Håvard Eggen Kirstensen

Cycling Comfort on Different Winter Road Conditions

Master's thesis in Bygg- og miljøteknikk
Supervisor: Alex Klein-Paste & Mathis Dahl Fenre
June 2019

Master's thesis

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Preface

This document is the result of the master's thesis at the Department of Civil and Environmental Engineering at NTNU, written during the spring semester 2019. The master's thesis was written as a scientific paper. The guidelines for the thesis was an article consisting of 5,000 - 10,000 words and relevant appendices. Tables and figures counted as 250 words.

The thesis has been supervised by PhD-candidate Mathis Dahl Fenre and Professor Alex Klein-Paste. I would like to thank you both for the discussions and feedback through the semester. Potential future submissions of this paper will be with Håvard Eggen Kristensen, Mathis Dahl Fenre and Alex Klein-Paste as authors.

The thesis was written in cooperation with the Norwegian Public Roads Administration (NPRA). I would like to thank the NPRA for a scholarship to cover expenses related to the master's thesis and lending equipment for the testing.

Finally, I would like to show my gratitude towards family and friends for their academical and moral support.

Trondheim, June 06, 2019

Håvard Eggen Kristensen

Abstract

Transportation by cycling has several benefits for the society, but the share of cyclists is decreased during winter in cold regions. Reduced cycling comfort is one of the problems caused by the winter conditions. Cycling comfort on bare roads can be measured by analysis of vibrations transmitted to the cyclist, where the correlation between vibrations and comfort is clear. Accelerometers are commonly used for this. However, there is no clear relation between cycling comfort and vibrations on winter conditions. A better understanding of the factors that affects cycling comfort on winter conditions is therefore of interest.

A bicycle instrumented with a sensor consisting of an accelerometer and a gyroscope was ridden on different winter conditions. The sensor was placed on the bicycle stem to measure angular velocities of the handlebars, related to steering and balancing the bicycle. Measurements of angular velocity around the x-axis had the highest correlation with perceived comfort. The parameter was found to be better suited for comfort analysis on winter conditions than vibrations.

The depth of loose snow was the most important parameter of the surface condition related to cycling comfort. However, the depth of compacted snow influenced cycling comfort as well. Therefore, requirements for total depth of snow on bicycle lanes is of essence when facilitating for winter cycling. Better knowledge of cycling comfort on winter conditions can be applied to optimize winter maintenance of bicycle lanes, which can ensure comfortable cycling conditions during winter.

Key words

Cycling comfort; Winter cycling; Accelerometer; Gyroscope; Maintenance

Sammendrag

Sykkeltransport har en rekke fordeler for samfunnet, men andelen sykkelreiser om vinteren synker i kalde regioner. Vinterføre på veiene fører til en rekke problemer for syklister, blant annet redusert sykkelkomfort. På bare veier kan sykkelkomfort bli beregnet ved å analysere vibrasjonene syklisten blir utsatt for. Sammenhengen mellom økte vibrasjoner og redusert sykkelkomfort er tydelig, og kan bli målt ved bruk av akselerometre. På vinterføre er det derimot ingen tydelig sammenheng mellom sykkelkomfort og vibrasjoner. En bedre forståelse av hvilke faktorer som påvirker sykkelkomfort på vinterføre er derfor av interesse.

Datainnsamlingen foregikk ved å sykle på ulike typer vinterføre med én sykkel. Sykkelen var utstyrt med et akselerometer og et gyroskop på styrestemet for å måle vibrasjoner og vinkelhastigheter til styret. Vinkelhastighet rundt x-aksen hadde den høyeste korrelasjonen med opplevd komfort, og viste seg å være bedre egnet til komfortanalyser på vinterføre enn analyser av vibrasjoner.

Dybde av løssnø var den viktigste egenskapen til føret relatert til sykkelkomfort, men dybde av kompaktert snø hadde også en påvirkning. Krav til maksimal snødybde på sykkelveier er derfor viktig for å sikre komfortable sykkelforhold gjennom vinteren. Bedre kunnskap om sykkelkomfort på vinterføre kan bli anvendt til å drifte sykkelveier slik at vintersykling blir mer komfortabelt. Kunnskapen kan benyttes til å kostnadseffektivisere vinterdrift av sykkelveier samtidig som syklistenes behov blir oppfylt.

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Acronyms

a_x - Acceleration in the x-axis (Standard deviation of each test ride)

a_y - Acceleration in the y-axis (Standard deviation of each test ride)

a_z - Acceleration in the z-axis (Standard deviation of each test ride)

DCI - Dynamic Comfort Index

g_x - Angular velocity around the x-axis (Standard deviation of each test ride)

g_y - Angular velocity around the y-axis (Standard deviation of each test ride)

g_z - Angular velocity around the z-axis (Standard deviation of each test ride)

NPRA - Norwegian Public Roads Administration

STD - Standard deviation

1. Introduction

Transportation made by cars has various negative impacts on the environment and society, such as greenhouse gas emissions, air pollution, noise, congestion and land use for roads and parking (Nejat *et al.*, 2015; Medalen, Frøyen and Skjeggedal, 2016). A reduction in the number of car trips would be positive for the environment and the society. It could be achieved by an increase in the number of bicycle trips. A mode switch from car to cycling would also provide health benefits for the users (Hillman, 1993).

The Norwegian National Transport Plan states that the increase of transportation in the cities must be covered by walking, cycling and public transport. The goal for cycling is to increase the mode share from todays 4,6 % to 8 % (Statens Vegvesen, 2019). The mode share for cycling is lower during the winter than the summer in cold climates (Bergström and Magnusson, 2003; Nordström *et al.*, 2014; Amiri and Sadeghpour, 2015). In order to achieve the goal of 8 % bicycle trips in Norway, it is important to increase the cycling share during both the summer and the winter.

Better winter maintenance of the bicycle lanes is the most important action to increase the cycling share during the winter (Bergström and Magnusson, 2003; Miranda-Moreno, Nosal and Kho, 2013; Nordström *et al.*, 2014). However, it is difficult to evaluate the winter maintenance effort of bicycle lanes. Requirements for winter maintenance of bicycle lanes can be improved by introducing cycling comfort as a measure for the winter maintenance efforts. Better winter maintenance will increase the accessibility, the safety and the attractiveness for the road users during winter (Wallman, Wretling and Öberg, 1997).

The attractiveness of the roads for cyclists can be represented by Bicycle Level of Service (Landis, Vattikuti and Brannick, 1997). Cyclists' perception of the quality of the cycling roads consist of parameters related to motorized traffic and the state of the cycling roads (Landis, Vattikuti and Brannick, 1997). According to Ayachi, Dorey and Guastavino (2015), cycling comfort is influenced by factors related to bicycle components, environmental factors and factors related to the cyclist. Surface conditions and type of road are classified as environmental factors, which affects comfort (Ayachi, Dorey and Guastavino, 2015).

Analysis of cycling comfort based on vibrations from the bicycle has been carried out in several researches (Hölzel, Höchtl and Senner, 2012; Olieman, Marin-Perianu and Marin-Perianu, 2012; Vanwalleghem *et al.*, 2013; Bíl, Andrášik and Kubeček, 2015). The analysis can be carried out in numerous ways, and are based on the fact that increased vibrations reduce comfort (Griffin, 2012).

Bíl, Andrášik and Kubeček (2015) suggested dynamic comfort index (DCI) to objectively represent vibrations from the bicycle, see equation 1. The index is calculated every second by the values of vertical accelerations greater than the gravity.

$$DCI = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2}^{\,-1} \qquad 1$$

Another approach was proposed by Vanwalleghem *et al.* (2013), who investigated how absorbed power at the handlebars and saddle affected cycling comfort. The analysis was carried out by measurements of strain.

Hölzel, Höchtl and Senner (2012) examines cycling comfort by calculating the effective values of the frequency valuated acceleration. The factor is calculated by the frequencies and amplitudes of the vertical vibrations, see equation 2. $a_w^2 t$ is the squared value of the amplitudes multiplied by the frequency of the vibrations.

$$a_{wT} = \sqrt{\frac{1}{T}\int_0^T a_w^2 t(dt)} \qquad 2$$

Frequencies analysis of vibrations are relevant for cycling comfort since most of the limbs and organs in the body have eigen frequencies between 0.5 Hz and 10 Hz (Griffin, 2012).

The surface conditions of the pavements vary during the winter in cold regions. Winter surface conditions cause various problems for cyclists, among others, reduced cycling comfort. However, cycling comfort on winter conditions has not been evaluated yet. The Norwegian Public Roads Administration (NPRA) have requirements for maintenance of walking- and cycling roads during the winter (Statens vegvesen, 2014). It is reasonable to assume that two of the parameters in the NPRA requirements, depth of loose snow and unevenness along the road, affects cycling comfort.

The mechanical properties of snow are among others affected by the density (Arenson, Colgan and Marshall, 2015). Higher density and more compacted snow result in higher mechanical strength(Arenson, Colgan and Marshall, 2015). Therefore, loose snow has other properties than compacted snow, which may affect cycling comfort different.

Previous studies have analyzed cycling comfort on different types of pavements based on vibrations. In this study, cycling comfort was analyzed on winter road conditions by measuring vibrations and angular velocity of the handlebars. Different surface conditions were investigated and related to cycling comfort. Analysis of angular velocity of the handlebars gave an indicator of how the bicycle was steered, which was assumed to affect cycling comfort on winter conditions.

This research aims to fill a gap in the knowledge about cycling comfort on winter road surface conditions. The results may be of use for NPRA to get more knowledge about how extensive the winter maintenance should be executed in order to meet the needs of the cyclists.

2. Method

2.1. Test Execution

A mountain bicycle with front suspension was used for the data collection. The bicycle was equipped with studded tires which is commonly used during winter to ensure grip on winter conditions. The tires were Suomi Tyres Extreme 294, 26''x2.10'' with 3 bar tire pressure.

Figure 1: The bicycle used during the testes. The sensor was light blue and placed on the stem.

A HAM-IMU sensor, provided by Gulf Coast Data Concepts was used to measure vibrations and angular velocity of the handlebars. The sensor was placed on the bicycle stem to measure acceleration in the x-, y- and z-axis, and angular velocity around x-, y- and z-axis. The sample rate of the sensor was 200 Hz, with a range of +/- 16 g and +/- 2000 degrees per second. A bicycle computer was used to measure the velocity. The computer measured velocity by a magnet on the front wheel that made one measurement per revolution. Figure 2 is an explanation of the angular velocities measured by the sensor.

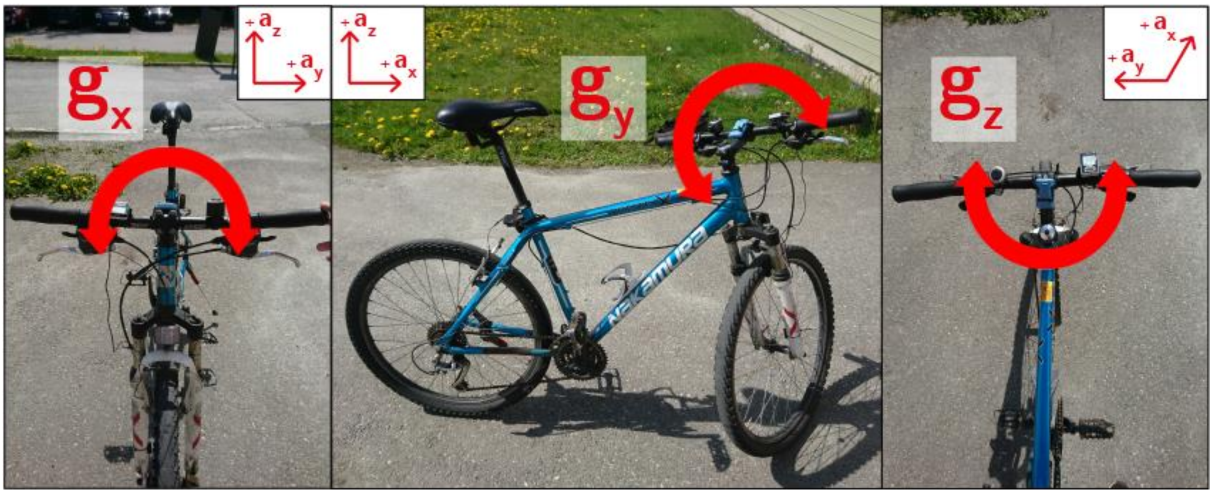

Figure 2: An explanation of g_x, g_y and g_z.

Several parameters were recorded during each test ride: depth of snow, depth of compacted snow, depth of loose snow, depth of wheel tracks, unevenness in the snow, air temperature, weather history, velocity, perceived comfort and an overall classification of the surface condition. The snow depths were measured by using a ruler. Unevenness in the snow was the largest corrugation in 60 cm, measured by a ruler. Perceived comfort was recorded by the cyclist as a value between 1 and 6, where 1 was uncomfortable and 6 was comfortable. The overall classification of the surface conditions was divided into four categories: bare asphalt, dry snow, wet snow and deep snow.

Roads where the surface condition was homogenous for at least 100 meters were selected for the data collection. The surface condition had to be homogenous to be able to analyze a specific condition. The tests were carried out in four speed levels between 10 km/h and 25 km/h and lasted between 20 seconds and 80 seconds. The tests were carried out in January, February and March 2019. Table 1 is a summary of the executed tests.

Table 1: Summary of the executed tests.

Winter cycling						
Surface conditions	Surface properties	Velocities				Total nr. of rides
		10 km/h	15 km/h	20 km/h	25 km/h	
Bare asphalt	Nr. of rides	2	2	2	2	8
Dry snow	Nr. of rides	5	5	5	5	20
	Snow depth [cm]	1 - 5	1 - 5	1 - 5	1 - 5	
	Unevenness [cm]	1 - 3	1 - 3	1 - 3	1 - 3	
Wet snow	Nr. of rides	6	6	6	6	24
	Snow depth [cm]	1.5 - 5	1.5 - 5	1.5 - 5	1.5 - 5	
	Unevenness [cm]	1 - 3	1 - 3	1 - 3	1 - 3	
Deep snow	Nr. of rides	2	4	2		8
	Snow depth [cm]	8 - 14	8 - 14	8		
	Unevenness [cm]	3	3	3		
Total	Nr. of rides	15	17	16	12	60

Cycling on bare roads							
Road surface	Velocities						Total nr. of rides
	10 km/h	15 km/h	20 km/h	25 km/h	30 km/h	40 km/h	
Asphalt	2	2	2	2	1	1	10
Cobblestone	1	1	1	1	1		5
Asphalt, standing on pedals	2						2
Total	5	3	3	3	2	1	17

Nine tests were executed during April and May to compare cycling on bare roads to cycling on winter conditions. The additional tests were two tests on bare asphalt in higher velocities, five tests on cobblestones and two tests in an incline while standing on the pedals. A category of cycling on bare roads was made, consisting of the tests executed during the spring and the tests on bare asphalt during the winter. Hence, the test on bare asphalt in velocities between 10 km/h and 25 km/h were included both in "Winter cycling" and "Cycling on bare roads".

2.2. Data Processing

The sensor had another coordinate system than the Earth when placed on the bicycle. By applying Euler's angle transformation, the coordinate system of the sensor was converted to the coordinate system of the earth (Fossen, 2011). Accelerations of the sensor when the bicycle was held still had components of a_x, a_y and a_z. However, the accelerations in the coordinate system of the Earth are $a_x = a_y = 0$ and a_z = -1g. Differences in the accelerations were used to find the orientation of the sensor and apply the angle transformation.

Standard deviations of a_x, a_y, a_z, g_x, g_y and g_z for each test ride was calculated. The values were compared to perceived comfort and parameters related to the surface conditions.

The raw data was converted to series of frequencies by applying Fourier transform. Average values of the frequencies were calculated and compared to the surface conditions.

3. Results

3.1. Correlations Between Parameters

Data of accelerations and angular velocities from each test were data series of values around an equilibrium line. The equilibrium line was -1g for acceleration in the z-axis and 0 for the other parameters. The variation in each data series was represented by the standard deviation. Higher standard deviation results in larger variation, which was a measure for the intensity of the accelerations and angular velocities. From here on, the standard deviations of the accelerations in each data series are denoted as a_x, a_y and a_z. The standard deviations of the angular velocities are denoted as g_x, g_y and g_z.

a_x, a_y, a_z, g_x, g_y and g_z were compared to perceived comfort, presented in Figure 3. Regression lines and R^2 for the regression lines are presented. R^2, the coefficient of determination, is a statistical value that indicates how well the data fits to a regression line. When $R^2 = 0$, the data does not fit the regression line at all. On the contrary, $R^2 = 1$ indicates that all the data is on the regression line.

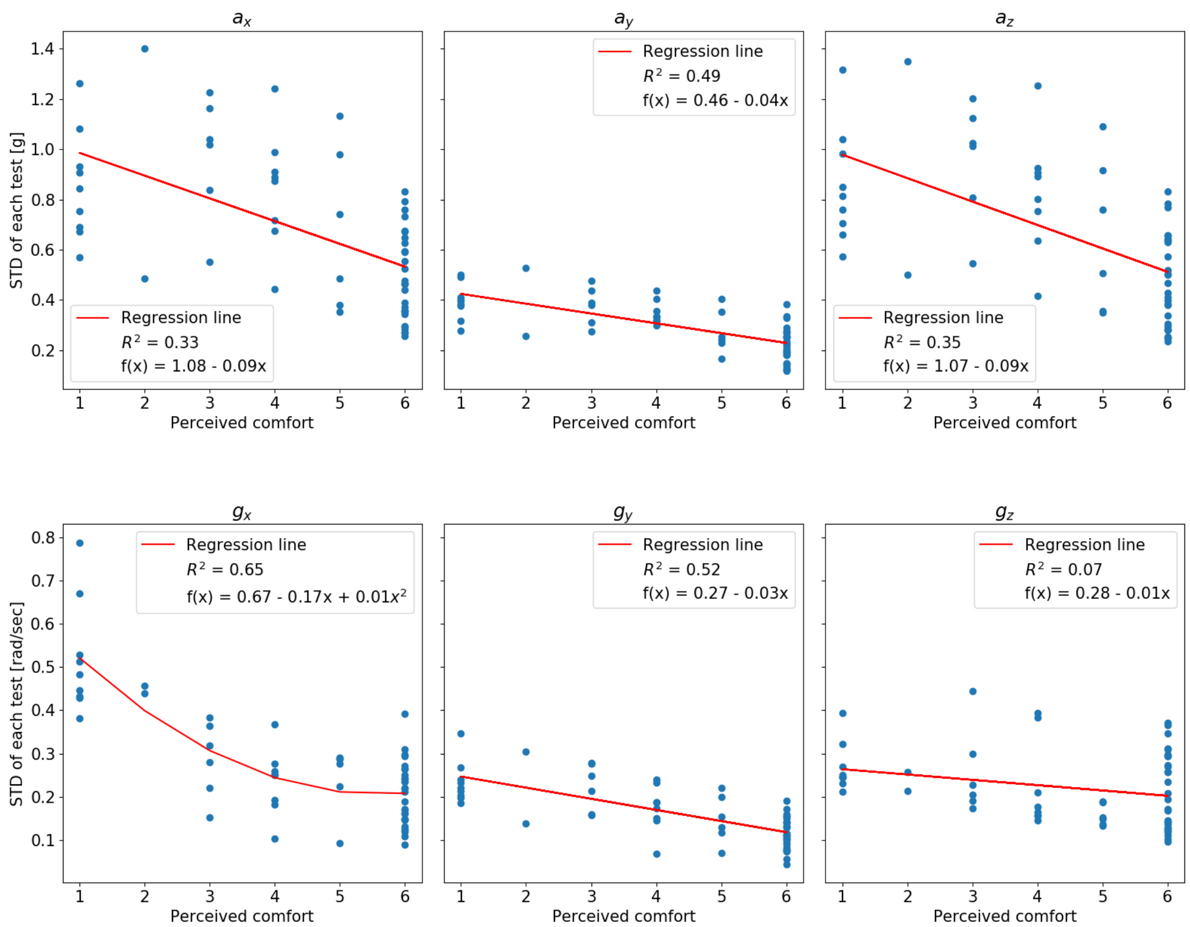

Figure 3: Correlations between perceived comfort, accelerations and angular velocities.

Table 2 is a presentation of the correlations between perceived comfort, parameters related to the surface conditions and sensor data. R^2 and the regression lines for the correlations are presented. It was found that velocity affected the parameters in different ways. Therefore, correlations for all the tests and correlations for the tests executed in 15 km/h are presented.

Table 2: Correlations between perceived comfort, surface conditions and sensor data.

Parameters	All velocities		15 km/h	
	R^2 linear regression	Regression line	R^2 linear regression	Regression line
Sensor parameters and comfort				
a_x	0.33	1.08 - 0.09x	0.37	0.84 - 0.06x
a_y	0.49	0.46 - 0.03x	0.64	0.42 - 0,03x
a_z	0.35	1.07 - 0.09x	0.30	0.83 - 0,05x
g_x	0.58	0.52 - 0.06x	0.72	0.65 - 0,07x
g_x 2. degree reg.	0.65	$0.67 - 0.17x + 0.01x^2$	0.73	$0.73 - 0.15x + 0.01x^2$
g_y	0.52	0.27 - 0.03x	0.60	0.27 - 0,03x
g_z	0.07	0.28 - 0.01x	0.11	0.30 - 0,01x
Surface conditions and comfort				
Depth of snow	0.53	9.98 - 1.34x	0.75	13.68 - 1.87x
Loose snow	0.51	7.00 - 0,97x	0.79	9.97 - 1.42x
Compacted snow	0.22	2.98 - 0,37x	0.35	3.71 - 0.46x
Unevenness	0.23	3.00 - 0,29x	0.23	3.02 - 0.26x
Sensor parameters and surface conditions				
Depth of snow and g_x	0.51	0.16 + 0.03x	0.71	0.14 + 0.03x
Loose snow and g_x	0.54	0.17 + 0.04x	0.71	0.15 + 0.05x
Unevenness and a_z	0.21	0.45 + 0.12x	0.58	0.33 + 0.14x
Cycling on bare roads				
a_z and comfort	0.88	2.47 - 0.34x		
g_x and comfort	0.00	0.27 - 0.01x		

Perceived comfort and g_x had the highest correlation of the sensor parameters. R^2 was highest, and the slope of the regression line was steepest when calculating percentage change. The correlation with perceived comfort fitted noticeable better when applying a second-degree regression line. Both values are therefore presented. When isolating the tests executed in 15 km/h, the following changes occurred for the sensor parameters: R^2 for a_z decreased, while a_x, a_y, g_x, g_y and g_z increased. The slopes of the regression lines for a_x and a_z decreased, while the slopes of the other regression lines increased.

3.2. Comfort Model

Figure 4 presents the differences between perceived comfort and calculated comfort for a_z and g_x. Calculated comfort was based on the linear regressions between perceived comfort and a_z and g_x. The comfort scale was the same as for perceived comfort; 1 was uncomfortable and 6 was comfortable. A red rectangle is drawn around the values that represents a deviation in comfort of plus or minus one. 60.0 % of the a_z-data and 81.7 % of the g_x-data had a comfort deviation of plus minus 1. The average deviation between perceived- and calculated comfort was 1.25 for a_z and 0.83 for g_x.

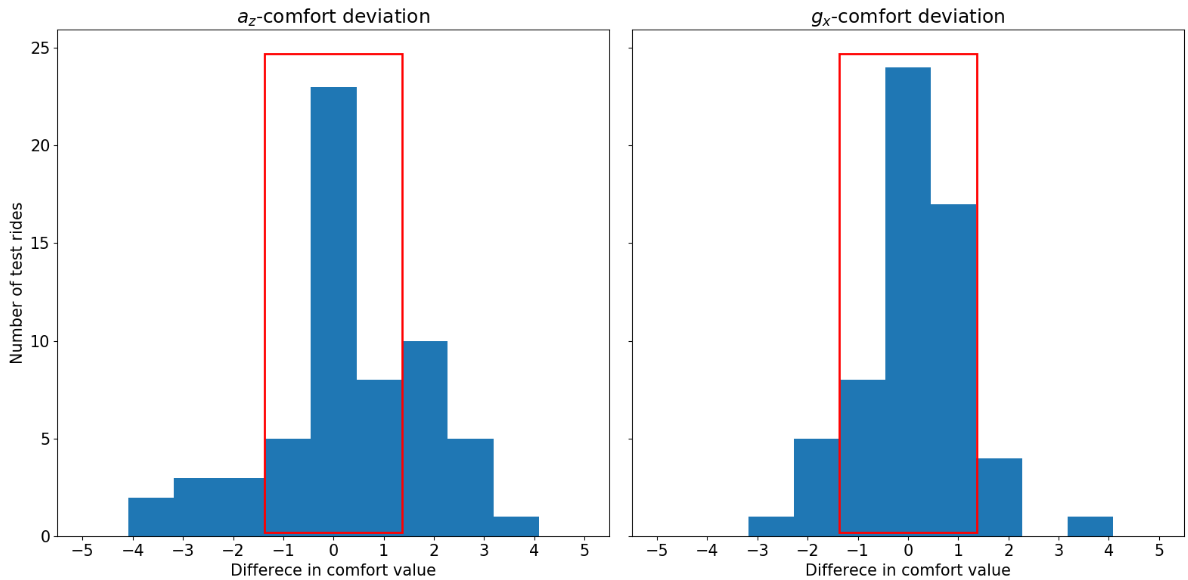

Figure 4: Deviation between perceived comfort and calculated comfort for a_z and g_x.

A one tailed t-test was applied to investigate if g_x had a lower derivation between calculated- and perceived comfort than a_z. The p-value was 0.06, which is a measure for the significance of g_x having less deviation between calculated- and perceived comfort than a_z. Lower deviation signifies that the parameter is better suited for comfort analysis.

When including the tests on cobblestone and rides while standing on the pedals on bare asphalt, the correlation between comfort and g_x became less clear. However, the additional tests had a clear correlation between increased a_z and reduced comfort. Data from winter conditions with additional tests are presented in Figure 5.

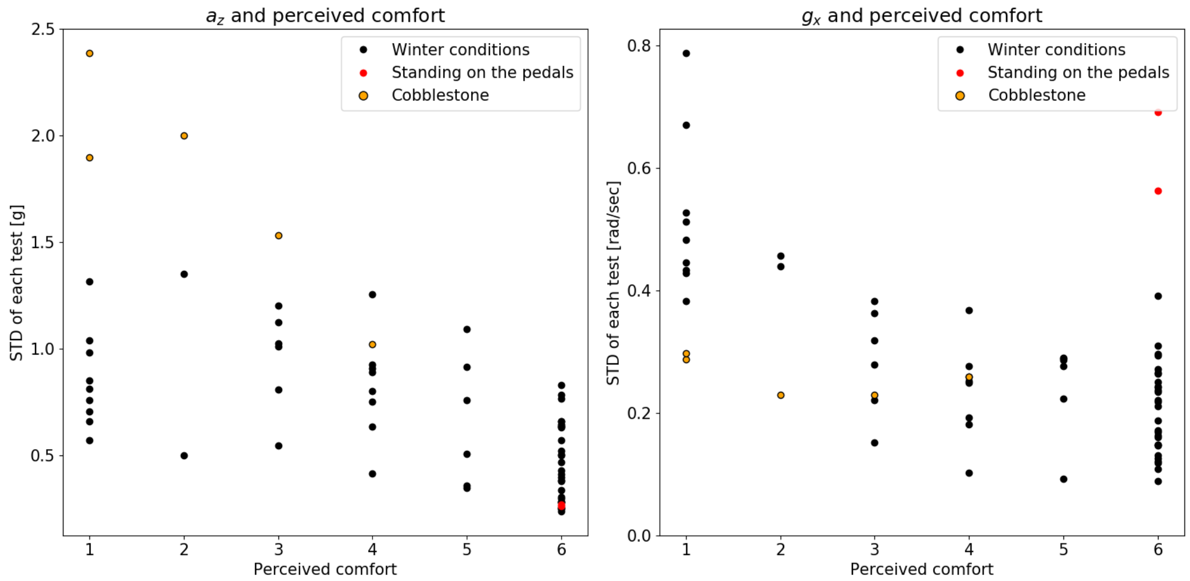

Figure 5: a_z and g_x compared to perceived comfort when including cobblestones and cycling while standing on the pedals.

Figure 6 is a presentation of how velocity affects a_z and g_x. The figure shows a_z and g_x on four different surface conditions in different velocities. a_z was visibly more affected by velocity than g_x.

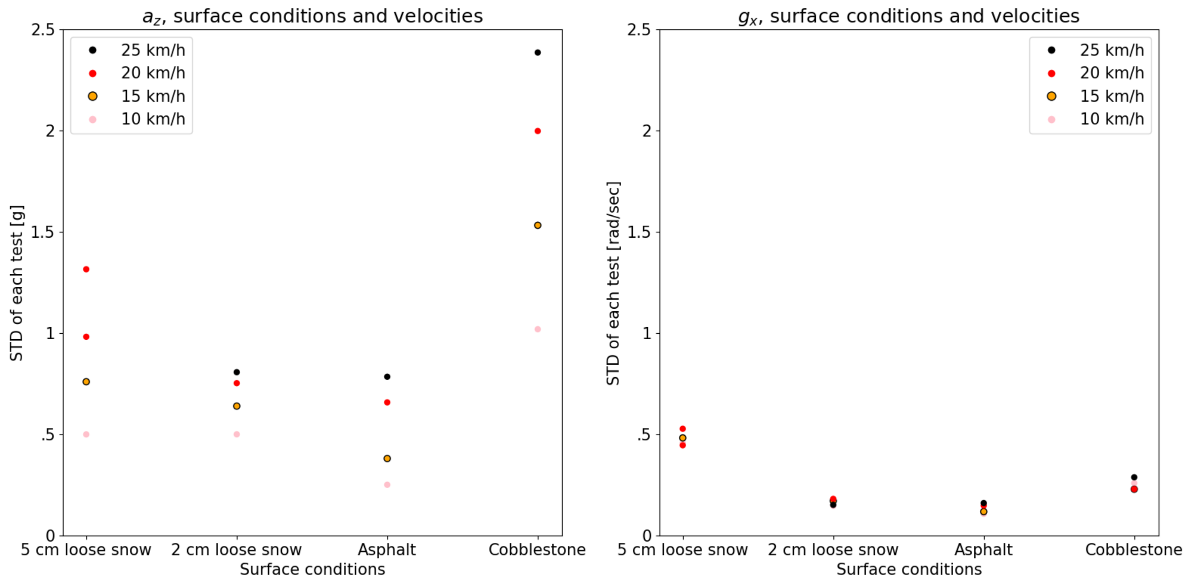

Figure 6: Changes in a_z and g_x for different velocities.

Thirteen of the test days during the winter had tests executed in 10 km/h, 15 km/h, 20 km/h and 25 km/h. a_z increased 150.4 % and g_x increased 27.0 % in average when the velocity was increased from 10 km/h to 25 km/h. The increase of a_z corresponded to the increased velocity, but the increase of g_x was only 18 % of the increased velocity. For two of the test days, g_x was decreased for the given increase in velocity. Average perceived comfort decreased 2.08 for the increase of velocity. The decrease of perceived comfort was higher for deeper snow, see Figure 7. The figure presents regression lines of decreased comfort for both depth of snow and depth of loose snow.

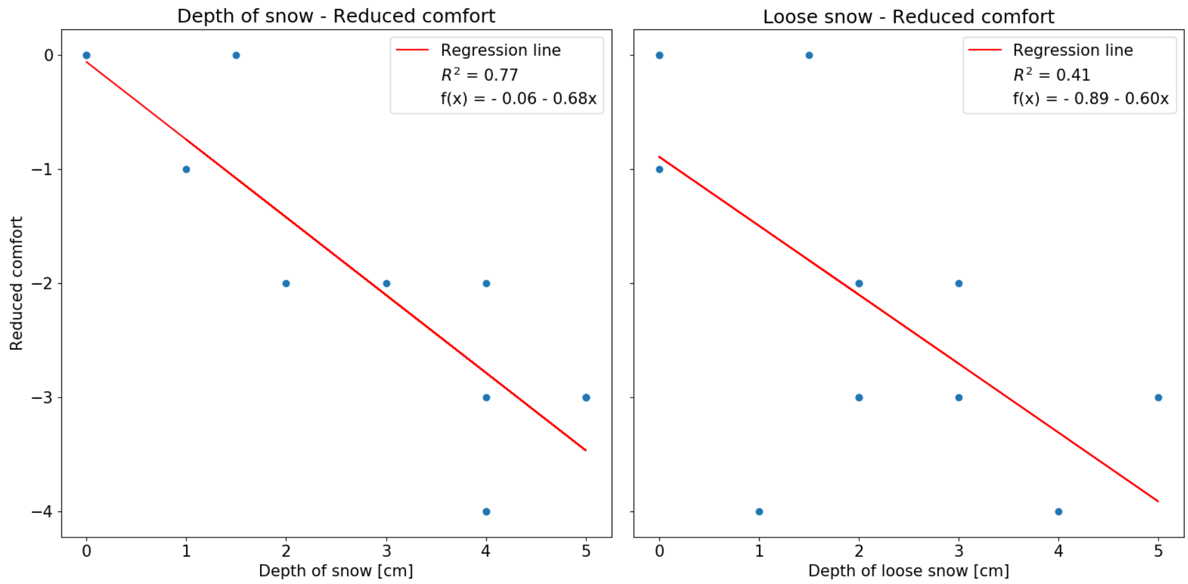

Figure 7: Reduced comfort for snow depths and depths of loose snow.

3.3. Surface Conditions

The average value of perceived comfort on the different surface conditions was 6.00 on asphalt, 4.95 in dry snow, 4.65 in wet snow and 1.13 in deep snow. The average value of g_x was 0.16 on asphalt, 0.22 in dry snow, 0.28 in wet snow and 0.54 in deep snow.

Average frequencies of the accelerations for different surface conditions are presented in Figure 8. The figure represents the frequency of the vibrations transmitted to the cyclist. The average frequency of a_x and a_z decreased when the surface condition changed to conditions with deeper snow. However, the same trend was not present for a_y. There was just a reduction of a_y when the surface condition was classified as deep snow.

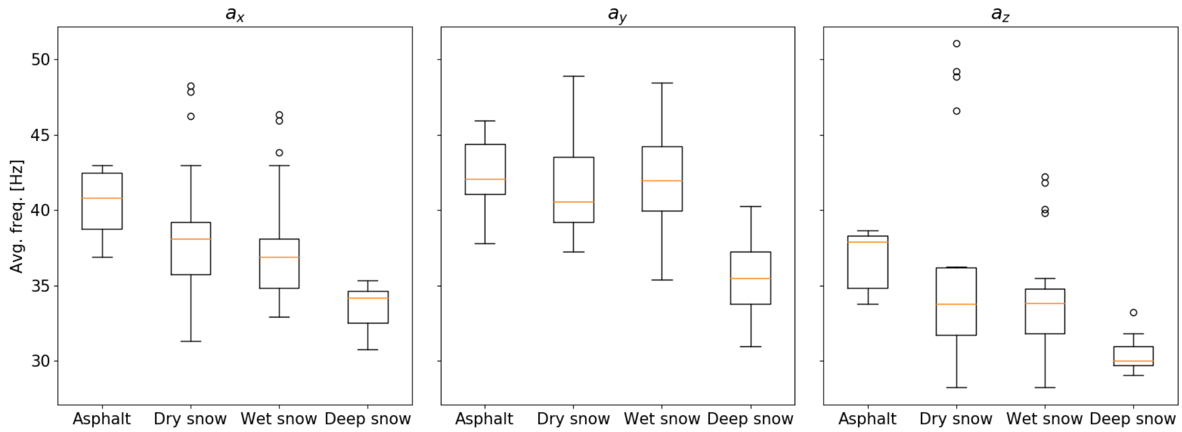

Figure 8: The relation between surface conditions and average frequencies of the vibrations.

4. Discussion

4.1. Comfort Model

When calculating comfort by DCI, perceived comfort did not match calculated comfort for the rides in deep snow. Perceived comfort was lower than DCI calculated comfort. DCI is based on vertical vibrations, which causes discomfort for the cyclist. Velocity and type of surface affects the harshness of the vibrations (Hölzel, Höchtl and Senner, 2012; Olieman, Marin-Perianu and Marin-Perianu, 2012; Bíl, Andrášik and Kubeček, 2015; Gao *et al.*, 2018). The velocities during the test executions were too low to produce vibrations equivalent to uncomfortable cycling. Hence, the reduced comfort experienced during rides in deep snow was not induced by vibrations.

Perceived comfort had the highest correlation with g_x among the accelerations and angular velocities. The factor was compared to vertical vibrations, which is the most common parameter for analysis of cycling comfort. g_x was better suited for comfort analysis on winter conditions than a_z, based on the p-value, the R^2-values and the deviation between perceived- and calculated comfort.

R^2 for perceived comfort and a_x and a_z respectively increased 0.04 and decrease 0.05 when isolating the tests in 15 km/h. In addition, the slopes of the regression lines became flatter. However, R^2 for a_y, g_x and g_y and perceived comfort increased 0.08 or more when isolating the tests in 15 km/h. The slopes of the regression lines were equal or increased. Increased R^2 when isolating tests in one velocity indicates that the compared parameters are affected different by velocity. When isolating the tests in 15 km/h, the variation in the sensor data was only caused by different surface conditions. Hence, g_x is a good measure for comfort related to the surface conditions, but not variation in comfort related to changes in velocity.

Figure 6 compares a_z and g_x for different surface conditions in different velocities. a_z and g_x increased respectively 150.4 % and 27.0 % in average when the velocity was increased from 10 km/h to 25 km/h. Perceived comfort decreased 2.08 for the given increase of velocity. Decreased comfort was noticeably higher than the increase of g_x for the comfort scale between 1 and 6.

Hence, changes in g_x for different velocities did not correspond to the changes in comfort. a_z on the other hand was well suited to represent the variation.

Velocity affects cycling comfort (Hölzel, Höchtl and Senner, 2012; Olieman, Marin-Perianu and Marin-Perianu, 2012; Bíl, Andrášik and Kubeček, 2015; Gao *et al.*, 2018), but g_x was affected less by changes in velocity than what comfort was. Therefore, the parameter is not suited for a comprehensive cycling comfort model. Figure 5 is a presentation of the tests on winter conditions with additional tests on cobblestone and tests while standing on the pedals. The additional tests had a large increase of a_z for increased velocity, which matches comfort analysis on bare roads (Hölzel, Höchtl and Senner, 2012; Olieman, Marin-Perianu and Marin-Perianu, 2012; Bíl, Andrášik and Kubeček, 2015; Gao *et al.*, 2018). However, the additional tests did not fit a correlation between perceived comfort and g_x. g_x for the tests on cobblestone was almost equal for all the rides, while perceived comfort varied between 1 and 4. The tests while standing on the pedals had a high g_x, although the rides were comfortable. The high value was induced by the bicycle being tilted from side to side while standing on the pedals. Hence, g_x is not suited for comfort analysis on bare roads or while standing on the pedals.

g_x represents how the bicycle is balanced, and increased g_x indicates that the cyclist has more problems with balancing the bicycle. Thereof, it seems reasonable to assume that discomfort induced by g_x is related to the difficulty of balancing the bicycle. This may be the fear of falling of the bicycle or losing control, which is a psychological comfort aspect. Therefore, cycling comfort is most likely a combination of mechanical comfort, vibrations, and the psychological comfort aspect. On a bare road, the mechanical comfort is prominent, and can be measured by an accelerometer. However, on winter conditions, the surface conditions reduce cycling comfort. Cycling comfort on these conditions are best measured by g_x, which is assumed to be related to a psychological perspective of comfort.

4.2. Surface Conditions

The classification of surface conditions as "bare asphalt", "dry snow", "wet snow" and "deep snow" was a convenience division and had a clear correlation with cycling comfort. Asphalt was comfortable and had low g_x, while the conditions with increased snow depths were less comfortable and had higher g_x. The differences in perceived comfort between dry snow and wet snow were small, which is assumed to be caused by the fact that the categories include the same snow depths. Dry snow was slightly more comfortable and had lower g_x than wet snow. The differences could be a product of higher density in wet snow, which increases the strength of snow (Arenson, Colgan and Marshall, 2015). However, the differences were too small to be supported statistically.

When comparing depth of snow and depth of loose snow to perceived comfort, R^2 was respectively 0.75 and 0.79 when isolating the tests in 15 km/h. The slopes of the regression lines were accordingly -1.87 and -1.43. This indicates than an increase of perceived comfort by 1 was equivalent to 1.87 cm less snow or 1.43 cm less loose snow. The steeper slope of depth of snow indicates that 1 cm of snow depth has less effect on comfort than 1 cm of loose snow. Since depth of snow consists of loose snow and compacted snow, compacted snow is less important for cycling comfort than loose snow.

A linear regression between snow depth and reduction in comfort was made for the tests when the velocity increased from 10 km/h to 25 km/h. An increase of snow depth by 1 cm reduced comfort by 0.68, $R^2 = 0.77$. This indicated a clear correlation between the snow depth and how much comfort was reduced when the velocity increased. However, the correlation was less clear for loose snow and reduction in comfort. 1 cm increased loose snow reduced comfort by 0.60, $R^2 = 0.41$. The lower R^2 signifies that the depth of loose snow was less capable to describe the reduction of perceived comfort than total snow depth. Hence, compacted snow has some impact on cycling comfort.

Most of the test rides were executed within a day after the snow fall. The compacted snow was therefore less compact than it would have been if the tests were executed long after the snowfall. Mechanical strength increases with the density of the snow (Arenson, Colgan and Marshall, 2015). Therefore, the compacted snow had less strength than it could have had. Hence, the compacted snow may have affected comfort more than harder compacted snow would do. Snow that is so hard packed that it becomes ice is assumed to have the same effect on cycling comfort as an asphalt pavement. The mechanical strength of the compacted snow seemed to be somewhere between loose snow and the pavement since compacted snow had some effect on cycling comfort.

The trend with reduced comfort due to increased velocity is present on bare roads as well; less even pavements leads to a greater reduction in comfort (Hölzel, Höchtl and Senner, 2012; Bíl, Andrášik and Kubeček, 2015). The relation between reduced comfort and increased a_z and g_x for different velocities was almost non existing. g_x increased 4.0 % for a decrease in perceived comfort by one level, $R^2 = 0.07$. a_z decreased 3.1 % for a decrease in perceived comfort by one level, $R^2 = 0.00$. Since the rides became less comfortable without a clear correlation with increased sensor parameters, a psychological aspect of comfort was present.

The correlation between unevenness and perceived comfort was low. R^2 was 0.23 for all the tests and for the tests executed in 15 km/h. Unevenness is a product of the depth of snow since the factor never can be deeper than the depth of the snow. The unevenness did never exceed 3 cm, even when the snow depth was 14 cm. Hence, it was difficult to extract data about how unevenness affected comfort since the changes in snow depths was dominant. The low R^2 for correlation between unevenness and comfort is assumed to be caused by the influence of snow depths. Unevenness are assumed to impact vertical vibrations since the surface becomes less smooth. R^2 for unevenness and a_z increased from 0.21 to 0.58 when isolating the rides in 15 km/h. However, there was a large variation in a_z for the same unevenness depths, which indicates that the depth of snow was influencing the results. The analysis of unevenness did not give reliable answers since the snow depth was highly important for the results.

It is assumed that g_x is connected to the rolling resistance of the bicycle. According to Hölzel, Höchtl and Senner (2012), there is a correlation between rolling resistance and cycling comfort. This corresponds to the correlation between g_x and perceived comfort. R^2 for g_x and depth of snow and depth of loose snow was 0.75 and 0.71 for the tests executed in 15 km/h. According to Lidström (1979), the depth of the snow is related to rolling resistance. The rolling resistance was not measured but was noticeable higher when riding in deep snow. The force of the rolling resistance is almost independent of the velocity in lower velocities (Taghavifar and Mardani, 2013), which corresponds to the low correlation between g_x and velocity.

4.3. Frequencies

Figure 8 shows a trend in reduced average frequencies of a_x and a_z when the surface condition changed to conditions with deeper snow. Since the Eigen frequencies of most limbs and organs in the human body are between 0.5 Hz and 10 Hz (Griffin, 2012), vibrations in that domain is most important for cycling comfort. Vibrations with frequencies larger than 10 Hz is less important for cycling comfort (Clevenson, Dempsey and Leatherwood, 1978; Griffin, 2012). The average frequencies were reduced when the surface conditions got worse. Thereof, a larger portion of the frequencies were in the frequency domain that is uncomfortable for the human body. Hence, the rides were less comfortable on these surface conditions.

The average frequencies of a_y did not have the same trend as a_x and a_z. a_y was also affected different than a_x and a_z when isolating the tests in 15 km/h. This indicates that the behavior of a_y varies from a_x and a_z. The parameter may be more related to psychological elements of comfort than the vibration itself.

4.4. Angular Velocities

Little or no research of cycling comfort has included angular velocity of the handlebars. Hence, there is little knowledge of how these values affects cycling comfort. Angular velocity is not a kind of vibration which makes discomfort for the organs in the body.

g_x represent how the cyclist is balancing the bicycle. When the angular velocity is increasing, it may indicate that the cyclist has more problems with balancing the bicycle. This fact is assumed to be the reason for g_x being related to comfort. g_y was related to the vibrations; R^2 for g_y and a_x, a_y and a_z were 0.81, 0.78 and 0.82. g_y is related to the vibrations since the sensor begins to revolute when the dampers are moving up and down, which is a result of the bicycle being exposed to vibrations. g_z is the parameter related to steering the handlebars. The parameter had low correlations with perceived comfort, velocity and surface conditions.

4.5. Impacts of the Limitations

Comfort is a subjective experience, but when several people are asked about comfort, the result will be more objective. The index "perceived comfort" was based on the opinion of one cyclist, which makes the index highly subjective. Several participants would reduce the uncertainty and result in more reliable data. The cyclist that executed the tests was a 23 years old male experienced cyclist. Males and younger cyclists focus less on how comfortable the ride was than older people and females (Bergström and Magnusson, 2003). However, experienced cyclist emphasizes cycling comfort more than inexperienced cyclists (Bergström and Magnusson, 2003). Therefore, perceived comfort of the cyclist may vary from what the average person would perceive.

Since one bicycle was used for all the data collection, the specific components of the bicycle will affect the vibrations and angular velocity. The bicycle was equipped with a front suspension, which reduces the impact of vibrations. Comfort related to vibrations was therefore less prominent in this research than it would have been for a bicycle without suspensions. Because of the uncertainty related to only one cyclist and one bicycle, it is not possible to conclude how comfortable different surface conditions are. However, the differences between different surface conditions will still be present.

5. Conclusions

Cycling comfort on winter conditions is best represented by angular velocity around the x-axis of the bicycle, g_x. g_x is an indicator for the surface condition but is little affected by changes in velocity. Therefore, g_x is not suitable for a comprehensive comfort model. g_x is a measure for how well the cyclist can balance the bicycle, which is assumed to be related to a psychological comfort perspective. Hence, cycling comfort consist of both mechanical comfort, vibrations, and the psychological comfort perspective.

Depth of loose snow was the most important parameter of the surface conditions related to cycling comfort. R^2 for the regression line was 0.79 if applying a linear regression for the tests executed in 15 km/h. Nevertheless, the depth of compacted snow influenced cycling comfort as well. A requirement for total snow depth on bicycle lanes is therefore sensible to provide comfortable cycling conditions during winter. Further work includes research where several participants and bicycles are used. Studies of how velocity affects cycling comfort on winter conditions is needed, since this research did not find a correlation between reduced comfort and increased g_x or a_z when velocity was increased.

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Appendix

Appendix A. Recommendations to R610

Appendix B. Table of Recorded Attributes of Each Test Ride

Appendix C. Raw Data of Accelerations

Appendix D. Raw Data of Angular Velocities

Appendix E. Fourier Transformed Data of Accelerations

Appendix F. Fourier Transformed Data of Angular Velocities

Appendix A. Recommendations to R610

Depth of loose snow was the most important parameter of the surface conditions related to cycling comfort. Nevertheless, the depth of compacted snow influenced cycling comfort as well. Therefore, a requirement regarding the total depth of snow would be preferable for cycling comfort.

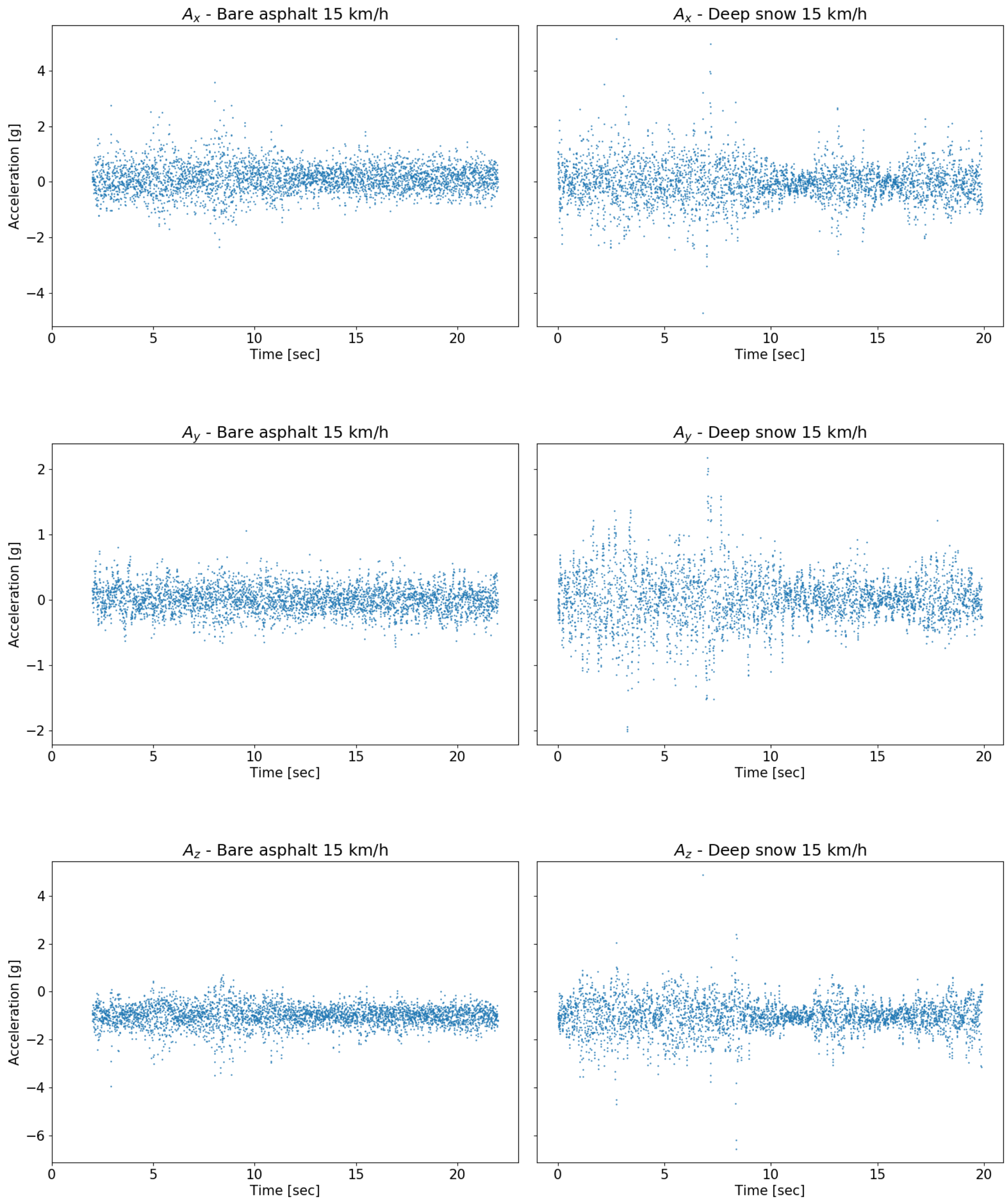
Unevenness are vertical bumps in the snow or ice which will transmit vertical vibrations to the cyclist. The correlation between unevenness and comfort was low, and the correlation with vertical vibrations was highly influenced by the total depth of snow. Therefore, the analysis of unevenness did not give reliable results. However, unevenness may still cause problems for the cyclist.

A requirement involving the total depth of snow would eliminate reduced comfort caused by a layer of compacted snow. Based on perceived comfort of the tests, 2-3 cm total depth of snow was acceptable. A requirement based on total depth of snow would eliminate the need for a requirement regarding unevenness, since the total snow depth would prevent deep unevenness. If making a requirement of 2-3 cm total snow depth, the need for winter maintenance straight after snowfall is reduced if the cycle lanes were clear of snow before the snowfall. In addition, the requirement could make maintenance easier since the only parameter related to snow that should be evaluated is the total depth of snow.

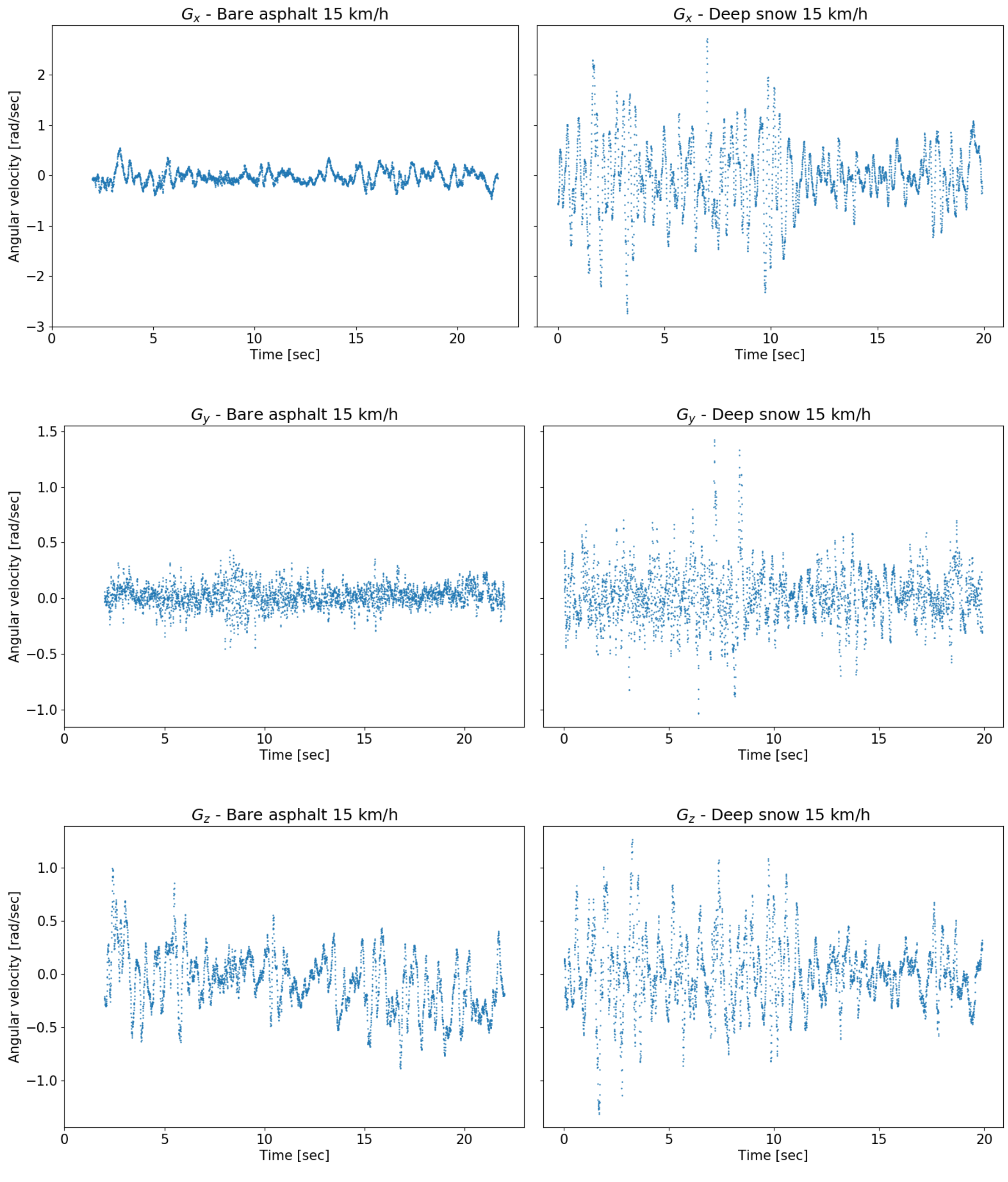
Appendix B. Table of Recorded Attributes of Each Test Ride

Parameter	Value	Unit	Comments
Date			
Air temperature		Celsius	
Depth of snow		cm	
Depth of hard/compacted snow		cm	
Detph of loose snow		cm	
Depth of wheel tracks		cm	
Unevenness		cm	
Overall classification			
Velocity		km/h	
Perceived comfort			
Weather history			

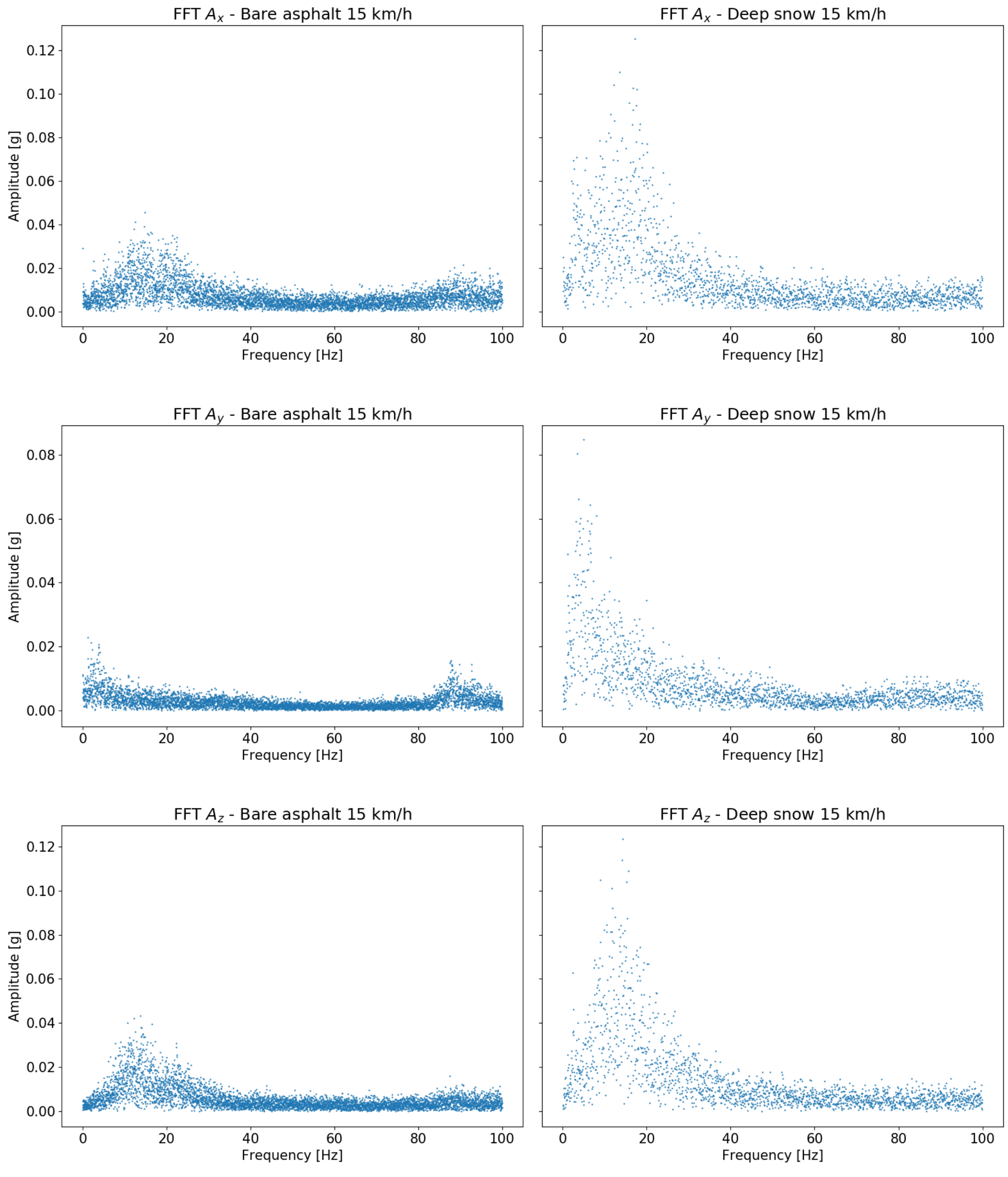
Appendix C. Raw Data of Accelerations



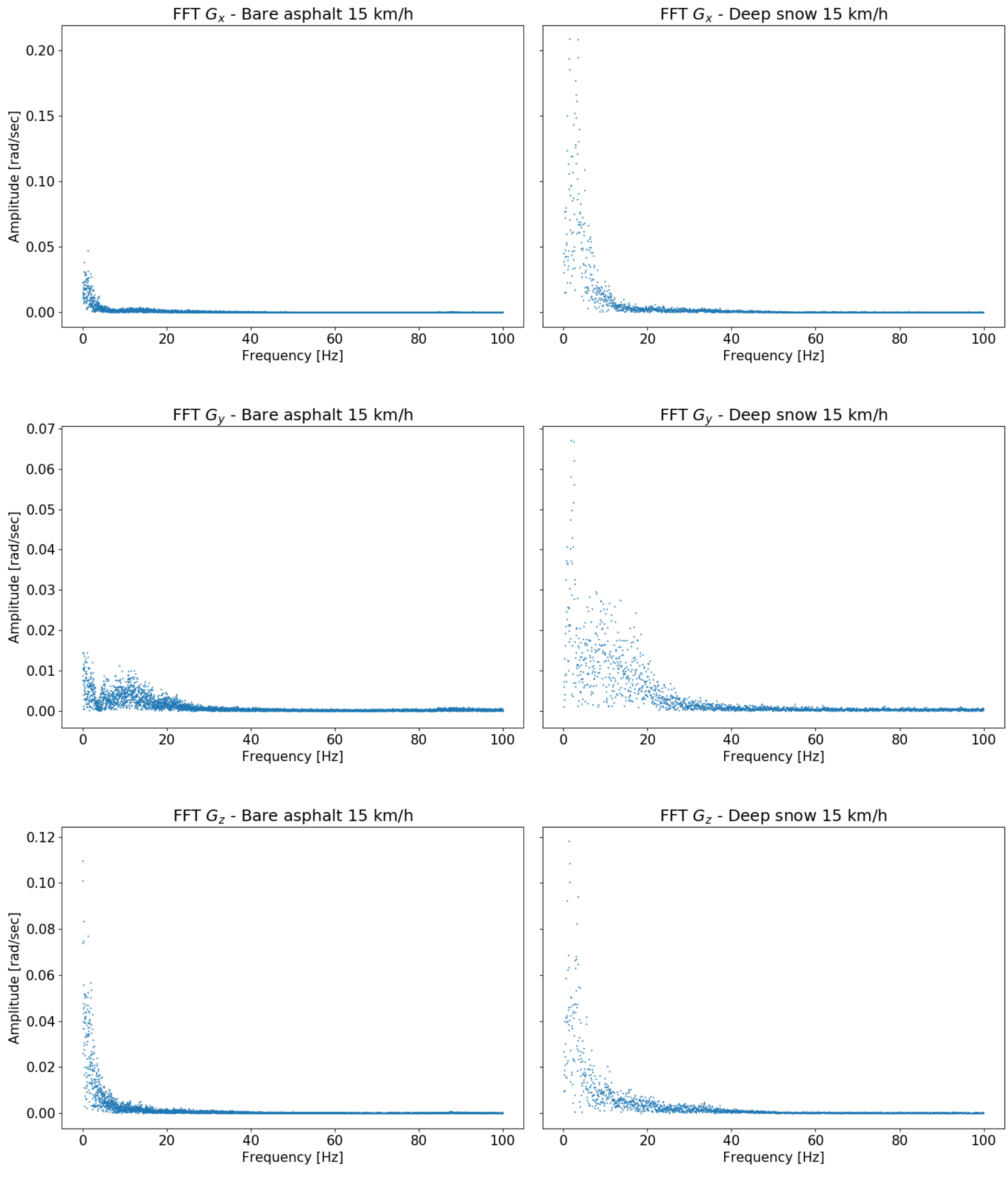
Appendix D. Raw Data of Angular Velocities



Appendix E. Fourier Transformed Data of Accelerations



Appendix F. Fourier Transformed Data of Angular Velocities



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