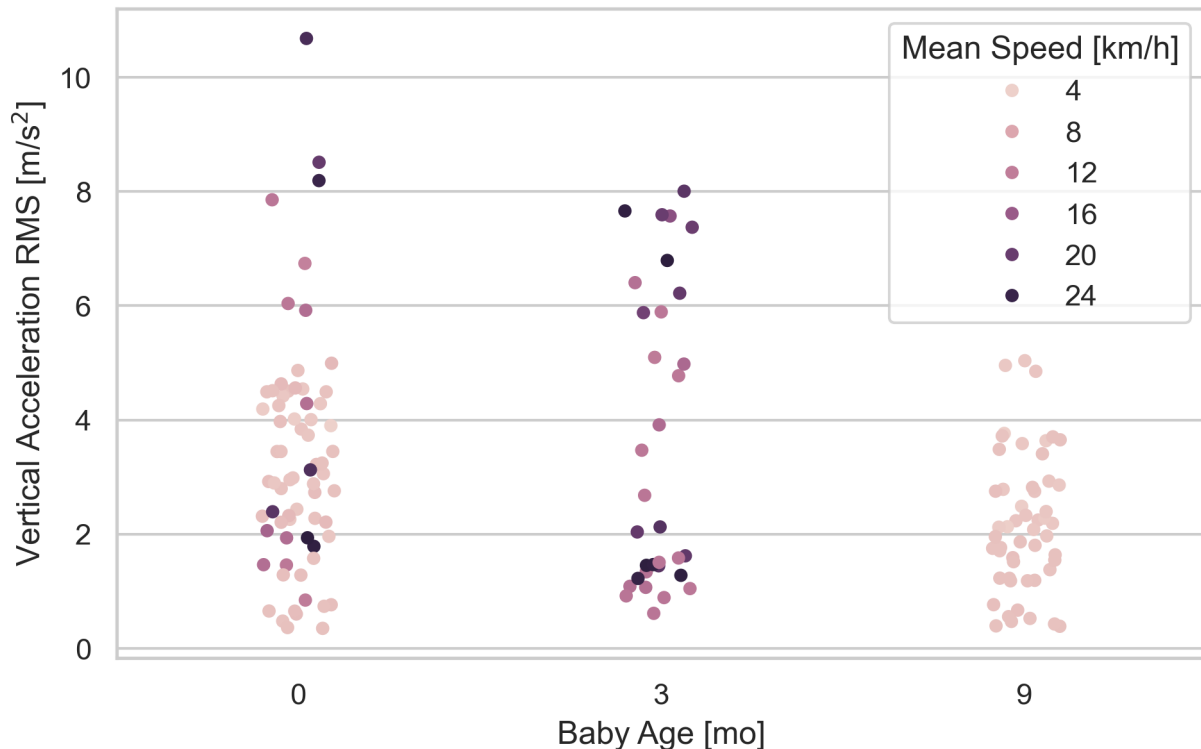


Figure 7: Seat pan ISO 2631-1 weighted vertical RMS acceleration grouped by baby age (and thus size & mass) for all repetitions with colour indicating the mean speed of the trial. The lightest colour dots are strollers and the remaining are cargo bicycles.

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 seem to have a similar range of RMS acceleration for the same  $5 \text{ km h}^{-1}$  walking speeds. Paver bricks cause relatively large accelerations at high travel speeds in the cargo bicycles.

### 3.4 Effect of Vehicle Model

Figure 9 shows the vertical RMS accelerations for each road surface for each of the five strollers, lumping seat configurations and dummy sizes. The Maxi-Cosi Street Plus and Stokke BABYZEN YOYO 0+ strollers have similar mean values across repetitions. The Bugaboo Fox 5 has a slightly lower mean for cobblestones, paver bricks, and sidewalk pavers. The Green Machine performs better than the modern strollers on paver bricks, but similarly otherwise. The Old Rusty performs better than the modern strollers on all surfaces except tarmac. All strollers seem to experience the same acceleration on tarmac. There may be no significant difference in the acceleration experienced in each modern stroller model. All road surfaces compared to tarmac cause at least double the RMS acceleration.

Figure 10 compares the two cargo bicycle models we tested. Each cargo bicycle was fitted with the same set of two baby seats (Melia baby shell and Maxi-Cosi Pebble Pro baby seat). On tarmac the two-wheel cargo bicycle delivers lower accelerations to the seat pan, but on paver bricks the two vehicles show little difference in RMS accelerations. Both vehicles show increasing vertical RMS acceleration with speed.

### 3.5 Dominant Frequency and Bandwidth

Figure 11 shows the distributions of dominant (peak) frequency compared among road surface types for each of the target speeds. Peak frequencies range from about 4 Hz to 11 Hz across all trials. For strollers ( $5 \text{ km h}^{-1}$ ), the median frequency increases from sidewalk slabs to cobblestones and sidewalk pavers and then to tarmac and paver bricks. The peak frequency median does not correlate sequentially with the geometric width of the dimension of the road surface feature. For the cargo bicycles, difference in peak

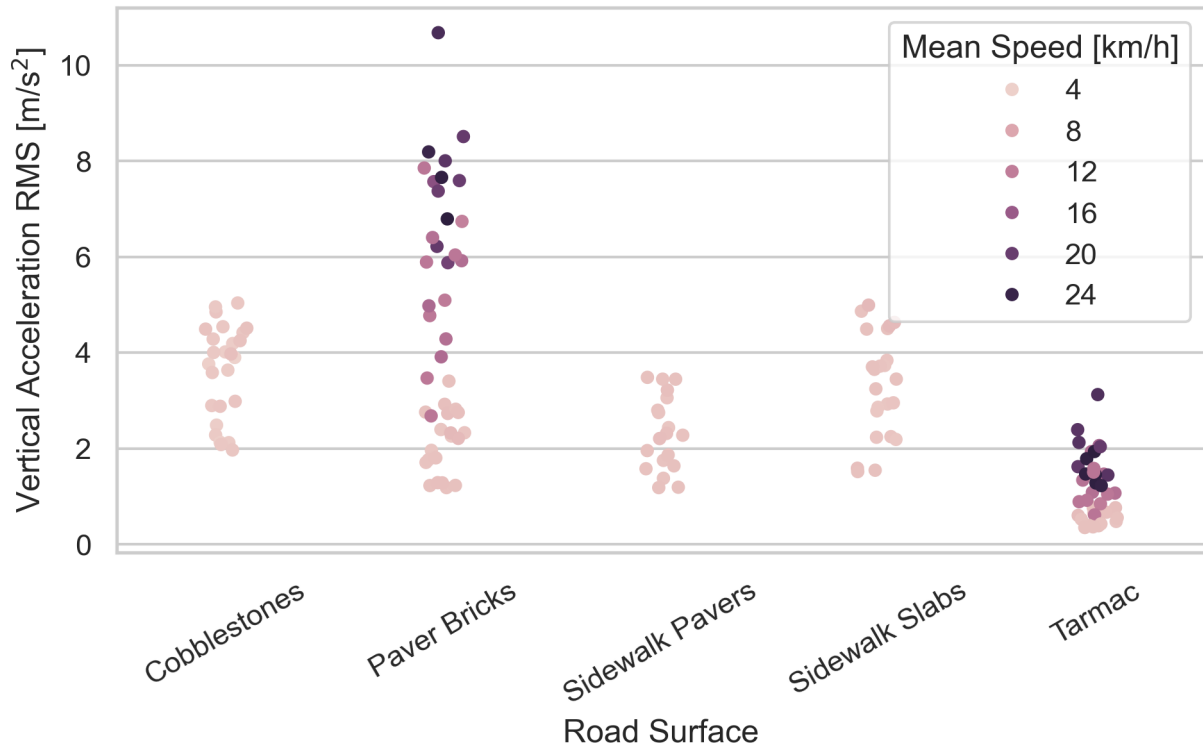


Figure 8: Seat pan ISO 2631-1 weighted vertical RMS acceleration grouped by road surface with colour indicating the mean speed of the repetition. The lightest colour dots are strollers and the rest are cargo bicycles.

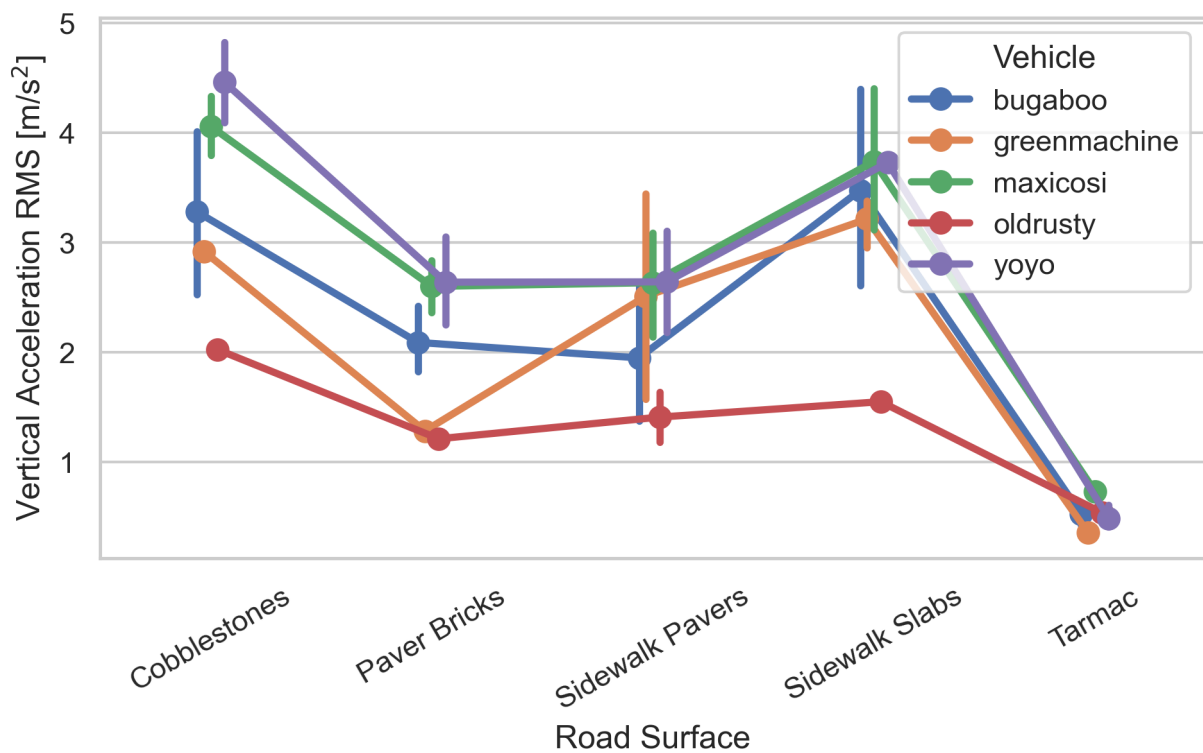


Figure 9: Mean seat pan ISO 2631-1 weighted vertical RMS acceleration per road surface for each stroller. Vertical lines indicate the standard deviation for categories that have more than one repetition.

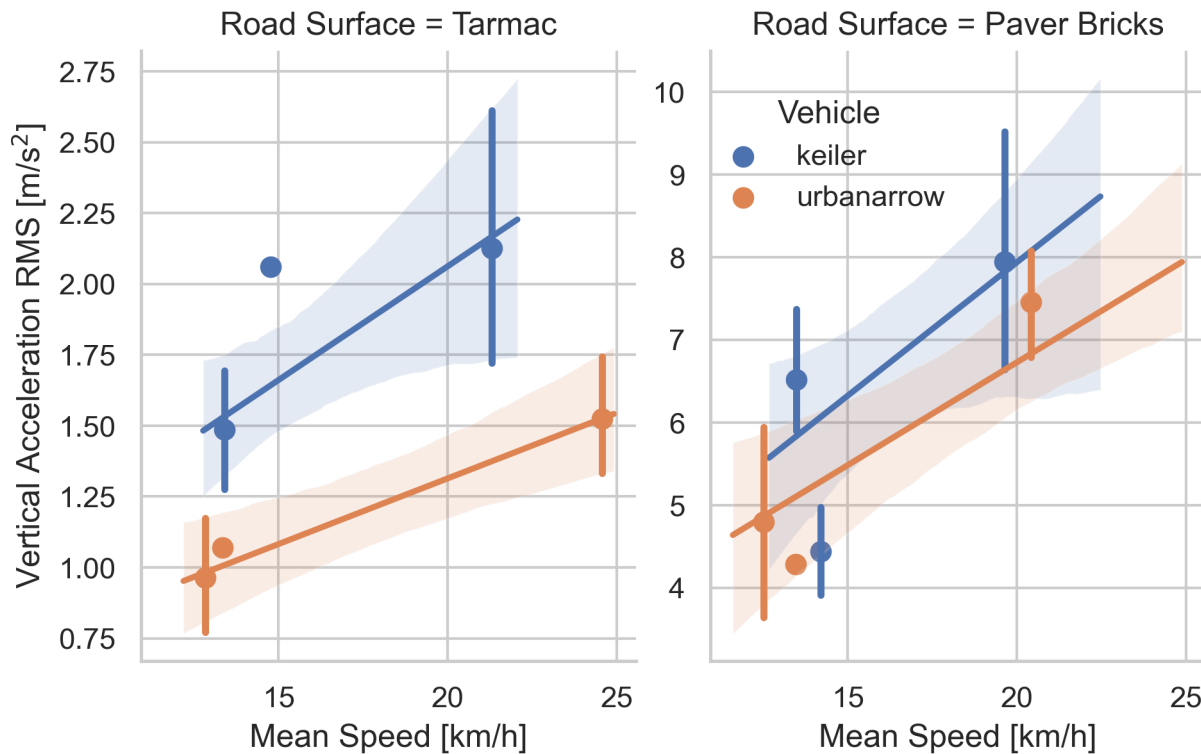


Figure 10: Seat pan ISO 2631-1 weighted vertical RMS acceleration versus speed grouped by road surface and cargo bicycle model. Slanted lines indicate a linear regression, vertical lines are the standard deviation at those speeds, and shaded regions show the 95% confidence intervals for the regression.

frequency between the two road surfaces is not so apparent or consistent.

Figure 12 gives a general indication of bandwidth (80% of the amplitude spectrum content) distributions for each of the target speed groups. Most frequency content is below 45 Hz for all trials. The median bandwidth across all trials is 20 Hz. For the cargo bicycles, the frequency content is spread wider for paver bricks than for tarmac, but for strollers there is likely no significant difference in these surfaces. For strollers, sidewalk pavers, sidewalk slabs, and cobblestones have similar bandwidths. However this is based on the ISO filtering which attenuated the higher frequencies. For the tested lying postures this weighting may have to be reconsidered, as will be addressed further in the discussion.

### 3.6 Health Assessment

Figures 13 and 14 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 boundary of the “health caution” and “health risk” zones in the standard, which has a dependence on exposure duration. 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 the 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 daily continuous exposure is less than 10 min. Additionally, all strollers pushed over tarmac were below the zone if the daily continuous exposure is less than 4 h. Pushing the Bugaboo Fox 5 and Maxi-Cosi Street Plus with a 0 month infant or the Stokke BABYZEN YOYO 0+ with a 9 month infant over cobblestones and sidewalk slabs may have health risks if the duration exceeds 20 min. For almost all of the strollers pushing over any surface except tarmac exceeded the 1 h risk boundary. Notably the Bugaboo Fox 5 and Old Rusty with a 9 mo infant fell under the 1 h threshold for all surfaces. The 0 month dummy experienced worse accelerations than the 9 month dummy in the Bugaboo Fox 5 and Maxi-Cosi Street Plus, but that was opposite for the Stokke YOYO 0+. Old rusty showed the least overall acceleration magnitudes.

For both cargo bicycles, the accelerations exceeded the 10 min health risk threshold when ridden above 20 km h<sup>-1</sup> on paver bricks and exceeded the 1 h health risk threshold when ridden more than

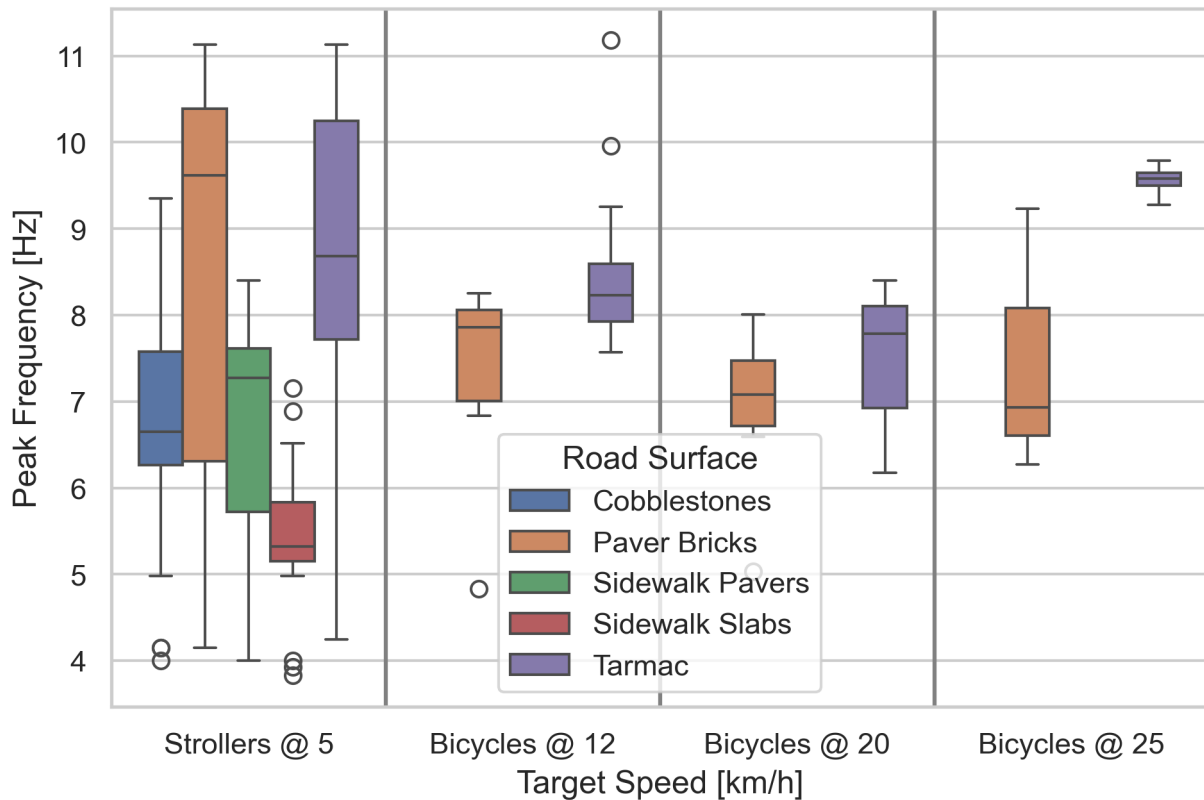


Figure 11: Peak frequency distributions comparisons among road surfaces for each target speed group for non-shock repetitions. The boxes bound the quartiles and indicate the median. The whiskers indicate the 95<sup>th</sup> percentile and circles are any outliers.

1 h above 12 km h<sup>-1</sup> on paver bricks. All but the Keiler with the Maxi-Cosi seat and the 0 mo dummy were under the 1 h threshold for riding on tarmac at any target speed. Only the Urban Arrow with the 3 month dummy is (mostly) under the 4 h threshold when ridden at either speed over tarmac. The accelerations may be less when using the Meila Baby Shell seat versus the Maxi-Cosi car seat, this is statistically considered later in the results.

### 3.7 Comfort Assessment

ISO 2631-1 recommends using the magnitude of the weighted seat pan acceleration vector for comfort assessment. Figures 15 and 16 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 is designed for adults and may not result in a representative comfort assessment for infants or older children. We also include a line representing cyclists' discomfort threshold reported by Gao et. al [5]. It is important to recognize that cyclists perched on a bicycle seat seem to tolerate more vibration discomfort than the 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 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 is the only stroller that falls under the cyclist threshold discomfort line for all surfaces.

Both of the two cargo bicycles ridden at any tested speed over paver bricks, as well as the Keiler with the Maxi-Cosi seat ridden over tarmac at high speed fall into the category "extremely uncomfortable". Those are also above the the cyclist discomfort threshold. The other vehicle setups fall between "fairly uncomfortable" and "very uncomfortable" over tarmac for the range of speeds. The Urban Arrow with

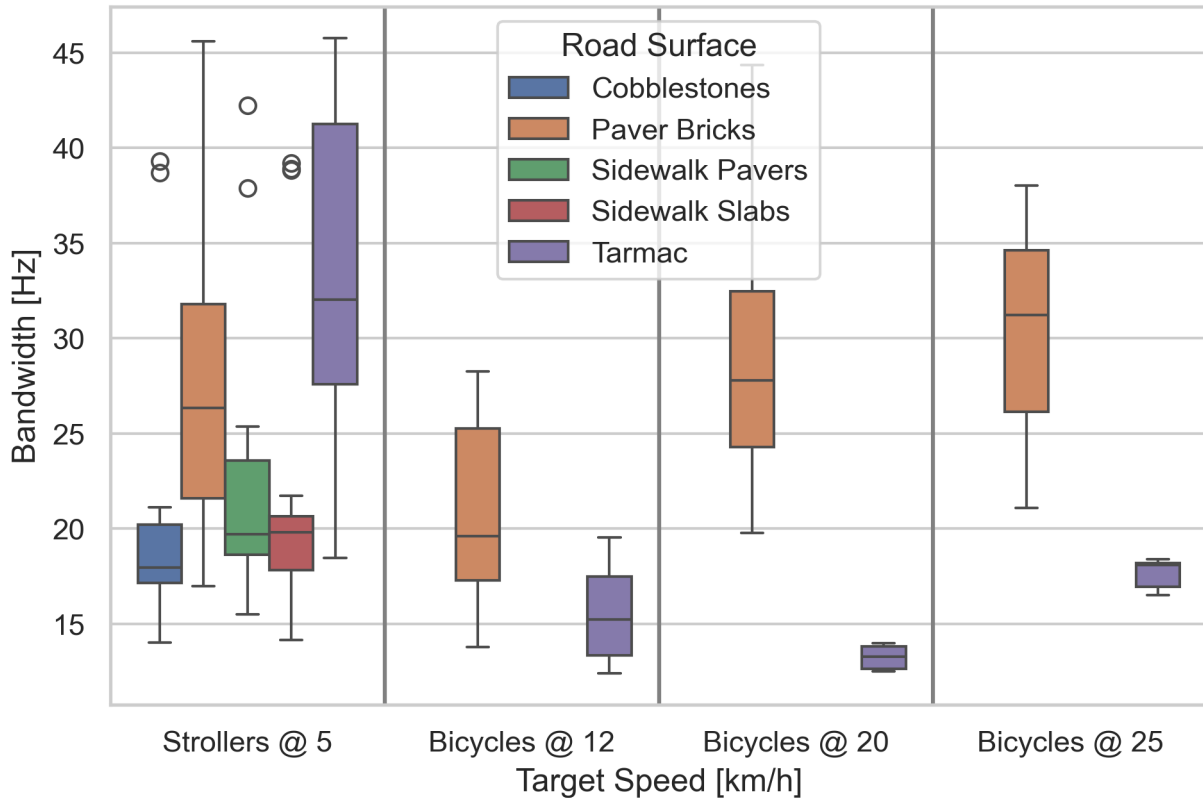


Figure 12: Bandwidth (based on 80% of the area under the ISO 2631-1 filtered amplitude spectrum) for each target speed group for non-shock repetitions. The boxes bound the quartiles and indicate the median. The whiskers indicate the 95<sup>th</sup> percentile and circles are any outliers.

the Melia Baby Shell performs, on average, the best on paver bricks and tarmac at all speeds tested.

### 3.8 Shock

We identified the maximum peak acceleration values for each trial (Equation 6), then averaged them across repetitions to obtain the results listed in Table 3 for different vehicles and configurations. There is a significant variation among tests, with the peaks for the bicycles sometimes reaching the accelerometer's full scale ( $\pm 16$  g). While the seat pan accelerations for the strollers are generally lower than those experienced with the bicycles, the configuration (0 or 9 months) may play a large role. Among bicycles, the use of Melia baby shell seems to transmit lower accelerations compared to Maxi-Cosi, 3 months, for both the Keiler tricycle 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 oldest strollers (Old Rusty and Green Machine) performed very well during the shock test, resulting in the lowest seat pan acceleration among all the tested vehicles. Figure 17 shows the peaks of the vertical acceleration recorded at the seat pan, grouped by different vehicles, for the shock test. As noted in Table 3, the old 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 the tests involving Keiler tricycle and strollers, we cannot exclude that the front wheels (left and right) hit the bump at slightly different time instants.

### 3.9 Statistical Results

Table 4 shows the results of the 11 degrees of freedom stroller 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 stroller pushed over tarmac, which is not significant. All road surfaces cause significantly more acceleration than tarmac with cobblestones having the largest relative effect ( $3.0 \text{ ms}^{-2}$  larger), followed by sidewalk slabs ( $2.7 \text{ ms}^{-2}$  larger), sidewalk pavers ( $1.8 \text{ ms}^{-2}$  larger), and paver bricks ( $1.6 \text{ ms}^{-2}$  larger). The 'Bugaboo, Seat, 9 mo' and 'Maxi-Cosi, Seat, 9 mo' are not

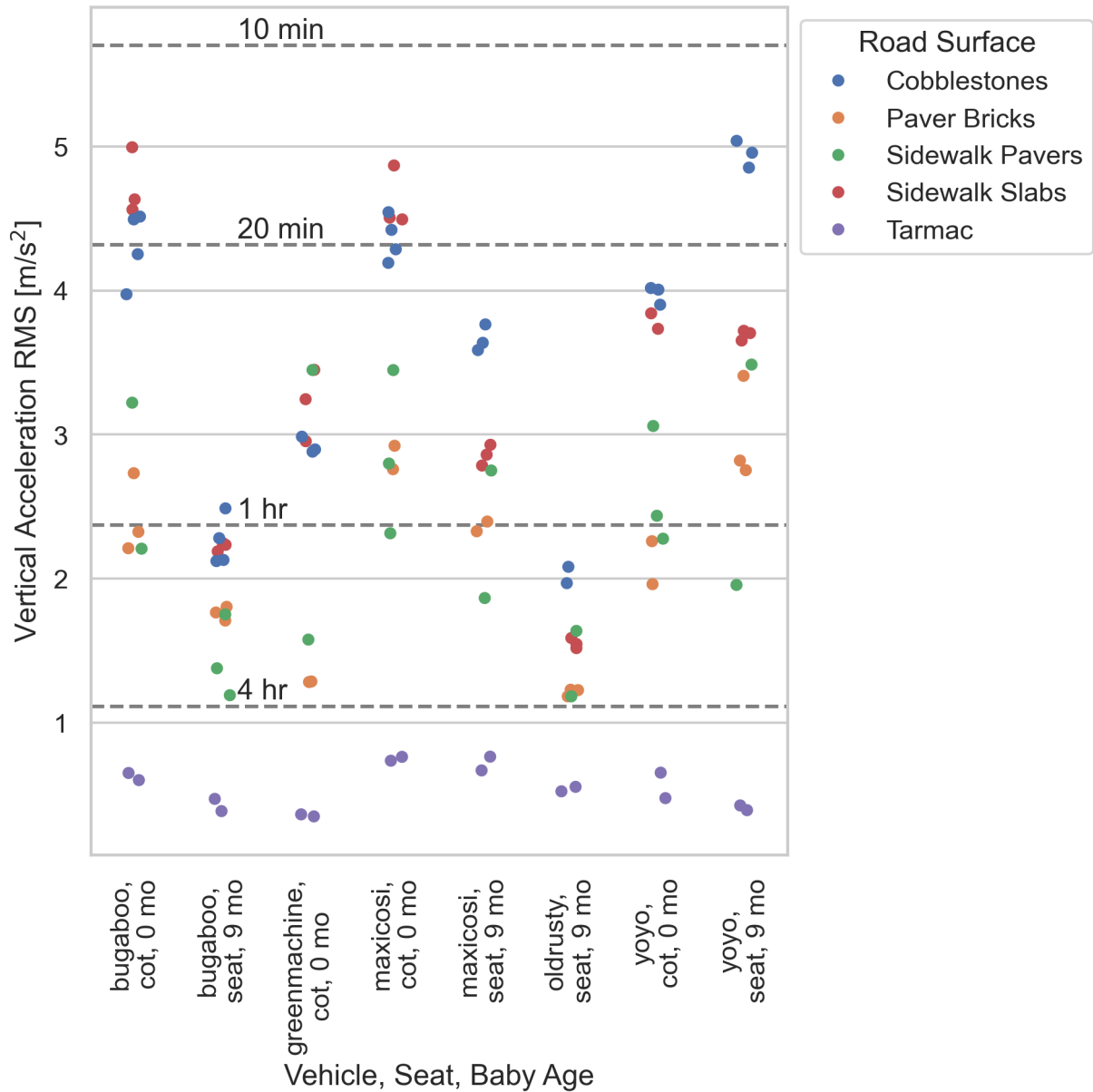


Figure 13: ISO 2631-1 weighted seat pan vertical RMS acceleration of all stroller repetitions with colour representing road surface. The horizontal dashed grey lines with time duration indicators are the upper bound of the ISO 2631-1 “health caution zone” at for adults seated erectly experiencing vibrations for continuous duration in a daily dose.

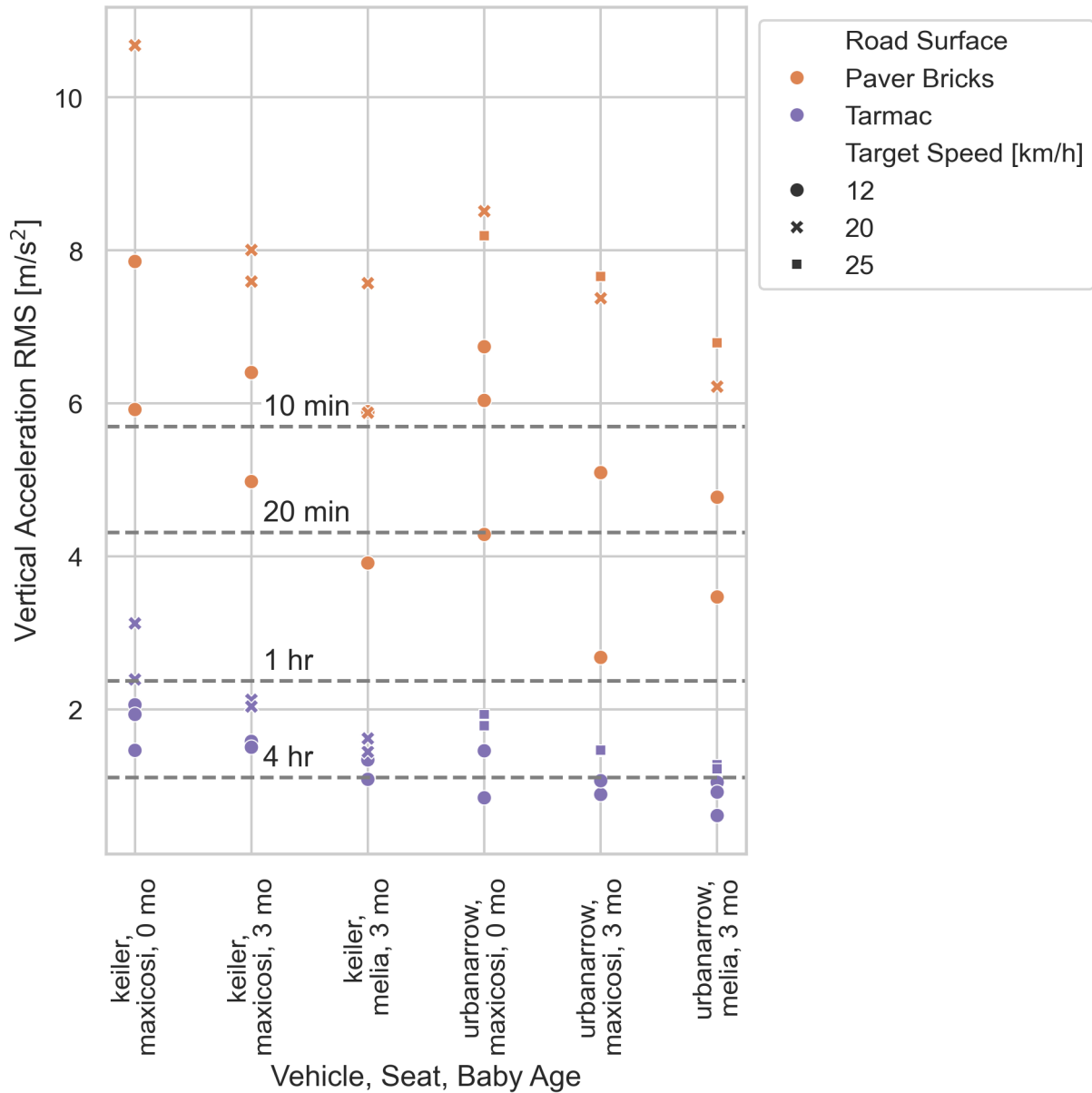


Figure 14: ISO 2631-1 weighted seat pan vertical RMS acceleration of all cargo bicycle trials with colour representing road surface and marker style indicating the target speed. The horizontal dashed grey lines with time duration indicators are the upper bound of the ISO 2631-1 "health caution zone" for adults seated erectly experiencing vibrations for continuous duration in a daily dose.

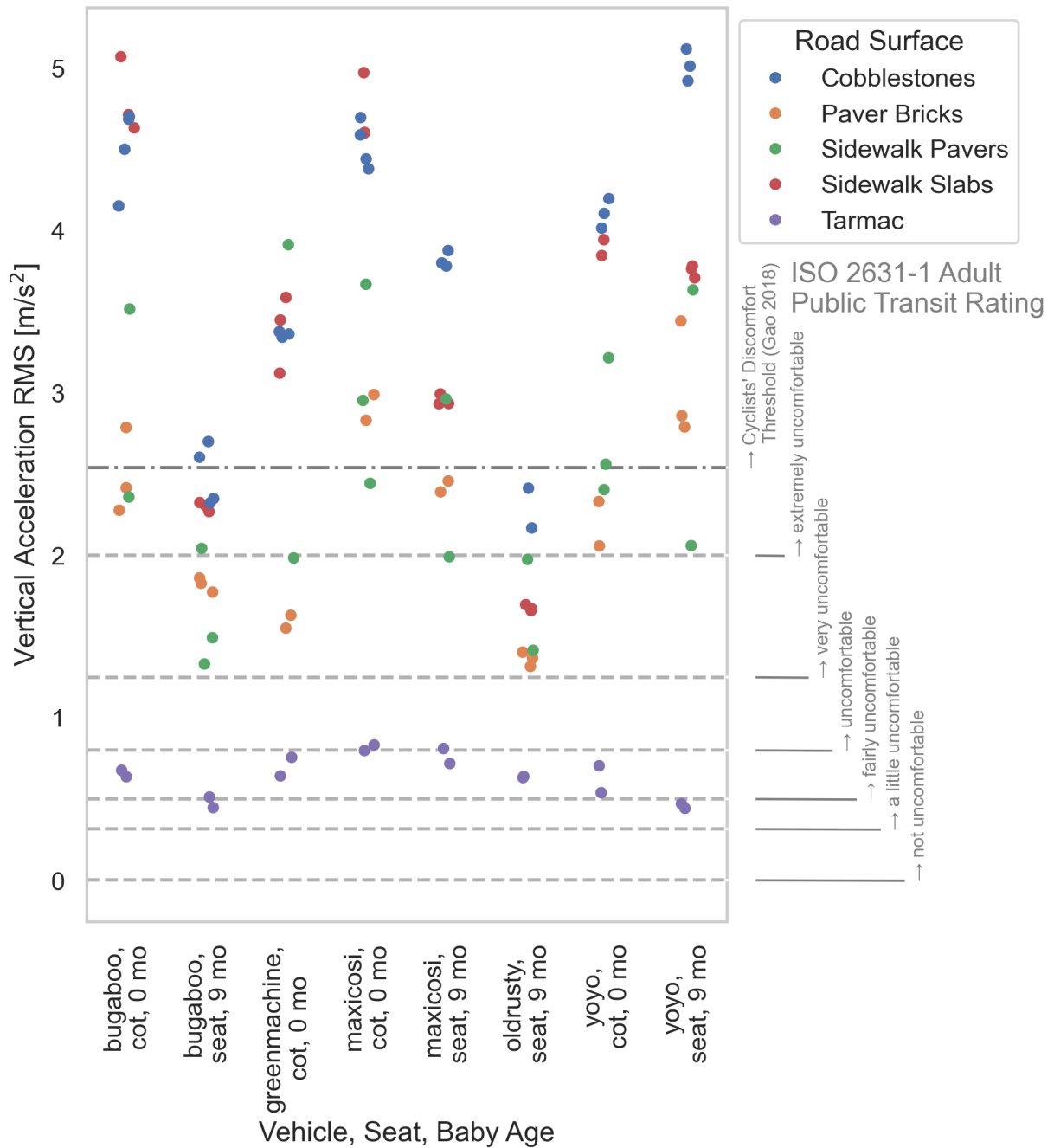


Figure 15: ISO 2631-1 weighted seat pan magnitude RMS acceleration of all stroller repetitions with colour representing road surface. The horizontal dashed lines are the lower bound of the ISO 2631-1 “comfort zones” for adults seated erectly experiencing vibrations in public transit. The horizontal dashed dotted line is the cyclists’ vibration discomfort threshold as reported by Gao et. al [5].

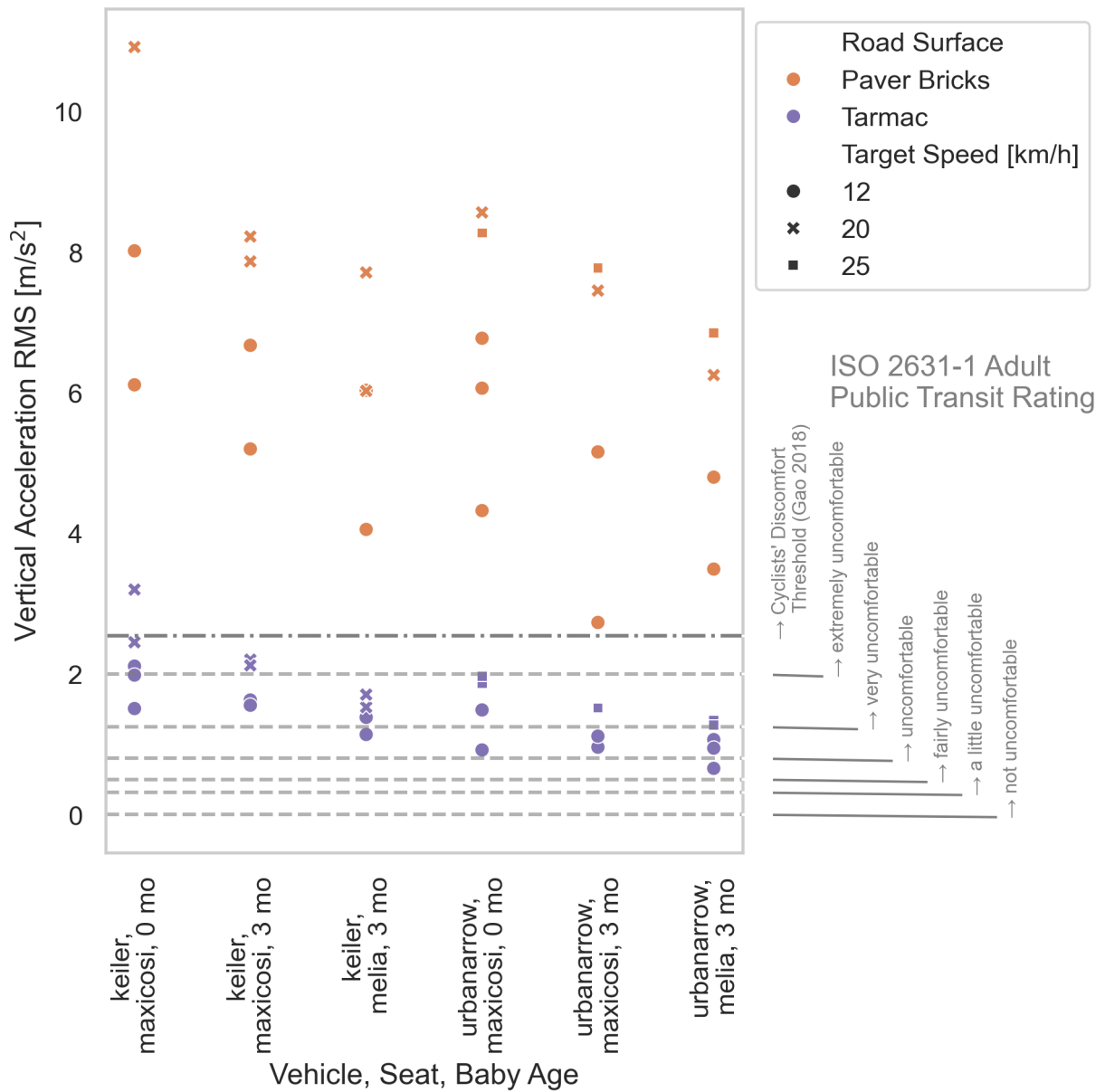


Figure 16: ISO 2631-1 weighted seat pan magnitude RMS acceleration of all cargo bicycle repetitions with colour representing road surface and marker style representing target speed. The horizontal dashed lines with the upper bound of the ISO 2631-1 “comfort zones” for adults seated erectly experiencing vibrations in public transit. The horizontal dashed dotted line is the cyclists’ vibration discomfort threshold as reported by Gao et. al [5].

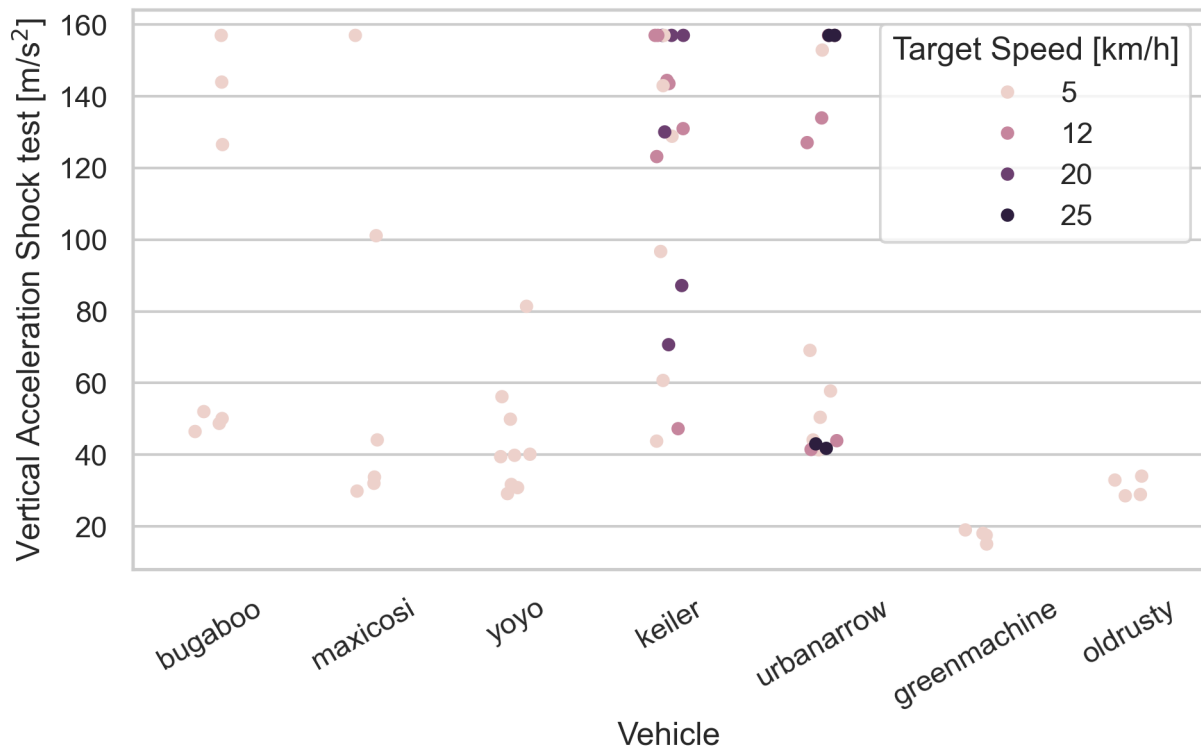


Figure 17: Vertical acceleration recorded at the seat pan during the shock test per each trial, grouped by vehicles. The colour indicates the mean speed of the trial. The lighter the colour the lower the speed.

Table 3: Mean of the maximum seat pan acceleration across trials in  $\text{ms}^{-2}$  recorded for shock test, for different vehicles and baby masses.

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

Table 4: Ordinary Linear Regression Results for Stroller. Tarmac and Green Machine Cot month are the references for the categorical Road Surface and Stroller variables, respectively. The columns give the effect  $\beta$ , standard error, T-statistic, p-value, and the 95% confidence interval lower and upper bounds.

	coef	std err	t	P>  t	[0.025	0.975]
<b>Intercept</b>	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
maxicosi, cot, 0 mo	1.0795	0.202	5.353	0.000	0.679	1.480
maxicosi, seat, 9 mo	0.3012	0.209	1.441	0.153	-0.114	0.716
oldrusty, seat, 9 mo	-0.7551	0.209	-3.605	0.001	-1.171	-0.339
yoyo, cot, 0 mo]	0.5766	0.209	2.753	0.007	0.161	0.993
yoyo, seat, 9 mo	0.9706	0.205	4.731	0.000	0.563	1.378

Table 5: Ordinary Linear Regression Results for Cargo Bicycle. Tarmac and ‘Keiler, Maxi-Cosi, 3 mo’ are the references for the categorical Road Surface and Cargo Bicycle variables, respectively. The columns give the effect  $\kappa$ , standard error, T-statistic, p-value, and the 95% confidence interval lower and upper bounds.

	coef	std err	t	P>  t	[0.025	0.975]
<b>Intercept</b>	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, maxicosi, 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
urbanarrow, maxicosi, 0 mo	-0.0512	0.404	-0.127	0.900	-0.867	0.764
urbanarrow, maxicosi, 3 mo	-0.8895	0.415	-2.141	0.038	-1.728	-0.051
urbanarrow, 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

significantly different than the ‘Green Machine, Cot, 0 mo’ but the other strollers are. The ‘Old Rusty, Seat, 9 mo’ and ‘Bugaboo, Cot, 0 mo’ showed lower RMS acceleration than ‘Green Machine, Cot, 0 mo’ by 0.8 and 0.5  $\text{ms}^{-2}$ , respectively. The remaining strollers have larger accelerations than the ‘Green Machine, Cot, 0 Mo’ on tarmac: ‘Maxi-Cosi, Cot, 0 mo’ (1.1  $\text{ms}^{-2}$ ), ‘Bugaboo, Cot, 0 mo’ (1.0  $\text{ms}^{-2}$ ), ‘YOYO, Seat, 9 mo’ (1.0  $\text{ms}^{-2}$ ), and ‘YOYO, Seat, 0 mo’ (0.6  $\text{ms}^{-2}$ ).

Table 5 shows the results of the 8 degree of freedom cargo bicycle model for the 50 repetitions ( $R^2 = 0.925$ ,  $F = 63.17$ ). The vehicle setup categorical variable has significant effects, the road surface categorical variable alone does not, but the speed and interaction of speed with road surface do have significant effects. The intercept should theoretically be zero, because there is no vertical vibration when the speed is zero and the intercept is not significantly different than zero. Speed is not a significant predictor on tarmac, but the interaction variable shows that 0.8  $\text{ms}^{-2}$  is gained in acceleration for each 1  $\text{km h}^{-1}$  increase on paver bricks. Only the Urban Arrow with the 3 mo infant in either seat has significant difference to the ‘Keiler, Maxi-Cosi, 3 mo’, both showing reduction in relative acceleration.

**Vehicle Comparisons** Given that the vehicle setup ( $x_{\text{Stroller}}$  and  $x_{\text{Cargo Bicycle}}$ ) is a significant effect, we perform a post-hoc analysis to compare vehicles on each road surface. Table 6, derived from Figure 39 in Appendix C, 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 ‘YOYO, Seat, 9 mo’ is the worst stroller tested and, interestingly, the the heavier dummy performs worse than the lighter dummy, 2) the 9 mo dummy experiences less 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) ‘YOYO, Seat, 9 mo’ sees more acceleration than the 0 mo configuration. For sidewalk pavers, there is no significant difference among the strollers. For side walk 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 the YOYO when comparing dummy sizes. For tarmac: the Green Machine, ‘Bugaboo, Seat, 9 mo’, and ‘YOYO, Seat, 9 mo’ are better than

Table 6: Stroller Significance Ranking Groups (based on Figure 39). 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
yoyo, seat, 9 mo	7	8	6-8	1-8	5-6	1-6
yoyo, cot, 0 mo	4	4-5	3-5	1-8	5-6	1-8
oldrusty, seat, 9 mo	1	1-2	1-3	1-8	1	1-8
maxicosi, seat, 9 mo	4	4-5	3-6	1-8	3-4	4-8
maxicosi, seat, 0 mo	8	6-7	6-8	1-8	7-8	4-8
greenmachine, cot, 0 mo	3	3	1-3	1-8	3-4	1-4
bugaboo, seat, 9 mo	1	1-2	1-3	1-8	2	1-6
bugaboo, cot, 0 mo	6	6-7	3-6	1-8	7-8	2-8

Table 7: Cargo Bicycle Significance Ranking Groups (based on Figure 40). 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
urbanarrow, melia, 3 mo	1	1-6	1-5	1-5	1-5
urbanarrow, maxicosi, 3 mo	2	1-6	1-6	1-5	1-5
urbanarrow, maxicosi, 0 mo	4	1-6	1-6	1-6	1-5
keiler, melia, 3 mo	2	1-6	1-6	1-5	1-5
keiler, maxicosi, 3 mo	5	1-6	1-6	1-6	1-6
keiler, maxicosi, 0 mo	6	1-6	2-6	3-6	4-6

Maxi-cosi with either dummy size and 2) the Green Machine is better than the ‘Bugaboo, Cot, 0 mo’.

When comparing the cargo bicycles, Table 7, 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 the Meila Baby Shell and a 3 mo dummy has significantly less acceleration than the Keiler with the Maxicosi and 0 mo 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 the Meila seat and the 3 mo dummy is significantly better than the Keiler with the Maxicosi and the 0 mo 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 mo dummy, which does not support the hypothesis in Section 3.6.

## 4 Discussion

We have presented a comprehensive set of acceleration measurements from experiments that simulate the vibrations experienced by dummy infants in the 0-9 month mass range during transportation in both 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 while moving at typical vehicle travel speeds. Excluding the shock tests, ISO 2631-1 weighted average acceleration can range from  $0.4 \text{ m s}^{-2}$  to  $10.7 \text{ m s}^{-2}$  across all tested scenarios. Strollers induced  $0.4 \text{ m s}^{-2}$  to  $5.0 \text{ m s}^{-2}$  average acceleration for a mean walking speed of  $5.3 \text{ km h}^{-1}$ . Cargo bicycles induced  $0.6 \text{ m s}^{-2}$  to  $10.7 \text{ m s}^{-2}$  over a speed range of  $12 \text{ km h}^{-1}$  to  $25 \text{ km h}^{-1}$ .

### 4.1 Surface and Speed

Travelling over a tarmac surface offers the least vibration to all vehicle types at any speed with a maximum average acceleration of  $1.2 \text{ m s}^{-2}$ . For strollers, travelling over surfaces rougher than tarmac at normal walking speed can cause, on average,  $5 \times$  the acceleration experienced on tarmac with average accelerations

reaching  $5.0 \text{ m s}^{-2}$ . Cobblestones and the large gaps in the sidewalk slabs caused the largest magnitude of vibrations at the seat pan in the strollers. Cobblestones and sidewalk slabs approximately double the vibration amplitude relative to sidewalk paver and paver bricks, with them all being significant larger than tarmac vibrations.

For cargo bicycles, travelling over paver bricks at the same speeds can quadruple the magnitude of the average acceleration the dummy experiences. Travelling at the maximum allowed speed of an electric cargo bicycle ( $25 \text{ km h}^{-1}$ ) over paver bricks caused the dummy to experience average accelerations exceeding  $8 \text{ m s}^{-2}$ . The effect of speed on vibration is significant for paver bricks but not for tarmac.

Whereas speed strongly affected the acceleration amplitude it does not strongly affect the peak frequency and the bandwidth below which 80% of power is contained. This suggests that peak frequencies represent oscillations induced by the systems tested rather than dominant frequencies resulting from the road surface.

## 4.2 Baby Mass

The size of the dummy (mass and build) had no obvious and systematic effect on the average acceleration at the seat pan body-seat interface. These vibrations are transmitted to an infant's body and the physical properties (mass, stiffness, 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 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 hard 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 has less acceleration than the heavier dummy for the Stokke BABYZEN YOYO 0+ stroller.

## 4.3 Health

The vibrations measured in the different scenarios showed that RMS acceleration can be relatively large when compared to the smoothest experience on tarmac. There is a large gap in the literature connecting acceleration magnitude to discomfort and/or health consequences, which is particularly absent for infants. The most used health and comfort assessment tool for whole-body vibration is the ISO 2631-1 standard. When we investigated health risks using the standard we found that:

- only strollers pushed over tarmac at  $5 \text{ km h}^{-1}$  had average acceleration below the “health risk zone” for 4 h daily duration,
- strollers pushed over cobblestones and sidewalk slabs can deliver accelerations in the “health risk zone” with durations less than 20 min,
- cargo bicycles ridden at  $12 \text{ km h}^{-1}$  to  $25 \text{ km h}^{-1}$  over tarmac overwhelmingly delivered accelerations below the 1 h “health risk zone”, and
- cargo bicycles ridden at  $12 \text{ km h}^{-1}$  to  $25 \text{ km h}^{-1}$  over paver bricks delivered accelerations well into the 10 min “health risk zone”.

When we compare the vibration we measured for infants in strollers and cargo bicycles with the vibration “health risk zone” as defined for adults in the ISO 2631-1 standard, we see that:

- cycling with an infant in a cargo bicycle on paver bricks with  $20 \text{ km h}^{-1}$  for 10 min gives the infant a vibration load that equals or exceeds the “health risk zone” for adults seated erectly experiencing vibrations,
- cycling with an infant in a cargo bicycle on tarmac at  $12 \text{ km h}^{-1}$  can be maintained for approximately two hours before exceeding the “health risk zone” for adults seated erectly experiencing vibrations,
- walking with an infant in a stroller on cobblestones can exceed the “health risk zone” for adults seated erectly experiencing vibrations within 15 min to 1 h, depending on the stroller model and the age of the child, and
- walking with an infant in a stroller on tarmac can be continued for four hours without exceeding the “health risk zone” for adults seated erectly experiencing vibrations.

We can conclude that strollers can be pushed over paver bricks and sidewalk pavers continuously for maximal about half an hour. On extreme surfaces like cobblestones and sidewalk slabs, strollers should be pushed slower than  $5 \text{ km h}^{-1}$  with a duration of maximal 10 min. Only on tarmac a stroller can be walked continuously for four hours (but only if the infant is in the cot, for if it is sitting it needs appropriate breaks to enable movement). Cargo bicycles carrying infants over paver bricks should slow down to  $12 \text{ km h}^{-1}$  or preferably less and the duration should be kept under 10 min. When riding a cargo bicycle over tarmac at  $20 \text{ km h}^{-1}$ , the duration should be kept under 1 h. At  $12 \text{ km h}^{-1}$  cargo bicycles can ride over tarmac for maximal 2 h.

#### 4.4 Comfort

When considering comfort, the ISO 2631-1 guidelines indicate 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 this scale is unlikely appropriate to apply for our situation. Gao et al. [5] reports that cyclists do not rate vibrations as extremely uncomfortable on normal road surfaces, indicating some contradiction.

#### 4.5 Vehicle and Seat Design

Different vehicle, seat, and baby mass combinations cause different average vertical accelerations at the seat pan. We are only able to compare vehicle setup to vehicle setup, other than comparing the same two different baby seats in both cargo bikes. A striking discovery is that the two 1970’s strollers we tested were significantly better than many of the modern stroller setups on most road surfaces. The vintage strollers actually had more sophisticated suspension systems that used springs, straps, and mechanisms, and they also had larger wheels. Stroller manufacturers may have reduced suspension as a side effect to decreasing the size and weight of strollers and introducing swivelling front wheels (which makes steering lighter but can technically not be combined with the design of old suspension types). As an example, the “Old Rusty” stroller was the only one that did not exceed the 1 h health risk line for all road surfaces.

Both the Bugaboo Fox 5 and Maxi-Cosi Street Plus stroller showed lower acceleration for the heavier baby, as expected, but the Stokke BABYZEN YOYO 0+ showed the opposite trend for cobblestones and paver bricks. This points to design choices that may cause resonance on certain surface profiles. The ‘Bugaboo, Seat, 9 mo’ configuration performed better than the other modern strollers for all non-tarmac road surfaces. Urban Arrow performed better than Keiler on tarmac but there is no difference on paver bricks. Additionally, there was no difference in the different seats for the 3 month infant. Performance of a vehicle setup is not necessarily constant with respect to cot or seat configuration, contrarily, performance is often significantly different when converting for different baby ages. This points towards designs that are only optimized for one configuration.

#### 4.6 ISO Filters and Bandwidth

We report RMS accelerations up to 120 Hz as well as accelerations weighted according to the ISO standards for vibration (VDV). Vibrations at frequencies between 4.9 Hz to 10.7 Hz showed to have the largest magnitude contribution to the vibrations, but there is a frequency content of magnitudes of interest in a bandwidth of up to 45 Hz. 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 [6]). Adult experiments show that significant discomfort can be measured across all tested frequencies being 80 Hz [16] or even 315 Hz [15] 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 which filter out such high frequencies [34, 14]. However, adult experiments show higher discomfort for frequencies above 8 Hz when lying with head supported with  $30^\circ$  to  $90^\circ$  back inclination as compared to erect without head support. 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  $5 \text{ m s}^{-2}$  [39]. In some conditions, the RMS exceeds the ISO Weighted RMS substantially, warranting further research on the effects of higher frequencies in particular for head supported conditions and for children. The VDV showed even higher values warranting further research on the relevance of peaks and transients.

## 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 go very slow over them when the cargo is an infant, there are potential health risks if the large vibrations are experienced daily and repeatedly over a longer time. In most likelihood, users do adjust their travel behaviour, but maybe not enough or possibly they are neglectful, but this has yet to be studied. There is no direct evidence that connects whole-body vibration as measured in this study to infant harm or negative health effects, so we can only extrapolate from the limited guidelines on adults in occupational settings. But 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.

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

### 5.2 Recommendations

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

**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. Stroller, cargo bicycle, and seat manufacturers should test for vibration for all expected surface types and ranges of relevant body sizes and posture to ensure 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 stroller mass.
2. Manufacturers should collaborate in testing and report their results publicly, similar to the automobile industry safety ratings. 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. Cycling roads should have a tarmac-like smoothness. Cobblestones should be avoided.
7. Sidewalks should have a tarmac-like smoothness. Cobblestones should be avoided for strollers.
8. Users should limit their speed when walking with strollers or riding over surfaces rougher than tarmac, as bumpier surfaces can quickly multiply the experienced accelerations.
9. 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 (existence 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 give the infant opportunity to move.
10. Preferably ride any cargo bicycle at a speed of maximal  $12 \text{ km h}^{-1}$  over surfaces rougher than tarmac. E-cargo bicycles can easily reach the maximum speed of  $25 \text{ km h}^{-1}$ . Infants should only be transported for short durations when riding over non-tarmac surfaces at these speeds.
11. Standard ISO 2631-1 is not validated to characterize 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.

### 5.3 Future Work

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

**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:** There are products and variables that have not yet been investigated for their effect on vibration. For example, running with an infant in a sports stroller is not tested. Investigating this is important because we expect that vibrations when running may quickly exceed health limits. In addition, recumbent posture in sports strollers is 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 are made for the vibrational properties of child transport systems in the standards for strollers, cargo bicycles, bicycle seats, and car seats. Due to the magnitude of vibrations that can occur during child transport, it is imperative to include a requirement to the vibrational properties in the standards for these products. At this moment, no new requirements can be defined 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. This will enable the inclusion of minimal requirements for vibration properties in the standards, which would greatly increase the health and comfort of the infants who must use these products.

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## A Experimental Equipment

In this section, we report the pictures of the strollers and bicycles used for the experiments. The reader can find the measurements, wheelbase, wheel diameter, sensor location and orientation for all the tested vehicles.

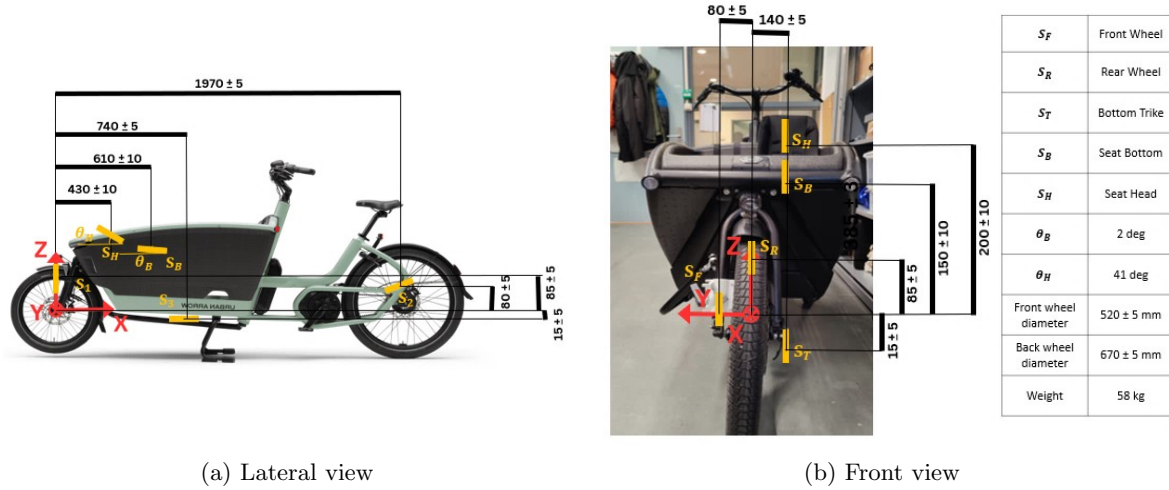


Figure 18: IMU locations on the Urban Arrow cargo bicycle, equipped with the Maxicosi-Joolz baby Pebble.

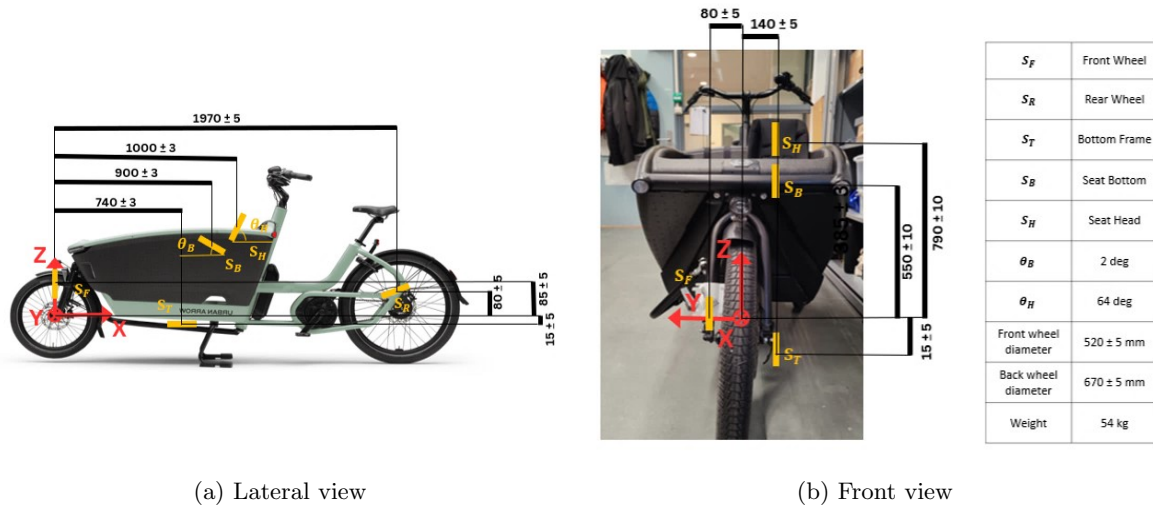


Figure 19: IMU locations on the Urban Arrow cargo bicycle, equipped with the Melia baby shell.

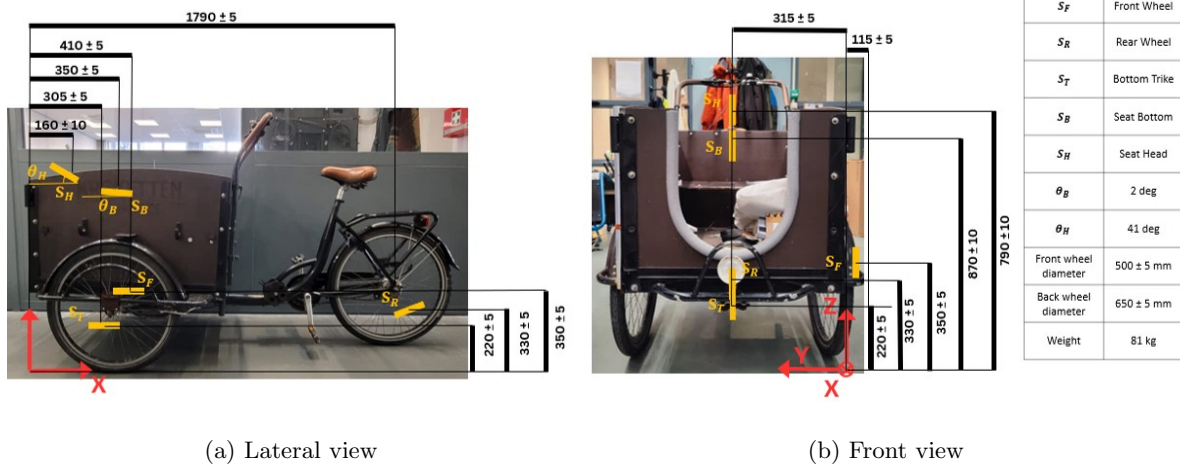


Figure 20: IMU locations on the Keiler Tricycle, equipped with the Maxicosi-Joolz baby pebble.

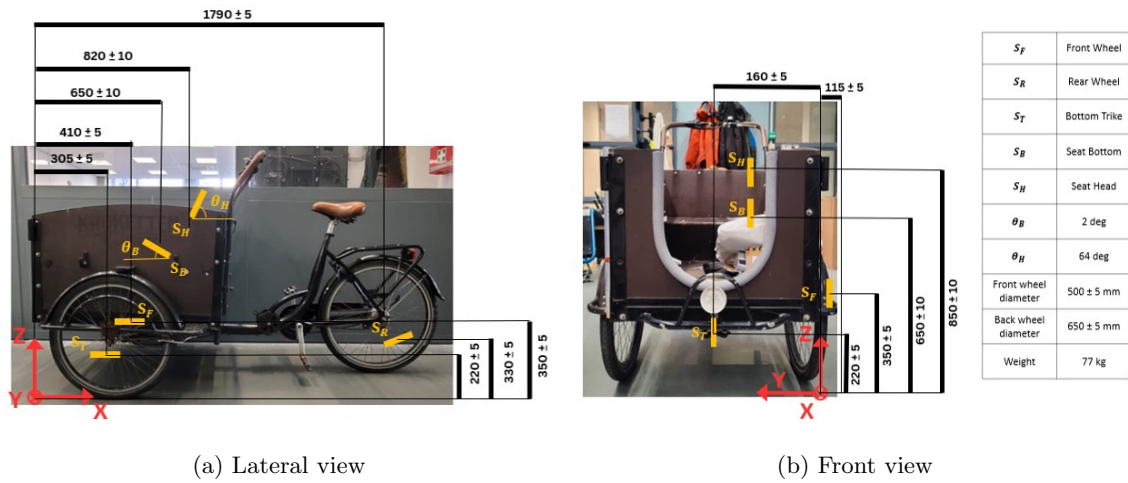
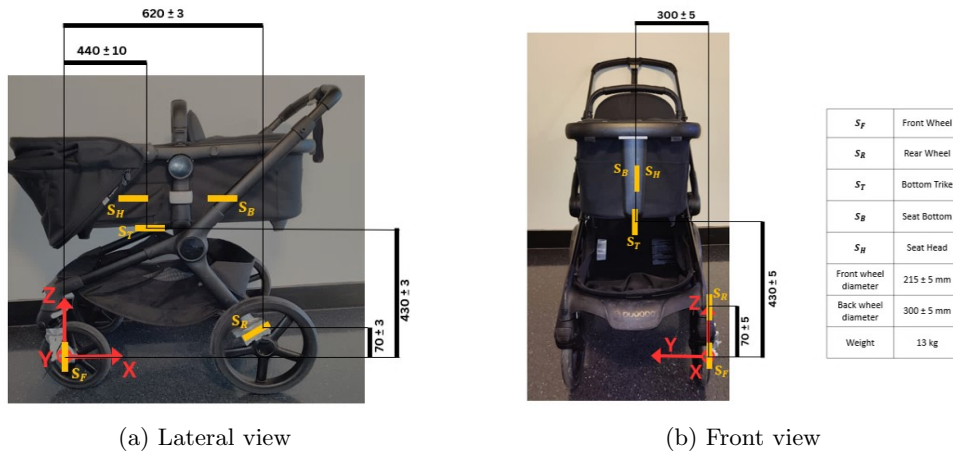


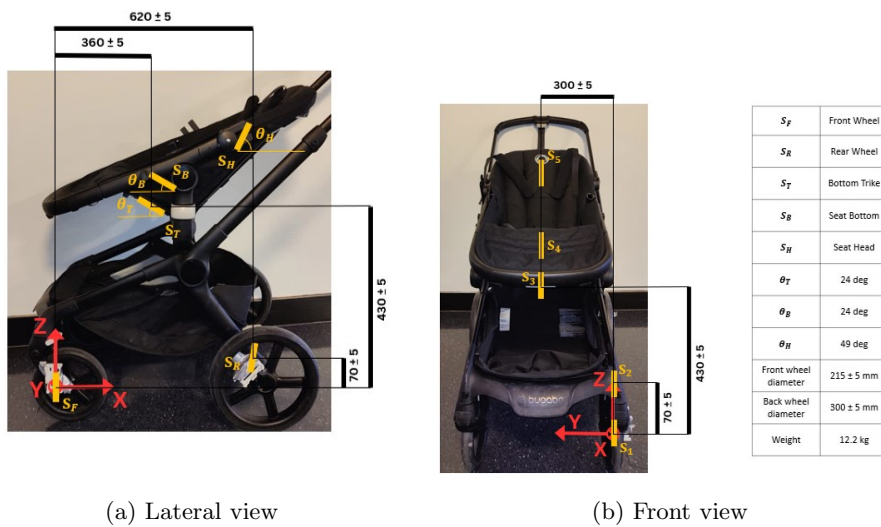
Figure 21: IMU locations on the Keiler Tricycle, equipped with the Melia baby shell.



(a) Lateral view

(b) Front view

Figure 22: IMU locations on the stroller Bugaboo Fox 5, configured for 0-months baby.



(a) Lateral view

(b) Front view

Figure 23: IMU locations on the stroller Bugaboo Fox 5, configured for 9-months baby.

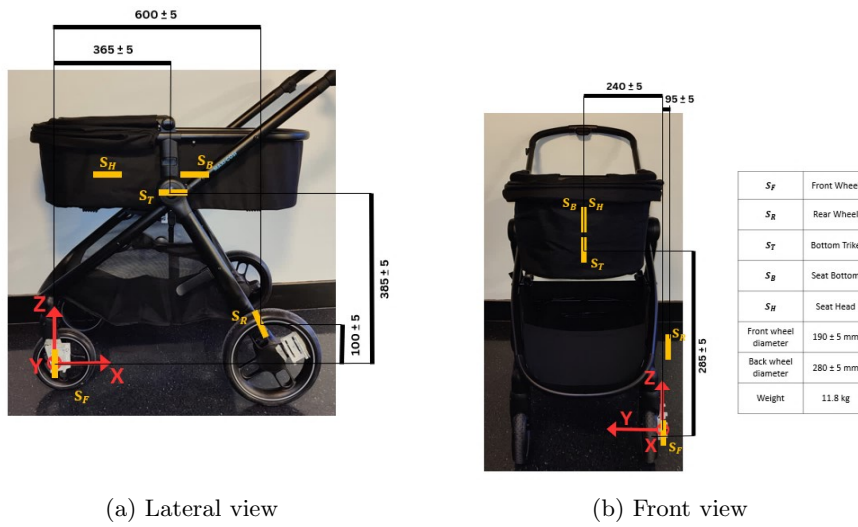


Figure 24: IMU locations on the stroller Maxi-Cosi Street Plus, configured for 0-months baby.

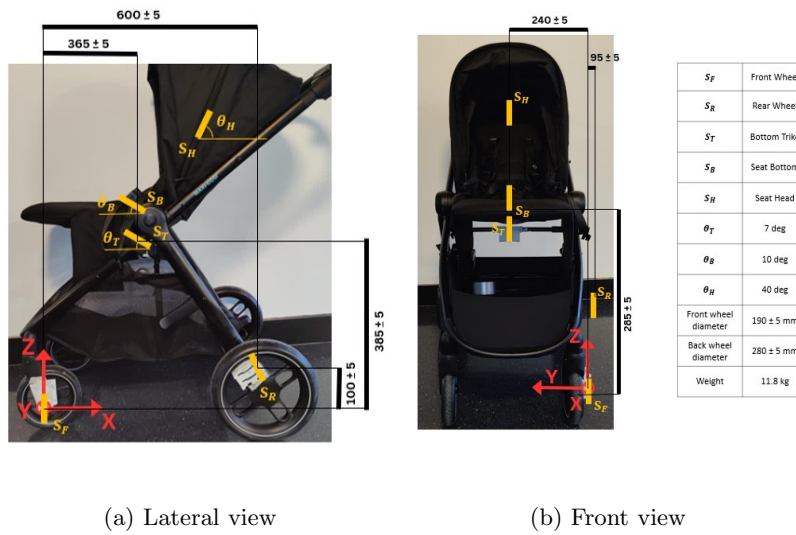


Figure 25: IMU locations on the stroller Maxi-Cosi Street Plus, configured for 9-months baby.

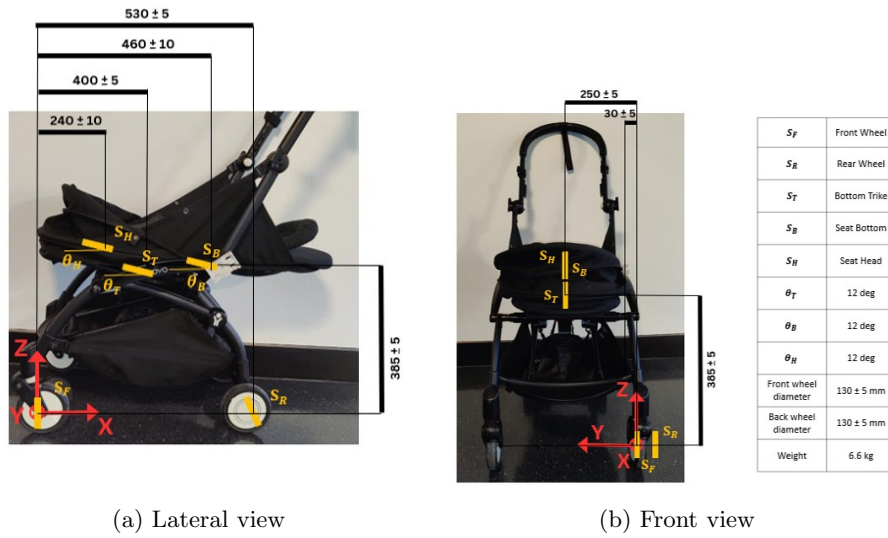


Figure 26: IMU locations on the stroller Stokke BABYZEN YOYO 0+, configured for 0-months baby.

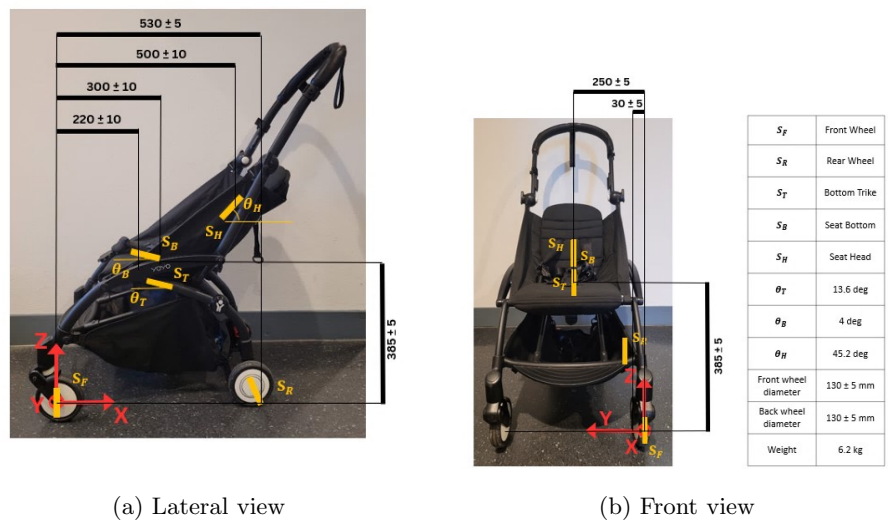


Figure 27: IMU locations on the stroller Stokke BABYZEN YOYO 0+, configured for 9-months baby.

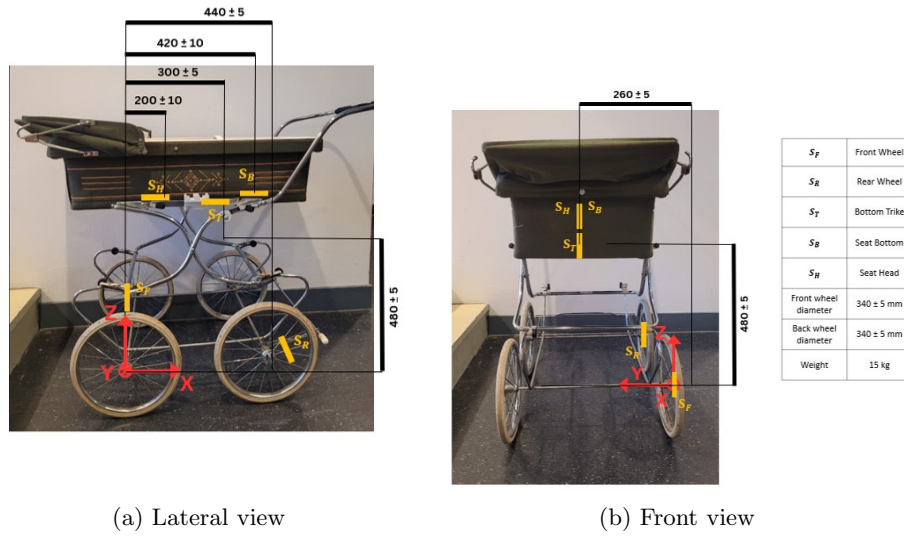


Figure 28: IMU locations on the old stroller Green Machine, configured for 0-months baby.

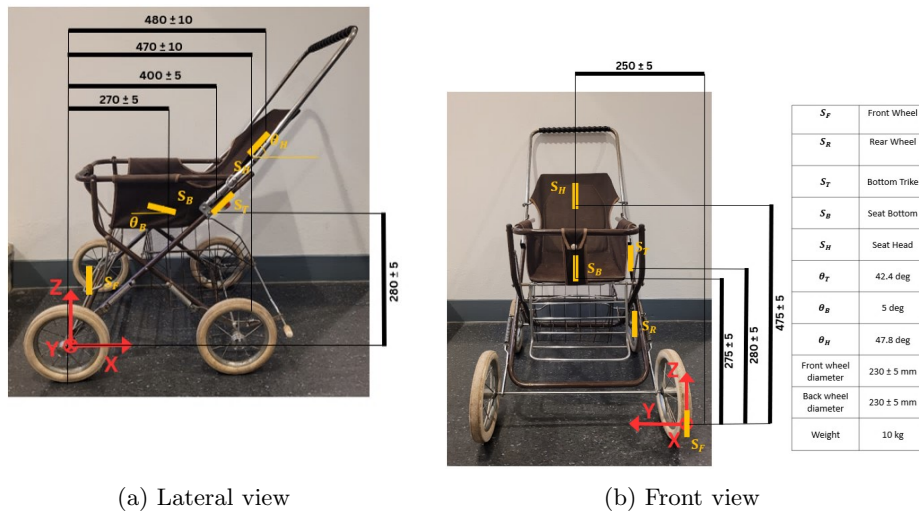


Figure 29: IMU locations on the old stroller Old Rusty, configured for 9-months baby.

## A.1 Location and pictures of the experiment areas

### A.1.1 For Bicycles

- Tarmac

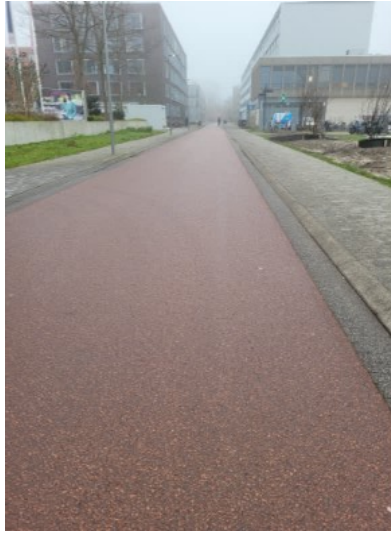


Figure 30: Tarmac surface where we tested bicycles.

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

- Paver bricks



Figure 31: Paver bricks surface where we tested bicycles.

The bicycle experiment on the paver bricks was conducted along Kanaalweg, 2611 DD Delft, The Netherlands (GPS coordinates: 52.006264, 4.363013).

Details of paver brick: rectangular shape, dimensions 195 x 95 mm (gap in between:  $7 \pm 2$  mm).

- Shock



Figure 32: 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 squared section aluminium bar 30 x 30 mm.

#### A.1.2 For Strollers

- Tarmac



Figure 33: Tarmac test area.

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

- Cobblestone



Figure 34: Cobblestone surface where we tested strollers.

The bicycle experiment on the cobblestone was conducted along Julianalaan Straat, 2628 BG Delft, The Netherlands (GPS coordinates: 52.002727, 4.366845). Details of cobblestone: rectangular shape, dimensions 180 x 125 mm (gap in between:  $20 \pm 4$  mm).

- Sidewalk pavers



Figure 35: 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 290 x 290 mm (gap in between:  $12 \pm 2$  mm).

- Sidewalk slabs



Figure 36: Sidewalk slab test area where we conducted 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 2000 x 990 mm (gap in between:  $160 \pm 3$  mm).

- Paver bricks

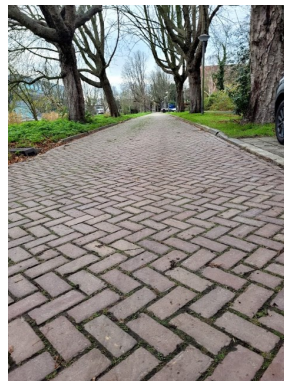


Figure 37: Details of the paver bricks test area.

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 195 x 95 mm (gap in between:  $7 \pm 2$  mm).

- Shock



Figure 38: 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 squared section aluminium bar 30 x 30 mm.

## B Table of Repetition Metrics

Table 8 shows the mean over the scenario repetitions unweighted and ISO 2631-1 weighted seat pan vertical RMS acceleration, unweighted seat pan vertical VDV, crest factor, peak frequency, bandwidth, and duration for all 52 combinations of vehicle setup, road surface, and target speed.

Table 8: Mean computed metrics for all 52 non-shock scenarios, using seat pan vertical accelerations.

Vehicle	Seat, Baby	Road Surface	Target Speed [km h <sup>-1</sup> ]	Trial Count	RMS Accel [m s <sup>-2</sup> ]	ISO Weighted RMS Accel [m s <sup>-2</sup> ]	VDV Accel [m s <sup>-2</sup> ]	Crest Factor	Peak Freq. [Hz]	Bandwidth [Hz]	Duration [s]
bugaboo	cot, 0 mo	Cobblestones	5	4	4.4	4.3	6.6	6.2	6.5	14.3	20.4
		Paver Bricks	5	3	2.6	2.4	3.4	4.1	9.5	17.2	23.3
		Sidewalk Pavers	5	2	2.9	2.7	7.5	13.5	6.1	18.5	25.4
		Sidewalk Slabs	5	3	4.8	4.7	7.9	6.4	5.8	15.1	20.2
		Tarmac	5	2	0.7	0.6	0.9	3.3	10.1	18.5	23.1
	seat, 9 mo	Cobblestones	5	4	2.5	2.3	3.4	4.7	6.6	20.7	22.5
		Paver Bricks	5	3	2.3	1.8	3.0	3.8	9.4	26.4	22.6
		Sidewalk Pavers	5	3	1.7	1.4	2.5	5.5	7.7	23.8	24.7
		Sidewalk Slabs	5	3	2.4	2.2	3.6	5.3	6.0	20.3	24.5
		Tarmac	5	2	0.6	0.4	0.8	6.5	8.4	29.3	34.6
greenmachine cot, 0 mo	Cobblestones	5	3	3.2	2.9	4.6	5.3	4.1	17.3	23.7	
	Paver Bricks	5	2	1.6	1.3	2.1	4.5	4.2	26.8	29.6	
	Sidewalk Pavers	5	2	2.7	2.5	4.2	6.5	4.1	18.5	28.2	
	Sidewalk Slabs	5	3	3.5	3.2	5.5	6.7	3.9	16.8	23.9	
	Tarmac	5	2	0.5	0.4	0.6	4.1	4.2	33.4	22.1	
keiler	maxicosi, 0 mo	Paver Bricks	12	2	7.0	6.9	11.2	7.2	7.6	16.7	23.8
			20	1	12.6	10.7	27.1	9.9	6.8	26.9	34.0
		Tarmac	12	3	1.8	1.8	3.3	8.3	8.1	13.3	24.6
			20	2	2.8	2.8	3.9	5.1	7.8	13.2	29.2
	maxicosi, 3 mo	Paver Bricks	12	2	6.3	5.7	12.3	11.0	8.0	21.9	28.9
			20	2	9.8	7.8	23.5	14.4	7.2	30.7	21.4
		Tarmac	12	2	1.5	1.5	2.6	8.1	7.6	12.8	27.8
			20	2	2.1	2.1	2.8	3.9	6.4	12.7	23.8
	melia, 3 mo	Paver Bricks	12	2	5.4	4.9	8.9	8.1	7.9	21.9	26.3
			20	2	9.5	6.7	19.7	10.2	6.8	34.8	23.0
		Tarmac	12	2	1.2	1.2	2.1	8.2	7.8	14.2	25.4
			20	2	1.6	1.5	2.1	3.8	8.3	13.8	22.6
maxicosi	cot, 0 mo	Cobblestones	5	4	4.6	4.4	6.4	4.9	8.1	18.3	20.7
		Paver Bricks	5	2	3.2	2.8	4.2	3.9	10.4	21.1	27.2
		Sidewalk Pavers	5	3	3.0	2.9	4.5	5.5	7.6	18.1	21.4
		Sidewalk Slabs	5	3	5.0	4.6	8.4	8.2	5.1	20.7	16.3
		Tarmac	5	2	0.9	0.8	1.4	8.0	9.6	24.4	34.3
	seat, 9 mo	Cobblestones	5	3	4.1	3.7	5.8	5.8	8.0	20.3	25.9
		Paver Bricks	5	2	3.0	2.4	3.9	3.4	9.7	24.0	27.8
		Sidewalk Pavers	5	2	2.6	2.3	4.1	5.5	7.3	21.2	27.8
		Sidewalk Slabs	5	3	3.1	2.9	4.7	5.4	6.9	20.1	25.6
		Tarmac	5	2	1.0	0.7	1.4	5.8	10.2	30.0	36.1
oldrusty	seat, 9 mo	Cobblestones	5	2	4.7	2.0	7.5	6.0	5.1	39.0	29.9
		Paver Bricks	5	3	3.4	1.2	4.9	6.1	5.2	44.2	21.9
		Sidewalk Pavers	5	2	3.3	1.4	5.5	9.7	5.4	40.1	27.3
		Sidewalk Slabs	5	3	3.2	1.6	6.1	11.6	5.3	39.0	23.8
		Tarmac	5	2	1.1	0.5	1.6	5.7	7.0	42.1	22.6
urbanarrow	maxicosi, 0 mo	Paver Bricks	12	3	6.5	5.7	14.5	9.6	7.6	21.4	20.8
			20	1	9.2	8.5	15.9	9.9	8.0	19.8	39.1
			25	1	11.6	8.2	30.4	13.7	6.9	38.0	38.3
		Tarmac	12	2	1.3	1.2	2.4	8.3	9.3	18.5	29.0
			25	2	2.1	1.9	2.9	5.2	9.7	18.1	21.5
	maxicosi, 3 mo	Paver Bricks	12	2	4.5	3.9	11.0	13.5	5.8	21.6	29.1
			20	1	10.8	7.4	30.2	14.7	5.0	32.4	32.1
			25	1	10.6	7.7	29.4	14.7	6.3	31.2	30.3
		Tarmac	12	2	1.1	1.0	2.0	9.6	8.8	18.3	25.3
			25	2	1.6	1.5	2.3	4.9	9.5	18.3	21.6
	melia, 3 mo	Paver Bricks	12	2	4.5	4.1	7.3	8.3	7.5	18.9	24.1
			20	1	6.9	6.2	11.5	8.6	7.9	21.2	36.8
			25	1	7.6	6.8	11.9	7.2	9.2	21.1	31.7
		Tarmac	12	3	0.9	0.9	2.0	9.3	9.4	16.7	20.4
			25	2	1.4	1.3	2.0	5.8	9.4	16.6	23.0
yoyo	cot, 0 mo	Cobblestones	5	3	4.1	4.0	5.7	4.8	6.4	16.9	21.3
		Paver Bricks	5	2	3.0	2.1	4.0	4.1	9.4	41.7	29.5
		Sidewalk Pavers	5	3	2.8	2.6	4.2	5.5	6.7	18.8	22.2
		Sidewalk Slabs	5	2	4.0	3.8	6.7	6.4	5.2	19.6	25.7
		Tarmac	5	2	0.9	0.6	1.4	7.4	7.7	42.9	19.5
	seat, 9 mo	Cobblestones	5	3	5.2	4.9	7.1	4.4	7.7	17.6	21.5
		Paver Bricks	5	3	3.6	3.0	4.7	3.8	10.4	25.0	22.5
		Sidewalk Pavers	5	2	3.1	2.7	5.8	9.9	8.3	23.4	28.5
		Sidewalk Slabs	5	3	4.0	3.7	6.0	6.2	5.3	19.0	23.3
		Tarmac	5	2	0.7	0.4	1.0	6.3	11.1	41.7	39.1

## C Vehicle Statistical Comparisons

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

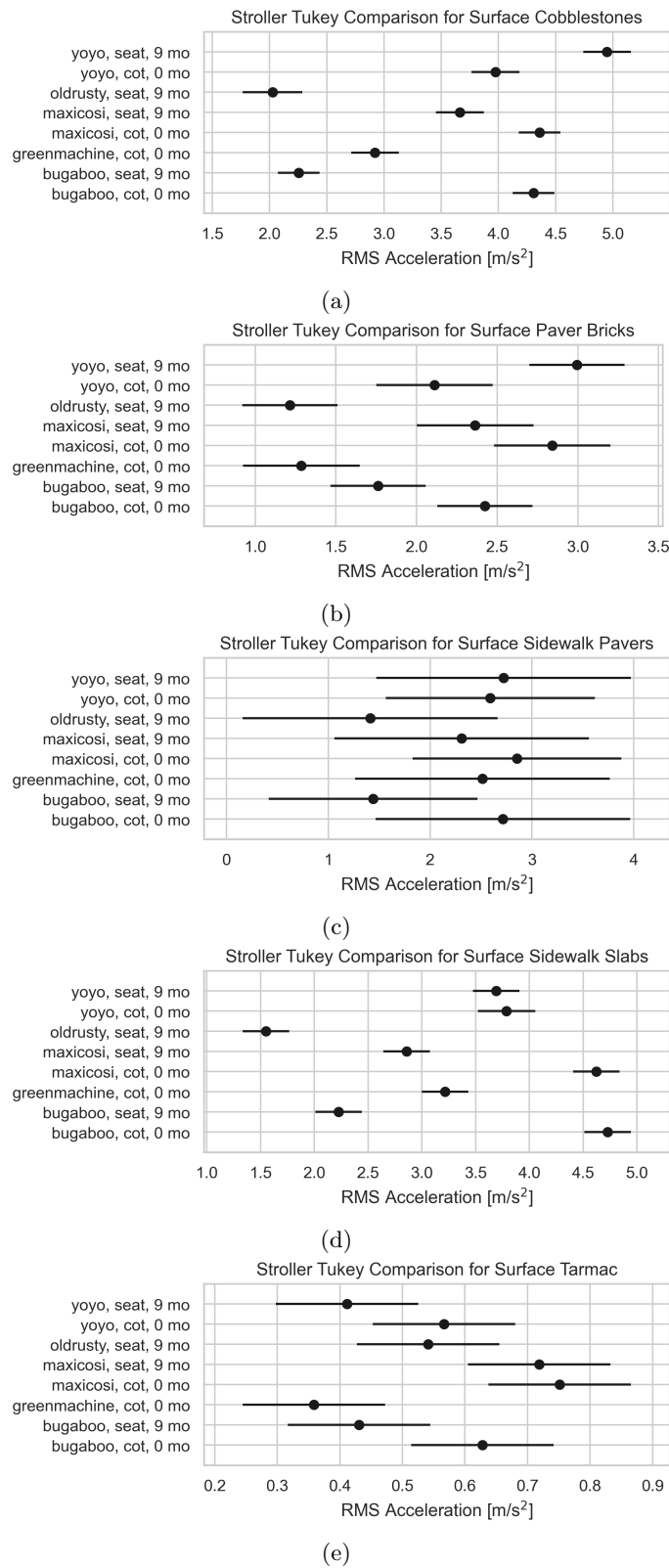


Figure 39: Tukey Comparison Plots for the Strollers

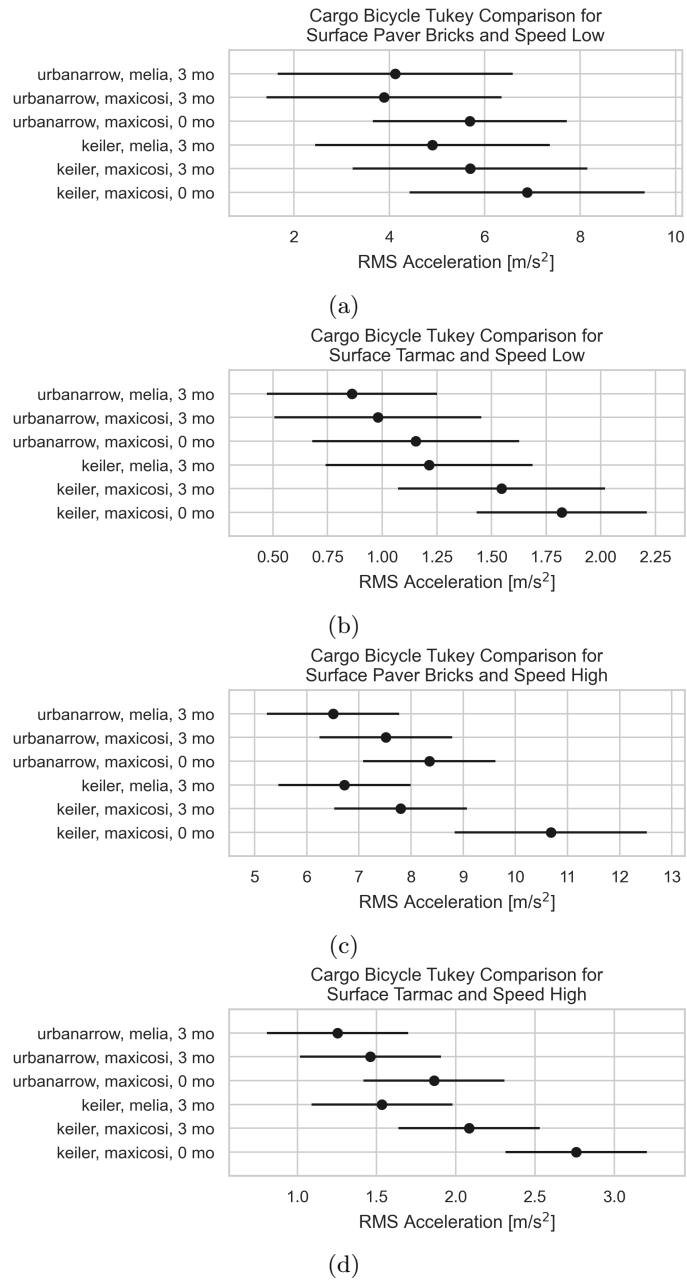


Figure 40: Tukey Comparison Plots for the Cargo Bicycles