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Exposure of Children in a Bicycle Trailer to Whole-Body Vibration †

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Abstract: This study investigated the effects of road surface (tarmac, gravel, cobblestones), load case (single passenger, two passengers), tire pressure (3.0, 4.0, 5.0 bar), and cycling velocity (10.0, 17.5, 25.0 km/h) on the whole-body vibration of children being transported in a bicycle trailer. Two types of passive dummies were utilized to mimic a baby and a toddler passenger in terms of weight and height. Road type and cycling velocity caused statistically significant change on the magnitude of whole-body vibrations. Overall, vibration total values were on the "uncomfortable" level of the vibration discomfort scale or even above. The major limitation of the study is the application of passive dummies, which might not represent the biodynamics of the target population.

Keywords: bike; transportation; child; baby; toddler; ISO 2631; cycling; frequency-weighted acceleration; passenger; root mean square

1. Introduction

Using bicycles as a means of transportation continually enjoys great popularity. In order to keep their mobility even in parenthood, many cyclists use bicycle trailers to carry their children in a dry, safe and—to some extent—comfortable cabinet.

Exposure to shock and whole-body vibration (WBV) originating from the mechanical vibrations acting on vehicles in general and the related stress of the passengers have been of interest to many research groups. The extent of WBV is often quantified by means of the root mean square (RMS) of the frequency-weighted accelerations (FWA) measured at the contact area between passenger and seat. WBV of seated persons is linked to discomfort, health issues, as well as motion sickness [1].

An analysis of vertical vibrations acting on children in child car seats [2] reported RMS values of 0.3 m/s² for asphalt roads and up to 2.7 m/s² for rough road surfaces. The authors employed a crash test dummy in order to mimic the passengers. Another WBV analysis for children in midi school busses [3] obtained vibration total values (resultant of RMS at the x, y, and z-axis) of 2.2 m/s² for highway roads and 4.2 m/s² on rough roads when observing children aged four years. That study reported decreasing values for older children age groups (six, eight, and ten years). Compared to the levels of discomfort provided in ISO 2631-1 (see Table 1), the ride comfort in the school busses shall be classified as *extremely uncomfortable*.

The aim of this study was to quantify the exposure of babies and toddlers in a bicycle trailer to WBV. By means of vibration total value, the subjective severity of vibration discomfort should be evaluated.

Table 1. Levels of vibration discomfort as proposed by ISO 2631-1, based on the magnitude of the vibration total value in public transport [4].

Vibration Total Value [m/s²]	Discomfort Scale
<0.315	Not uncomfortable
0.315–0.63	A little uncomfortable
0.5–1.0	Fairly uncomfortable
0.8–1.6	Uncomfortable
1.25–2.5	Very uncomfortable
>2.0	Extremely uncomfortable

2. Materials and Methods

2.1. Trailer, Bicycle, and Dummy Passengers

In this study, a two-wheeled bicycle trailer made by Hamax AS (Moss, Norway) was utilized. The trailer model *Outback* is in accordance with EN 15018 [5] and provides two seats for babies above six months of age and/or toddlers with a maximum height of 1.17 m or maximum weight of 22 kg. The carrying capacity is 42 kg, which includes the weight of passengers as well as luggage. The trailer runs on 20″ wheels, which are linked through a steel spring suspension chassis to the aluminum frame. The towing bar of the trailer is connected to the left dropout of the bicycle rear wheel. The trailer was towed using a pedal electric bicycle (Multiroad Carbon, Storck Bicycle GmbH, Idstein, Germany). A tachymeter displayed the actual speed to the cyclist. A photograph of the harnessed team is displayed in Figure 1a.

In order to mimic passengers sitting inside the trailer, two dummies (EURO 112 PLUS, HELPI, Zirndorf, Germany) were employed (see also Figure 1d). The dummies consisted of a shell of Cordura fabric and were filled with sand. The typical application area of those dummies is in exercises for civil protection. The dummies were representing a baby (height 0.7 m, weight 5 kg) and a toddler (height 1.3 m, weight 10 kg).

(**a**) (**b**) (**c**) (**d**)

Figure 1. This figure displays the test setup: (**a**) Drawing vehicle and trailer; (**b**) Seats inside the trailer with accelerometers mounted on the seat pans of left and right passenger seat; (**c**) Inertial measurement unit mounted on the hub of the left trailer wheel; (**d**) Both dummies (baby: left, toddler: right) positioned in the trailer.

2.2. Instrumentation

The trailer was instrumented employing a set of three *Envisible Dialogg* IMU sensors (Steinbeis Research Center Human Centered Engineering, Chemnitz, Germany), operating at a sampling frequency of 500 Hz [6]. Two sensors were mounted to the seat areas (see Figure 1b), measuring linear accelerations with a range of ±16 g in fore-aft (x-axis), left-right (y-axis), and vertical (z-axis) direction. The third sensor was used to log the angular velocity around the hub axle of the left trailer wheel (see also Figure 1c) in order to calculate the velocity. The sensor network was operated through a WIFI connection and a tablet PC with a corresponding graphical user interface.

2.3. Data Collection and Design of Experiment

The data collection took place in the city of Chemnitz (Germany) in summer 2019. All rides were performed by the same cyclist on nearly flat tracks. The *road surface*s were differently paved (see Figure 2a–c for details). As second independent variable, the *load case* was investigated. The WBV was studied for both of the dummies when being transported as single passenger as well as in combination with the second dummy. Furthermore, *tire pressure* was altered within three levels of the recommended range provided by the tire manufacturer (3.0, 4.0, and 5.0 bar). The tests were implemented performing also three different *velocities* (10.0, 17.5, and 25.0 km/h).

A Tagushi approach of the design of experiment [7] was employed to reduce the work plan to 54 combinations of road surface, load case, tire pressure, and velocity. Each combination was performed three times.

(**a**) (**b**) (**c**)

Figure 2. Different road surfaces involved in this study: (**a**) Tarmac, (**b**) Gravel, (**c**) Cobblestones.

2.4. Data Processing

Data was processed using the software package DIAdem 2017 Professional (National Instruments Inc., Austin, United States of America). Datasets were limited to a 100 m long section, starting at the point where the cyclist reached the target velocity. A tolerance range of ±5% was selected and average velocity was calculated. Then, frequency-weighted accelerations a_w were calculated applying the weighting filters w_k for z-axis and w_d for the x- and y-axes, as proposed by ISO 2631-1 [4]. The weighted RMS acceleration for each axis was calculated as follows:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \quad (1)$$

The vibration total value of frequency-weighted accelerations a_v obtained at toddler and baby dummy was calculated as the vector sum of the frequency-weighted accelerations in x-, y-, and z-direction without applying an axis weighting (k = 1 for all three orthogonal axes) [4]:

$$a_v = \sqrt{k_x^2 \cdot a_{wx}^2 + k_y^2 \cdot a_{wy}^2 + k_z^2 \cdot a_{wz}^2} \quad (2)$$

The arithmetic means of a_v in three repeated trials in each condition was used for further data processing in the statistical software package Minitab 18 (Minitab Inc., State College, PA, USA). Two analysis of variances (ANOVA) were performed for analyzing the main effects on WBV of toddler and baby dummy. Vibration total values were compared to the discomfort scale (cf. Table 1) in order to evaluate the discomfort.

3. Results

Tables 2 and 3 provide insight into the statistics of the ANOVAs. For both dummies, the sources of variation *road surface* and *velocity* have a statistically highly significant effect on the WBV ($p = 0.000$). On the other hand, *tire pressure* did not systematically influence the exposure to vibrations ($p > 0.05$). In addition, it was not relevant whether the trailer was loaded with a single passenger or both dummies ($p > 0.05$). The total variability was nearly two times greater for the baby dummy values.

Table 2. Analysis of variance for means of a_v obtained for the toddler dummy, sources of variability, degrees of freedom (DF), sequential sums of squares (Seq SS), corrected sum of squares (Cor SS), corrected mean square (Cor MS), F-value (F), and *p*-value (p), α-level 0.05.

Source	DF	Seq SS	Cor SS	Cor MS	F	p
Road surface	2	60.4823	60.483	30.2411	760.93	0.000
Load case	1	0.0000	0.0000	0.0000	0.00	0.996
Tire pressure	2	0.0745	0.0745	0.0372	0.94	0.409
Velocity	2	3.9264	3.9264	1.9632	49.40	0.000
Residual Error	19	0.7551	0.7551	0.0397	19	0.7551
Total	26	65.2382				

Table 3. Analysis of variance for means of a_v obtained for the baby dummy, sources of variability, degrees of freedom (DF), sequential sums of squares (Seq SS), corrected sum of squares (Cor SS), corrected mean square (Cor MS), F-value (F), and *p*-value (p), α-level 0.05.

Source	DF	Seq SS	Cor SS	Cor MS	F	p
Road surface	2	104.318	104.318	52.1590	215.11	0.000
Load case	1	0.330	0.330	0.3299	1.36	0.258
Tire pressure	2	0.299	0.299	0.1493	0.62	0.551
Velocity	2	12.873	12.873	6.4363	26.54	0.000
Residual Error	19	4.607	4.607	0.2425		
Total	26	122.426				

The vibration total values obtained for toddler and baby dummy passenger are reported in Figure 3. Overall, WBV of the baby was 20% higher compared to the toddler. In terms of road surfaces, tarmac caused the lowest magnitudes ($\overline{x} = 1.6$ m/s^2). Cycling on gravel increased WBV by factor 2.75 compared to the tarmac condition and, respectively, by factor 3.63 while cycling on cobblestones.

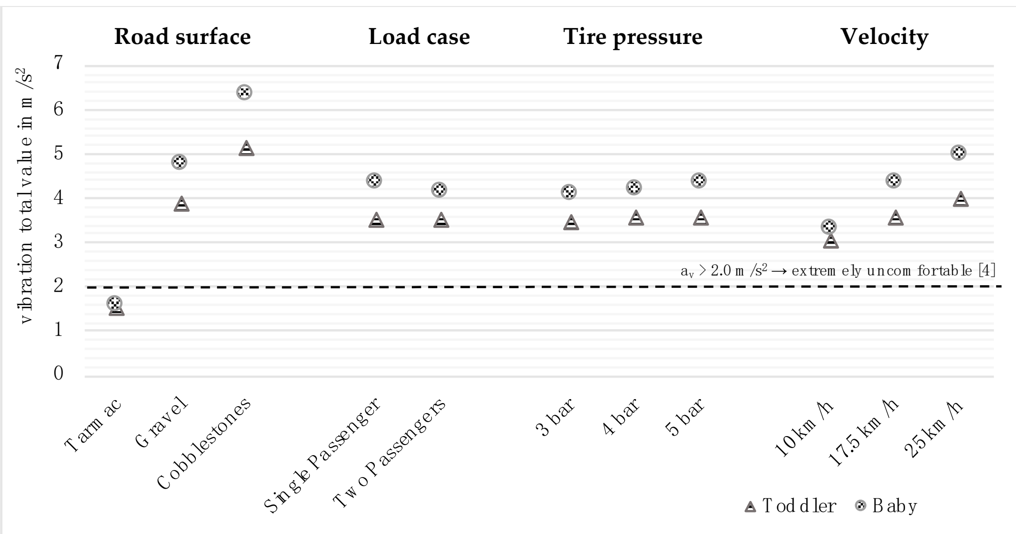

Figure 3. Whole-body vibration by means of vibration total values obtained at toddler and baby dummy in dependence on different road surfaces, load cases, tire pressures, and velocities. Vibration discomfort threshold value 2.0 m/s^2 is indicated with a dashed line.

Higher cycling velocities led to increased WBV. In detail, WBV was on average 1.24 times higher when cycling 17.5 km/h instead of 10 km/h. Speeding up to 25 km/h caused 40% higher WBV. The increase of WBV due to velocity was more intense for the baby passenger compared to the toddler.

4. Discussion

Besides the trials performed on tarmac, all test rides led to vibration total values greater than the threshold of 2.0 m/s^2. Thus, transportation of children in a bicycle trailer needs to be considered as *extremely uncomfortable* for the passengers [4]. Even cycling on tarmac was at least *uncomfortable* or *very uncomfortable* when applying the vibration discomfort scale provided in ISO 2631-1 (cf. Table 1).

In terms of load case, additional weight did not reduce the WBV, neither for the baby dummy (5 kg bodyweight) nor the toddler (10 kg). Even with both dummies laden for testing, the total mass was considerably below the total load capacity of trailer (42 kg). The suspension chassis may work more efficiently at higher loads.

Surprisingly, lowering the tire pressure did not reduce the WBV significantly. This is in contrast with studies reporting dampening effects for low tire pressures when investigating cyclists [8]. An explanation might be that the lowest inflation pressure suggested by the tire manufacturer (3.0 bar) was still comparably high according to anecdotical evidence. Furthermore, the low loading weight might also reduce the possible increase in comfort due to lowering the tire pressure.

The overall higher WBV obtained for the lighter and smaller dummy is in accordance with the findings of Rao et al. [3], who also reported decreasing vibration total values for older, respectively larger and heavier, children.

The major limitation of this study was the use of passive dummies in order to mimic typical passengers of bicycle trailers. Both dummies represented a child of certain height, but were comparably light-weighted. The body mass index (BMI) of the baby dummy was approximately 10, while BMI of the toddler was 6. The toddler dummy was also slightly larger than the recommended maximum height. The weights of the single body segments also may hardly represent a real human body of the designated age group. However, there are no biofidelic child dummies available, which exhibit validated biodynamic properties [9]. Such dummies do exist for male adults. Hybrid crash test dummies, as used by Gromadowski and Więckowski [2], also do not mimic the biodynamic properties like apparent mass, stiffness and impedance [10].

5. Conclusions

The transportation of children in bicycle trailers exposes the passengers to WBV of high magnitudes. Since WBV is linked to comfort and health as well as motion sickness [1], users have to be informed by the manufacturers or distributers of the risks associated with the use. Further investigations are necessary including dummies with a greater biofidelity. Possible negative effects on the health of the passengers shall be thoroughly investigated. Therefore, axis weighting ($k_x = k_y = 1.4$, $k_z = 1$, see Equation (2)) is required in order to respect a greater contribution on health issues of horizontal WHB compared to vertical WHB [4].

Conflicts of Interest: The authors declare no conflict of interest.

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