Assessing whole-body vibration transmissibility in children's bicycle trailers

by

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Abstract

The overall objective of this thesis was to assess whole-body vibration (WBV) exposure in bicycle trailers to determine 1) vibration exposure characteristics associated with children riding in bicycle trailers, 2) the effectiveness of the bicycle trailer seat in reducing vibration transmitted to children riding in a bicycle trailer, and 3) to determine if gel seat cushions were effective in reducing vibration transmissibility through the seat/gel cushion to the buttock of a child in a bike trailer. These objectives were accomplished through a field study and a laboratory study.

The first study, was conducted in the field with the primary objective to 1) to document vibration exposure characteristics measure on the bicycle trailer frame, at the interface between the seat and buttock of a seated child, and at the back of the child's head, 2) to determine health risks based on an ISO 2631-1 health guidance caution zone (HCGZ) analysis, and 3) to determine if vibration exposure characteristics differed when riding on gravel compared to a paved terrain. The findings revealed an associated health risk, with levels of vibration measured at the buttock/seat interface consistently exceeded ISO 2631-1 health guidance caution zone guidelines. Moreover, vibration exposure magnitude, and associated health risk, was higher when the bicycle trailer was ridden on gravel terrain at higher speeds. When adjusted for a two-hour exposure time, vibration experience by the children sitting in the bicycle trailer, for the majority of the trials, revealed a moderate health risk according to the ISO 2631-1 HGCZ. Additionally, all 12 trials had seat-to-head transmissibility levels above 1.00, indicating an amplification in vibration from the child's seat to their head when riding in the bicycle trailer.

The second study, was conducted under controlled laboratory settings with the aim to determine the impact of independent variables terrain type, trailer type, and cushion type, on dependent variable vibration magnitude measured at the interface between the trailer seat and simulated buttock of a child. Terrain type had the largest influence on vibration exposure levels ($p<0.001$), followed by trailer type (rigid-frame vs. suspension-frame) ($p<0.001$). Gel cushions did not significantly influence vibration measured at the seat/buttock interface but were found to reduce vibration measured at the rigid-frame trailer.

Findings from this thesis suggest that if children were to spend greater than 2 hours a day in a bicycle trailer, they would exceed the ISO 2631-1 HCGZ, and ultimately be at an increased risk for a vibration-induced injury. Children were also exposed to higher levels of vibration when the bicycle and trailer travelled at a higher speed and travelled over rougher (gravel) terrain. Laboratory analysis found the gel seat pad was not effective at attenuating vibration at the seat. Additional research should be conducted with a larger sample of bicycle trailer types. Furthermore, this study highlighted the need for additional research to determine health risks associated with vibration exposure in young children as current international standards are designed to determine health risks of vibration exposure for health adults in an occupational context.

Keywords

Whole-body vibration, children, bicycle trailers, transmissibility

Co-Authorship Statement

The enclosed thesis has been written in a manuscript-based format. For the purposes of this document, the original manuscripts have been reformatted to disseminate the research in one cohesive work. A list of the manuscript, in the format they will be submitted to each journal, and author institutions, is provided here. The nature and scope of the work of the individual co-authors for each manuscript is summarized in the associated tables.

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Table of Contents

List of Tables

List of Figures

List of Appendices

Glossary

Abbreviation	Long Form
A(8)	8-hour equivalent vibration total value
ANOVA	analysis of variance
$\mathbf{a_{wx}}$	frequency-weighted r.m.s. acceleration in the x-axis (ISO 2631-1)
$\mathbf{a_{wy}}$	frequency-weighted r.m.s. acceleration in the y-axis (ISO 2631-1)
$\mathbf{a_{wz}}$	frequency-weighted r.m.s. acceleration in the z-axis (ISO 2631-1)
CF	crest factor
DF	dominant frequency
HGCZ	health-guidance caution zone
ISO	International Organization for Standardization
LBP	low-back pain
r.m.s.	root-mean-square
SBS	shaken baby syndrome
SEAT	seat-effective amplitude transmissibility
SPSS	statistical package for the social sciences
VATS	vibration analysis toolset
WBV	whole-body vibration
WHO	World Health Organization
$\mathbf{W_d}$	weighting factor, applied to the x and y axes, as described in ISO 2631-1
$\mathbf{W_k}$	weighting factor, applied to the z axis, as described in ISO 2631-1

Terminology and Definitions

***A*(8):** Daily vibration exposure, typically measured for an 8-hour work shift. Measured in m/s^2.

Accelerometer: a data collection unit used to measure accelerations in certain directions, typically used to measure vibrations in the field. For example, a triaxial accelerometer can detect accelerations in the x, y, and z direction.

Amplification: An increase in amplitude and intensity of a signal

Attenuation: The reduction in amplitude and intensity of a signal.

Dominant frequency: Frequency at which a maximum value occurs in a spectral density curve.

Frequency-weighted: A term indicating that a wave-form has been modified according to some defined frequency-weighting

ISO 2631-1: The International Standard for Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration.

Resonance: Vibration produced by an object when it exposed to vibration of the same frequency as another object.

Resonant Frequency: The frequency where resonance occurs. Maximal vibration/oscillation will occur in a system when it exposed to its resonant frequency. When the human body is exposed to its resonant frequency, maximum displacement between organs and skeletal structures occurs, causing potential damage to the tissues.

Root-mean-square (r.m.s.): The square root of the average value of a given set of numbers.

Seat effective amplitude transmissibility (SEAT): Ratio of vibration experienced at the top of the seat (human exposure), compared to the base of the seat (the floor).

Sinusoidal sweep signal: Sinusoid that passes through a range of frequencies. Often used to determine resonant frequencies.

Transmissibility: The ratio of vibration measured between two points.

VATS: Vibration analysis toolset. A software application used to derive the various measures required by ISO 2631-1 standard for assessing health effects of whole-body vibration exposure.

Vibration: An oscillatory motion about a fixed reference point.

Whole-body vibration (WBV): Vibration that is transmitted to a human supported by a vibrating surface. Exposure areas while seated include the buttocks, back, and/or feet.

CHAPTER 1: Introduction and Literature Review

1.1 Introduction

Cycling is a popular way to incorporate daily physical activity into a family's routine. Since riding a bicycle can be taught at a young age, and without the need for sport organization involvement, it is a family inclusive activity. To accommodate younger children, many parents opt to use a bicycle trailer, which are wheeled carriers that are typically connected to the back wheel of the bicycle. A common use for bicycle trailers is to tow their child behind them in order to accommodate them, particularly on long distance bicycle rides. Most carriers are advertised to be suitable for paved, gravel, and trailed terrains; however, limited research on whole-body vibration (WBV) exposure to children seated inside bicycle trailers exists. With limited information about the effect of WBV exposure from bicycle trailers, there is a need for research to be completed in this area.

1.2 Whole-Body Vibration

Vibration is a mechanical stimulus characterized by an oscillatory motion, that can enter the body through direct contact (Cardinale & Wakeling, 2005). More specifically, WBV is vibration that affects the entirety of an exposed person. When one refers to WBV, they are typically referring to vibration entering an individual who is seated, where the vibration enters the body through the supporting areas, such as the back, buttocks, and/or feet (Mansfield, 2005). Four factors are required to assess human response to vibration. The first factor is magnitude, which describes the strength of the vibration peaks that are experienced. The second factor is frequency, which describes the number of peaks that occur per second, and is typically measured in Hz. The third factor is the direction with vibration along the x axis typically representing forward and backwards movement, vibration along the y axis typically representing lateral movement, and vibration along the z axis typically representing vertical movements. The fourth factor is duration of vibration exposure. Generally speaking, the longer one is exposed to vibration, the greater the risk will be of experiencing negative health effects (Cardinale & Wakeling, 2005; Gooyers et al., 2012; Paddan & Griffin, 2002).

Another factor that is important to consider when evaluating the human exposure to vibration is resonance. Resonance is the tendency of a system (e.g. the human body) to oscillate at its maximum amplitude, and is associated with specific frequencies (Bressel et al., 2010). In terms of human exposure to vibration, when vibration enters the body at a frequency which corresponds to the resonant frequency of a particular tissue, the risk of tissue damage due to the high oscillation increases (Mansfield, 2005). Different areas of the human body have a different resonance frequency. For example, an adult spine has a resonant frequency between 10-12Hz, while resonance of the pelvis typically occurs between 3-5Hz. Other areas of the body, such as the eyeballs, can resonate at frequencies between 30-80Hz, impacting one's vision (Stott et al., 1993, as cited in Mansfield, 2005).

Human response to vibration can also be determined by calculating vibration transmissibility as a ratio between an output and an input. For example, floor-to-seat, and seat-to-head are common measures of vibration transmissibility and represent the ratio of vibration measured as output at the seat and input at the floor and output at the head and input at the seat, respectively (Mansfield, 2005). If the ratio is 1:1, this means that the transmissibility is a unity, and vibration is neither amplified or attenuated to another area. Human health problems can occur when vibration is amplified as it travels through the body indicative of a transmissibility value greater than one (Mansfield, 2005). Another calculation that can be done is the seat effective amplitude transmissibility (SEAT). The SEAT value is described as the "ratio of the vibration experienced on the top of seat and the vibration that one would be exposed to when sitting directly on the floor" (van Niekerk et al., 2003). The most common use for this value is to measure dynamic seat comfort (van Niekerk et al., 2003).

1.3 ISO 2631-1 (1997) Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration

When assessing human exposure to WBV, the international standard is ISO 2631-1. ISO 2631-1 is used to determine vibration exposure when vibration is transferred to the body through the feet of a standing person, through the buttocks, back, and feet of a seated person, and the supporting areas of a person in a recumbent position (ISO 2631-1, 1997). To measure WBV exposure in accordance with ISO 2631-1 standards, the accelerometer should be located between the body and the source of its vibration (ISO 2631-1, 1997). One important factor to note about ISO 2631-1 is that this is a standard that has been created based off of healthy, adult individuals. Currently, there is no international standard recommended for use in assessing vibration specifically in children.

ISO 2631-1 has outlined a health guidance caution zone (HGCZ), which directly states, "for exposure below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely" (ISO 2631-1, 1997).The 8-hour health guidance caution zone (HGCZ) for frequency-weighted r.m.s. acceleration value is between 0.45m/s^2 and 0.90m/s^2 (Table 1.1).

Table 1.1: ISO 2631-1 Health Guidance Caution Zone (ISO 2631-1, 1997)

ISO 2631-1 Assessment of Adverse Health Effects	**Predicted Health Risk**	**Values**	
		A(8) (m/s^2 r.m.s.)	**VDV_{total} ($m/s^{1.75}$)**
"For exposures below the zone (HGCZ), health effects have not been clearly documented and/or objectively observed"	LOW	<0.45	<8.5
"in the zone (HGCZ), caution with respect to potential health risks is indicated"	MODERATE	0.45-0.90	8.5-17
"above the zone (HGCZ) health risks are likely"	HIGH	>0.90	>17

1.4 WBV Exposure and Health Risks

Long-term exposure to WBV is associated with low back pain (LBP), spinal degeneration, and can affect the digestive system, peripheral veins, vestibular system, and the female reproductive system (Seidel & Heide, 1986; Bovenzi, 1996; Bovenzi & Hulshof, 1999; Mansfield, 2005; Bovenzi, 2010). In a review of epidemiological data, it was noted that there is an increased risk of LBP, sciatic pain, and spinal herniation (Bovenzi & Hulshof, 1999). Bovenzi (1996, 2010) also reported increased LBP due to prolonged exposure to WBV. Prolonged sitting impairs the postural control as the trunk is relaxed (Slota et al., 2008). Without proper spinal stability during periods of WBV exposure, impairments in neuromuscular control can be observed (Slota et al., 2008). DeShaw and Rahmatalla (2014) found that the greatest discomfort was reported when the subject had both back and arm support (DeShaw & Rahmatalla, 2014). Therefore, when evaluating WBV in a child riding in a bicycle trailer, their seated posture should be considered.

1.4.1 WBV Studies in Children

Literature that focuses on WBV exposure in children is quite limited. Studies that explore physiological effects of WBV are mainly done in adults, particularly in occupational settings, such as mining, construction, and transportation where workers are exposed to high levels of vibration due to their daily work tasks. However, studies to date on WBV exposure in children have focused on vibration exposure due to shaken baby syndrome (SBS), vibration exposure in neonatal transport, and vibration transmission to children in vehicles.

1.4.2 Shaken Baby Studies

Violently shaking an infant to the point of severe brain injury is commonly associated with a shaken baby syndrome (SBS) diagnosis (Bandak, 2005). The consequences of SBS are severe, and include brain damage, blindness, hearing loss, speech and learning disorders, seizures, and death (Cleveland Clinic, 2011). While SBS is caused by the violent shaking of an infant, studies have investigated SBS to determine the amount of vibration the infant experiences during the shaking, and compare it to an infant's everyday movements to see if normal tasks can put them at risk for SBS (Lloyd, 2011; Koizumi et al., 2013; Lancon, Haines, & Parent, 1998).

Lloyd et al. (2011) sought to establish a baseline for commonly generated linear and angular head motion by comparing infant surrogates during abusive shaking as well as various activities of daily living (ADLs) experienced by infants. From the results of the trials, the authors were able to determine that peak accelerations of the infant ADLs were indistinguishable compared to the shaking of a baby model (954.4rad/s^2 and 1068rad/s^2, respectfully), meaning that the peak accelerations that occur to an infant during their ADL do not statistically differ from those experienced during a violent shake (Lloyd et al., 2011). The result from this study were able to demonstrate that high amounts of acceleration can be experienced in an infant's everyday life, and is not limited to rare occurrences such as shaking of a baby. Koizumi, Tsujiuchi, Hara & Miyazaki (2013), aimed to clarify the generating mechanisms of acute subdural hematoma (ASDH) in infants. The authors concluded that ASDH occurs at a frequency of 3.0Hz, with an amplitude of 50.0mm (Koizumi et al., 2013). Resonance frequency of an infant was found to occur at 2.5-3.0Hz, which is smaller than an adult's pelvis and spine resonance frequency of 3.0-5.0Hz (Koizumi et al., 2013). Having a smaller resonance frequency does not necessarily mean infants are more sensitive to vibrations; however, a smaller resonance frequency does indicate that vibrations are amplified at lower frequencies compared to adults. The study concluded that lower vibration frequencies in a younger person can place them at a much higher risk compared to an adult. This raises several questions: what is the dominant vibration exposure experienced by a child in a bicycle trailer, how much vibration is transmitted to the child, and are there interventions to reduce vibration transmission to a child in a bicycle trailer?

1.4.3 Neonatal Transport

Infants and young children are also exposed to vibration during emergency transport. Emergency neonatal transports occur when an infant requires urgent medical care, and must be transported to another hospital to receive this care, either by ground ambulance or air ambulance. In 2017, Toronto Sick Kids Hospital's Acute Care Transport Team (ACTS) performed 1600 transports to Toronto (The Hospital for Sick Children, 2017). Receiving 2-4 emergency transport calls per day, it is estimated that approximately 3200 neonatal and pediatric patients are transported via ambulance every year (The Hospital for Sick Children, 2017). As transporting a neonatal patient requires both delicate care and urgency, neonates are transported only when the benefits of transporting the infant outweigh the risks of not transporting them. Since time can be a factor in the survival rate of a neonate transport, it is unreasonable to have ambulances travel at slower speeds. While the fast speeds are crucial, this does increase the amount of vibration transmitted by the ambulance, and subsequently transferred to the child, placing an already critically-ill infant at greater risk for developing a WBV-related injury.

Studies have shown that the amount of vibration that is transmitted via inter-hospital transfer pose potential harm to an already ill neonate patient (Blaxter et al., 2017; Bouchut, Van Lancker, Chritin, & Gueugniaud, 2011). In a study which aimed to provide a baseline assessment of the exposure of neonates to head and torso vibration, and compare them to ISO 2631-1, it was discovered that vibration exposure exceeded an A(8) value of 0.5m/s^2, which indicates a "moderate" risk of developing WBV-related injury, as per ISO 2631-1 health guidelines (Blaxter et al., 2017). Blaxter et al. (2017) also discovered that the most hazardous vibrations for a neonatal transfer patient were found between a 5-20Hz frequency band, with the resonance frequency of the mattress and the harness used to secure the neonatal patient being between 9-10Hz, and the chassis of the incubator at around 14Hz. The authors emphasized the importance of the selection of the mattress, harness, and incubator system (i.e. suspended), as all have the potential to attenuate vibration to the neonate, particularly a system that decreases the resonant peak to below 7Hz being shown to provide an overall decrease in vibration exposure, ensuring a safer inter-hospital transfer for the neonatal patient (Blaxter et al., 2017).

When measuring the effects of WBV and sound on an infant's heart rate (HR) and heart rate variability (HRV) during ambulance and air ambulance transport, Karlsson et al. (2012) found that the mean WBV level exposed was 0.19m/s^2, with the highest peak in vibration being 3.9m/s^2, which greatly exceeds the upper level of the ISO 2631-1 health guidance caution zone (HGCZ) of 0.9m/s^2. Throughout the different transfers, infants were exposed to sound and vibration levels that exceeded the recommended limits for sound and vibration levels found to be harmful to adults (Karlsson et al., 2012). It is important to note that while there were no significant changes in HR during the neonatal transfers, it was shown that there were times when the HR was lowered, and the overall stress of the infant was decreased, which allowed for the infant's overall condition to stabilize (Karlsson et al., 2012). The authors did note that while the overall stress of the infant will lead to a more stable trip, individual transfers can vary, based on a variety of factors, such as the weight of the infant, and the condition of the infant upon transfer (Karlsson et al., 2012).

Despite the high levels of vibration, the neonatal patient is exposed to during an inter-hospital transfer, the risk of exposure is critical to the well-being to the child. To reduce vibration transferred to the child, different mattresses have been evaluated to test their attenuation abilities. When evaluating a foam mattress and a gel mattress, gel mattresses were found to be the system with the best vibration attenuating properties between the base of the incubator and the forehead of the supine neonatal mannequin (Gajendragadkar et al., 2000). Without the mattress, or with the foam mattress alone, frequency of the system ranged from 12-16Hz; however, with the gel mattress, the system frequency decreased to between 8-10Hz (Gajendragadkar et al., 2000). While the authors did conclude that the gel mattresses had the best vibration attenuating properties, they also noted that the weight of the neonatal patient had a much stronger influence on the vibration transmissibility, as these attenuating properties were decreased with a smaller neonatal mannequin (Gajendragadkar et al., 2000). Additionally, gel has been shown to be an effective shock absorber against vibration (Gajendragadkar et al., 2000; Blaxter et al., 2017; Boi Du et al., 2018; Lee et al., 2018). Gel mattresses were also confirmed to be the most effective medium to attenuate vibration in the Blaxter et al. (2017) study, which determined the resonance frequency of the gel mattress to be 10Hz.

1.4.4 WBV Exposure in Children in Vehicles

While infants and children traveling in domestic vehicles (cars; buses; vans) are not exposed to vibration magnitudes associated with the operation of heavy machinery, the condition of the vehicle they are in and roads they are traveling on could result in vibration exposures associated with health risks. Giacomin & Gallo (2003), measured the amount of vibration that is transfer to a child in several different combination of automobiles, car seats and children, and compared them to the vibration arriving at the adult driver in the car. They found that the vibration transmitted to the child was greater than the vibration transmitted to the driver, with larger difference observed as the speed of the car increased (Giacomin & Gallo, 2003). Additionally, it was found that the child's car seat transferred more vibration to the child at frequencies above 10Hz, with the greatest transmission occurring between the 20-40Hz frequency range (Giacomin & Gallo, 2003). Giacomin & Gallo (2003) reported that in terms in attenuating vibration, the child car seats were less effective compared to the vehicle seats. They determined this by assessing the car seat's acceleration transmissibility function, which rarely dropped below 50% between the 1-60Hz frequency range (Giacomin & Gallo, 2003). The authors also reported the resonance frequency of the child/seat to be at 8.5Hz, which differs from the resonance frequency of an adult's pelvis and spine (3.5-5.0Hz) (Giacomin & Gallo, 2003). The difference in resonance frequency does not necessarily mean that children are more or less sensitive to vibration compared to an adult; however, it does mean that certain frequencies are amplified more in children compared to adults, and vice versa. Despite the findings from Giacomin & Gallo, it is important to note that vibration transmissibility is heavily dependent on the type of car seat (i.e. standard, iso-fixed), the type of vehicle, and the child's age and weight (Gromadowski & Wieckowski, 2013).

Another mode of transportation that has been studied to determine vibration transmissibility in children is the school bus. Rao, Sivapiraksam, & Arora (2018) evaluated WBV in school-aged children (aged 4-10) travelling in a school bus over different terrain, and at different speeds. They measured vibration exposure at the seat for 12 children, aged 4-10 years old, on a smooth highway travelling at 40km/hr, and a rough road travelling at 20km/hr (Rao et al., 2018). Results indicated that the youngest children have the greater amount of vibration transferred to them, since the smaller the mass of the child leads to higher exposure levels. ISO 2631-1 frequency weight r.m.s. accelerations (in the vertical direction) ranged between 0.88m/s^2 to 0.97m/s^2 paved, and between 0.77m/s^2 to 2.13m/s^2 on rough road. It is important to note that the authors did not specify where on the bus the child was sitting, so it is unclear how sitting position on the bus interacted with the reported findings.

1.5 WBV in Cycling

Previous research on exposure to WBV in cycling has examined the influence of road conditions, seating positions, and suspension conditions of the bicycle on vibration transmission to the cyclist.

1.5.1 Road Conditions

Several researchers have reported that the roughness of the road is positively correlated with the amount of vibration transmitted to the cyclists (Arpinar-Avsar, Birlik, Szegin, & Soylu, 2013; Gromadowski & Wieckowski, 2013; Levy & Smith, 2005; Macdermid, Miller, Macdermid & Fink, 2015; Parkin & Sainte Cluque, 2014). Levy & Smith (2005) investigated the effectiveness of different suspension forks over different surface conditions and found that regardless of the suspension fork used, higher vertical accelerations were recorded when riding over rough roads. This finding was confirmed by Arpinar-Avsar et al. (2013) who studied the physiological effect of road roughness and bicycle types on forearm muscle activity. Ayachi, Drouet, Champoux & Guastavino (2018) utilized hydraulic shakes under the wheels of a bicycle to alter the vibration intensity. Along with significant differences in vibration levels picked up by the accelerometers, participants also distinguished small increases in vibration intensity, with their just-noticeable difference level (JNDL) being significantly higher with higher vibratory intensities. Parkin & Sainte Cluque (2014) confirmed this relationship, and went further by repeating the types of road conditions, types of bicycle suspensions and frames, as well as rider positions. They found the road condition had the greatest impact on the vibration dose value (VDV) recorded, with a significant amount of vibration transmitted at the spoke of the back wheel compared to the bicycle seat. Based on the findings from these studies, it is clear that when analyzing vibration transmissibility in a bicycle trailer, the terrain the bicycle trailer rides over needs to be considered.

1.5.2 Influence of the Bicycle on WBV

Along with road conditions and seating position, the bicycle itself is another factor to consider when investigating the effects of WBV exposure in cyclists. The type of bicycle, bicycle frame, and bicycle suspension conditions can impact WBV exposure levels. Road bicycles are intended for use on paved roads, where the terrain is not as rough, while mountain bicycles are intended for mountain-like terrain such as trails. As mountain bicycles are made to handle rougher terrain, the suspension systems on bicycles are more advanced. Arpinar-Avsar et al., (2013) determined that the types of bicycle do have an impact on muscle activity while cycling, as levels of vertical vibration at the handlebars was significantly higher in the road bicycles compared to the mountain bicycles while cycling at 20km/h. When comparing rigid frames to suspension forks on different bicycles, suspension forks were found to transmit significantly less vibration to the frame on railroad track gravel (rough terrain) compared to the rigid frame (Levy & Smith, 2005). Along with the type and frame of bicycle, tire pressure and size also have an influence on the vibration transmission to the cyclist. In a study done by Macdermid et al. (2015), vibration transmission was reduced with an increase in tire size, while an increase in tire pressure intensified the exposure accelerations. To date, research regarding WBV exposure in cycling has only considered the cyclist, and has not considered exposure to passengers in bicycle trailers. As shown in Parkin & Sainte Cluque's (2014) study, the greatest amount of vibration exposure occurs at the spoke of the back wheel. As bicycle trailers attach to the spoke of the back wheel, it raises the question whether or not vibration exposure in the bicycle trailer is greater than that in the bicycle.

1.6 Bicycle Trailers

A bicycle trailer is described as an enclosed seat with three wheels, typically with two at the back of the trailer and one at the front (Murray & Ryan-Krause, 2009). Bike trailers are typically designed to attach to the rear wheel of a bicycle, primarily using the rear axle mechanism. Bicycle trailers are typically designed to accommodate up to two children, and are recommended for children between the ages of 1 and 5 years old, and can usually hold up to 100lbs (Murray & Ryan-Krause, 2009). Bicycle trailers are the most recommended attachment by the American Academy of Pediatrics, compared to a bicycle seat or a trail-a-bike (Murray & Ryan-Krause, 2009). Between the bicycle seat and the trail-a-bike, bicycle trailers are the most recommended because they are equipped with the most safety features. First, they are low to the ground, meaning that they are not at risk of exposing children to adult level forces during a crash. Additionally, trailers have a feature called a rollover hitch, which allows the trailer to remain upright in the event of a bicycle crash; and along with a 5-point harness for the child, it reduces the chance of injury to the child in the event of a crash (Murray & Ryan-Krause, 2009).

Powell & Tanz (2000) investigated the safety of bicycle trailers, using the National Electronic Injury Surveillance System of the US Consumer Product Safety Commission, over a

9-year period. The authors of this study conducted a retrospective analysis of data to describe the incidence, type, and severity of injuries that were related to the use of bicycle trailers and compared them to injuries obtained by children bicycle mounted seats (Powell & Tanz, 2000). Through their analysis, Powell & Tanz (2000), concluded that less injuries were reported with the bicycle trailer than the bicycle seats. Out of the 49 injuries reported in the 9-year period, 6 were related to bicycle-trailers, whereas 43 were related to the bicycle seats. Most of the injuries for both attachments were a result of falls, motor vehicle collisions and mechanism malfunctions followed behind in occurrence (Powell & Tanz, 2000). The results that Powell & Tanz's (2000) found in their analysis were not significant ($P>0.05$); however, they were able to provide evidence that injuries do occur in these attachments, and that trailers have less reported injuries than the bicycle seats. While this article provides evidence that bicycle trailers are safer in the event of an accident, the article is limited in that it does not account for vibration transmission from the bicycle trailer to the child, thus the question about the safety implication for daily use of trailers remains unanswered. Therefore, there is a need to document levels of WBV present in the trailer-bike system, and quantify the amount of WBV that is transferred from the bicycle trailer to the child during a typical ride.

1.7 Purpose of Study

Occupational exposure to WBV is associated with low back pain, spinal herniation, sciatica, and other injuries due to its impact on the peripheral nervous system. The literature also shows that WBV exposure is not just a cause for concern amongst those working with large industrial machines. Child car seats studies, SBS studies, and neonatal transport studies have shown significant levels of vibration transmission to infants and children. Recreational cyclists can also be exposed to levels of WBV that can cause negative physiological effects. It is also important to note that much of the vibration occurs in the back wheel of the bicycle, which is where most bicycle trailers attach to the bicycle. However, little is known about vibration exposure experienced by children riding in bicycle trailers.

Therefore, the purpose of this study is to quantify WBV exposure to children riding in bicycle trailers, and to determine if bicycle trailers transfer significant levels of vibration to children, making them more susceptible to WBV exposure injuries. Additionally, this study will investigate the effectiveness of the bicycle trailer seat cushion, and determine if there are different materials that will reduce vibration transmission to the child.

CHAPTER 2: Assessing the Health Risk and Vibration Transmissibility of Children’s Bicycle Trailers on Gravel and Paved Terrain

2.1 Introduction

Bicycle trailers are enclosed seats that can be attached to the back of a bicycle, and are often used to transport children on bicycle rides because the child is not able to ride a bicycle themselves, or they cannot cycle for a prolonged period of time. The American Academy of Pediatrics has stated that bicycle trailers are the safer method to transport children with adult bicycle riders when compared to child seats attached to the adult bicycle seat, and trail-a-bikes (Korioth, 2009). Bicycle trailers are preferred as they feature a roll-over hitch (to ensure that the trailer remains upright if the rider falls over), a 5-point harness, and they are lower to the ground, preventing the child from experiencing adult levels forces from a crash (Murray & Ryan-Krause, 2009). While it is crucial for children to be protected from a crash, it is unclear whether or not these safety features in a bicycle trailer also protect the child from vibration exposure. Although long-term exposure to whole-body vibration (WBV) in adults has been associated with low back pain, spinal degeneration, and problems of the digestive system, and vestibular system (Seidel & Heide, 1986; Bovenzi, 1996; Bovenzi & Hulshof, 1999; Mansfield, 2005; Bovenzi, 2010), few studies have evaluated health effects associated with vibration exposure to children.

Limited studies on the health effects of vibration exposure in children have evaluated exposure during neonatal transport and commuting domestic vehicles including cars and school buses. Neonatal transport can expose young infants to levels of vibration that consistently exceed daily vibration exposure levels set by international standard bodies for healthy adults (Blaxter et al., 2017; Karlsson et al., 2012). The low-birth weight of neonatal patients was of particular concern as less massive objects experience greater displacement when compared to more massive objectives (Gajendragadkar et al., 2000). Moreover, due to their smaller mass, many children cannot attenuate vibration as well as adults can (Koizumi et al., 2013; Rao et al., 2018;

Towers, Bonebrake, Padilla, & Rumney, 2000) suggesting the possibility for an increased injury risk.

An international standard (ISO 2631-1) has been developed to evaluate health risk for adults exposed to WBV. Daily exposure is compared to a health guidance caution zone (HGCZ) where exposure below the zone is associated with a low probability of adverse health effects and exposure above the zone is associate with likely health effects (ISO 2631-1, 1997). However, it is important to note that exposure levels associated with the ISO 2631-1 HGCZ are based off of healthy, adult individuals and have not been validated for use with children. Furthermore, there is currently no international standard used to assess vibration specifically in infants and children. Despite these limitations the ISO 2631-1 HGCZ could offer a benchmark to compare daily vibration exposure associated with riding in a bicycle trailer, with other reported occupational exposure measures where health risk to an adult population have been reported.

When evaluating injury risk associated with exposure to WBV, posture also needs to be considered. Most bicycle trailers have a 5-point safety harness which restricts the movement of the child while seated in the trailer. Drawing on findings from occupational exposure to WBV, Slota et al, 2008 reported increased risk of LBP and discomfort when the individual was exposed to prolonged WBV while in a seated position, as neuromuscular control is compromised when the trunk is relaxed, impairing postural control. Vibration exposure measures from cycling and industrial operators also highlights the importance of terrain and driving speed when evaluating exposure to WBV (Chen et al., 2003; Eger et al., 2011; Parkin & Sainte Cluque, 2014).

Terrain quality has a direct impact on vibration transmitted to the cyclist with rougher road conditions (i.e. gravel paths and trails) transmitting greater vibration to the cyclist compared to smoother road conditions (i.e. paved bike lanes and sidewalks) (Arpinar-Avsar, Birlik, Szegin, & Soylu, 2013; Gromadowski & Wieckowski, 2013; Levy & Smith, 2005; Macdermind, Miller, Macdermind & Fink, 2015; Parkin & Sainte Cluque, 2014). Along with terrain quality, bicycle design also influences vibration transmissibility to the cyclist. The bicycle, its frame, and its suspension conditions can impact WBV exposure levels. Bicycles with suspensions systems are commonly used when the cyclist is travelling on rougher terrain, such as a trail or a gravel path, and have been shown to transmit significantly less vibration to the frame on rough terrain compare to a rigid frame bicycle (Levy & Smith, 2005). It has also been shown that one of the areas on the bicycle that has high frequency exposures is the back wheel of the bicycle (Parkin & Sainte Cluque, 2014). This raises concern for the child in the bicycle trailer, as the back wheel is where most bicycle trailers attach to the bicycle.

It is evident that vibration exposure can lead to serious health problems, and that mass must be considered when evaluating potential health risks associated with vibration exposure. Moreover, cyclists are exposed to vibration when riding and exposure is dependent on speed of travel, bike type, and terrain. However, an analysis of vibration exposure and associated health risks to children riding in bicycle trailers has yet to be completed.

Therefore, the purpose of this study was to 1) document vibration exposure characteristics measured on the bicycle trailer frame arm, trailer wheel-axle, at the interface between the seat and buttock of a seated child, and at the back of the child's head, 2) to determine whether vibration exposure characteristics differed when riding on gravel compared to paved terrain, at a slower compared to a faster speed, and with trailer type, and 3) to determine health risks based on an ISO 2631-1 health guidance caution zone analysis of exposure at the interface between the seat and the buttock of the child.

2.2 Methods

Laurentian University's Research Ethics Board (LUREB) approved the study methodology. Informed consent was obtained for both the adult and child (by their legal guardian) prior to starting any test procedures.

2.2.1 Participants

Twelve family units were recruited for this study. A family unit was defined as 1 adult and 1 child, who was between the ages of 12 months to 5 years old. Participants were recruited from the public recreation building on the Laurentian University campus, a municipal bicycle group through social media, as well as a sample of convenience. Each family was encouraged to use their own bicycle and bicycle trailer, but one was also provided to them if they did not own one. Both the adult and child were required to have a fitted bicycle helmet, which was to be worn at all times when riding. Additionally, the child inside the trailer was required to be harnessed into the trailer using the factory installed 5-point harness. Prior to arriving to the testing procedure, family units were advised to prepare for the weather conditions, and were encouraged to protect themselves from sun exposure and from heat exhaustion. Prior to completing the bicycle course, the age of the child, as well as their weight was recorded. The participant's bicycle trailer model was recorded, and a photo was taken of the trailer, with permission from the adult participant.

The general procedure involved the adult in each family unit reading and signing informed consent form (Appendix A), prior to the bicycle ride. The participants were then informed how WBV would be measured in their bicycle trailer with the installation of the accelerometers, and the route they were required to ride was explained and shown on a map.

2.2.2 Vibration Measurement

WBV was measured in accordance with ISO 2631-1. Four Series 2 10G tri-axial accelerometers (NexGen Ergonomics, Montreal, QC, CND) were used for the data collection process. All accelerometers were calibrated prior to data collection. The first accelerometer was placed in a rubber seat pad, and secured to the seat of the bicycle trailer (Figure 2.1). This accelerometer measured the vibration levels the child experienced throughout the test ride. The child riding in the bicycle trailer was asked to sit on the seat pad for the duration of the procedure. The second accelerometer was secured in a child's sport head band with double-sided adhesive (Figure 2.2) and was worn by the child, underneath their helmet, for the test. This accelerometer measured vibration levels transmitted from the child's buttock through their body to the head to enable calculation of seat-to-head WBV transmissibility. A third accelerometer was placed on the arm of the bicycle trailer to determine if accelerations were transmitted from the bicycle to the bicycle trailer (Figure 2.3). A fourth accelerometer was placed on the axle of the bicycle trailer, which was used to determine the vibration transmissions between the wheel and the seat of the bicycle trailer (Figure 2.4). The accelerometers were secured to the bicycle trailer with duct tape and the associated wires were secured and hidden in a way that they could not be tampered with by the child. Two portable data loggers (DataLog MWX8; Biometrics Ltd., Newport, UK) were used to record vibration, sampled at 500Hz throughout the bicycle ride. The head and seat accelerometers were attached to one of the data loggers, while the arm and wheel accelerometers were attached to the other datalogger. A REF 1400 cable was used to connect the two dataloggers together to ensure synchronization of the data recording.

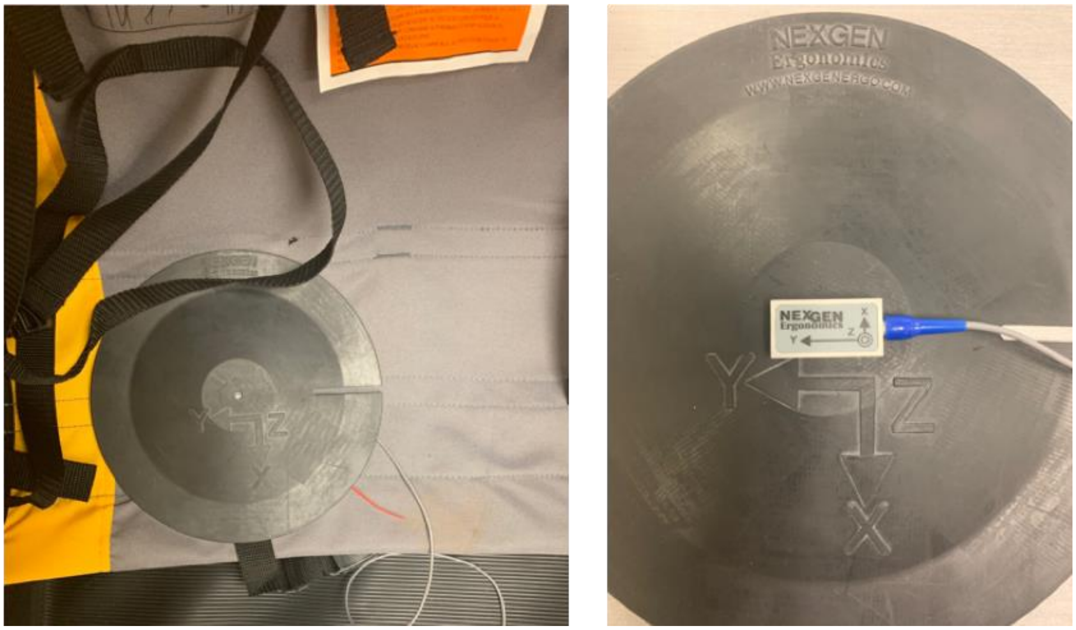

Figure 2.1: Seat pan accelerometer placement (left). Accelerometer orientation (right).

Figure 2.2: Headband accelerometer placement, with the headband worn where the accelerometer (inside of the headband) is in contact with the subject's occipital bone

Figure 2.3: Accelerometer placement on the bicycle trailer's arm, indicated by the red circle.

Figure 2.4: Accelerometer placement on the wheel's axle on the bicycle trailer, accelerometer placement indicated in red.

2.2.3 Course

The participants were asked to cycle on a course (Figure 2.5) set up at Laurentian University, and surrounding areas which included gravel and paved road sections. Gravel road was defined as an unpaved path covered in packed gravel. Paved was defined as smooth concrete (i.e. a sidewalk, bicycle lane, or road). Participants were instructed to start at the track (indicated by the yellow star), cycle down a 2km gravel trail, cycle back, approximately 10 minutes, depending on the speed of the participant. The participants then cycled on paved roads on the Laurentian University campus, for a continuous 10-minute period; however, the majority of the participants opted to cycle around the parking lot of the medical school building.

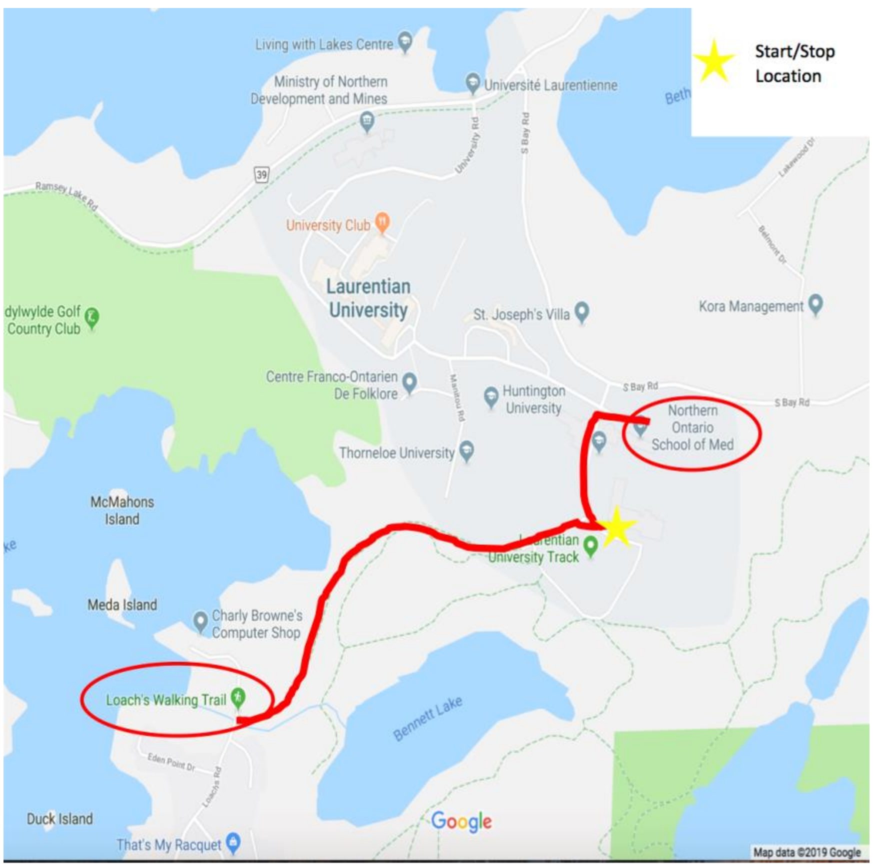

Figure 2.5: Standard route (in red) all participants followed, starting on Loach's Walking Trail, followed by the Northern Ontario School of Medicine parking lot. Participants' start/stop location is indicated by the yellow star.

Participants were instructed to cycle at a pace that they felt comfortable cycling at, and felt they could sustain for at least 20 minutes. They were also instructed to be mindful of their child in the back of the bicycle trailer, and not cycle at a pace that would make them feel uncomfortable. A Garmin Forerunner 235 Watch (Garmin International, Olathe, KS, USA) was attached to each participant's bicycle in order to track their location, speed, and cadence, throughout the course, with a mobile device that was monitored by the researcher during the route.

2.2.4 Vibration Analysis

Vibration analysis was conducted through the Vibration Analysis Tool-Set (VATS 3.4.4) software (NexGen Ergonomics, Montreal, QC, CND), in accordance to ISO 2631-1. Data collected from all 4 accelerometers in each trial were analyzed in VATS. Combined vibration exposure, and exposure associated with riding on gravel and paved roads were reported. A 2nd order Butterworth filter was applied, with a low cut-off frequency of 0.1Hz, and a high cut-off frequency of 250Hz. A Hanning filtering window was also applied. The appropriate frequency-weighting curves were also applied, as per ISO 2631-1 guidelines (x-axis=W_d; y-axis=W_d; z-axis= W_k). Scaling factors associated with the determination of health for seated exposure were also applied (x-axis, k=1.4; y-axis, k=1.4, z-axis, k=1.0). Frequency- weighted root-mean-square (r.m.s.) accelerations (a_{wx}; a_{wy}; a_{wz}), and vector sum (a_{wxyz}) were calculated using Equation 1:

$$a_w = [\Sigma_i (W_i a_i)^2]^{\frac{1}{2}} \tag{1}$$

where a_w is the frequency weighted acceleration; W_i is the weighting factor for the ith 1/3 octave band; a_i is the r.m.s. acceleration for the ith 1/3 octave band.

Crest factors were also calculated, to assess the ratio between the r.m.s. acceleration in the vertical direction and the peak accelerations in the vertical direction for all trials using Equation 2:

$$CF = \frac{\max\left(a_w(t)\right)}{r.m.s.\left(a_{w)}\right)} \qquad (2)$$

where a_w is the frequency weighted acceleration (Mansfield, 2005).

Vibration levels at the seat for each trial, for both gravel and paved terrain, were compared to the ISO 2631-1 HGCZ, to determine whether or not the levels experienced indicate a low, moderate, or high health risk to the child. It is important to note that the HGCZ assumes an 8-hour daily exposure limit (between 0.45m/s^2-0.9m/s^2), and is set for healthy adults. ISO 2631-1 HGCZ has not yet been validated in children for any context.

To determine how much vibration was transmitted to the trailer, as well as the child during the bicycle ride, seat-to-head, wheel axle-to-seat, and arm-to-wheel axle transmissibility values were calculated in the z-axis using Equation 3:

$$T(f) = \frac{a_{seat}(f)}{a_{floor}\,(f)} \quad = T(f) = \frac{a_{head}(f)}{a_{seat}\,(f)} \qquad (3)$$

where $T(f)$ is the transmissibility, $a_{seat}(f)$ is the acceleration on the seat and $a_{head}(f)$ is the acceleration at the base of the seat at frequency f (Mansfield, 2005). The same equation was used for the seat-to-head transmission analysis; however, the locations changed accordingly. Ratios below 1.00 (below unity) are considered to have an attenuating effect, meaning that there is a reduction in vibration transmission. Ratios above 1.00 are considered to have an amplifying effect, meaning that there is an increase in vibration transmission (Mansfield, 2005).

2.3 Results

2.3.1 Participant Demographics

Twelve family units participated in this study with an average child age of 4.03 years (±1.47 years), and mass of 16.44kg (± 3.09 kg) (Table 2.1). The course was designed to take approximately 20 minutes with the average completion time determined to be 24.97 minutes (± 4.84 minutes). The average speed for each participant on the course was 12.11km/h (±1.87km/h). Eight of the twelve participants used the Everyday Bike Trailer, and one family unit each used a Wike Double Bicycle Trailer, Bell Double Bicycle Trailer, Thule Chariot Carrier Cougar Trailer, and Thule Chariot Carrier CX1 Trailer. Technical specificities for each bicycle trailer, as well as images of the trailers can be found in Appendix B.

Table 2.1: Summary of the age and mass of the child participant from each family unit along with total ride time, average speed and associated bicycle trailer specifications

Participant #	Age (years)	Mass (kg)	Duration on Course (min)	Average Speed(km/h)	Bicycle Trailer Model
1	4.5	18.14	28.20	12.7	Wike Double Bicycle Trailer
2	4.75	16.33	39.15	11.0	Bell Double Bicycle Trailer
3	3	12.70	23.44	14.1	Thule Chariot Cougar Carrier
4	5	12.70	22.29	11.4	Everyday Bike Trailer
5	2.5	18.14	23.23	11.5	Thule Chariot CX1 Carrier
6	1.83	10.89	22.32	11.0	Everyday Bike Trailer
7	5.5	17.24	21.14	15.8	Everyday Bike Trailer
8	7	21.77	25.15	11.4	Everyday Bike Trailer
9	4	15.88	27.14	10.1	Everyday Bike Trailer
10	3	17.69	22.53	10.6	Everyday Bike Trailer
11	3	16.33	25.02	10.7	Everyday Bike Trailer
12	5	19.50	20.06	15.0	Everyday Bike Trailer

2.3.2 Whole-body Vibration Characteristics

Vibration exposure measurements, including frequency-weight r.m.s. accelerations (aw_x, aw_y, aw_z), summative frequency-weight r.m.s. accelerations (aw_{xyz}), crest factors (CF), and dominant frequencies are reported in Table 2.2 at the seat, Table 2.3 at the head, Table 2.4 at the bicycle trailer arm, and Table 2.5 at the wheel axle. Gravel and paved separations, as well as dominant exposures are not reported in trials 1, 2, and 3 as technical issues with data storage occurred.

Dominant frequencies at the seat measured between 4-16Hz in the vertical direction (Table 2.2). There were a few instances where the dominant frequency occurred in the fore-aft direction between 1-2Hz, and in the lateral direction, which ranged between 1-1.60Hz. Compared to other areas of the trailer, WBV exposure magnitude was lower at the seat. When assessing the measurements between the gravel and paved terrain, exposure levels were higher while riding over gravel terrain (Table 2.2). The mean frequency-weighted r.m.s. acceleration in the vertical direction was $1.14m/s^2$ ($\pm 0.24m/s^2$) over gravel terrain, and $0.95m/s^2$ ($\pm 0.19m/s^2$) over paved terrain. While travelling over gravel terrain, the lowest frequency-weighted r.m.s. acceleration in the vertical direction was $0.80m/s^2$ (Trial 5), while the highest was $1.43m/s^2$ (Trial 6). Over paved terrain, the lowest frequency r.m.s. acceleration in the vertical direction was $0.63m/s^2$ (Trial 5), while the highest was $1.23m/s^2$ (Trial 6) (Table 2.2). Crest factors recorded were higher when the participants were travelling over the paved terrain as opposed to gravel, with the exception of 3 trials (Trials 4, 5, and 11) (Table 2.2). The high crest factors over paved terrain is likely due to the speed bumps and potholes the participants rode over. The ISO 2631-1 HGCZ indicates that exposure levels over $0.90m/s^2$ indicate a high-health risk (ISO 2631-1, 1997). As there is only one trial with an exposure level below $0.90m/s^2$ at the seat/child interface, there is concern that the exposure could lead to potential health risks, particularly if the child is riding in the trailer for a long duration.

WBV characteristics that were measured at the child's head are reported in Table 2.3. Dominant frequencies at the child's head measured between 4-5Hz in the vertical direction. However, most of the dominant exposures occurred in the fore-aft and lateral directions. Dominant exposures in the fore-aft direction ranged between 1-2Hz, while lateral dominant exposures ranged between 1-1.60Hz. The mean frequency-weighted r.m.s. acceleration in the vertical direction was 1.70m/s^2 ($\pm$0.35m/s^2) over gravel terrain, and 1.49m/s^2 ($\pm$0.30m/s^2) over paved terrain. While travelling over gravel terrain, the lowest frequency-weighted r.m.s. acceleration in the vertical direction was 0.81m/s^2 (Trial 7), while the highest was 1.96m/s^2 (Trial 9). Over paved terrain, the lowest frequency r.m.s. acceleration in the vertical direction was 0.95m/s^2 (Trial 7), while the highest was 1.85m/s^2 (Trial 9) (Table 2.3). With the exception of 4 trials (Trials 5, 6, 8, and 11), all crest factors that were recorded on paved terrain were higher compared to those recorded on gravel terrain (Table 2.3).

WBV characteristics that were measured at the arm of the bicycle trailer are reported in Table 2.4. Dominant frequencies at the arm measured between 8-25Hz in the vertical direction, with peak exposures at 10Hz and 12.5Hz. Exposure levels at the arm were higher than those at the seat and head, but lower than at the wheel axle. Exposure levels were also higher on gravel terrain compared to paved. The mean frequency-weighted r.m.s. acceleration in the vertical direction was 3.68m/s^2 ($\pm$0.69m/s^2) over gravel terrain, and 2.72m/s^2 ($\pm$0.68m/s^2) over paved terrain. While travelling over gravel terrain, the lowest frequency-weighted r.m.s. acceleration in the vertical direction was 2.40m/s^2 (Trial 5), while the highest was 4.59m/s^2 (Trial 8). Over paved terrain, the lowest frequency r.m.s. acceleration in the vertical direction was 1.57m/s^2

(Trial 5), while the highest was $3.95m/s^2$ (Trial 7) (Table 2.4). All crest factors were higher over paved terrain compared to those on gravel terrain (Table 2.4).

WBV characteristics that were measured at the wheel axle of the bicycle trailer are reported in Table 2.5. Dominant frequencies at the wheel-axle arm measured between 4-25Hz in the vertical direction, with peak exposures at 10Hz and 12.5Hz. Exposure levels at the wheel axle were higher than all other areas that were measured. Exposure levels were also higher on gravel terrain compared to paved. The mean frequency-weighted r.m.s. acceleration in the vertical direction was $3.78m/s^2$ ($\pm 0.98m/s^2$) over gravel terrain, and $2.91m/s^2$ ($\pm 0.86m/s^2$) over paved terrain. While travelling over gravel terrain, the lowest frequency-weighted r.m.s. acceleration in the vertical direction was $1.64m/s^2$ (Trial 5), while the highest was $5.06m/s^2$ (Trial 8). Over paved terrain, the lowest frequency-weighted r.m.s. acceleration in the vertical direction was $1.10m/s^2$ (Trial 5), while the highest was $4.40m/s^2$ (Trial 4) (Table 2.5). All crest factors were higher over paved terrain compared to those recorded on gravel terrain (Table 2.5).

Table 2.2: Summary of WBV characteristics measured at the seat of the bicycle trailer in accordance with ISO 2631-1

Trial	**Duration (min)**	**Average Speed (km/h)**	**Terrain**	**Frequency-weighted RMS accelerations (m/s^2)**				**Crest Factor**	**Dominant Frequency (Hz)**
				a_{wx}	**a_{wy}**	**a_{wz}**	**sum**	**CF**	**DF_{xyz}**
1	28.20	12.70	Overall	0.24	0.27	0.77	0.85	16.05	N/A
2	39.15	10.95	Overall	0.24	0.32	0.91	0.99	12.12	N/A
3	23.44	14.12	Overall	0.16	0.19	0.62	0.67	11.46	N/A
4	22.29	11.40	Gravel	0.47	0.44	1.09	1.41	19.11	2.00 (x)
			Paved	0.39	0.34	0.91	1.17	16.22	1.00 (y)
5	23.23	11.50	Gravel	0.48	0.32	0.80	1.14	13.50	1.00 (x)
			Paved	0.40	0.26	0.63	0.92	11.83	1.00 (x)
6	22.32	11.00	Gravel	0.55	0.43	1.49	1.79	10.19	12.50 (z)
			Paved	0.49	0.37	1.23	1.50	17.35	1.60 (x)
7	21.14	15.80	Gravel	0.52	0.45	0.96	1.35	8.72	4.00 (z)
			Paved	0.63	0.45	1.10	1.54	10.29	5.00 (z)
8	25.15	11.40	Gravel	0.42	0.47	1.40	1.66	12.41	16.00 (z)
			Paved	0.37	0.39	0.84	1.13	21.27	1.00 (y)
9	27.14	10.10	Gravel	0.37	0.39	1.22	1.44	10.71	10.00 (z)
			Paved	0.35	0.34	1.00	1.21	16.92	5.00 (z)
10	22.53	10.60	Gravel	0.41	0.43	1.37	1.60	9.65	16.00 (z)
			Paved	0.38	0.37	1.14	1.35	19.09	5.00 (z)
11	25.02	10.70	Gravel	0.44	0.36	0.96	1.24	14.69	2.00 (x)
			Paved	0.38	0.45	0.79	1.15	13.34	1.00 (y)
12	20.06	15.00	Gravel	0.54	0.44	0.95	1.37	7.37	2.00 (x)
			Paved	0.46	0.39	0.88	1.22	15.59	1.00 (y)

Table 2.3: Summary of WBV characteristics measured at the head in accordance with ISO 2631-1

Trial	**Duration (min)**	**Average Speed (km/h)**	**Terrain**	**Frequency Weighted RMS Accelerations (m/s^2)**				**Crest Factor**	**Dominant Frequency (Hz)**
				a_{wx}	**a_{wy}**	**a_{wz}**	**sum**	**CF**	**DF_{xyz}**
1	28.20	12.70	Overall	0.65	0.79	1.59	1.89	12.34	N/A
2	39.15	10.95	Overall	0.99	0.88	1.49	1.99	14.57	N/A
3	23.44	14.12	Overall	0.59	0.90	1.26	1.66	9.77	N/A
4	22.29	11.40	Gravel	0.96	0.86	1.84	2.58	16.02	1.00 (x)
			Paved	0.75	0.77	1.36	2.03	16.59	1.00 (x)
5	23.23	11.50	Gravel	1.53	1.23	1.71	3.24	24.49	1.60 (x)
			Paved	1.24	1.24	1.63	2.95	12.53	5.00 (z)
6	22.32	11.00	Gravel	1.00	1.50	1.67	3.03	12.81	1.60 (y)
			Paved	0.86	1.36	1.16	2.53	6.00	1.00 (y)
7	21.14	15.80	Gravel	0.64	0.45	0.81	1.36	6.57	4.00 (z)
			Paved	0.66	0.45	0.95	1.47	8.37	4.00 (z)
8	25.15	11.40	Gravel	1.09	0.88	1.95	2.76	20.42	1.00 (x)
			Paved	1.21	0.97	1.44	2.60	14.46	1.00 (y)
9	27.14	10.10	Gravel	1.02	0.79	1.96	2.67	8.38	1.00 (x)
			Paved	1.08	0.97	1.85	2.74	15.94	1.00 (x)
10	22.53	10.60	Gravel	1.07	0.98	1.82	2.72	11.61	1.00 (y)
			Paved	1.06	0.94	1.80	2.68	13.43	1.00 (x)
11	25.02	10.70	Gravel	1.12	0.86	1.84	2.70	17.24	1.25 (y)
			Paved	1.20	1.18	1.47	2.77	14.45	1.00 (y)
12	20.06	15.00	Gravel	1.83	0.93	1.73	3.38	7.44	2.00 (x)
			Paved	1.61	1.01	1.75	3.18	23.09	2.00 (x)

Table 2.4: Summary of WBV characteristics measured at the arm of the bicycle trailer in accordance with ISO 2631-1

Trial	Duration (min)	Average Speed (km/h)	Terrain	Frequency-weighted RMS Accelerations (m/s^2)				Crest Factor	Dominant Frequency (Hz)
				a_{wx}	a_{wy}	a_{wz}	sum	CF	DF_{xyz}
1	28.20	12.70	Overall	0.33	0.42	1.84	1.92	18.19	N/A
2	39.15	10.95	Overall	0.34	0.43	2.54	2.60	10.99	N/A
3	23.44	14.12	Overall	0.26	0.30	1.27	1.33	17.92	N/A
4	22.29	11.40	Gravel	0.65	0.61	3.85	4.05	7.09	12.50 (z)
			Paved	0.52	0.57	2.33	2.56	13.28	12.50 (z)
5	23.23	11.50	Gravel	0.77	0.59	2.40	2.76	9.66	1.00 (x)
			Paved	0.57	0.49	1.57	1.90	17.40	1.00 (x)
6	22.32	11.00	Gravel	0.79	0.69	4.11	4.39	11.39	10.00 (z)
			Paved	0.70	0.62	3.39	3.63	16.98	10.00 (z)
7	21.14	15.80	Gravel	0.81	0.77	4.35	4.62	9.26	25.00 (z)
			Paved	0.77	0.77	3.95	4.23	11.90	8.00 (z)
8	25.15	11.40	Gravel	0.62	0.58	4.59	4.74	11.80	12.50 (z)
			Paved	0.53	0.54	2.55	2.76	16.81	12.50 (z)
9	27.14	10.10	Gravel	0.54	0.51	4.00	4.13	9.58	12.50 (z)
			Paved	0.50	0.47	2.90	3.06	14.61	10.00 (z)
10	22.53	10.60	Gravel	0.61	0.61	3.54	3.74	10.70	12.50 (z)
			Paved	0.53	0.51	2.89	3.07	12.92	10.00 (z)
11	25.02	10.70	Gravel	0.57	0.47	3.17	3.34	9.20	12.50 (z)
			Paved	0.53	0.61	2.33	2.59	11.57	12.50 (z)
12	20.06	15.00	Gravel	0.70	0.63	3.12	3.38	9.11	12.50 (z)
			Paved	0.61	0.61	2.53	2.80	13.71	10.00 (z)

Table 2.5: Summary of WBV characteristics measured at the wheel-axle of the bicycle trailer in accordance with ISO 2631-1

Trial	Duration (min)	Average Speed (km/h)	Terrain	Frequency-weighted RMS Accelerations (m/s^2)				Crest Factor	Dominant Frequency (Hz)
				a_{wx}	a_{wy}	a_{wz}	sum	CF	DF_{xyz}
1	28.20	12.70	Overall	0.43	0.34	1.71	1.80	16.34	N/A
2	39.15	10.95	Overall	0.47	0.34	3.23	3.28	11.12	N/A
3	23.44	14.12	Overall	0.32	0.27	1.79	1.84	14.21	N/A
4	22.29	11.40	Gravel	0.64	0.76	4.40	4.61	7.35	12.50 (z)
			Paved	0.64	0.76	4.40	4.61	7.35	12.50 (z)
5	23.23	11.50	Gravel	0.79	0.53	1.64	2.11	14.98	1.00 (x)
			Paved	0.59	0.42	1.10	1.49	15.74	1.00 (x)
6	22.32	11.00	Gravel	0.78	0.63	4.21	4.43	9.81	10.00 (z)
			Paved	0.69	0.60	3.43	3.66	12.13	10.00 (z)
7	21.14	15.80	Gravel	0.75	0.83	3.04	3.42	9.14	25.00 (z)
			Paved	0.76	0.79	2.91	3.28	14.48	4.00 (z)
8	25.15	11.40	Gravel	0.62	0.77	5.06	5.25	14.36	12.50 (z)
			Paved	0.52	0.60	2.68	2.90	20.78	12.50 (z)
9	27.14	10.10	Gravel	0.55	0.68	4.36	4.53	11.83	12.50 (z)
			Paved	0.49	0.56	3.13	3.30	17.11	10.00 (z)
10	22.53	10.60	Gravel	0.61	0.71	3.74	3.96	9.52	12.50 (z)
			Paved	0.53	0.58	2.96	3.16	17.06	12.50 (z)
11	25.02	10.70	Gravel	0.59	0.59	3.85	4.02	10.91	10.00 (z)
			Paved	0.53	0.66	2.69	2.94	13.87	10.00 (z)
12	20.06	15.00	Gravel	0.73	0.71	3.76	4.02	10.69	10.00 (z)
			Paved	0.62	0.63	2.92	3.17	17.16	10.00 (z)

2.3.3 ISO 2631-1 Health Risk Assessment

Health risk determination in accordance with ISO 2631-1, was assessed at the seat/child interface, and are reported in Table 2.6. While the eight-hour equivalent exposure value (A(8)) was calculated, it is important to note that it is unlikely that a child would be riding in a bicycle trailer for eight-hours in one day. As such, an A(8) value was calculated which assumed a two-hour exposure, to represent a more realistic exposure time for a child riding in a bicycle trailer. To recall, according to the ISO 2631-1 HGCZ the probability of adverse health effects is low for adults with an A(8) value below $0.45 m/s^2$, and likely for adults with an A(8) value greater than $0.90 m/s^2$. In this study, the health risk determination was broken down for each trial by terrain type, with the exception of Trials 1, 2, and 3, due to technical issues with data storage.

When assuming an 8-hour exposure time in the bicycle trailer, 14 of 21 trials had A(8) values that were above the ISO 2631-1 HGCZ, indicating that health risks are likely to occur (Table 2.6). However, when the A(8) was adjusted to reflect a 2-hour exposure time, the same 14 trials' A(8) values fell within the ISO 2631-1 HGCZ, indicating moderate health risk. At an 8-hour exposure time, 7 of the trials had A(8) values between the ISO 2631-1 HGCZ (moderate health risk), which also fell below the ISO 2631 HCGZ when adjusted for a 2-hour exposure time, indicating a low risk of negative health effects (Table 2.6). With the exception of one trial (5), the trials found to be below the ISO 2631-1 HGCZ occurred on paved terrain (Table 2.6). Additionally, the two lowest values occurred in Trial 3 ($0.31 m/s^2$) and Trial 5 ($0.32 m/s^2$) when a bicycle with a suspension frame trailer was ridden over paved terrain.

Table 2.6: Health risk determination according to ISO 2631-1 HGCZ

Measurement Duration(min)	Trial	Gravel Terrain/Paved Terrain	Health Risk Determination (ISO 2631-1: HGCZ)	
			Frequncy-weighted RMS Acceleration (A8)	Frequency-weighted RMS Accleration (A8) *Based on 2-hours of exposure
28	1	Overall	0.77	0.39
39	2	Overall	0.91	0.46
23	3	Overall	0.62	0.31
22	4	Gravel	1.09	0.55
		Paved	0.91	0.46
23	5	Gravel	0.80	0.40
		Paved	0.63	0.32
22	6	Gravel	1.49	0.75
		Paved	1.23	0.62
21	7	Gravel	0.96	0.48
		Paved	1.10	0.55
25	8	Gravel	1.40	0.70
		Paved	0.84	0.42
27	9	Gravel	1.22	0.61
		Paved	1.00	0.50
22	10	Gravel	1.37	0.69
		Paved	1.14	0.57
25	11	Gravel	0.96	0.48
		Paved	0.79	0.40
20	12	Gravel	0.95	0.48
		Paved	0.88	0.44

Note: The risk of adverse health effects is indicated in green (low), yellow (moderate) and red (high)

2.3.4 Transmissibility

Seat-head vibration transmissibility, calculated in the vertical axis, for all 12-trials was greater than 1 suggesting vibration was amplified between the buttock and head of the child when riding in the bicycle trailer (Figure 2.6). The highest transmissibility ratio occurred in Trial 7, with a transmissibility ratio of 2.54. The cyclist in Trial 7 was using a rigid-frame trailer, and travelling at a speed of 15.8km/h, which was the fastest speed recorded out of all twelve participants. The child in the bicycle trailer during Trial 7 had a mass of 17.24kg. The smallest transmissibility ratio occurred in Trial 6 (1.08), where the cyclist used a rigid-frame trailer but travelled slower (11.00km/h), while towing a child that weighed 10.89kg, which was the smallest mass recorded out of all trials. Trials 3 and 5, the only trials in which a suspension-frame trailer was used, resulted in a seat-head transmissibility ratio of 2.19 and 1.51 respectively. Trial 8 was the trial with the largest mass recorded at 21.77kg, while riding speed was the slowest in Trial 9 (10.10km/h) (Table 2.1).

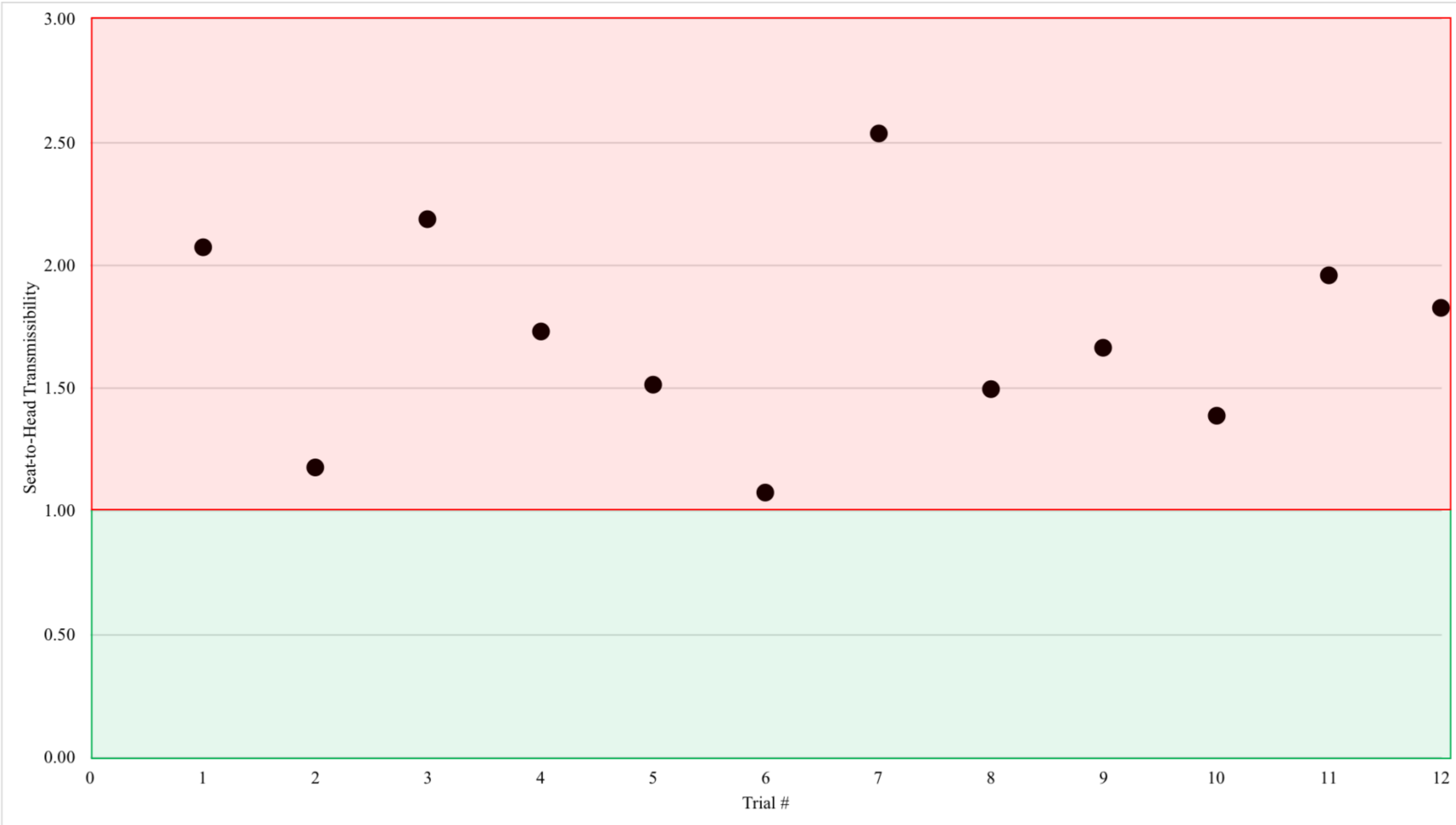

Figure 2.6: Transmissibility ratios between the between the seat of the bicycle trailer and the child’s head. Ratios in the green indicate vibration attenuation between the points. Ratios in red indicate vibration amplification between the points.

2.4 Discussion

The first objective of this study was to determine the characteristics of WBV exposure for children riding in bicycle trailers. Tri-axial vibration measurements were taken at the trailer wheel axle, arm of the trailer, buttock/seat interface and at the head of the child. The mean accelerations recorded at the seat, which had the lowest overall accelerations out of the four locations tested, were 1.14m/s^2 ($\pm$0.24m/s^2) over gravel terrain, and 0.95m/s^2 ($\pm$0.19m/s^2) over paved (Table 2.2). These values are in line with exposures previously reported for children riding in car seats (1.44m/s^2) when travelling at a speed of 20km/h (Giacomin & Gallo, 2003). Furthermore, frequency-weighted r.m.s vertical accelerations at the seat, when riding in a school bus, ranged between 0.88m/s^2 to 0.97m/s^2 on paved roads, and between 0.77m/s^2 to 2.13m/s^2 on rough road (Rao et al., 2018). Aside from domestic transportation, studies in neonatal transportation have also been completed. Studies in neonatal transport have showed that vertical r.m.s. accelerations consistently exceed 0.315m/s^2, which is the ISO 2631-1 comfort threshold (Blaxter et al., 2017).

Vibration exposure measures previously reported for cycling are higher than the values reported in this study. For example, mean r.m.s. acceleration in the vertical direction for a rigid bike was reported to be 20.36m/s^2 ($\pm$5.25m/s^2), and 9.65m/s^2 ($\pm$1.12m/s^2) on a mountain bike which had a more sophisticated suspension system (Arpinar-Avsar et al., 2013). This differs from our values, particularly those that measured vibration at the arm of the bicycle trailer (3.68m/s^2 on gravel; 2.72m/s^2 on paved) and at the trailer wheel axle (3.78m/s^2 on gravel; 2.91m/s^2 on paved). One reason for the difference could be due to the fact that the vibration transmission chain is not rigid between the bicycle and the point where the bike trailer attaches to the bicycle. Therefore, vibration levels are lower for the child in the trailer which ultimately means that the child is not experiencing the same levels of vibrations as the cyclist. Future research should measure vibration levels on the bicycle frame and at the arm of the bicycle trailer to confirm this hypothesis.

The second objective of this study was to determine if terrain, riding speed or trailer type had an impact on measured vibration exposure. Vibration exposure, in the vertical axis, was consistently higher when riding on gravel compared to paved roads. This finding is in-line with previous vibration studies that have reported higher vibration exposure when industrial vehicles travel over rougher roads (McPhee, 2004; Eger et al., 2011). The effect of terrain quality on vibration exposure has also been noted in studies involving bicycles (Levy & Smith, 2005; Arpinar-Avsar et al., 2013; Parkin & Sainte Cluque, 2014; Macdermid et al., 2015). Along with terrain quality, travelling speed has been shown to have an effect on WBV exposure, across various industries (Chen et al., 2003; Eger et al., 2011). Furthermore, cycling research has reported a positive association between cycling speed and vibration exposure magnitude (Parkin & Sainte Cluque, 2014). Chen et al. (2003) also noted that driving speed was a high predictor in vibration exposure among taxi drivers. Overall, vibration characteristics reported in this study reflect previous literature in the area, and add new data on vibration exposure experienced by children.

The third purpose of this study was to determine the health risk for children riding in bicycle trailers, based on the ISO 2631-1 HGCZ and the seat-to-head transmissibility. In this study 14 of 21 study participants were exposed to vibration levels within the HGCZ when riding durations of 2 hours were considered (Table 2.6). Vibration exposure A(8) values associated with neonatal transport have also been reported at levels found to be within the HGCZ (Blaxter et al., 2017; Karlsson et al., 2012).

The two trials with suspension bike trailers (Trial 3 and Trial 5) resulted in the lowest A(8) values resulting in exposure below the ISO 2631-1 HGCZ. Although there were not enough trials with and without suspension trailers in this study to make a definitive statement about vibration attenuation effectiveness, future research is warranted. When analyzing the effectiveness of a suspension fork on a bicycle to attenuate vibration, the current literature is mixed. Macdermid et al. (2017), determined that suspension systems do not improve performance, and did not reduce overall exposure. However, studies from Levy & Smith (2005), and Liu et al. (2013), both determined that the suspension system in the bicycle were effective in reducing vertical vibration to the human body when cycling on rougher road conditions.

Along with determining the health risk for a child in a bicycle trailer based on the ISO 2631-1 HGCZ, seat-to-head vibration transmissibility was also calculated (Figure 2.6). All of the twelve trials had seat-to-head transmissibility's greater than 1.00, indicating a possible amplification of vibration to the child's head from the seat. Vibration that occurs at the head is a concern (Bressel et al., 2010), as it can lead to vestibular and eye-sight issues. However, the weaker neck muscles which reduce the ability of the child to hold the head upright, along with weaker connective tissues in the brain, could lead to injury (Lancon et al., 1998; Bandak, 2005; Koizumi et al., 2013). As a child ages, the muscle strength in their neck increases, as well as the ligaments in the neck (Huelke, 1998). While the neck muscles and ligaments are not as weak as they are in infancy, they are much weaker compared to an adult. Combined with the typically larger head mass of a child compared to an adult, along with the weak neck muscles and ligaments, it provides less support to the child to rapid head movements, possibly leading to injury (Huelke, 1998). Along with vertical accelerations at the child's head in this study, high accelerations and dominant exposures in the fore-aft and lateral direction were also noted, which may indicate that the child's head was bouncing around in various directions while riding in the bicycle trailer. Due to the young age of the children in this study (average age of 4 years old), it would be unrealistic to have them try not to move their head while in the trailer. This may however reflect a typical bicycle ride, where the head is bouncing around. This could suggest an increased risk of injury; however, further research in a controlled setting would be required in order to examine the relationship between vibration transmissibility, posture and neck and spinal neck muscle activation.

2.4.1 Limitations

There were several limitations associated with this study. First, the ISO 2631-1 HGCZ was developed to determine vibration exposure health risk for healthy, adult individuals, rather than children. For example, when evaluating absorbed power in small children, Giacomin (2005) argued that ISO 2631-1 may not be appropriate to use with children under 18kg, which represented the weight of the majority of our participants. Along with being able to better evaluate vibration exposure in children, a vibration standard specifically for children would also aid in building safer equipment for children. One example of this is with neonatal transportation systems. While it is likely that international vibration standards influenced the design of the systems, without a proper standard for children, it is unclear whether or not these systems are properly designed to attenuate vibration to neonatal patients (Green et al., 2019). Since the values outlined in ISO 2631-1 HGCZ do not consider children, it is unclear whether or not the health risk for children is greater, the same, or worse. The values outlined in the ISO 2631-1 HGCZ are values that would indicate a health risk if the individual was exposed to those vibration levels for an 8-hour duration, which would represent a typical work shift. While one of the benefits of bicycle trailers is that they can transport children, who are not able to cycle for long periods of time, it is unlikely that a child would be in the trailer for 8 hours, which is why this study assumed a two-hour maximal exposure duration. It is likely that there is less health risk associated with a smaller duration time, and a greater health risk associated with a greater duration time. However, it is important to note that a clear dose-response relationship for vibration and injury has not been epidemiologically established.

Second, only 12 children participated in this study, with a limited weight range that did not enable the investigator to determine if there was a correlation between the combined weight of the participant/trailer and vibration transmitted from the seat to the head of the child. Third, this study was not able to evaluate the effectiveness of a suspension system in the bicycle trailer as only two of the trailers used by participants had a suspension system, while the other 3 did not have one. While previous studies have confirmed that a suspension system can attenuate vibration in bicycle (Levy & Smith, 2005; Arpinar-Avsar et al., 2013), it is unclear whether or not this applies to the bicycle trailers used in this study. In order to confirm the effect of weight, and the suspension system in vibration attenuation, further tests need to be completed.

A third limitation to consider is the interaction of the helmet, and the head movement of the child on measured accelerations at the back of the head. As the child was required to wear the helmet in order to participate in this study for safety reasons, the option to eliminate the helmet was not a realistic option. That being said, it is possible that the accelerometer could have shifted during the bicycle ride, due to the helmet pressing up against the accelerometer at the back of the head. Additionally, the head accelerations recorded could have been attributed to the child's head movement, as evident by the dominant frequencies in the x and y axes, primarily. While children were instructed to limit their movement while they were in the trailer, the researcher had no control over the head movement once the bicycle ride commenced. The average age of the child in the bicycle was 4 years old; therefore, to rely on the child to not move their head at all is unrealistic. It is also important to note that the method used to collect head accelerations in this study was not the standard method of data collection. Typically, head accelerations are collected with a device called a bite bar, which is a device that collects accelerations at the head while the participant bites down on an instrumented bar. This method of data collection is quite invasive, and is not designed for small children; therefore, it would be unethical to have a child use one during the data collection process. While the head data were likely influenced by the movement of the child's head, it does reflect typical head movement that would occur during a typical ride in a bicycle trailer. Although the head movement likely influenced the results, they cannot be ignored.

2.4.2 Future Research

This study found that children riding in bicycle trailers are exposed to vibration levels associated with low to moderate injury risk for a healthy adult male population. Additional research is required to develop a standard to evaluate health risks to children exposure to vibration. Further research is required to determine if changes in road condition, biking speed, and the design of the bike trailer and seat can result in a reduction in vibration transmitted to a child riding in a bicycle trailer. As previously shown in the literature, a rigid body unit and a suspension system unit have different vibration exposure levels, with the suspension system providing more attenuation properties compared to the rigid body.

2.5 Conclusion

The overall purpose of this study was to document the vibration exposure experienced by children riding in bicycle trailers. Exposures suggest a moderate risk of negative health outcomes for children riding in bicycle trailers, particularly when riding for periods of 2 hours or more.

Higher exposure levels were also reported when the bicycle trailer was ridden over gravel terrain compared to paved roads, and when at higher speeds (above 11.40km/h). Additionally, this study found that vibration transmission from the seat to the child's head were amplified in all 12 trials, further suggesting increased risk for a WBV-induced injury. Based on the findings of this study, it is important for parents to understand the different variables associated with vibration exposure to their child when using a bicycle trailer. Since this study demonstrated lower exposure levels when travelling on smoother roads, and with a slower speed (below 11.40km/h), parents should travel on well-maintained roads, and at a speed below 11.40km/h, particularly when travelling on smoother roads is not possible. Additionally, since our study demonstrated an increased risk of health effects when in a trailer for 2 hours or more, it is possible that the child's risk of vibration injuries will be small, so long as they are not in the trailer for more than 2 hours. Further research is also required to evaluate potential risk mitigation strategies including trailer suspension and seat cushion materials.

CHAPTER 3: Evaluating the Effectiveness of Gel Cushions in Vibration Attenuation in Children's Bicycle Trailers

3.1 Introduction

Bicycle trailers are typically attached to the back wheel of a bicycle to allow a parent/guardian to tow 1-2 children behind their bicycle. A bicycle trailer is an enclosed seat with two to four wheels, typically with two at the back of the trailer and one at the front (Murray & Ryan-Krause, 2009). Bike trailers are designed to attach to the back-wheel of a bicycle, and can typically accommodate up to two children between the ages of 1 and 5 years old with a combined weight up to 100lbs (Murray & Ryan-Krause, 2009). Whole-body vibration (WBV) exposure studies on bicycle trailers are limited; however, several authors have studied the effect of WBV during cycling.

The bicycle, its frame, and its suspension components can impact WBV exposure levels. Bicycles with suspensions systems are commonly used when the cyclist is travelling on rougher terrain, such as a trail or a gravel path, and have been shown to transmit less vibration to the frame on rough terrain compare to a rigid frame bicycle (Levy & Smith, 2005). In previous work by Kanya-Forstner (Chapter 2) children riding in bicycle trailers with suspension were exposed to lower levels of vibration when compared to children riding in bicycle trailers without suspension. Additionally, the terrain quality has shown to have a direct relation to the amount of vibration transmitted to the cyclist during a bicycle ride, with the rougher road conditions (i.e. gravel paths and trails) transmitting greater vibration to the rider compared to smoother road conditions (i.e. paved bike lanes and sidewalks) (Arpinar-Avsar, Birlik, Szegin, & Soylu, 2013; Gromadowski & Wieckowski, 2013; Levy & Smith, 2005; Macdermind, Miller, Macdermind & Fink, 2015). Kanya-Forstner (Chapter 2) also reported higher frequency-weighted r.m.s. accelerations in the vertical direction, when bicycle trailers were ridden on gravel terrain (1.14 m/s^2) compared to paved ($0.95 m/s^2$).

When analyzing ways to attenuate vibration transmitted to a seated person, the design of the seat cushion is often considered. Gel cushions have been shown to be an effective material for seat cushions, as they promote postural correction, and can promote musculoskeletal stability (Boi Du et al., 2018). Furthermore, Boi Du et al. (2018) found that the gel elastomers in the cushion used in their study acted as a shock absorber, which prevented the vibration generated by the vehicle from reaching the seat of the occupational driver, possibly contributing to the observed reduction of low-back pain (LBP) reported by the participants. Gel has also been shown to be an effective material for cushions when assessing vibration attenuation in children, specifically as a mattress pad during neonatal transfer. When comparing the effectiveness of foam and gel in vibration attenuation, gel was shown to be the more effective material for this task, decreasing overall vibration exposure to the child (Gajendragadkar et al., 2000; Blaxter et al., 2017). The gel cushion was also found to have a resonance frequency at around 10Hz (Gajendragadkar et al., 2000; Blaxter et al., 2017). The dominant frequencies on the seat of bicycle trailer were noted to be 4-16Hz in the vertical direction, with one trial recording exactly 10Hz in the vertical direction (Kanya-Forstner, Chapter 2). While gel cushions have been shown to be effective in occupational settings, and with wheelchair users by redistributing across the cushion (Koo et al., 1996; Aissaoui et al., 2001), it's effectiveness to attenuate vibration in bicycle trailers has not yet been evaluated.

It is evident that vibration exposure can lead to serious health issues, and those with a lower mass can be at higher risk of developing a vibration related injury. Additionally, previous studies have suggested that not only is the cyclist exposed to high levels of vibration, but the child in the bicycle trailer can experience levels of vibration that may put them at an increased risk for vibration injuries (Kanya-Forstner, Chapter 2). The main gap in the research is that an analysis on factors that can help reduce vibration exposure to children in bicycle trailers has yet to be completed. Therefore, the purpose of this study was to examine the impact of independent variables (terrain type, trailer type, and cushion type) on the dependent variable of vibration magnitude measured at the interface between the trailer seat and simulated location for a seated child.

3.2 Methods

Vibration exposure transmitted to the seat of two bicycle trailers, with four seat types under five simulated vibration conditions were evaluated in this study.

3.2.1 Vibration Simulator and Profiles

A Rotopod 3000 (Figure 3.1) (Mikrolar, New Hampshire, USA), was used to replicate vibration profiles that were collected in a previous field study (Chapter 2).

Figure 3.1: Rotopod 3000 (Mikrolar, New Hampshire)

Four vibration profiles, as well as one sinusoidal sweep signal were used during this study. Two of the profiles, named Gravel 01 and Gravel 02, were derived from previously collected tri-axial acceleration data measured at the wheel-axle of a bicycle trailer travelling on a gravel portion of a closed course. The other two profiles, named Paved 01 and Paved 02, were collected from the wheel-axle when the bicycle trailer was travelling on a paved portion of a closed course (Chapter 2). The travelling speed, duration, frequencies, and un-weighted exposure magnitudes of each of the profiles, as well as the sinusoidal sweep signal are provided in Table 3.1.

Table 3.1: Vibration characteristics of the profiles

Name	Terrain	Travelling Speed (km/h)	Duration (sec)	Frequency (Hz)	Frequency-weighted RMS accelerations (awz)
Gravel 01	Gravel	11.4	200	16.62	0.20
Gravel 02	Gravel	11.5	100	3.68	0.11
Paved 01	Paved	11.4	200	20.67	0.24
Paved 02	Paved	15	200	5.65	0.12
Sinusoidal Sweep	N/A	N/A	200	<25	0.50

3.2.2 Bicycle Trailers

Two bicycle trailers were used in this study. A sheet of plywood was secured onto the Rotopod table with bolts, which allowed the bicycle trailers to be securely attached to the Rotopod (Figure 3.2). Both bicycle trailers were attached while in their strolling configurations (i.e. with the front wheels on), to ensure that the bicycle trailers were properly secured onto the Rotopod.

Figure 3.2: Bicycle trailer attached to the Rotopod 3000

A rigid-frame bicycle trailer, Everyday Traveler Lite Trailer (ETLT), (Figure 3.3) and a bicycle trailer with a suspension frame Thule Chariot Cougar 2 (Cougar 2) (Figure 3.4) were selected for the study (Table 3.2).

Table 3.2: Specifications of each bicycle trailer used

Classification In Study	**Model**	**Manufacturer**	**Rear Wheel Diameter**	**Weight of Trailer Chassis (kg)**	**Child Weight & Height Limits**	
					Weight (kg)	**Height (cm)**
Rigid-Frame Trailer	Everyday Traveler Lite Trailer	Everyday Bicycles	40.64	14.6	45	59.5
Suspension-Frame Trailer	Chariot Cougar 2	Thule	50.8	12.7	45	111

The ETLT is considered a lower-end bicycle trailer model and is marketed as “a bicycle trailer for an active family on the go, as it is quick to assemble, take down, and store, a fold flat design with quick release wheels for easy storage, as well as a swivel stroller wheel attachment” (Everyday Bicycles, n.d.). While in its bicycle trailer configuration, the rear of the ETLT is supported by two 50.8 (20-inch) wheels (Everyday Bicycles, n.d.). The ETLT is a double trailer;

however, it can be configured to seat one child in the middle. It is equipped with both a shoulder strap and a seat belt to safely secure the child into the bicycle trailer. Everyday Bicycle advises that this bicycle trailer be used by children between the ages of 12 months to 5 years old, with the weight of each child not exceeding 23kg, or 45kg combined. They also advised that the upper body height of the child not exceed 59.5cm (Everyday Bicycles, n.d.).

Figure 3.3: Everyday Traveler Lite Trailer

The Cougar 2 is a bicycle trailer model that is no longer in production, it is considered a more "top-of-the-line model", with its newer model equivalent, the Thule Chariot Cheetah 2 (REI Co-Op, n.d.). Similar to the ETLT, the Cougar 2 is a multi-functional piece equipment. The Cougar 2 however can be used for multiple sports, such as biking, walking, strolling, and hiking (REI Co-Op, n.d.). While in its bicycle configuration, the bicycle trailer is supported by two 50.80cm (20-inch) rear wheels. Unlike the ETLT, the Cougar 2 has an adjustable suspension system that allows for the bicycle rider to adjust the trailer according to their child's weight (REI

Co-Op, n.d.). While in the bicycle trailer, the child is secured into the trailer with two shoulder and hip straps, which attach together in the middle of the child's torso (REI Co-Op, n.d.). Thule advises the weight not exceed 45kg in the trailer, with the maximum body height to remain under 111cm, while the child is wearing a helmet. (REI Co-Op, n.d.).

Figure 3.4: Thule Chariot Cougar 2 (REI Co-Op, n.d.).

3.2.3 Replicating the Child's Weight

The average weight of a 12-month old and a 5-year-old child were replicated for this study, in accordance with The World Health Organization Growth Charts for Canada (World Health Organization, 2014). The 50th percentile of each growth chart was used, and an average weight between boys and girls was calculated (Table 3.3).

Table 3.3: WHO 50th percentile weights for 12-month old and 5-year old children

Age of Child (years)	**Gender**	**WHO Growth Chart 50th percentile weight (kg)**	**Average Weight (kg)**	**(lbs)**
1	Boy	9.6	9.3	20.50
	Girl	9		
5	Boy	18	18	39.68
	Girl	18		

To replicate the average weight, 10lb plates were used, which were stacked and secured with zip-ties onto to each other to correspond to the correct weight. Two 10lb plates were used to represent the 12-month old, while four 10lb plates were used to represent the 5-year old (Figure 3.5)

Figure 3.5: 1-year old simulated rider, with two 10lb plates on the gel cushion (left). 5-year old simulated rider, with four 10lb plates on the gel cushion (right)

3.2.4 Gel Seat Pads

Three gel cushions were used in this study. These gel cushions are traditionally used as wheelchair seat cushions, which provides wheelchair users comfort and protection against pressure ulcers and vibration damping (Blake Medical, 2012). The first gel seat pad that was used (Gel 01) was a sheet of gel from the Geo-Matrix Seating System (Blake Medical, Hamilton ON, CND). Gel 01 consisted of multiple gel squares that were 1cm wide, that covered the entire 40.64cm by 40.64cm cushion (Figure 3.6). Gel 01 was the softest cushion used during the trials, and was able to be depressed with very little direct pressure. The second gel seat pad that was used (Gel 02) was a sheet of gel from the Geo-Matrix Seating System (Blake Medical, Hamilton ON, CND). Gel 02 consisted of multiple gel squares that were 2cm wide, that covered the entire 40.64cm by 40.64cm cushion (Figure 3.7). Gel 02 was firmer than Gel 01, but was still able to depress upon direct pressure. The third gel seat pad that was used (Gel 03) was a sheet of gel from the Geo-Matrix Seating System (Blake Medical, Hamilton ON, CND). Gel 03 consisted of multiple gel squares that were 3cm wide, that covered the entire 40.64cm by 40.64cm cushion (Figure 3.8). Gel 03 was the firmest of the 3 cushions used, but was still able to depress slightly when direct pressure was applied. All trials were also performed on the factory-installed seat, which acted as a control for the study.

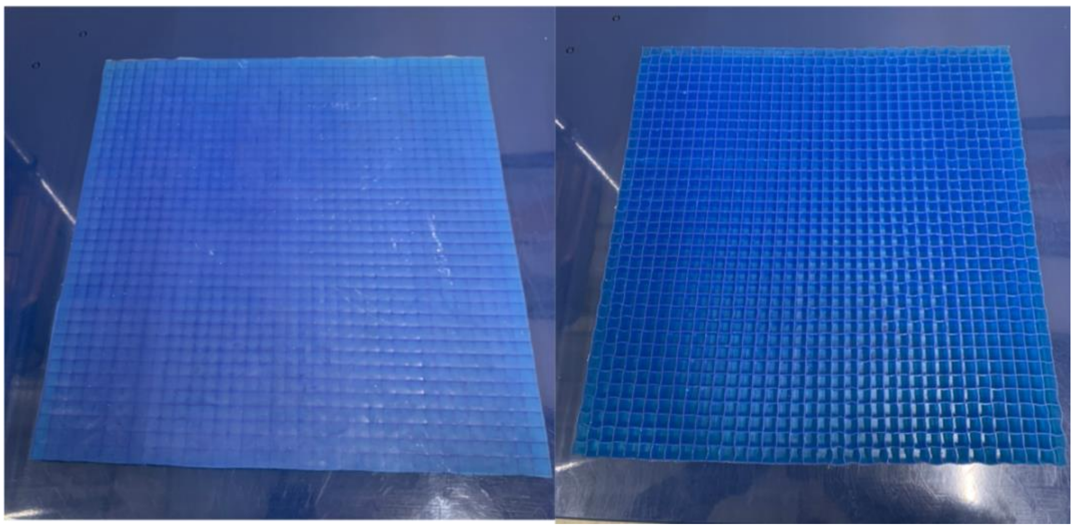

Figure 3.6: Gel 01 (Blake Medical, Hamilton, ON, CND). Top of cushion (left), and underside of cushion (right)

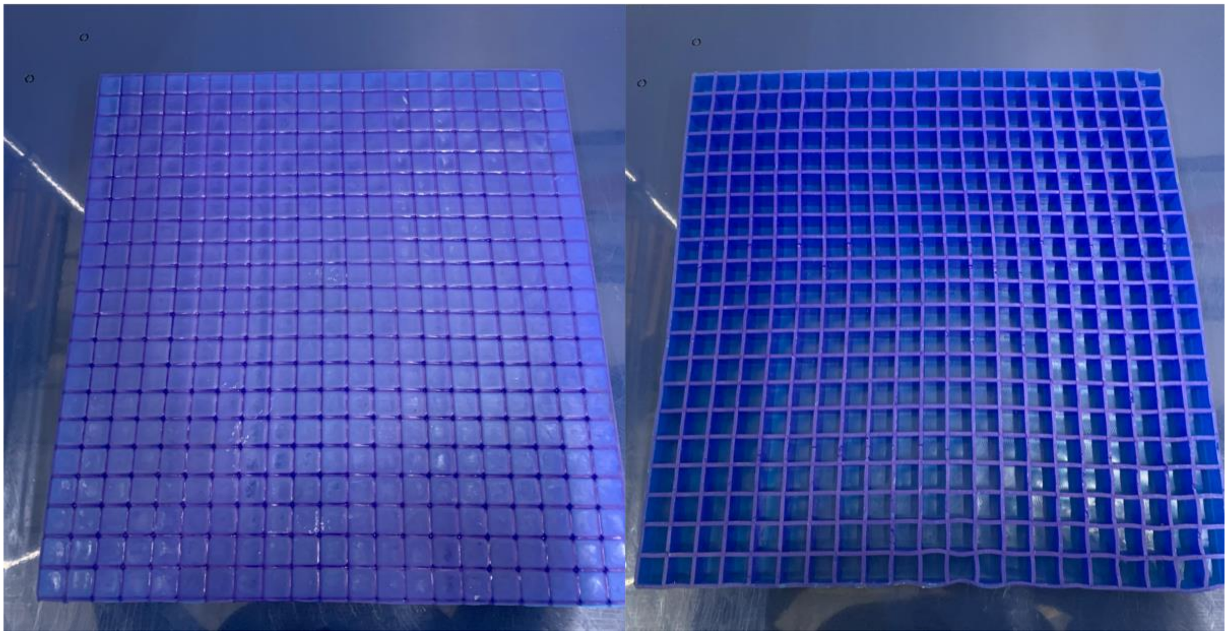

Figure 3.7: Gel 02 (Blake Medical, Hamilton, ON, CND). Top of cushion (left), and underside of cushion (right)

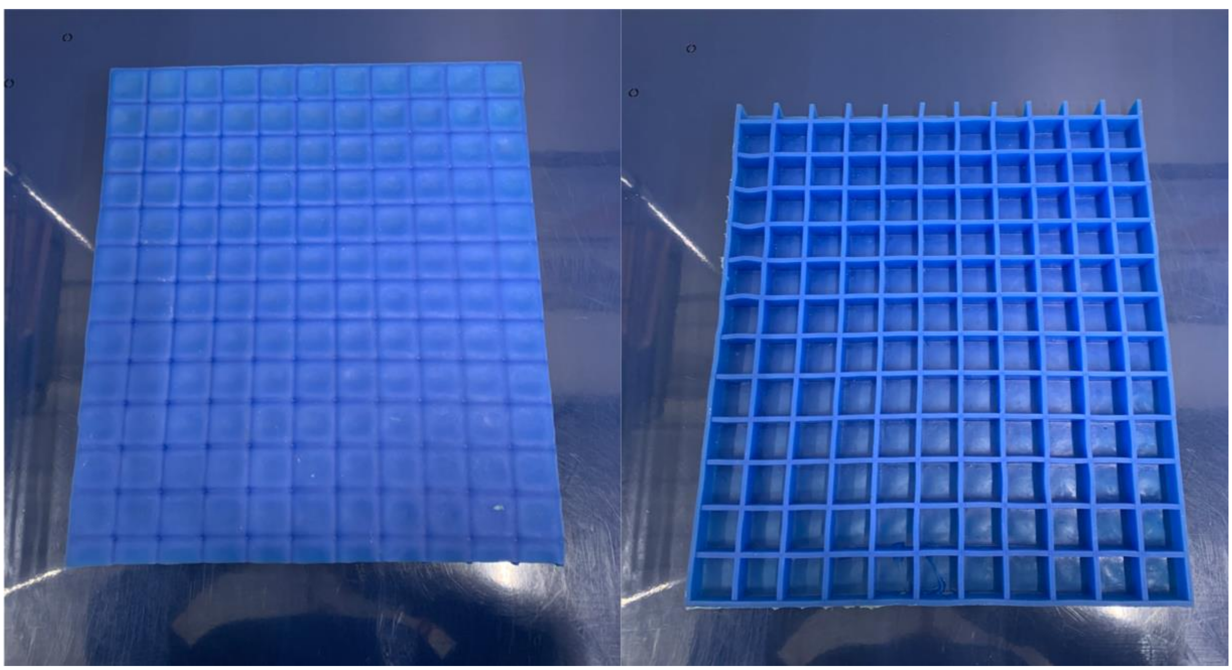

Figure 3.8: Gel 03 (Blake Medical, Hamilton, ON, CND). Top of cushion (left), and underside of cushion (right)

3.2.5 Vibration Measurement

WBV was measured in accordance with ISO 2631-1. Three Series 2 10G tri-axial accelerometers (NexGen Ergonomics, Montreal, QC, CND) were used in this study. The first accelerometer was placed in a rubber seat pad, and secured to the seat of the bicycle trailer. When testing the factory-installed seat of the bicycle trailer, the 10lb plates were placed on rubber seat pad, containing the accelerometer. During the tests where the different gel seat cushions were used, the cushions were placed on top of the accelerometer (Figure 3.9). An additional accelerometer was then used on top of the gel seat pad, which was placed in a rubber seat pad, and secured onto the cushion (Figure 3.10). This particular accelerometer placement allowed for the transmissibility between the seat and the seat pad to be measured to determine the effectiveness of the seat pad in vibration attenuation. A third accelerometer was placed on the wheel axle of the bicycle trailer to determine the vibration transmissions between the wheel and the seat of the bicycle trailer (Figure 3.11). Two portable dataloggers (DataLog MWX8; Biometrics Ltd., Newport, UK) were used during the collection process, with 2 of the accelerometers paired with 1 datalogger. All accelerometers were set at a sampling rate of 500Hz.

Figure 3.9: Accelerometer on the seat of the bicycle trailer, remained on the bicycle for the duration of the trials. Accelerometer on the gel cushion, changed for every cushion tested

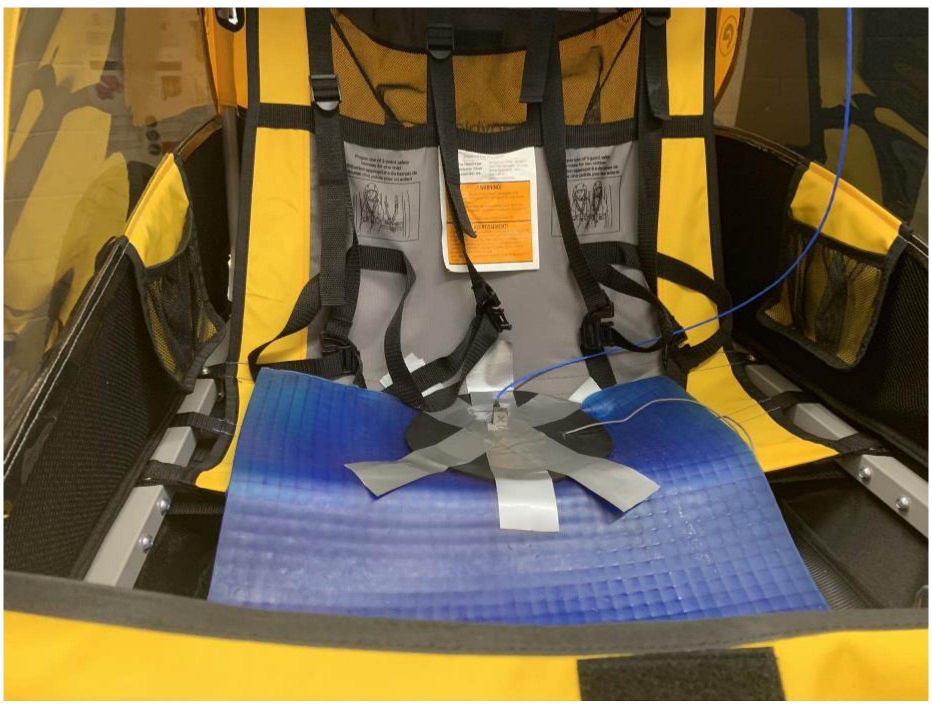

Figure 3.10: Accelerometer on the gel cushion, changed for every cushion tested

Figure 3.11: Overview of ground and wheel-axle accelerometer placement (top). Yellow markers indicate location of the wheel-axle accelerometer (bottom right).

3.2.6 Data Analysis

3.2.6a Vibration Exposure Analysis

Vibration analysis was conducted through the Vibration Analysis Tool-Set (VATS 3.4.4) software (NexGen Ergonomics, Montreal, QC, CND), in accordance to ISO 2631-1. Frequency-weighted r.m.s. accelerations (a_{wx}; a_{wy}; a_{wz}) were calculated using Equation 1:

$$a_w = [\Sigma_i (W_i a_i)^2]^{\frac{1}{2}} \tag{1}$$

where a_w is the frequency weighted acceleration; W_i is the weighting factor for the i^{th} 1/3 octave band; a_i is the r.m.s. acceleration for the i^{th} 1/3 octave band (ISO 2631-1, 1997).

A 2nd order Butterworth filter was applied, with a low cut-off frequency of 0.1Hz, and a high cut-off frequency of 250Hz. A Hanning filtering window was also applied. The appropriate frequency-weighting curves were also applied, as per ISO 2631-1 guidelines (x-axis=W_d; y-axis=W_d; z-axis= W_k). Scaling factors associated with the determination of health for seated exposure were also applied (x-axis, k=1.4; y-axis, k=1.4, z-axis, k=1.0). Additionally, dominant frequencies frequency-weighted r.m.s vector sum values (a_{xyz}) were calculated:

To determine the effectiveness of the gel seat cushions in attenuating vibration to the simulated rider, the seat-effective amplitude transmissibility (SEAT) was calculated using Equation 2:

$$SEAT(\%) = \left(\frac{vibration_{cushion}}{vibration_{seat}}\right) * 100 \tag{2}$$

Where $vibration_{seat}$ is the frequency-weighted r.m.s. acceleration in the vertical direction at the seat of the bicycle trailer, and $vibration_{cushion}$ is the frequency-weighted r.m.s. acceleration in the vertical on top of the cushion. The SEAT value will also provide insight into the possible comfort the rider will experience when sitting on these cushions in a realistic setting.

3.2.6b ISO 2631-1 Health Guidance Caution Zone Analysis

The International Organization for Standardization (1997) ISO 2631-1 Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General

Requirements includes guidance on evaluation of probable health risks to healthy adults with daily exposure to occupational sources of vibration. Although the health guidance caution zone (HGCZ) was not developed to consider health risk to children it will be used in this paper to stimulate discussion around potential risks. Vibration measured at the seat will be compared to the HGCZ. The lower boundary, and upper boundary of the 8-hour health guidance caution zone (HGCZ) are 0.45m/s^2 and 0.90m/s^2 (frequency-weighted r.m.s. acceleration) respectively. According to the standard, "for exposure below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely" (ISO 2631-1, 1997).

3.2.6c Statistical Analysis

All statistical analyses in this study were completed using SPSS. The impact of independent variables of bicycle trailer (2), seat type (4) and vibration profile (5) were determined on dependant variable SEAT value. Multiple 2-way repeated measure analysis of variance (ANOVA) were performed to examine the relationship of the terrain and cushion, the terrain and trailer, and the trailer and cushion with vibration exposure. Paired t-tests were performed post-hoc, in order to determine any significant differences between the variables. A false detection rate (FDR) adjustment was made using the Benjamini-Hochberg (B-H) procedure (Benjamini & Hochberg, 1995) for all of the paired t-tests performed.

3.3 Results

3.3.1 Whole-body Vibration Characteristics

3.3.1a Characteristics of Vibration Measured at the Wheel Axle

Frequency-weighted r.m.s. accelerations, measured at the wheel axle of each bicycle trailers are reported in Table 3.4. For every exposure condition, summative vibration levels measured at the wheel-axle of the suspension-framed trailer were lower in magnitude (Table 3.4) suggesting the suspension trailer was able to attenuate vibration better than the rigid-framed trailer. Frequency-weighted r.m.s. accelerations taken at the wheel-axle of both trailers

Table 3.4: Frequency-weighted r.m.s. accelerations taken at the wheel-axle of both trailers

Terrain	Rigid Frame Trailer (ETLT) Frequency-weighted RMS accelerations (m/s^2)				Suspension-Frame Trailer (C2) Frequency-weighted RMS accelerations (m/s^2)			
	a_{wx}	a_{wy}	a_{wz}	sum	a_{wx}	a_{wy}	a_{wz}	sum
Gravel 01	0.10	0.07	0.93	0.94	0.12	0.09	0.76	0.79
Gravel 02	0.05	0.05	0.24	0.26	0.05	0.05	0.22	0.24
Paved 01	0.09	0.07	0.78	0.80	0.13	0.08	0.67	0.71
Paved 02	0.09	0.06	0.51	0.53	0.10	0.07	0.46	0.49

3.3.1b Vibration Measured with the Factory Installed Seat and Gel Cushions

WBV characteristics, including the frequency-weighted r.m.s. accelerations (in all three axes), the summative frequency-weighted r.m.s. accelerations, are reported at the seat of the rigid-frame trailer (Table 3.5), and the suspension-frame trailer (Table 3.6), for both the 1-year old and 5-year old simulated rider. Vibration measurements were taken directly on the factory installed seat for both of the bicycle trailers. Regardless of the trailer that was used and across all vibration terrain profiles, the 1-year-old simulated rider experienced higher vibration levels at the seat compared to the 5-year-old simulated rider. Furthermore, on the rigid-frame trailer, for all vibration profiles for both simulated riders, the mean frequency-weighted r.m.s vertical acceleration was $0.54m/s^2$ ($\pm 0.24m/s^2$), compared to $0.33m/s^2$ ($\pm 0.14m/s^2$) for the suspension trailer.

Vibration measured with the factory installed seat and gel cushions are reported in Tables 3.5-3.9. These results were obtained from the accelerometer placed on top of the gel cushion placed on top of the factory installed seat. For all vibration profiles for both simulated riders, the mean frequency-weighted r.m.s vertical acceleration at the seat with the rigid-frame trailer was $0.54 m/s^2$ ($\pm 0.24 m/s^2$). When gel 1, gel 2, and gel 3 cushions were individually added on top of the factory installed seat the mean-frequency weighted r.m.s acceleration in the vertical axis was $0.47 m/s^2$ ($\pm 0.20 m/s^2$), $0.42 m/s^2$ ($\pm 0.17 m/s^2$), $0.47 m/s^2$ ($\pm 0.20 m/s^2$), respectively. However, the ability of the gel cushions to reduce vibration transmission to a simulated rider with the suspension framed trailer appeared to be less promising. The mean frequency-weighted r.m.s. at the seat for the suspension frame trailer was $0.33 m/s^2$ ($\pm 0.14 m/s^2$) and changed to $0.40 m/s^2$ ($\pm 0.18 m/s^2$), $0.38 m/s^2$ ($\pm 0.17 m/s^2$), and $0.37 m/s^2$ ($\pm 0.21 m/s^2$), when gel cushion 1, 2, and 3 were added respectively.

Table 3.5: WBV characteristics for the rigid-frame trailer, at the factory installed seat

Trailer	Terrain Profile	Simulated Rider	Frequency-weighted RMS accelerations (m/s^2)			
			a_{wx}	a_{wy}	a_{wz}	sum
Everyday Traveler Lite Trailer (rigid-frame)	Gravel 01	1 year old (9.3kg)	0.07	0.05	0.75	0.76
		5 year old (18kg)	0.07	0.05	0.68	0.70
	Gravel 02	1 year old (9.3kg)	0.04	0.04	0.17	0.18
		5 year old (18kg)	0.04	0.04	0.16	0.18
	Paved 01	1 year old (9.3kg)	0.08	0.05	0.77	0.78
		5 year old (18kg)	0.08	0.04	0.62	0.63
	Paved 02	1 year old (9.3kg)	0.06	0.05	0.60	0.61
		5 year old (18kg)	0.07	0.05	0.55	0.56

Table 3.6: WBV characteristics at the suspension-frame trailer, at the factory-installed seat

Trailer	Terrain Profile	Simulated Rider	Frequency-weighted RMS accelerations (m/s^2)			
			a_{wx}	a_{wy}	a_{wz}	sum
Thule Chariot Cougar 2 (suspension-frame)	Gravel 01	1 year old (9.3kg)	0.10	0.06	0.51	0.53
		5 year old (18kg)	0.10	0.06	0.36	0.40
	Gravel 02	1 year old (9.3kg)	0.04	0.04	0.17	0.18
		5 year old (18kg)	0.05	0.04	0.11	0.14
	Paved 01	1 year old (9.3kg)	0.10	0.06	0.50	0.53
		5 year old (18kg)	0.10	0.05	0.31	0.34
	Paved 02	1 year old (9.3kg)	0.08	0.05	0.41	0.43
		5 year old (18kg)	0.08	0.05	0.27	0.30

Table 3.7: WBV characteristics for Gel 01

Cushion	Trailer	Terrain Profile	Simulated Rider	Frequency-weighted RMS accelerations (m/s^2)			
				a_{wx}	a_{wy}	a_{wz}	sum
Gel 01	Everyday Traveler Lite Trailer (rigid frame)	Gravel 01	1 year old	0.13	0.07	0.67	0.70
			5 year old	0.14	0.07	0.61	0.65
		Gravel 02	1 year old	0.06	0.06	0.16	0.20
			5 year old	0.08	0.07	0.15	0.21
		Paved 01	1 year old	0.13	0.07	0.58	0.61
			5 year old	0.14	0.06	0.51	0.55
		Paved 02	1 year old	0.11	0.07	0.55	0.58
			5 year old	0.13	0.07	0.51	0.55
	Thule Chariot Cougar 2 (suspension frame)	Gravel 01	1 year old	0.17	0.09	0.55	0.61
			5 year old	0.14	0.09	0.49	0.54
		Gravel 02	1 year old	0.07	0.06	0.16	0.21
			5 year old	0.04	0.04	0.09	0.12
		Paved 01	1 year old	0.15	0.08	0.53	0.58
			5 year old	0.15	0.08	0.42	0.49
		Paved 02	1 year old	0.16	0.09	0.52	0.58
			5 year old	0.14	0.09	0.41	0.47

Table 3.8: WBV characteristics for Gel 02

Cushion	Trailer	Terrain Profile	Simulated Rider	Frequency-weighted RMS accelerations (m/s^2)			
				a_{wx}	a_{wy}	a_{wz}	sum
Gel 02	Everyday Traveler Lite Trailer (rigid frame)	Gravel 01	1 year old	0.12	0.07	0.61	0.64
			5 year old	0.14	0.07	0.50	0.54
		Gravel 02	1 year old	0.06	0.07	0.17	0.21
			5 year old	0.07	0.07	0.15	0.21
		Paved 01	1 year old	0.12	0.07	0.52	0.56
			5 year old	0.14	0.07	0.42	0.48
		Paved 02	1 year old	0.11	0.07	0.54	0.57
			5 year old	0.13	0.08	0.44	0.49
	Thule Chariot Cougar 2 (suspension frame)	Gravel 01	1 year old	0.12	0.07	0.61	0.64
			5 year old	0.14	0.07	0.50	0.54
		Gravel 02	1 year old*	0.07	0.07	0.16	0.19
			5 year old	0.08	0.07	0.17	0.23
		Paved 01	1 year old*	0.19	0.10	0.53	0.57
			5 year old	0.15	0.08	0.27	0.36
		Paved 02	1 year old*	0.14	0.09	0.42	0.45
			5 year old	0.14	0.09	0.34	0.42

*Results were obtained using TLD356A14 Triaxial Accelerometers, 100mV/G (PCB Piezotronics, Depew, NY,

Table 3.9: WBV characteristics for Gel 03

Cushion	Trailer	Terrain Profile	Simulated Rider	Frequency-weighted RMS accelerations (m/s^2)			
				a_{wx}	a_{wy}	a_{wz}	sum
Gel 03	Everyday Traveler Lite Trailer (rigid frame)	Gravel 01	1 year old	0.11	0.08	0.68	0.70
			5 year old	0.14	0.08	0.57	0.61
		Gravel 02	1 year old	0.06	0.06	0.18	0.22
			5 year old	0.07	0.07	0.15	0.21
		Paved 01	1 year old	0.12	0.07	0.59	0.62
			5 year old	0.13	0.07	0.47	0.51
		Paved 02	1 year old	0.11	0.07	0.58	0.61
			5 year old	0.13	0.08	0.53	0.57
	Thule Chariot Cougar 2 (suspension frame)	Gravel 01	1 year old	0.11	0.08	0.68	0.71
			5 year old*	0.25	0.23	0.21	0.40
		Gravel 02	1 year old*	0.07	0.06	0.15	0.18
			5 year old*	0.34	0.39	0.12	0.53
		Paved 01	1 year old	0.12	0.07	0.62	0.65
			5 year old	0.15	0.08	0.35	0.43
		Paved 02	1 year old*	0.15	0.08	0.43	0.46
			5 year old	0.14	0.09	0.40	0.47

*Results were obtained using TLD356A14 Triaxial Accelerometers, 100mV/G (PCB Piezotronics, Depew, NY,

3.3.2 Impact of Terrain Profile, Trailer Suspension, and Gel Cushion on Vibration at the Seat

A Pearson correlation was performed to confirm any relationship between mass of the simulated rider and vibration measured at the seat, which resulted in an r value of 0.879, which also proved to be significant ($p<0.01$). Several 2-way repeated measures ANOVAs were performed to assess the interaction between the trailer type and gel cushion, the terrain profile and the gel cushion, and the terrain profile and the trailer type. Paired t-tests were performed as a post-hoc analysis (Appendix C & D). An FDR adjustment was made using the B-H procedure for all of the paired t-tests.

A 2-way repeated measures ANOVA was used to assess the interaction between cushion type and bicycle trailer type. Main effects of the trailer ($p=0.002$) and the interaction between the trailer and cushion ($p=0.003$) were significant. The main effect of the cushion ($p=0.283$) was not significant (Figure 3.12). Paired t-tests were performed as a post-hoc analysis (Appendix C). The

B-H procedure determined the critical cut-off p-value (hereinafter, p_{crit}) to be equal 0.042, when analyzing the interaction between the rigid trailer with all cushion arrangements, and for the suspension trailer with all the cushion arrangements. When analyzing the interactions between the cushions on both trailers, the pcrit value is equal to 0.025. Vibration measured at the factory installed seat was significantly different (p_{crit}=0.0125*)* for trailer types with exposure levels lower for the suspension framed trailer. Vibration measured at the seat of the rigid-frame trailer was significantly different with the gel cushions; however, there was not a significant difference between Gel 01 and Gel 03 (p_{crit}=0.05).Vibration measured at the seat, for the suspension framed trailer, with the addition of gel seat cushions was not significantly different. Furthermore, there were no significant differences in vibration measured, regardless of trailer type, with the installation of Gel 02 (p_{crit}=0.0375) and Gel 03 (p_{crit}=0.05). Results from this analysis revealed that while the interaction between the bicycle trailer and cushion has an effect on vibration magnitude, it is the bicycle trailer itself that has a bigger effect on vibration. Vibration exposure to a simulated rider in the suspension-frame trailer was significantly lower vibration compared to the rigid-frame trailer (Tables 3.4 & 3.5). Moreover, adding the gel cushions to the rigid-frame trailer decreased vibration transmitted to the simulated rider; however, exposure levels were still above values obtained with the suspension trailer alone and adding gel cushions to the suspension-frame trailer were not beneficial.

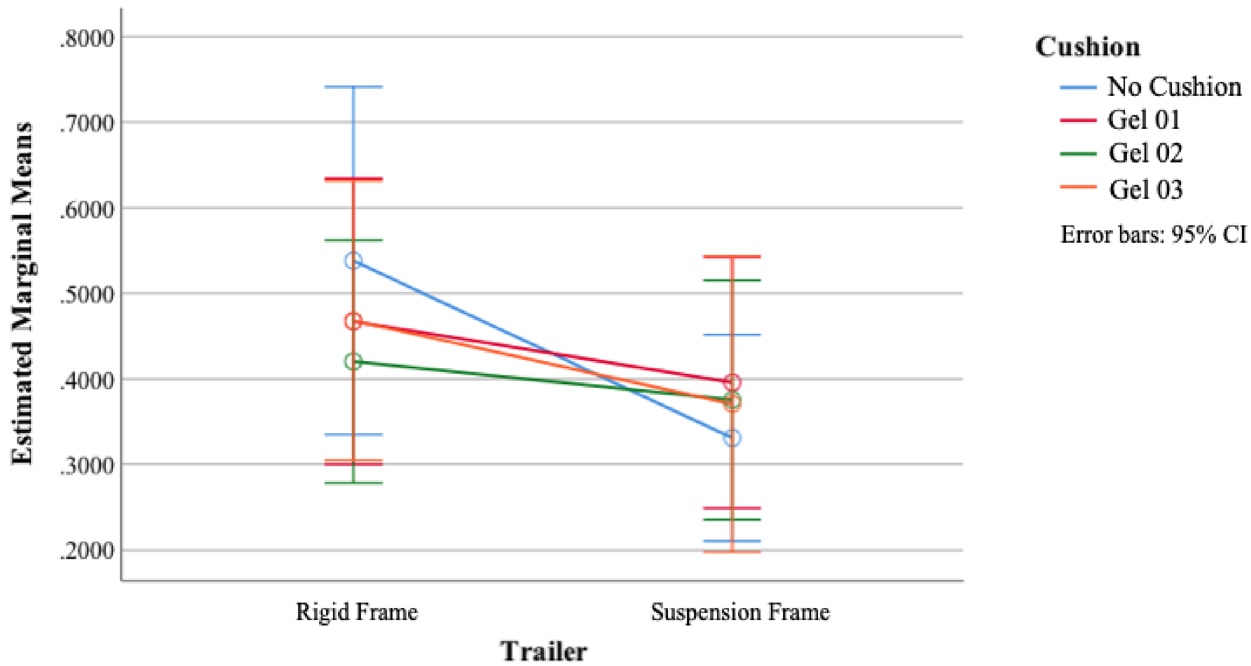

Figure 3.12: Interaction between the bicycle trailer and the type of cushion used

A 2-way repeated measures ANOVA was performed to examine the interactions between the terrain profiles and the two trailers. Main effects of the terrain ($p<0.001$) and trailer ($p<0.001$), as well as the interaction between the terrain and trailer ($p<0.001$) were significant (Figure 3.13). The analysis of the terrain and trailer interaction revealed the type of trailer matters, depending on the terrain the cyclist will be riding on. In this case, the Gravel 01 vibration profile had a higher dominant frequency and higher vibration exposure magnitude (16.62Hz; 0.20m/s^2) than Paved 01 (20.67Hz; 0.24m/s^2) resulting in lower seated exposures to the simulated child when riding in the suspension-frame trailer. Paired t-tests were performed as a post-hoc analysis (Appendix D). The B-H procedure determined p_{crit} value to be equal to 0.042, when analyzing the interaction between the rigid trailer on the different terrain, and the different terrain on both trailers. When analyzing the interaction between the suspension trailer on the different terrain, a p_{crit} value to less than 0.025. For terrain, Gravel 01 (p_{crit}=0.025), Paved 01,

(p_{crit} =0.0375), and Paved 02 (p_{crit}= 0.0125), had significantly different results based on the trailer that was used. The rigid trailer had significantly different results across all terrain, except between Paved 01 and Paved 02 (p_{crit} =0.05).The suspension trailer had significantly different results, except between Gravel 01 and Paved 01 (p_{crit} =0.05), Gravel 01 and Paved 02 (p_{crit} =0.03), and Paved 01 and Paved 02 (p_{crit} =0.042).

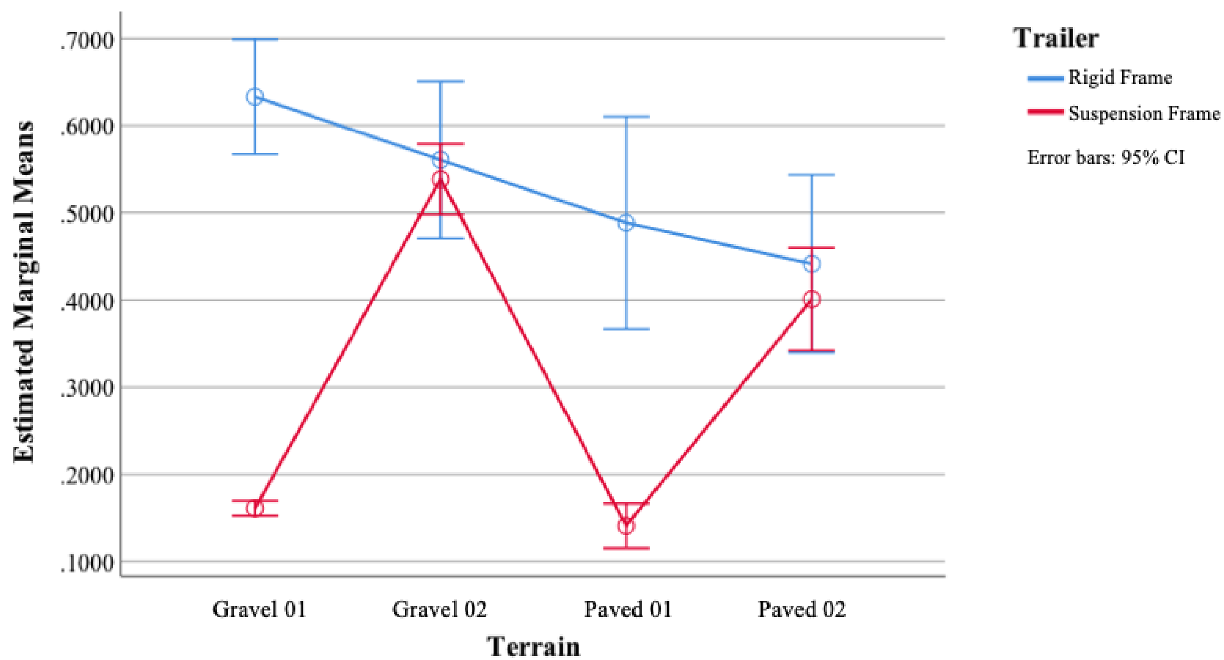

Figure 3.13: Interaction between trailer and terrain profile

A 2-way repeated measures ANOVA was performed to assess the interaction between the terrain profiles and the gel cushions. The analysis revealed a main effect of terrain to be significant ($p<0.001$). The main effect of the cushion ($p=0.677$) and the interaction effect of the terrain and cushion ($p=0.497$) were not significant (Figure 3.14). This test revealed that the terrain type had a larger influence on vibration exposure levels compared to the cushions, and the cushions themselves did not significantly influence vibration exposure to the rider (Appendix E).

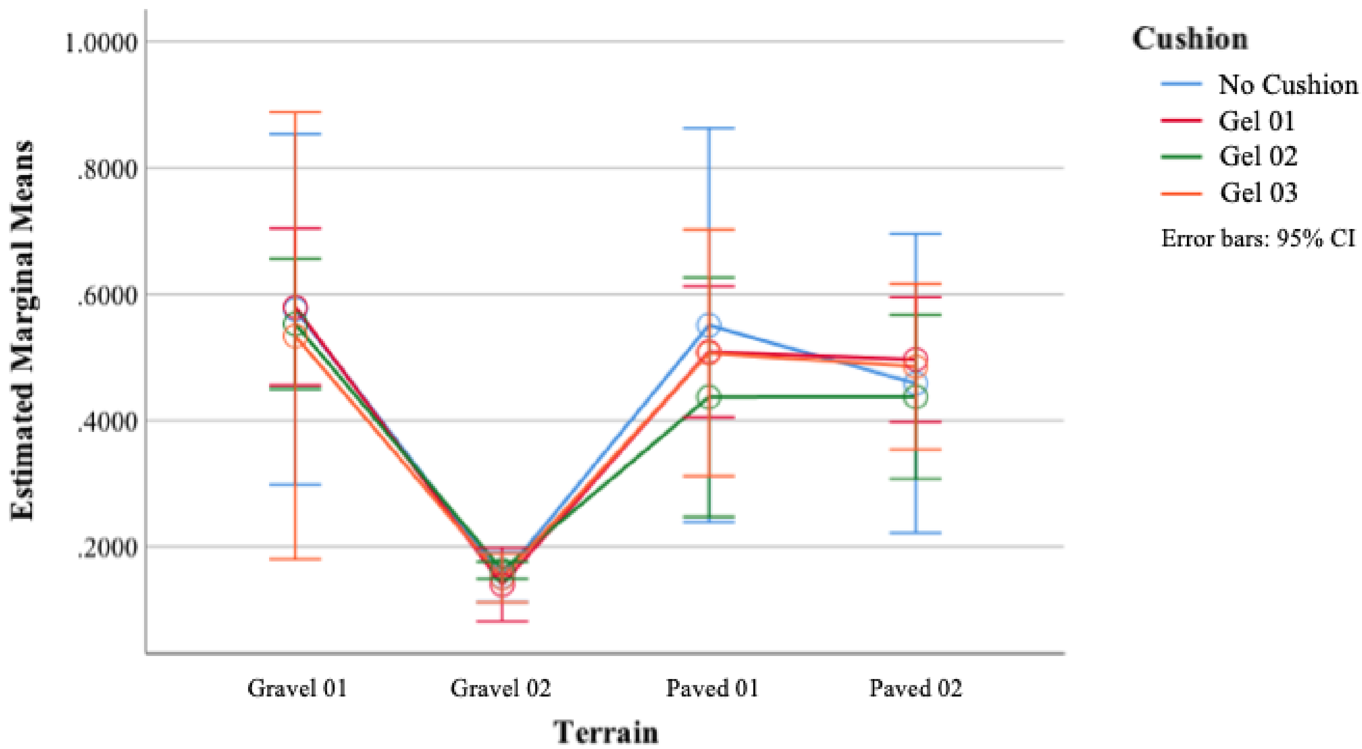

Figure 3.14: Terrain profile and cushion type interaction

3.3.3 SEAT Assessment of the Seat Cushion

A seat effective amplitude transmissibility, SEAT, calculation was performed for all 3 gel cushions for both trailers (Figure 3.15). SEAT values above 100% (unity) indicate an amplification of the vibration from the seat pan of the bicycle trailer to the cushion, while values under 100% indicate an attenuation of the vibration from the seat pan of the trailer to the cushion (Mansfield, 2005).

SEAT values for the 3 cushions on the rigid-frame trailer are reported in Figure 3.15a for the 1-year old rider, and 3.15b for the 5-year old rider. Gel 01 had a mean SEAT value of 88.92% (±11.13) for both the 1-year old and 5-year old rider. SEAT values were below 100% for all terrain, with the exception of Paved 02 with the 1-year old rider, indicating an amplification of vibration to the child on the Gel 01 cushion (Figure 3.15a). Gel 02 had a mean

SEAT value of 86.23% ($\pm$12.10%) for the 1-year old and 5-year old rider. SEAT values were below 100% for all terrain except Gravel 02 with the 1-year old rider, indicating an amplification of vibration to the child on the Gel 02 cushion (Figure 3.15a). Gel 03 had a mean SEAT value of 87.25% ($\pm$10.80%) for the 1-year old and 5-year old rider. SEAT values were below 100% for all terrain, except for Gravel 02 with the 1-year old rider, indicating an amplification of vibration to the child on the Gel 03 cushion (Figure 3.15a).

SEAT values for the 3 cushions on the suspension-frame trailer are reported in Figure 3.15c for the 1-year old rider, and 3.15d for the 5-year old rider. Gel 01 had a mean SEAT value of 113.08% ($\pm$19.92%) for the 1-year old and 5-year old rider. SEAT values were above 100%, indicating an amplification of vibration to the child, for all trials except for Gravel 02 with both riders (Figure 3.15c,d). Gel 02 had a mean SEAT value of 116.84% ($\pm$22.61%). SEAT values were above 100%, indicating an amplification of vibration to the child, for all trials except for Gravel 02 with the 1-year old rider, and Paved 01 with the 5-year old rider (Figure 3.15c,d). Gel 03 had a mean SEAT value of 116.92% ($\pm$27.76%) for the 1-year old and 5-year old rider. SEAT values were above 100%, indicating an amplification in vibration to the child, for all trials except for Gravel 02 with the 1-year old rider, and Gravel 01 with the 5-year old rider (Figure 3.15c,d). Overall, the gel cushions provided a vibration attenuation effect when used on the rigid frame trailer, while the same gel cushions amplified vibration to the simulated rider while on the suspension-frame trailer. Additionally, it was shown, particularly in the rigid-frame SEAT values, that the vibration amplification occurred only in the 1-year old rider, while the SEAT values that were obtained with the 5-year old rider were all below 100%, indicating an attenuation of vibration from the bicycle trailer, to the cushion.

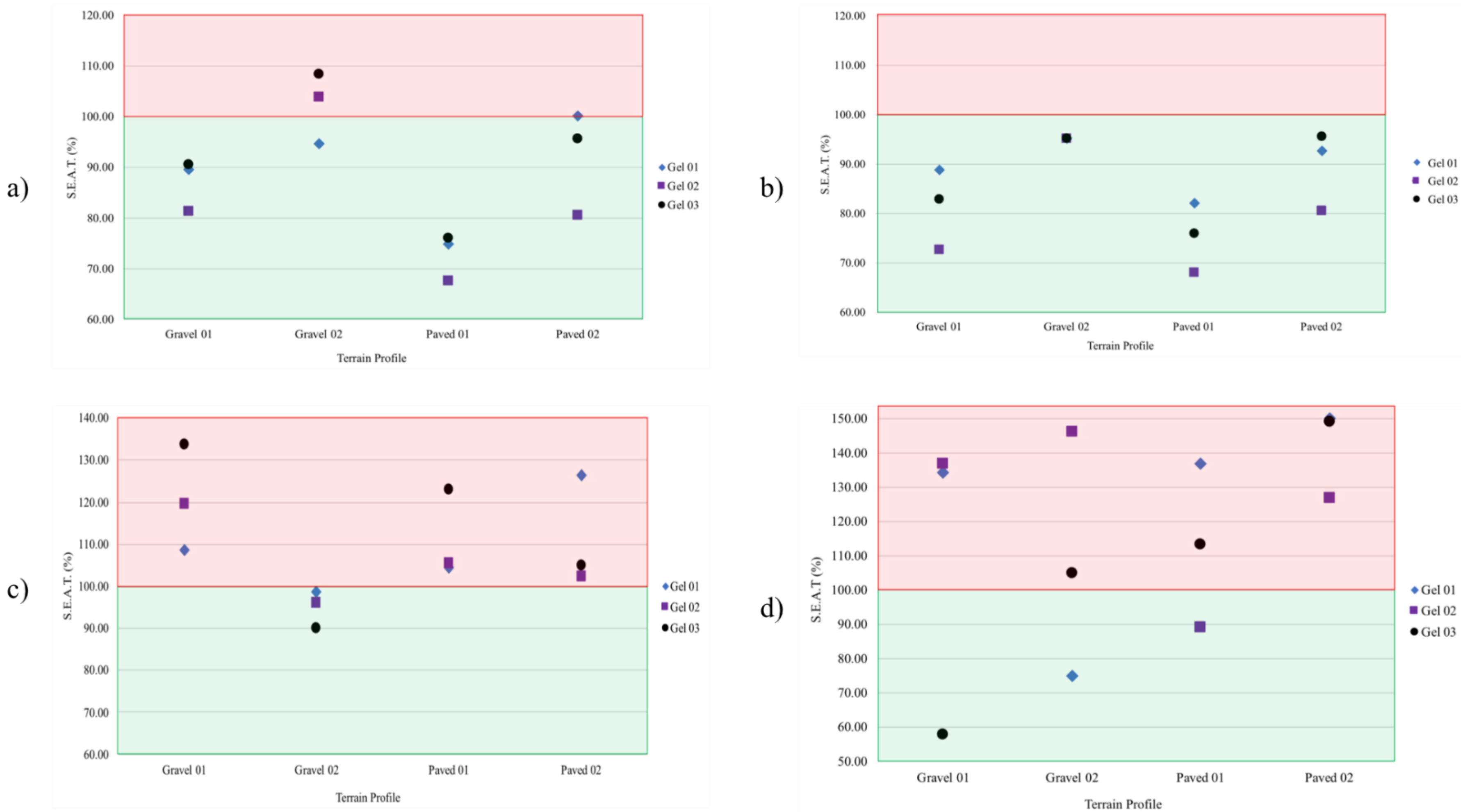

Figure 3.15: SEAT for the 3 gel cushions for the rigid-frame trailer (a &b), and the suspension frame trailer (c & d). Red indicates a SEAT value above 1 and green a SEAT value below 1. Images on the right are for the 1year old simulated rider and on the left the 5-year-old simulated rider

3.3.4 Evaluation of Cushion Response at Different Exposure Frequencies

The frequency associated with the greatest magnitude of vibration transmitted to the simulated riders was determined by exposing the trailers and cushions to a sinusoidal sweep signal between 1-25Hz (Table 3.10). These measurements were taken either on top of the factory installed seat of bicycle trailer, or on top of the gel cushion. The highest magnitude of vibration was transmitted to the simulated rider in the vertical axis, and occurred at 8.0Hz for the factory-installed seat of the rigid-frame bicycle trailer and between 6.30-10.0Hz for the suspension-frame trailer.

Table 3.10: Frequency associated with the highest magnitude (dominant frequency) of the vibration transmitted to the simulated rider for the factory-installed seat and gel cushions for each trailer

Trailer	**Simulated Rider**	**Measurement Location**	**Dominant Frequency (Hz)** DF_{xyz}
Everyday Traveler Lite Trailer	1 year old (9.3kg)	Factory Seat	8.00
		Gel 01	8.00
		Gel 02	6.30
		Gel 03	6.30
	5 year old (18kg)	Factory Seat	8.00
		Gel 01	6.30
		Gel 02	6.30
		Gel 03	6.30
Thule Chariot Cougar 2	1 year old (9.3kg)	Factory Seat	8.00
		Gel 01	6.30
		Gel 02	7.00
		Gel 03	6.00
	5 year old (18kg)	Factory Seat	6.30
		Gel 01	10.00
		Gel 02	5.00
		Gel 03	6.30

*Note: all dominant frequencies occur in the z-axis unless otherwise specified.

The frequency associated with transmission of maximal vibration to the simulated rider was influenced by the addition of a gel cushion to the factory installed seat for the rigid frame trailer. Regardless of the mass of the simulated rider with gel cushion 02 and 03 maximal vibration was transmitted at 6.30Hz compared to 8.00Hz with only the factory installed seat. Findings were less consistent with the suspension trailer; however, the gel cushion 01 transmitted maximal vibration to a 5year old simulated rider at 10.00Hz compared to 6.30Hz for the 1year old simulated rider suggesting mass also contributed to the performance of the cushions.

3.3.5 Health Guidance Caution Zone Analysis

The mean frequency-weighted r.m.s. acceleration (across all terrain types and simulated rider masses) measured at the interface between the simulated rider and the factory installed seat or factory installed seat and gel cushion combination are reported in Table 3.11. The reported numbers are assumed to represent an eight-hour equivalent vibration exposure value (A8) in order to compare the exposure to the ISO 2631-1 HGCZ to determine the impact of the gel cushion on injury risk from daily exposure to vibration. Vibration experienced by the simulated riders sitting on the factory installed seat with the rigid frame trailer was associated with a daily vibration exposure within the ISO 2631-1 HGCZ suggesting a moderate health risk. When any of the gel seat cushions were added to the factory installed seat with thee rigid trailer exposure dropped below the HGCZ. However, the factory installed seat in the suspension bike trailer resulted in the lowest A(8) value (0.33 m/s^2) and an exposure below the ISO 2631-1 HGCZ regardless of cushion installation, suggesting low probability of injury risk from daily exposure to vibration (Table 3.11).

Table 3.11:Impact of the gel cushions on health risks, according to the ISO 2631-1 health guidance caution zone

Seat Type	Rigid Frame A(8) m/s^2	HGCZ*	Suspension Frame A(8) m/s^2	HGCZ*
Factory Seat (FS)	0.54	within	0.33	below
FS & Gel 01	0.47	below	0.40	below
FS & Gel 02	0.42	below	0.38	below
FS & Gel 03	0.47	below	0.37	below

*the lower boundary of the ISO 2631-1 health guidance caution zone (HGCZ) is $0.45m/s^2$ and the upper boundary is $0.90m/s^2$. Health risks from vibration exposure are low below the HGCZ, moderate, within the zone, and high above the zone.

3.4 Discussion

The purpose of this study was to determine the impact of terrain condition, trailer design and seat cushion design on the transmission of WBV to a simulated rider in a bicycle trailer. Four different terrain profiles, with two different bicycle trailers, and three different gel seat cushions were evaluated in combination for a 1 and 5-year-old simulated rider. Vibration transmitted to the simulated rider was significantly lower with the suspension frame trailer compared to the rigid frame trailer. The gel seat cushions showed some benefit when combined with the factory installed seat in the rigid frame trailer but were not effective when combined with the factory installed seat in the suspension frame trailer.

This study revealed mixed results with regard to the effectiveness of gel seat cushions. The 3 gel cushions performed well while when on the rigid-frame trailer seat, as most of the trials had a SEAT score below 100%, indicating an attenuation in vibration from the seat to the rider; however, mean SEAT values for the 3 gel cushions exceeded 100% when used in the suspension-frame trailer, indicating that the vibration was not attenuated, and possibly amplified from the seat to the rider. Improved performance with the rigid-framed trailer likely occurred because the frequency that resulted in the maximal vibration transferred to the simulated rider occurred at 6.3-10Hz for Gel 01, 5-6.3Hz for Gel 02, and 6.3Hz for Gel 03 which was below the dominant frequency of the terrain profiles, which were 16.62Hz for Gravel 01and 20.67 for Paved 01. However, the dominant frequencies for Gravel 02 (3.68Hz) and Paved 02 (5.65Hz) were lower, and as such, the gel cushions were not as effective for these vibration profiles. Previous studies have reported gel to be an effective material to act as a shock absorber for vibration (Gajendragadkar et al., 2000; Blaxter et al., 2017; Boi Du et al., 2018; Lee et al., 2018). Additionally, Blaxter et al., (2017) reported the resonance frequency of a gel mattress pad to be between 8-10Hz, which is in-line with findings in this study (Table 3.10) where the resonant frequency ranged between 5-10Hz for the combined gel cushion and simulated rider. Along with vibration damping, seat cushions, including those made of gel, have been shown to be effective for preventing and protecting riders from LBP as it encourages proper postural control (Boi Du et al., 2018; Lee et al., 2018). More specifically, seat cushions have been shown to improve the balance of a seated person, as well as redistribute weight directly off of the ischial tuberosities, leading to improve comfort, and better posture overall (Koo et al., 1996; Aissaoui et al., 2001). This is mainly the reason why wheelchair users are encouraged to use seat cushions on top of their wheelchair seats, as it can not only prevent pain and absorb vibration that occurs during daily travel, but it can also prevent spinal deformation such as scoliosis, and delay the process of muscle degradation. Unfortunately, the current study did not have human subjects, therefore, we cannot definitively conclude that the gel cushions will be effective at improving seating comfort and decreasing vibration transmitted to a child when actively riding in a bicycle trailer. Further studies that explore the gel cushion's effectiveness in a bicycle trailer with human subjects should be explored.

This study also evaluated the difference in vibration transmitted to the simulated rider when in a rigid framed trailer vs, a suspension trailer. The main goal of a suspension-frame is to attenuate vibration from the ground to the seat, in hopes that the vibration that is transmitted to the rider is reduced, preventing a vibration-induced injury. This was evident in our study, as the suspension-frame trailer led to significantly lower vibration levels transmitted to the simulated rider. Summative r.m.s. accelerations averaged $0.56m/s^2$ ($\pm 0.25m/s^2$) at wheel-axle, and $0.36m/s^2$ ($\pm 0.14m/s^2$) at the factory-installed seat, for the suspension-frame trailer and $0.63m/s^2$ ($\pm 0.30m/s^2$) at the wheel-axle, and $0.55m/s^2$ ($\pm 0.24m/s^2$) at the factory installed seat for the rigid framed trailer. The vibration measured at the wheel axle of the suspension frame was lower in magnitude resulting in less vibration measured at the seat also.

As discussed above, the addition of a gel cushion to the factory installed seat in the suspension frame trailer was not effective. Since gel does not have adequate reactive properties, it can feel like a solid object upon impact, causing vibration exposure to increase (DiGiovine et al., 2000). Garcia-Mendez et al., (2012) found that when comparing foam, gel and air-based cushions for wheelchairs, the gel and foam cushions were outperformed by the air-based cushion, with the authors stating that there were significant differences between the transmissibility ratios (between the seat and the cushion), for each cushion used. The authors went on to encourage the use of air-based cushions, arguing that it did not amplify vibration to the wheelchair user (Garcia-Mendez et al., 2012). Based on the findings of this study, gel cushions appear to be beneficial to the rider when the bicycle trailer they are riding in has a rigid-frame, particularly when the dominant vibration exposure frequency associated with driving over the terrain is between 15-20Hz. However, our study also showed if the bicycle trailer has a suspension-frame, gel seat cushions should not be used. Future studies should examine the potential benefit of a foam or air-filled cushion.

The statistical analysis performed in this study was done to determine which of the three variables, terrain quality, trailer type, and seat cushion, had the biggest impact on attenuating vibration. Our results indicated that the factor that has the greatest influence on vibration transmission to the child while riding in the bicycle trailer is terrain quality. The terrain quality was a significant factor in determining vibration transmission to the simulated rider. More specifically the rougher the road, the higher the magnitude of vibration transmitted to the simulated rider. In this study, the terrain profiles that were rough were Gravel 01 and Paved 01, both with un-weighted exposure magnitudes of $0.20 m/s^2$ and $0.24 m/s^2$, respectively. This finding coincides with previously literature, which states that the poorer the terrain quality, the higher the vibration transmission will be to the rider (Arpinar-Avsar et al., 2013; Gromadowski & Wieckowski, 2013; Macdermid et al., 2015; Giuseppe & Giuseppe, 2010). While no previous literature exists assessing vibration transmission and road-roughness in bicycle trailers, previous literature on terrain quality on bicycles revealed that higher vibration levels were recorded when the bicycle was riding over rough roads (Levy & Smith, 2005).

While terrain quality had the greatest influence for vibration transmission in this study, it is unrealistic to assume that all roads will be well-maintained to ensure a safer ride for the children in the bicycle trailers, which is why other interventions were also investigated. While not as influential as the terrain quality, the type of trailer used did have an impact on vibration transmission to the child. When analyzing the relationship between terrain quality and trailer used, the trailer used had a significant effect on the vibration transmission. More specifically, our study found that the suspension-frame trailer resulted in significantly lower vibration measured at the seat when riding on Gravel 01 and Paved 01, the two terrain profiles with the highest magnitude of vibration. These findings correspond with previous literature, which suggests that suspension systems can be useful in attenuating vibration to the rider (Liu et al., 2013; Burdorf & Swuste, 1993; Han et al., 2006; Boileau & Rakheja, 1990; Blood et al., 2010; Levy & Smith, 2005). Levy & Smith (2005) found that while cycling across rough road conditions, bicycles with suspension forks transmitted significantly less vibration to the frame, compared to a rigid-frame bike. Moreover, Liu et al., (2013) reported suspension systems can significantly reduce vibration to the cyclist, particularly at frequencies above 10Hz. This supports our results, as the suspension-frame trailer had lower vibration levels at Gravel 01 and Paved 01, two profiles with frequencies above 10Hz.

When considering strategies to mitigate vibration transmitted to a child in a bicycle trailer the hierarchy of controls should be considered. The hierarchy of controls outlines the effectiveness of interventions to control a hazard (NIOSH, 2015) and include from most effective to least effective, a)elimination: physically remove the hazard, b)substitution: replace the hazard, c)engineering control: isolate people from the hazard, d)administrative control: change the way “work” is managed or people “work”, and e)personal protective equipment: protect the “worker” with personal protective equipment. The addition of a suspension system to the bicycle trailer, (suspension frame trailer) would be considered an engineering control, driving over paved or maintained roads (or working with municipal leaders for improved road conditions on bike pathways) would be considered an administrative control, and adding a gel seat cushion would be considered a piece of personal protective equipment.

3.4.1 Limitations

This study was not able to expose real children to vibration in the lab so the mass of a typical 1-year and 5-year old were simulated. 10lb weighted plates were used, with 2 plates used to replicate the average 1-year old (20lbs), and 4 plates used to replicate the average 5-year old

(40lbs). As a weighted plate is a rigid object, with equal weight distribution throughout, it does not truly reflect a child, whose weight is dispersed throughout different areas of their body, as well as their fat and lean-tissue mass. Additionally, children also have the ability to control their posture when riding in a trailer, unlike a weighted plate that bounces around after when in contact with an impact. While a natural response when preparing for an impact (i.e. hitting a pothole) is to brace one's muscle, there is currently no literature that supports that muscle bracing aids in vibration attenuation. Current research on muscle anticipation and impact for concussion is mixed, and it is unclear whether or not impact anticipation will improve head stabilization (Hrysomallis, 2016).

The method used to secure the bicycle trailers to the vibration platform required them to be in their strolling configuration, which meant that their front wheel was on and attached to the vibration platform. This was done to ensure that the trailer would not tip backwards once the weights were added. While the child is placed in the back of the bicycle trailer, and the weights in this study were reflected as such, the weight in the trailer was distributed across additional points on the trailer, which leads to the possibility of alteration in results based on the weight distribution. While the trailer is in the bicycle configuration, the weight would mainly be distributed across the back of the trailer, where the two rear wheels are located. As such, the configuration of the bicycle trailer throughout this study must be considered when analyzing the results.

The third limitation to this study is that material testing was not performed on the gel cushion; as such, the stiffness of the particular gel cushions used in this study are unknown. While the current literature does agree that gel is an effective material to attenuate vibration to its user, this current study does not validate whether or not the gel material itself is effective in vibration attenuation, or if it was the pressure-distributing squares in the cushion that made it an effective material for vibration attenuation.

3.4.2 Future Research

This study was able to confirm the effectiveness of different factors in reducing vibration measured at the interface of the seat and a simulated rider in a bicycle trailer; however, it also provides the ground work for future studies. First, future studies would benefit from using anthropometric models of children between the ages of 1 and 5 years old, as this is the average age range of children who can ride in bicycle trailers. By having realistic models of children in the bicycle trailer, it would provide further confirmation of the effectiveness of interventions, and further testing could be done to assess vibration transmissibility from the child's buttocks to their head. Any models that are used however must be able to sit up straight like an average child, as the seating posture of the child will need to be considered. Future studies should also consider the placement of the trailer on the vibration platform, and ideally have it in its bicycle riding configuration. This will require careful consideration to ensure the weight in the trailer does not cause the bicycle trailer to tip over; however, it would provide a more accurate representation of the bicycle trailer in a real-world setting. Additionally, future studies are encouraged to explore more cushion materials including gel, foam, air and/or a combination of the materials to identify the best cushion type for commonly used bicycle trailers. Finally seat cushion interventions found to be effective in laboratory testing should be evaluated in the field with real children in bicycle trailers riding over a variety of terrain conditions to verify effectiveness.

3.5 Conclusion

The purpose of this paper was to evaluate the impact of terrain type, trailer type and seat cushion type on vibration transmitted to a simulated child rider in a bicycle trailer. Significantly less vibration was transmitted to the simulated rider when in the suspension frame trailer, and when exposed to a less rough road profile. Less vibration was also transmitted to the simulated rider when a gel cushion was added to the factory installed seat in the rigid bike frame trailer; however, the gel cushions were not effective when added to the factory installed seat in the suspension framed trailer. Moreover, while gel cushions can help attenuate vibration to the child if the bicycle trailer has a rigid-frame, our results confirmed terrain condition (smooth) and trailer design (suspension) had a larger influence on vibration exposure reduction. This study confirms the need for vibration transmissibility measures to be considered when evaluating bicycle trailer designs. Municipalities should also evaluate "road conditions" on bike paths and implement a regular maintenance schedule. While regularly scheduled road maintenance is the ideal solution, it is also important to educate parents who use bicycle trailers encouraged to stick to well-maintained roads whenever possible, and avoid hitting large potholes. With improved design of bicycle trailers and maintained bike pathways vibration transmitted to children in bicycles can be reduced resulting in improved ride comfort and a decreased risk of a vibration-induced injury occurring in a child.

CHAPTER 4: Overall Discussion

4.1 Summary of Research Findings

This dissertation provides information about whole-body vibration (WBV) exposure to children while they are riding in bicycle trailers, which is an area where research was previously lacking. The purpose of this research study can be broken down into two parts. The first part being to quantify vibration exposure in bicycle trailers, and determine if exposure levels pose a health risks for children riding in them (Chapter 2); and the second part on finding which factors (i.e. terrain quality, trailer type, and seat cushion) are effective at reducing vibration transmitted to the child (Chapter 3). Both of these studies had significant research findings.

The results from Chapter 2 indicated that the vibration levels reported in a bicycle trailer indeed pose a health risk of a vibration-induced injury occurring in children. Based on a 2-hour exposure, 14 of the trials had vibration levels between 0.45-0.90m/s^2, indicating a moderate health risk per ISO 2631-1 HCGZ values. 7 of the trials had vibration levels below 0.45m/s^2, indicating a low health risk per ISO 2631-1 HCGZ values. While not statistically evaluated, the terrain quality appeared to be a factor in vibration transmission, with the 3 high-health risk tails occurring when cycling over gravel terrain. The results from this study also found that vibration transmission from the seat to the child's head was amplified in all 12 trials, further suggesting a potential risk for a vibration-induced injury. This study established the groundwork to confirm that vibration levels experienced by a child in a bicycle trailer may pose a health risk if they are in a bicycle trailer for more than 2 hours, suggesting a need for future studies to evaluate interventions.

The results from Chapter 3 found terrain quality, bicycle trailer design and seat cushion design all influenced vibration transmitted to the simulated child in a bike trailer. Terrain quality was shown to have a significant effect on vibration transmission to the child, with rougher road conditions producing higher vibration levels compared to smoother road conditions. The type of trailer was also shown to be a significant factor in vibration transmission with the suspension framed trailer resulting in a significant decrease in vibration transmitted to the simulated rider, compared to the rigid frame. Furthermore, the gel cushions were shown to the effective in vibration attenuation when used in a rigid-frame trailer, but not with the suspension framed trailer. However, overall terrain quality (smoother) and trailer type (suspension framed) were more effective at reducing vibration transmitted to the simulated rider than the addition of a gel cushion to the rigid framed trailer.

4.2 Research Implications

4.2.1 Relevance to Bicycle Trailer Manufacturers

One of the main goals with this research was to be able to share the results with bicycle trailer manufacturers, in hopes that future trailers would be designed with vibration exposure in mind. Throughout the study, it was evident that certain bicycle trailers are best suited for travelling over rougher terrain, while others are suited for travelling over smoother terrain. While the overall design of the trailer does not necessarily need to be changed, there are two suggestions that can be made based on the results of this study, which can greatly benefit both the manufacturer, and the consumer. First, it is important for bicycle trailer manufacturers to understand the risk associated with WBV and the potential impact it has on children's health. Therefore, it is strongly encouraged that future testing with bicycle trailers involve a complete assessment of the trailer's vibration attenuating capabilities. While not every bicycle trailer will be suitable for all terrain conditions, it is important for bicycle trailer manufacturers to know the risk of vibration to the child while riding on certain terrain, and this information should be communicated in technical specifications. Since bicycle trailers can be expensive, consumers will do research on the different types of bicycle trailer available on the market. When looking online at different bicycle trailer manufacturer's websites, it is not always clear whether or not their trailer is suited for rougher road conditions or if it is best suited for smoother, paved, or well-maintained road conditions. By making this information clear and easy-to-access, the consumers will be more confident with their purchase, and ride comfort could be improved for the child.

4.2.2 Relevance to Parents/Guardians

While one outcome of this research is to recommend vibration exposure measurement tests be conducted on future bicycle trailer designs, it is just as important to inform parents/guardians about the findings of this study. Results from this study, both field and lab, showed vibration exposure experienced by the child rider is higher when travelling over rough road conditions. Additionally, our study showed that a suspension-frame trailer has the ability to attenuate vibration to the rider, particularly when travelling on rougher terrain. These particular findings are important for parents/guardians to know, as they could choose to avoid rougher roads, travel slower over rougher roads, and/or purchase a suspension frame trailer if they predominantly travel over rougher roads. Rough roads do not necessarily mean gravel paths, but it can also include paved roads that are not properly maintained. Additionally, it has been shown that vibration exposure can be further amplified to the rider and the child when travelling over rough terrain at a fast speed. Regardless of which bicycle-attachment is used, it is important for parents/guardians to be aware of the consequences of travelling over rough terrain, particularly when travelling at high speed. In our study, trials that indicated a high-health risk occurred when the cyclist was travelling at an average speed of 15km/h. Trials that had low-to-moderate health risks occurred when the cyclist was travelling at speeds around 10-11km/h. While this study did not confirm the ideal cycle speed to reduce vibration exposure experience by children, parents should be mindful of their speed, particularly if riding on rougher roads.

Another significant finding from our research was the impact the trailer had on vibration attenuation. Over rough terrain, the suspension-frame trailer resulted in a significant decrease in vibration transmitted to the simulated rider compared to the rigid frame trailer and the rigid framed trailer with gel cushions added to the factory installed seat. This finding suggests suspension framed bicycle trailers are ideal for rough terrain. As a parent/guardian, this is important information to know when you are selecting a bicycle trailer. Even the cheapest bicycle trailers can still cost ~ $400, so they are an investment for many families. Like any investment, there are many factors that influence the purchase. This study has highlighted that one of these factors should include the terrain that the trailer will be travelling on. Based on our study, it is recommended that rigid-frame trailers are used when the majority of the travelling will be done over smooth terrain, such as well-maintained sidewalks and roadways, while suspension-frame trailers be used when the majority of the travelling will be done over rougher terrain, such as gravel paths, and roads that are not routinely maintained.

This study investigated the effectiveness of gel cushions as a way to attenuate vibration to the child riding in the bicycle trailer. One of the main reasons why these cushions were tested was to assess whether or not this could be an option to attenuate vibration without completely replacing the bicycle trailer, which can be expensive. The cushions had some benefit when used with rigid framed bike trailers but no benefit when used with suspension framed bike trailers. Therefore, if parents/guardians are interested in having their child sit on a gel cushion while they are riding in a trailer, it is recommended that they only use a gel cushion if their trailer has a rigid-frame, as using one with a suspension-frame may amplify the vibration transmission to their child, which will further increase the child's risk of developing a vibration-related injury.

4.2.3 Relevance to Children's Health

The findings from this study add to the overall body of research regarding children and WBV, and highlight an important factor around children in bicycle trailers. The results of our study demonstrated that vibration measured at the interface between the seat and the child's buttocks appears to be amplified as it is transmitted through the spine and is measured at the back of the head. The health implications of seat-to-head vibration amplification in children riding in bike trailers is unknown and our field study was limited to 12 participants. Therefore future research should be conducted to verify this finding and collect additional data on potential health implications. It was also noted that head movement of the child could be a limitation in the field study, as the child's head was not completely still for the entire bicycle ride. Although it was a limitation in our study, the head movements caused by the child during the bicycle ride are realistic to a typical bicycle ride, and should not be overlooked. Excessive head accelerations in children can be detrimental to their overall health, and can lead to very serious complications and/or death, as the generally weaker neck muscles in the child may not be able to full control and brace the head in the event of a major impact. When a child is strapped into a trailer with the 5-point harness their torso is strapped into the trailer, but their head is still free to move around. When you add a helmet onto the child, the extra weight of the helmet on their head, depending on the child's age, may cause extra head movement, and less head control when riding over rough terrain. While bicycle trailers are considered one of the safer options in terms of bicycle trailer attachments, this is largely due to mechanisms to prevent injury upon a collision, and limited attention has been given to vibration exposure. Future research should evaluate posture, head velocity and acceleration experienced by the child in the bicycle trailer.

The main limitation in this study is the current lack of standard for assessing vibration exposure in children. In our study, we assessed the health-risk using the guidelines outlined in ISO 2631-1, which is the current international standard for assessing WBV. The guidelines in ISO 2631-1 were created for a healthy adult population. Since there is no standard for safe vibration exposure levels in children, it is hard to assess the severity of the effect of WBV on children. It is evident through this study, as well as other studies, that WBV can have an impact on children, and vibration exposure is something that occurs during a child's everyday life. Giacomin (2005), who studied vibration in children's car seats, has also advocated for an international standard to be developed for children, in order to assess WBV. By developing a standard, based on data found in this study, as well as other studies that assess vibration exposure in children, an international standard can be developed, which will allow researchers to accurately assess the effect of WBV on children.

4.2.4 Knowledge Transfer & Mobilization

As the findings of this study have relevance to bicycle trailer manufacturers and parents/guardians, it is important that these findings are effectively communicated to all parties, so that proper interventions can occur. As parents/guardians and bicycle trailer manufacturers have different roles in vibration attenuation, it is important that the information present to both groups is relevant. For parents/guardians, the findings that would be the most important for them to know is 1) the potential impact WBV could have on their child's health, and 2) preventative measures they can implement to ensure their child is as protected as possible (i.e. controlling speed/terrain/time in trailer, trailer type, when to use a gel cushion, etc.). With this knowledge transfer, the goal is to establish that parents that they have an important role to play in WBV prevention for their child (Croom & Procter, 2008). Additionally, the method of knowledge transfer is important as well. As it is likely that parents would be unable and/or uninterested in attending a long seminar that highlights the risks of WBV in children riding in bicycle trailers, a more interactive approach would be more ideal, such as through social media cycling groups. For bicycle trailer manufacturers, the most pertinent information for them would be the effect a rigid frame vs a suspension frame has on vibration exposure to the child. As their role in this situation would be the overall design of the bicycle trailer, it would be important that they are presented with the data pertaining to vibration exposure in both a rigid-frame trailer and a suspension-frame trailer, and be presented in a manner that is accessible to all members (i.e. presentation).

4.3 Future Research

To our knowledge, this is the first study to evaluate vibration exposure in children's bicycle trailers. The laboratory study found the suspension frame bike trailer exposed the simulated rider to lower levels of vibration exposure. Future research should evaluate the suspension frame trailer in the field to confirm the results. The gel cushion was effective at reducing vibration transmission to the simulated rider when combined with the factory installed seat in the rigid framed trailer, but ineffective when combined with the suspension framed trailer. Future research should evaluate other cushion materials (foam; air bladder; gels; combinations) in combination with common bicycle trailer designs and factory installed seats to identify the best combination for paved (smooth) and rougher (gravel) roads. Effective combinations should then be evaluated in field tests. Additionally, future research should also investigate different suspension systems on bicycle trailers, in order to determine if there is a suspension system on a trailer that would be even more effective in vibration attenuation to the child inside.

4.4 Overall Conclusions

The overall purpose for this study was to evaluate WBV transmitted to children riding in bicycle trailers. Significantly higher levels of vibration are transmitted to a child in a bike trailer on rougher terrain. Riding in a trailer with a suspension frame resulted in significantly less vibration transmitted to the child. Riding at higher speeds resulted in a higher vibration magnitude measured at the interface between the seat and the child's buttock. The addition of gel cushions to the factory installed seat of the bike trailer was only effective when added to the rigid frame bike trailer. Future studies are required to further understand the interaction between road terrain, bike trailer suspension and cushion design. The development of an international standard for assessing health implications of vibration exposure experienced by children is required.

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APPENDICES

Appendix A: Ethics Certificate, Recruitment Poster, Consent Form, Survey (Chapter 2)

LaurentianUniversity
UniversitéLaurentienne

APPROVAL FOR CONDUCTING RESEARCH INVOLVING HUMAN SUBJECTS

Research Ethics Board – Laurentian University

This letter confirms that the research project identified below has successfully passed the ethics review by the Laurentian University Research Ethics Board (REB). Your ethics approval date, other milestone dates, and any special conditions for your project are indicated below.

TYPE OF APPROVAL / New X /	Modifications to project / Time extension
Name of Principal Investigator and school/department	Margaret Kanya-Forstner, Human Kinetics, supervisor, Tammy Eger
Title of Project	Assessing whole-body vibration transmissibility in children's bicycle trailers
REB file number	6017310
Date of original approval of project	
Date of approval of project modifications or extension *(if applicable)*	June 10, 2019
Final/Interim report due on: *(You may request an extension)*	June 10, 2020
Conditions placed on project	

During the course of your research, no deviations from, or changes to, the protocol, recruitment or consent forms may be initiated without prior written approval from the REB. If you wish to modify your research project, please refer to the Research Ethics website to complete the appropriate REB form.

All projects must submit a report to REB at least once per year. If involvement with human participants continues for longer than one year (e.g. you have not completed the objectives of the study and have not yet terminated contact with the participants, except for feedback of final results to participants), you must request an extension using the appropriate LU REB form. In all cases, please ensure that your research complies with Tri-Council Policy Statement (TCPS). Also please quote your REB file number on all future correspondence with the REB office.

Congratulations and best wishes in conducting your research.

Rosanna Langer

Rosanna Langer, PHD, Chair, *Laurentian University Research Ethics Board*

INFORMED CONSENT TO PARTICIPATE IN A RESEARCH STUDY

Full Title: Assessing whole-body vibration transmissibility in children's bicycle trailers

Principal Investigators: Margaret Kanya-Forstner, Professor Tammy Eger

Contact Information:

Margaret Kanya-Forstner	Professor Tammy Eger
mkanyaforstner@laurentian.ca	teger@laurentian.ca
705-262-0438	705-675-1151 ext. 1005

Sponsor: Centre for Research in Occupational Safety and Health (CROSH)

INFORMED CONSENT

You are being asked to consider participating in a research study. A research study is a way of gathering information on a treatment, procedure or program or to answer a question about something that is not well understood. This form explains the purpose of this research study, provides information about the study procedures, possible risks and benefits, and the rights of participants.

Please read this form carefully and ask any questions you may have. The researcher will explain this form and all information concerning the study to you verbally. Please ask the researcher to clarify anything you do not understand or would like to know more about. Make sure all your questions are answered to your satisfaction before deciding whether to participate in this research study.

Participating in this study is your choice (voluntary). You have the right to choose not to participate, and you have the right to withdraw from the study and stop your participation at any time. If you decide to stop participating, your data will be removed and there will be no consequences to you or the services you receive.

INTRODUCTION

You are being asked to consider participating in this study because you a parent who frequently engages in cycling and owns a bicycle and a bicycle trailer. You are also being considered as you have a child who is between the ages of 1-5 years old, who can safely ride in a bicycle trailer.

WHY IS THIS STUDY BEING DONE?
This study is being done to measure the amount of vibration that occurs in a bicycle trailer during a typical bicycle ride. Research on vibration in bicycle trailers is quite limited, therefore, this study will help in learning more about vibration transmission in bicycle trailers, ultimately aiding parents and bicycle trailer manufacturers.

WHAT WILL HAPPEN DURING THIS STUDY?
You will be asked to complete a bicycle ride on a route of your choice (within the city of Greater Sudbury) that contains both gravel and paved roads. You will be asked to disclose your start and finish location, the route you will be taking, and how estimate of how long you will cycle for. You and your child will be required to wear a helmet for the duration of the bicycle ride. Four (4) accelerometers will be attached to various parts of the bicycle trailer, which will allow the researchers to evaluate the movement that is experienced on various parts of the bicycle trailer. One of the accelerometers will be embedded into a headband, which will be worn by the child under their helmet. A GPS will also be used to track your location on the bicycle. A questionnaire will be administered following the bicycle ride to gather data into considerations made when purchasing your bicycle trailer, as well as your child’s attitude towards riding in the bicycle trailer. The estimated time for this experiment is 2 hours.

WHAT ARE THE RISKS OR HARMS OF PARTICIPATING IN THIS STUDY?
Should you experience a fall, you do run the risk of minor injuries, such as cuts, bruises and scrapes. You are encouraged to travel at a pace you are comfortable with, to prevent such falls. The researcher conducting this study is trained in First Aid, and will be able to aid (i.e. first aid, call for medical attention) if a fall were to occur. Muscle fatigue and pain may be experienced by the cyclist following the experiment as a result of the bicycle ride; however, it is encouraged that the participant performs light stretching to the affected muscle if this is to occur. Your child may also experience some discomfort from riding over bumpy terrain. You will be encouraged to cycle at a pace that you and your child are comfortable with. You do not need to answer questions in the questionnaire that make you uncomfortable or that you do not want to answer.

WHAT ARE THE POTENTIAL BENEFITS?
Individual Benefits - There are no direct benefits by participating in this study. By participating in a 20-mintue bicycle ride, you and your child’s overall well-being may be improved, as physical activities while being outdoors can be beneficial to one’s physical, mental, and emotional health.

Results from this study will be able to assist in the re-design of bicycle trailers if it is determined that the current design imposes health risks to the child riding in them. This study could encourage bicycle trailer manufacturers to consider vibration reduction in their design, which will ultimately improve the health of children riding in them.

Results from this study will also be able to help parents make a more informed decision when it comes to selecting a bicycle trailer for their child. While most of the bicycle trailers on the market emphasize their ability to protect children in case of an accident, none report on the vibration effects that can occur.

Contributing data could also inform future designs of trail maintenance programs.

ARE STUDY PARTICIPANTS PAID TO PARTICIPATE IN THIS STUDY?

You will not be paid for participation in this study. **Your participation is strictly voluntary.**

HOW WILL MY INFORMATION BE KEPT CONFIDENTIAL?

All information that is collected, used or disclosed for this study will be handled in a confidential manner. Anything that you say or do in the study will not be attributed to you personally. Anything that we find out about you that could identify you will not be published or told to anyone else, unless we get your permission. Reports based on the gathered data will contain no information that might link a specific participant. The information obtained will be kept in a locked filing cabinet in the office of the CROSH Laboratory Technologist and be only available to the investigator's team, as well on the LU Google Drive. The information (acceleration data) collected in the experiment will be kept for seven years unless you provide consent for it to be permanently stored in a vibration exposure database.

INFORMATION ABOUT THE STUDY RESULTS

You have the right to be informed of the results of this study once the study is complete. If you would like to be informed of the results of this study, please contact Margaret Kanya-Forstner (mkanyaforstner@laurentian.ca).

WHAT ARE THE RIGHTS OF PARTICIPANTS IN A RESEARCH STUDY?

You have the right to receive all information that could help you decide about participating in this study. You also have the right to ask questions about this study and your rights as a research participant, and to have them answered to your satisfaction, before you make any decision. You also have the right to ask questions and to receive answers throughout this study.

If you have any questions about this study you may contact the student researcher, Margaret Kanya-Forstner at mkanyaforstner@laurentian.ca or 705-262-0438.

If you have questions about your rights as a research participant or any ethical issues related to this study that you wish to discuss with someone not directly involved with the study, you may call **Research Ethics Officer, Laurentian University Research Office,** telephone: 705-675-1151 ext 3681, 2436 or toll free at 1-800-461-4030 or email ethics@laurentian.ca

DOCUMENTATION OF INFORMED CONSENT

There are two copies attached. One for the researcher, and one for you to keep. **Please note there are two participant lines: one for you, and one for your child.**

Full Study Title: **Assessing whole-body vibration transmissibility in children's bicycle trailers**

Name of Participants: ____

Participant/Substitute decision-maker

By signing this form, I confirm that:

- This research study has been fully explained to me and all of my questions answered to my satisfaction
- I understand the requirements of participating in this research study
- I have been informed of the risks and benefits, if any, of participating in this research study
- I have been informed of any alternatives to participating in this research study
- I have been informed of the rights of research participants
- I have read each page of this form
- I have agreed, or agree to allow the person I am responsible for, to participate in this research study

___________________________	____________________________	________________
Name of participant (print)	Signature	Date
___________________________	____________________________	________________
Name of participant (print)	Signature	Date
___________________________	____________________________	________________
Name of Researcher	Signature	Date

I would like to obtain a short summary of the findings from this study upon completion of the project

☐ YES ☐ NO (if yes, please provide email address):

DOCUMENTATION OF INFORMED CONSENT

There are two copies attached. One for the researcher, and one for you to keep.
Please note there are two participant lines: one for you, and one for your child.

Full Study Title: **Assessing whole-body vibration transmissibility in children's bicycle trailers**

Name of Participants: ____
Participant/Substitute decision-maker
By signing this form, I confirm that:

- This research study has been fully explained to me and all of my questions answered to my satisfaction
- I understand the requirements of participating in this research study
- I have been informed of the risks and benefits, if any, of participating in this research study
- I have been informed of any alternatives to participating in this research study
- I have been informed of the rights of research participants
- I have read each page of this form
- I have agreed, or agree to allow the person I am responsible for, to participate in this research study

______________________	______________________	____________
Name of participant (print)	Signature	Date
______________________	______________________	____________
Name of participant (print)	Signature	Date
______________________	______________________	____________
Name of Researcher	Signature	Date

I would like to obtain a short summary of the findings from this study upon completion of the project
☐ YES ☐ NO (if yes, please provide email address):

Appendix B: Technical Specificities of Each Bicycle Trailer, and Images of Each Trailer Used in Chapter 2

Model	Manufacturer	Suspension System (Y/N)	Rear Wheel Diameter (cm)	Weight of Trailer Chassis (kg)	Weight/Height Limitations		Additional Information
					Weight (kg)	Height (cm)	
Wike Special Needs Trailer	Wike	N	51	15	57	162	Frame is made out of alumininum. Trailer designed to accommodate those with special needs. Bicycle trailer has a larger weight and height capcacity - allowing for older individuals with special needs to ride comfortably in the chassis.
Bell 2 - Child Smooth Sailor Bicycle Trailer	Bell Sports Inc.	N	31	15	45	100	N/A
Thule Chariot Cougar 1	Thule	Y	51	11	34	111	Trailer is intended for a single rider. Suspension system in trailer is adjustable, and can be adjustable to accommodate child and cargo weight. Trailer is also intended for uses other than a bicycle trailer, as it can be used additionally as a stroller, jogging stroller, and cross-country ski carrier.
Everyday Traveler Lite Trailer	Everyday Bicycles	N	41	14.6	45	59.5	N/A
Thule Chariot CX1	Thule	Y	51	10	34	111	Trailer is intended for a single rider. Suspension system in trailer is adjustable, and can be adjustable to accommodate child and cargo weight. Trailer is also intended for uses other than a bicycle trailer, as it can be used additionally as a stroller, jogging stroller, and cross-country ski carrier.

Wike Special Needs Trailer

Bell 2 – Child Smooth Sailor Trailer

Thule Chariot Cougar 1 Trailer

Everyday Traveler Lite Trailer

Thule Chariot CX1 Trailer

Appendix C: Trailer*cushion paired t test results

Trailer vs Cushion		
Paired Factors	**Significiant?**	
Rigid-Frame Trailer vs Cushions	**Yes**	**No**
Rigid_No Cushion vs Rigid_Gel 01	▯	
Rigid_No Cushion vs Rigid_Gel 02	▯	
Rigid_No Cushion vs Rigid_Gel 03	▯	
Rigid_Gel 01 vs Rigid_Gel 02	▯	
Rigid_Gel 01 vs Rigid_Gel 03		▯
Rigid_Gel 02 vs Rigid_Gel 03	▯	
Suspension Frame Trailer vs Cushions	**Yes**	**No**
Suspension_No Cushion vs Suspension_Gel 01		▯
Suspension_No Cushion vs Suspension_Gel 02		▯
Suspension_No Cushion vs Suspension_Gel 03		▯
Suspension_Gel 01 vs Suspension_Gel 02		▯
Suspension_Gel 01 vs Suspension_Gel 03		▯
Suspension_Gel 02 vs Suspension_Gel 03		▯
Cushion vs Trailer	**Yes**	**No**
No Cushion_Rigid vs No Cushion_Suspension	▯ *	
Gel 01_Rigid vs Gel 01_Suspension	▯ *	
Gel 02_Rigid vs Gel 02_Suspension		▯ *
Gel 03_Rigid vs Gel 03_Suspension		▯ *

Pcrit=0.042 unless otherwise stated

*Pcrit=0.025

Appendix D: Trailer*terrain paired t-test results

Trailer vs Terrain		
Paired Factors	**Significiant?**	
Rigid-Frame Trailer	**Yes**	**No**
Rigid_Gravel 01 vs Rigid_Gravel 02	▯	
Rigid_Gravel 01 vs Rigid_Paved 01	▯	
Rigid_Gravel 01 vs Rigid_Paved 02	▯	
Rigid_Gravel 02 vs Rigid_Paved 01	▯	
Rigid_Gravel 02 vs Rigid_Paved 02	▯	
Rigid_Paved 01 vs Rigid_Paved 02		▯
Suspension-Frame Trailer	**Yes**	**No**
Suspension_Gravel 01 vs Suspension_Gravel 02	▯ *	
Suspension_Gravel 01 vs Suspension_Paved 01		▯ *
Suspension_Gravel 01 vs Suspension_Paved 02		▯ *
Suspension_Gravel 02 vs Suspension_Paved 01	▯ *	
Suspension_Gravel 02 vs Suspension_Paved 02	▯ *	
Suspension_Paved 01 vs Suspension_Paved 02		▯ *
Terrain vs Trailer	**Yes**	**No**
Gravel 01_Rigid vs Gravel 01_Suspension		▯ *
Gravel 02_Rigid vs Gravel 02_Suspension		▯ *
Paved 01_Rigid vs Paved 01_Suspension		▯ *
Paved 02_Rigid vs Paved 02_Suspension	▯ *	

Pcrit=0.042 unless otherwise stated

*Pcrit <0.025