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Mathis Dahl Fenre

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Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
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Trondheim, September 2021

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ABSTRACT

Authorities in many countries facilitate increased bicycle use in urban areas due to its numerous benefits. Still, the number of bicycle trips drops drastically during the wintertime, especially in areas with harsh winters. Inclement road conditions have been identified as a significant "barrier" to winter cycling. Moreover, previous research has found that better winter maintenance can significantly increase winter cycling. Quantitative knowledge about how the road conditions affect winter cycling is needed to improve winter maintenance and evaluate its costs and benefits. A quantifiable metric that describes the road condition quality would be helpful to investigate this correlation. A quantifiable metric that describes the road condition quality would be helpful to investigate this correlation. Rolling resistance equals the energy needed for a wheel to roll over a surface at a constant speed. It is directly dependent on surface irregularities and road contaminants such as snow or ice. Snow, ice, and uneven surfaces can all reduce cycling comfort and increase rolling resistance, making cycling more physically demanding. Therefore, rolling resistance shows potential as a valuable metric for quantifying the quality of cycleways under winter conditions.

The following work is outlined in this dissertation: A) A new measurement method for bicycle rolling resistance was developed using an instrumented bicycle. The method measured propulsive and resistive forces acting on the moving bicycle and utilized the force equilibrium to estimate the rolling resistance. B) This method was used to measure rolling resistance on various winter conditions and analyze the correlation between rolling resistance and perceived cycling comfort. C) These analyses were later used in an online survey to investigate the correlation between rolling resistance and people's stated willingness to cycle during the winter. The respondents (N=1318) based their answers on conditions shown in photos.

The results show that the developed method can measure the coefficient of rolling resistance, Crr, with a precision, represented as the standard error of the mean, of ±0.005 (1 Hz, n = 9) or ±0.002 (1 Hz, n = 55), depending on the number of recorded samples. The new method measured significant differences in rolling resistance between ten typical winter conditions. The Crr varied between around 0.01 on bare asphalt to around 0.06 in deep loose snow. The results also showed a negative correlation between rolling resistance and cycling comfort. The survey results showed that the cycling willingness among regular winter cyclists decreased close to linearly from around 90% to 19% for rolling resistances between Crr=0.01 to Crr=0.06. Summer-only cyclists showed a close to exponential decay in cycling willingness from around 70% to 7% for the same rolling resistance interval. The use of studded tires significantly increased cycling willingness while electric bicycle use did not. Low temperatures (29%) and a lack of safety (27%) were the main reasons for not cycling during the winter.

The results indicate that increased use of studded tires and slight winter maintenance improvements can increase the cycling frequency of regular winter cyclists. To recruit summer-only cyclists to winter cycling, it is necessary to provide cycleways with conditions perceived as safe and comfortable and low rolling resistance, preferably with Crr levels below 0.01.

PREFACE AND ACKNOWLEDGMENTS

This dissertation has been submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of *Philosophiae Doctor* (Ph.D.).

The work has been conducted between April 2018 and April 2021 at the Department of Civil and Environmental Engineering (IBM) at NTNU Trondheim (Norway). The research project presented in this dissertation was a part of the research program BEVEGELSE, initiated and funded by the Norwegian Public Roads Administration (NPRA). I express my gratitude to NPRA for their support. I would particularly like to thank NPRA and BEVEGELSE staff members Katja Skille and Bård Nonstad for their interest in the project and their advisement along the way.

I would like to thank my supervisor Alex Klein-Paste for believing in my abilities and allowing me to endure this adventure. I could not have done this without your guidance, encouragement, and enthusiasm. I would also like to thank my co-supervisor, Johan Wåhlin, for making me believe I could finish this project already from the very beginning.

Further, I would like to thank NTNU staff Frank Stæhli, Tage Westrum, Bent Lervik, Jan Erik Molde, and Per Asbjørn Østensen for their invaluable help and support with experimental equipment.

I also thank my friends and colleagues Henri, Magne, and Ole for our collaborations and for reading and reviewing my papers and dissertation. All my friends and colleagues at NTNU have made this Ph.D. an amazing adventure and I am thankful for all the fun trips, much needed cage-ball matches, lunch runs, ping-pong and coffee breaks.

Turid, thank you for your endless support and for making me laugh and smile every day. Thank you, Tobias, Mamma and Pappa for always being there for me.

Trondheim, April 7, 2021

Mathis Dahl Fenre

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

The winter season reduces bicycle transportation in many urban areas. Cold temperatures, darkness, and inclement road conditions make people reluctant to cycle on their daily commutes or errands. The drop in utilitarian cycling during the winter is especially seen in the Nordic countries (Aalto-Setälä et al., 2017; Bergström & Magnusson, 2003; Ellis et al., 2016; Nordström et al., 2014), and areas of Northern America with harsh winters (Amiri & Sadeghpour, 2015; Flynn et al., 2012; Orvin, 2020; Sears et al., 2012). A study of several Northern American cities found that the utilitarian bicycle use throughout the year can be estimated using a sinusoidal model that reaches its lowest point in January and peaks in July (Fournier et al., 2017).

Cycling has received increased attention in recent years because it has the potential to reduce the number of short car trips and relieve pressure on overcrowded public transportation systems (Bergström & Magnusson, 2003; Sun & Zacharias, 2017). Further, the energy cost per kilometer per person cycling at a speed of 16 km/h is about 17 times lower than that for one person driving a regular car at a speed of 50 km/h (Wilson et al., 2004). Besides being energy efficient, cycling is space-efficient and has benefits in terms of public health, economy, less congestion, and reduced pollution (Fishman et al., 2015; Gössling et al., 2019; Gössling et al., 2016; Koska & Rudolph, 2016; Teschke et al., 2012). Cycling has also shown excellent potential as pandemic-resilient transportation (De Vos, 2020; Litman, 2020).

Due to the acknowledged benefits associated with cycling, several governments facilitate cycling growth in urban areas. In Norway, the current goal is that walking and cycling should cover 40-60% of all passenger traffic increases in urban areas (NMTC, 2018). Sweden invested 100 million SEK in promoting more and safer cycling in a 2016-2017 initiative (SMEI, 2017). Finland's new energy and climate strategy include an official national goal to increase the number of trips made by bicycle or walking to 30% by 2030 (Huttunen, 2017).

Better winter maintenance can increase the number of people cycling during winter. Bergström and Magnusson (2003) concluded that better winter maintenance has the potential to increase winter cycling by 18% and, at the same time, reduce the number of short car trips by 6%. In Helsinki, more than 50% of the residents who cycle said that they would cycle more during the winter if the cycle paths were maintained better (Aalto-Setälä et al., 2017). 56% of winter cyclists in Oslo stated that a lack of snow removal has previously hindered them from cycling (Svorstøl et al., 2017). An analysis from Oslo show that a 10% increase in snow depth reduces chance of cycling by 2.5% (Ellis et al., 2016).

As a response to Norway's walking and cycling goals and previous winter cycling research results, the Norwegian Public Roads Administration (NPRA) launched a research and development program in 2018. The program's mission statement was: "Better winter maintenance to make more people walk and cycle more". The program abbreviation, BEVEGELSE in Norwegian, translates to MOVEMENT. NPRA wanted BEVEGELSE to increase the number of pedestrians and cyclists by exploring pedestrians' and cyclists' needs and prerequisites during the winter. Further, NPRA wanted to improve operations, methods, and equipment. Finally, NPRA wanted to build knowledge around how contracts, cooperation models and follow-up of users could improve winter maintenance.

An essential ingredient in improving winter maintenance of cycleways is an objective evaluation of the road conditions (Hamilton & Hyman, 2006). In many countries, including Norway, winter maintenance services are performed by private contractors. To evaluate whether the maintenance contracts are fulfilled according to the requirements, a standardized assessment of the current state of the pavement is desired. This can also be useful for comparing service levels across regions or periods (Xu et al., 2017). In Norway, the current state of the pavement is often evaluated in relation to the performance requirements in the levels of service developed by NPRA. NPRA has developed two levels of services for winter maintenance of bicycle road networks. These levels of services have minimum performance requirements for friction, loose snow depth, unevenness, and crossfall (NPRA, 2014).

Friction is used as a performance criterion in most winter maintenance contracts in the Nordic countries. The most crucial factor in reducing single bicycle accidents is a sufficiently high level of friction (Niska, 2010b). However, the number of people who choose to bicycle in the winter or the attractiveness of the bicycle infrastructure is not solely dependent on friction. Winter-cyclists often use studded tires and feel safe even on slippery roads (Grann, 2016). Cyclists are attracted to accessible roads, and an effective measure to increase accessibility is snow removal (Svorstøl et al., 2017). However, snow removal is expensive and often involves anti-icing chemicals that are detrimental to vehicles and the surrounding environment (Fay & Shi, 2012; Fay et al., 2008). It would be advantageous to achieve accessible cycleways without complete snow removal and the use of anti-icing chemicals. Depending on the snow's physical properties and the evenness of the surface, snow-covered roads sometimes offer a high level of attractiveness and accessibility. There seems to be a lack of knowledge on how the requirements for loose snow depth and unevenness correlate with the actual accessibility experienced by cyclists. This knowledge is needed to optimize and streamline winter maintenance of bicycle roads. A quantified correlation between road surface quality and pedestrian and cycling traffic is also needed to evaluate winter maintenance actions' cost and benefits.

Rolling resistance is an interesting parameter describing road surface conditions for cyclists. While friction is an important parameter regarding cycling safety, rolling resistance is related to the surface parameters governing cycling comfort. The rolling resistance describes how variations in the surface conditions affect the energy needed to cycle at a given velocity. The rolling resistance depends on the bicycle's properties, the snow depth and density, and the unevenness of the surface.

The goal of this Ph.D. project is to explore the usefulness of bicycle rolling resistance measurements in winter conditions. To reach this goal, this dissertation seeks to answer the following research questions:

1. Can rolling resistance on cycleways be quantified sufficiently accurately?
2. What is the rolling resistance level in typical winter conditions?
3. How does the rolling resistance level affect winter cycling?

Three papers, answering research questions 1, 2, and 3 are published, or accepted for publishing, in academic journals.

1.2 DISSERTATION STRUCTURE

This dissertation is divided into seven chapters, and the three published papers are attached as Appendices A to C. One additional study was also performed during the Ph.D. period. This study did not fall under the scope of this dissertation, but the paper presenting the study is available as Additional Paper in appendix D. After the introduction in chapter 1, chapter 2 provides a short review of the factors determining whether people cycle and illustrates the drop in cycling during the winter. Chapter 2 also provides a review of the theory and existing measurement methods of bicycle rolling resistance, as well as an overview of winter maintenance of cycleways. Chapter 3 describes the development of a new bicycle rolling resistance measurement method, the execution of bicycle rolling resistance measurements in winter conditions, and the development of an online survey investigating the correlation between rolling resistance and peoples' willingness to cycle during the winter. Chapter 4 describes the accuracy of the measurement method, how winter conditions affect rolling resistance, and the results from the online cycling willingness study. Chapter 5 contains a discussion of the usefulness of the new bicycle rolling resistance measurement method, and how winter maintenance can contribute to increased winter cycling. Conclusions of the dissertation are presented in Chapter 6. Chapter 7 presents suggestions for further work.

1.3 PUBLICATIONS

This section provides an outline of the papers written during this Ph.D. project:

Paper I

Fenre, Mathis Dahl & Klein-Paste, Alex (2021)

Rolling Resistance Measurements on Cycleways Using an Instrumented Bicycle.

Published January 20, 2021 in Journal of Cold Regions Engineering.
(doi:10.1061/(ASCE)CR.1943-5495.0000244)

This paper describes how an instrumented bicycle can measure bicycle rolling resistance on cycleways. An instrumented bicycle was built for this study, and this paper describes the measurement method concept and how the method was verified. The method measures propulsive and resistive forces and utilizes the force equilibrium on a moving bicycle to determine the rolling resistance. This method distinguishes itself from previous methods by taking road slope, acceleration, and air resistance into account when determining bicycle rolling resistance. This makes the method usable in all types of roads or cycleways, in all wind conditions, and at variable velocities. The method's accuracy and precision were tested by adding a dynamo with known resistance to the bicycle. The method produced measurements of the coefficient of rolling resistance, Crr, with a 96.5% accuracy. The precision, represented as the standard error of the mean, was between ±0.005 (1 Hz, n = 9) and ±0.001 (1 Hz, n = 220).

Contributions:

Mathis Dahl Fenre: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Alex Klein-Paste:** Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. In addition to the authors, **Johan Wåhlin** contributed with: Conceptualization and Supervision.

Paper II

Fenre, Mathis Dahl & Klein-Paste, Alex (2021)

Bicycle rolling resistance under winter conditions.

Published March 30, 2021 in Journal of Cold Regions Science and Technology. (doi:10.1016/j.coldregions.2021.103282)

This paper describes how the method developed by Fenre and Klein-Paste (2021), was used to investigate how typical winter conditions affect bicycle rolling resistance. Also, the paper investigates the correlation between rolling resistance and perceived unevenness, steerability, and general cycling comfort. The paper also investigates the effect of different winter maintenance standards on rolling resistance. Bicycle rolling resistance was measured on a 20 km long test route on roads, streets, and cycleways in Trondheim during January and February of 2019. During testing, the road conditions were video recorded with a steering bar-mounted smartphone. The road conditions were classified based on the video recordings and the test cyclists' subjective comfort perception.

Contributions:

Mathis Dahl Fenre: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Alex Klein-Paste:** Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. In addition to the authors, **Johan Wåhlin** contributed with: Conceptualization, Writing - Review & Editing and Supervision.

Paper III

Fenre, Mathis Dahl & Klein-Paste, Alex (2021)

The effect of rolling resistance on people's willingness to cycle during wintertime.

Published April 23, 2021 in Journal of Infrastructure Preservation and Resilience. (doi:10.1186/s43065-021-00022-5)

This paper describes how an online survey was used to investigate the correlation between the rolling resistance level on cycleways and peoples' willingness to cycle during the winter. The survey contained 37 photos of typical winter cycling conditions, and the respondents rated their willingness to cycle for the conditions in each photo. The survey results were compared to rolling resistance measurements previously performed on the conditions shown in the survey photos. A total of 1318 responses were recorded. The results show that the correlation between rolling resistance level and cycling willingness during the winter depends on cyclists' gender, age, the winter climate they are familiar with, whether they usually use studded tires, and their previous winter cycling experience and habits.

Contributions:

Mathis Dahl Fenre: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Alex Klein-Paste:** Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Additional Paper

Fenre, Mathis Dahl & Klein-Paste, Alex (2019)

A torque-based method for measuring bicycle braking friction.

Presented at Transportation Research Board Annual Meeting (TRB), Washington DC, January 18, 2019.

This paper describes a novel laboratory method for measurements of bicycle breaking friction. Unlike other bicycle braking friction measurement methods, this method measures the braking friction for all slip rates from a freely rolling wheel to a locked, sliding wheel. The measurements were performed at a velocity of 7 m/s (25 km/t), and the measurements were collected within 0.2 seconds. Braking friction versus slip rate curves was found for four different braking surfaces: plywood, ice, sanded ice, and ice with a few millimeters thick snow layer.

Contributions:

Mathis Dahl Fenre: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Alex Klein-Paste:** Conceptualization, Methodology, Validation, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. In addition to the authors, **Johan Wåhlin** contributed with: Conceptualization, Writing - Review & Editing and Supervision.

2 THEORY

2.1 CYCLING DETERMINANTS

Numerous factors determine whether people choose to use a bicycle instead of other transportation modes for their commute. These factors are known as cycling determinants. Previous research has divided the cycling determinants into four main categories, namely the natural environment (climate and topography), the built environment (infrastructure and land-use mix), temporal factors (calendar events and time-of-day), and other (cultural and individual) factors (Heinen et al., 2010). To increase cycling, one can induce changes in the cycling determinants to either recruit new cyclists or increase current cyclists' cycling frequency. To recruit new cyclists, there is often a need to reduce cultural or personal barriers such as a negative attitude towards cycling or work and family commitments. Occasional cyclists are often reluctant to increase their cycling frequency due to flexibility and practical matters, for example, if they need to transport cargo during the day (Gatersleben & Appleton, 2007). Moreover, to encourage summer cyclists to cycle more during the winter, proper winter maintenance, especially snow removal, is essential (Bergström & Magnusson, 2003; Niska, 2010a; Svorstøl et al., 2017; Sørensen & Mosslemi, 2009).

2.2 DROP IN CYCLING DURING WINTER

The drop in cycling during the winter is usually caused by changes in the natural environment and mainly climatic factors. Figure 1 shows that, on average, from 2013 through 2014, the average bicycle transportation share in Norway dropped by 50% from the summer (April - September) to the winter (October - March) (Lunke & Grue, 2018). Cold temperatures, darkness, increased precipitation, and inclement road conditions have been found to be the most critical factors for people choosing not to cycle during the winter (Bergström & Magnusson, 2003; Brandenburg et al., 2007; Godavarthy & Rahim Taleqani, 2017; Nahal & Mitra, 2018; Spencer et al., 2013a).

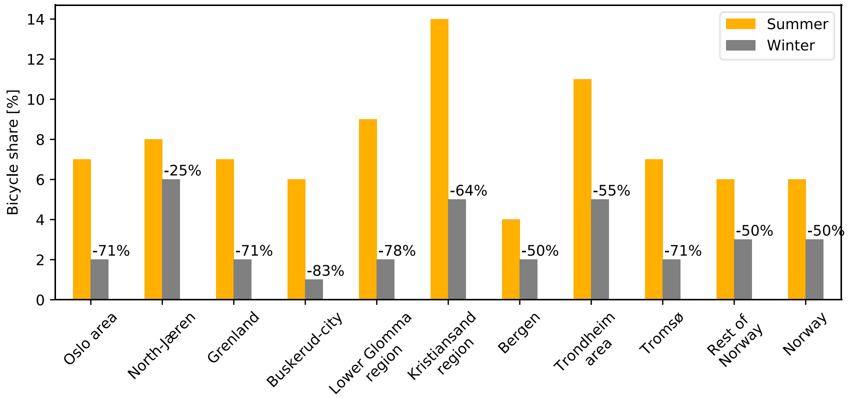


Figure 1: Bicycle transportation share in Norwegian regions during the summer (April – September) and the winter (October – March) of 2013 and 2014. The annotations show the percentwise change in cycling from summer to winter.

2.3 ROLLING RESISTANCE

Cold temperatures and snow and ice on the roads lead to increased rolling resistance. Rolling resistance is one of the factors impeding the forward motion of road vehicles. It occurs because of the interaction between the tires and the road surface. In addition to rolling resistance, the total resistance of a road vehicle in motion is the sum of aerodynamic resistance, internal friction resistance, gravitational resistance, and inertial resistance (when accelerating) (Michelin, 2003; Sandberg et al., 2011). Each factor's contribution depends on the speed, the type of vehicle, and the road surface properties. For example, the contribution of the aerodynamic resistance increase with higher speeds and the contribution of rolling resistance is larger on soft road surfaces than hard road surfaces (Michelin, 2003).

Rolling resistance in car traffic represents a large share of the total energy usage and greenhouse emissions in Europe. In 2011, 24% of Europe's total energy consumption was spent on transport, and 83% of that, was consumed by road vehicles. On average, rolling resistance accounts for 25% of a passenger car's mechanical energy output (Haider et al., 2011). When it comes to bicycling, research has found a dependency between increased cycling comfort and decreased rolling resistance (Hölzel et al., 2012). Moreover, the interest in electrified bicycles (e-bikes) over the last years

(Fishman & Cherry, 2016; Fyhri & Fearnley, 2015) indicates that more people are positive towards using a bicycle as a means of transportation when it is less physically demanding.

In cold regions, such as in Norway, snow and ice cover the roads for several months each year. As a response, winter maintenance actions are carried out to maintain high-quality road conditions. Still, in Norway, the bicycle transportation share drops drastically in the winter compared to the summer (Vågane et al., 2011). Snow and ice on the roads may increase the rolling resistance significantly (Blaisdell, 1981; Lidström, 1979; Shoop, 2001; van Es, 1999). The rolling resistance due to the deformation of soft ground, such as snow or slush, can be 10 to 100 times higher than the resistive force due to tire deformation (Michelin, 2003). Snow and ice can also lead to ruts and irregularities on the road surface, leading to even higher rolling resistance and making cycling less safe and uncomfortable (Descornet, 1990). In addition to other factors, inclement road conditions have been pointed out as barriers to winter cycling (Nahal & Mitra, 2018; Spencer et al., 2013b). Hence, the observed drop in cycling share during winter may be due to snow and ice and, consequently, increased rolling resistance values.

2.3.1 Definition

The rolling resistance of a pneumatic wheel occur because of non-elastic deformations in the tire and/or in the road surface. The load on a pneumatic wheel causes the tire to deform over the road surface, making a flat contact patch. The vertical force distribution in the contact patch for a non-rotating wheel with a pneumatic tire is symmetric, with the resultant force (F_Z) pointing towards the center of the wheel. If the wheel starts rolling, the tire deforms asymmetrically on the road surface. The tire is "squeezed" in front of the wheel, leading to an asymmetric distribution of the vertical force and a forward shift (e) of the resultant vertical force. Figure 2 shows a schematic of the forces acting on a rolling, pneumatic tire. The shift of the resultant vertical force increases drastically if the road surface also deforms (Michelin, 2003). The shift of the resultant vertical force results in a torque that opposes the motion of the wheel called rolling resistance torque (T_R), which can be presented as:

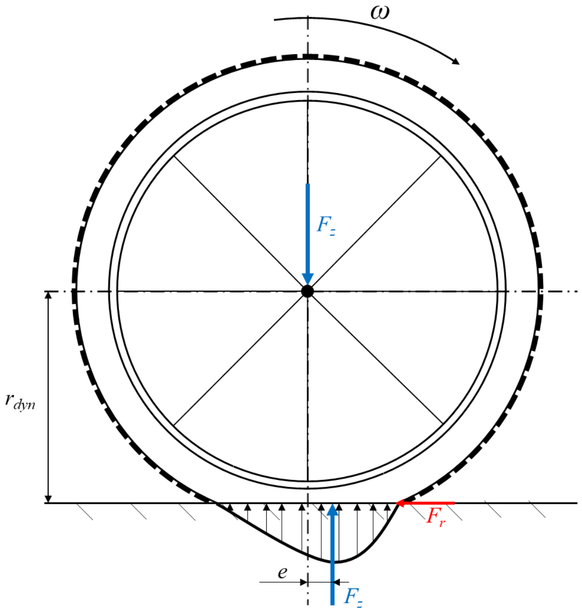


Figure 2: A rolling wheel with a pneumatic tire. Asymmetric load distribution in the contact patch leads to rolling resistance.

$$T_R = F_z \cdot e$$

The rolling resistance force (F_r) is the force needed to keep a wheel going at a constant speed on a flat surface despite the rolling resistance torque. On a flat surface, F_r depends on the deformed radius of the wheel (r_{dyn}) and can be obtained from:

$$F_r = \frac{F_z \cdot e}{r_{dyn}}$$

The shift of the resultant vertical force, which leads to increased rolling resistance force, results from mechanical energy converted into heat in the interaction between the tire and the road surface. Schuring (1980) defined rolling resistance as "*mechanical energy converted to heat*". Gent et al. (2006) agreed with Schuring and pointed out that heat is generated because of mechanical hysteresis, i.e., deformation of the tire material. Heat is also generated from the friction between the tire and the road and between the tire and the rim. Aerodynamic drag between the tire and surrounding air also leads to heat generation due to the dissipative action of the air's viscosity *(Gent & Walter, 2006).*

In ISO and SAE test standards, rolling resistance is defined as the energy loss per distance traveled (ISO28580, 2018; Wen et al., 2014). Rolling resistance can therefore be expressed as an energy with the unit newton-meters (Nm) per distance in meters (m), which is equivalent to a force expressed in newtons (N). For bicycles or e-bikes, a forward pedal or motor thrust is usually expressed as a power in watts (W). Rolling resistance for bicycles or e-bikes is therefore often expressed as energy in newton-meters (Nm) per time in seconds (s), which is equivalent to a power in watts (W), which is the power needed to overcome the rolling resistance.

Studies have found a nearly linear relationship between rolling resistance and wheel load due to increased bending and shearing of the tire. Since wheel load is not always constant, a dimensionless coefficient, RRC or C_{rr}, has been defined to represent the rolling resistance characteristics between a wheel and a road surface:

$$C_{rr} = \frac{F_r}{F_z}$$

C_{rr} is a relative measure, and it can be used to compare rolling resistance characteristics of tires or road surfaces. Typical C_{rr} values for passenger car tires are in the range between 0.085 to 0.13. Special tires for electric vehicles can reach C_{rr} values as low as 0.06. Heavy truck tires have C_{rr} values between 0.045 to 0.1. C_{rr} values for bicycle road tires are usually between 0.025 and 0.05 (Michelin, 2003).

2.3.2 Energy loss mechanisms

Several mechanisms contribute to the total rolling resistance on a pneumatic wheel. Energy loss in the tire material, non-elastic deformations in the tire construction, friction between the tire and the rim and between the tire and the road, and aerodynamic drag between the tire and the surrounding air contribute to the rolling resistance.

Pneumatic tires are made from viscoelastic rubbers, meaning that the material behaves both as an elastic solid and as a viscous fluid. When a viscoelastic material is deformed by loading and unloading it, some of the mechanical energy put into deforming the material is converted into heat. This energy conversion occurs due to the unique molecular structure of viscoelastic materials and is called hysteresis. The rubber compound, tire construction, and tire operation affect the hysteresis property of the tires.

Due to hysteresis, all deformations of the tire material lead to loss of mechanical energy and, hence rolling resistance. The most significant hysteric deformations are the bending of tire treads in the contact patch's leading and trailing edges (Sandberg et al., 2011). Compression of the treads under the contact patch also contributes to relatively high mechanical energy loss. When the vehicle is driving or turning, the contact patch's tire treads will experience horizontal and lateral deflections. These deflections are caused by the stick-slip friction between the tire and the road. This friction may lead to particles of the tire or road being worn off and thus energy loss due to the breaking of molecular bonds. The friction between the tire and the road may also lead to vibrations in the tire treads, leading to more deformations and loss of energy.

In addition to energy loss in the tire material, there will also be a loss of mechanical energy due to the deformation of the tire construction. The most prominent is the deformation of the tire sidewall due to wheel load.

Tire inflation pressure

In addition to the wheel load, the tire material and construction and the tire inflation pressure determine the deflection of the sidewalls and the size of the contact area. On a hard road surface, a high tire inflation pressure, less tire deflections, and a smaller contact area lead to lower rolling resistance. On softer road surfaces, higher inflation pressure results in increased ground penetration and, therefore, higher rolling resistance. The rolling resistance due to the deformation of soft ground can be as much as 10 to 100 times higher than the resistive force due to tire deformation (Michelin, 2003). Therefore, the optimum tire inflation pressure depends on the tire properties and the road surface deformation characteristics. On some medium deformable surfaces, such as dirt, the effect of inflation pressure on tire deformations and ground deformations approximately balance, and the rolling resistance remain nearly independent of inflation pressure (Gillespie, 1992).

Temperature

The heat generated from hysteresis and friction will naturally increase the temperature of the tire. The tire's mechanical properties are highly temperature-dependent, and an increased tire temperature leads to significantly lower rolling resistance (Descornet, 1990; Gillespie, 1992). The dependency between rolling resistance and temperature is not linear; however, between 10°C and 40°C, a 1°C increase results in approximately a 0.6% reduction in rolling resistance under regular road operation (Gent & Walter, 2006). Although the relationship between wheel load and rolling resistance is nearly linear, increased wheel load also causes the tire temperature to rise. Therefore, the C_{rr} is often found to decrease somewhat with increasing wheel load.

Velocity

Increased velocity leads to an increase in vibrations and flexing work in the tire body. The effect of this is an increase in energy loss from tire deformations and consequently higher rolling resistance. Higher velocities also increase the rolling resistance due to air drag around the tire. At very high velocities, centrifugal forces lead to increased deformations and energy loss in the tire's upper region opposite to the ground. However, higher velocities also increase the tire temperature, which reduces the rolling resistance. The combined effect of increased velocity is usually increased rolling resistance (Gent & Walter, 2006).

Road surface irregularity

Road surface irregularities influence the deformations and vibrations of the tire and, therefore also the rolling resistance. Investigations by Descornet (1990) suggest a dependency between rolling resistance and roughness levels. The highest rolling resistance was found on irregularities whose wavelength matches half the tire footprint length. For passenger car and bicycle tires, this corresponds to irregularities with a wavelength between 50 to 100 mm and 50 to 70 mm, respectively. Mean profile depth (MPD) and texture depth (TD) are standard measures of surface roughness. International roughness index (IRI) is a more modern measure of surface roughness. A study by Ejsmont et al. (2017) suggested that tire tread enveloping, or how the tire tread wraps around the asperities of the irregularities has a considerable influence on rolling resistance. The enveloping is primarily dependent on the shape of the peaks of the asperities and not so much on the profile depth. On dry surfaces with sharp and aggressive summits and edges, the rolling resistance is much higher than on surfaces with more round asperities, even if the MPD is similar on the two surfaces.

Wet conditions

The presence of surface water shifts the resultant load under the wheel further forwards and leads to increased rolling resistance. The tire must displace the water to gain traction on the pavement surface. The increase in rolling resistance depends on the amount of displaced water which again depends on the water depth, the tire geometry, and the vehicle speed (Carlson & Vieira, 2018). The amount of water on the roads is primarily determined by the road texture, crossfall, and drainage properties. Water also acts as a cooling agent and lowers the tires' temperature, leading to even higher rolling resistance.

Gengenbach (1967) discovered an exponential relationship between rolling resistance and velocity on wet roads:

$$F_w = b * \frac{9{,}807}{100}\left(\frac{v}{N}\right)^E$$

Where F_w is the rolling resistance force [N], b is the tire width [cm], v is the velocity [km/h], and N and E are constants for each water depth (Carlson & Vieira, 2018). A similar relationship between rolling resistance and velocity was later discovered by Olsson (1984).

Winter conditions

In cold regions, snow and ice often cover the roads during winter. The effect of snow on rolling resistance depends on the snow depth and its mechanical properties in addition to the speed of the vehicle (Lidström, 1979). The most important properties affecting snow's mechanical properties are grain size and formation, density, temperature, and liquid water content (Pytka, 2010).

Snow is a constantly changing material, and it is affected by wind, temperature, rain, time, and humidity. It is therefore challenging to determine the mechanical properties of snow at a given time. Hence, models for predicting rolling resistance are often based on parameters that are easier to measure, such as snow depth and density (Shoop, 2001).

When a pneumatic tire drives on a snow-covered road, the snow is either compressed under the tire or plowed to the sides, depending on the snow's liquid water content.

Harrison (1981) characterized snow with a high liquid content and a density over 750 kg/m^3 as slush that would be plowed to the sides instead of being compressed under the tire. How the snow behaves if it is compressed under the tire depends on its bearing capacity, which is a measure of how much the snow must be compressed to reach the strength needed to carry the weight of the vehicle compressing it (H. Shapiro et al., 1997). Usually, on commercial roads, the snow depth is classified as "shallow", which means that the pressure bulb under the compressed snow intersects a rigid underground (Pytka, 2010).

Lidström (1979) found a dependency between snow strength and snow density and the ratio between void and ice in the snow, i.e., the void ratio. This relationship was used to predict the work needed for a rolling tire to compress snow of a given depth and strength. Lidström based his theory on a uniform deformation of the snow. Richmond (1995), however, made a contrary discovery. He made narrow holes in the snow perpendicular and in the direction of vehicle travel and filled them with chalk dust. After a tire had rolled over the holes and compressed the snow, the chalk dust showed how the snow had compressed under the tire. The result was that the snow had deformed in three directions: vertical, lateral, and in the direction of vehicle travel. Later, van Es (1999) made further work on Lidströms model. Their rolling resistance models both build on the work needed to compress shallow new snow under the tire.

Due to the constant changing of the snow properties, no model has yet proved to estimate the rolling resistance in snow with more than 25% accuracy (H. Shapiro et al., 1997). However, there is a common understanding that the presence of snow increases the rolling resistance on roads. Most rolling resistance measurements in snow were performed in the 1970s and 1980s with aircraft and terrain vehicles. Since then, measurement methods have been improved, and the tires have better performance in snow. Also, all investigations of rolling resistance in snow have been restricted to unprocessed, dry snow. However, on winter roads, the snow is usually processed somehow, for example, compressed or made uneven by traffic, partly melted and re-frozen, mixed with dirt or salt, or a combination of these. Thus, further investigations are needed to understand better the rolling resistance aspect of the interaction between tires and snow on roads.

2.3.3 Rolling resistance measurement methods for cars and trucks

Traditionally, methods for measuring rolling resistance for cars and trucks have been divided into four categories: drum method, trailer method, coast-down method, and fuel consumption method (Sandberg et al., 2011).

Drum test

The laboratory drum method is a test for isolated measurements of tire rolling resistance. Rolling resistance testing of tires in a drum test is performed by holding a tire against a drum run by a motor. The braking effect applied by the tire is calculated from measurements of the forces acting on the drum (Gent & Walter, 2006). SAE and ISO have prescribed tire rolling resistance test standards for this procedure (ISO28580, 2018; Wen et al., 2014). The advantage of the drum test is that it isolates the measurement from various variables that may influence a tire's rolling resistance. The drum curvature makes the rolling resistance higher than it would have been on a flat surface. Clark (1976) and Luchini (1982) developed a formula to eliminate the curvature effect on the rolling resistance. This formula was recognized and used in SAE and ISO standards for many years before experiments by Freudenmann et al. (2009) led to an improved correction formula.

Trailer method

Another rolling resistance measurement method, the trailer method, measures the rolling resistance on one or more test wheels towed in a trailer. The trailer method is an outdoor test that can measure rolling resistance on tires if used on a standardized road surface or measure rolling resistance on different road surfaces if used with a standardized test tire. The method is well suited for rolling resistance measurements on all kinds of road surfaces, even those contaminated with water or snow. The first test trailer was developed by the Belgian Road Research Centre (BRRC) in the 1980s and later upgraded. Similar trailers have later been developed at the University of Gdansk (TUG), the Federal Highway Research Institute of Germany (BASt), and at Helsinki University of Technology (HUT). These trailers have some differences in design, but they all use the same measurement principle. The center of the wheel is mounted on a freely swinging vertical arm connected to the trailer's frame. A ballast of desired weight is mounted on the main trailer beam with a spring and shock absorber. The rolling resistance force produces momentum that pushes the vertical arm backward. The size of the rolling resistance force is estimated based on the change of the angle (θ) between the vertical arm and the trailer beam. The trailer developed by TUG has a patented counterbalance system to compensate for the acceleration and longitudinal slope of the road surface. The deflection of the vertical arm influences the angle of the main trailer beam. The TUG trailer compensates for this by measuring the trailer beam's angle relative to the road surface (Ronowski, 2016).

Coast-down method

A third rolling resistance method, the coast-down method, includes all contributions to driving resistance except engine and transmission losses. A vehicle is accelerated up to the desired speed, and then the deceleration is measured as the vehicle coasts in neutral gear or with the clutch down (Sandberg et al., 2011). The rolling resistance is not measured directly but can be estimated if parameters like wind, slope, and drag coefficient are determined. The velocity and distance are usually measured at a high frequency for accurate results.

Fuel consumption measurements

In addition to the mentioned rolling resistance methods, fuel consumption is a very general way of estimating rolling resistance. Tire rolling resistance affects fuel consumption, but many other factors also influence a vehicle's driving resistance (Jonsson, 2007). Therefore, it is difficult to pinpoint the rolling resistance contribution to fuel consumption.

2.3.4 Rolling resistance measurement methods for bicycles

Coast-down method

The coast-down method has also been used to measure rolling resistance for bicycles. A French study from 1999 measured the rolling resistance for bicycles in a level hallway, using the coast-down method. This study found a dependency between rolling resistance and inflation pressure, and wheel load (Grappe et al., 1999). Coast-down rolling resistance testing for bicycles was also later tested outside. However, wind, grade, and riding surface led to inconsistent measurement precision (Tengattini & Bigazzi, 2018).

Force equilibrium method

Meyer et al. (2016) investigated a new method for estimation of rolling resistance during cycling. They measured the power output at the pedals of a four-wheeled electric bicycle and estimated the rolling resistance by solving the power equilibrium on the bicycle:

$$P_{res} = \left(F_{slope} + F_{air} + F_{roll}\right) * v$$

Where P_{res} is the total power from cycling resistance and F_{slope}, F_{air} and F_{roll} are the resistive forces from the slope, air, and rolling resistance, respectively. Resistance from acceleration was neglected because the testing was performed at constant velocity. The slope factor was also neglected because the tests were run in both directions on the test stretch, hence eliminating the effect of the slope. The air resistance was estimated using the velocity, and any headwind was neglected as testing was performed at times with no wind. A smartphone recorded the vibrations on the handlebar. Results from tests showed a significant increase in rolling resistance from asphalt to fine gravel to coarse gravel. The results also showed a dependency between increased vibration amplitude at the handlebars and increased rolling resistance.

Power meter measurements

Estimating rolling resistance and aerodynamic resistance using a cycle-mounted power meter has also been performed earlier (Lim et al., 2011). This study concluded that "commercially available power meters are sensitive enough to independently detect the changes in aerodynamic and rolling resistances associated with modest changes in body position and substantial changes in tire pressure".

Eccentrically weighted oscillating wheel

Hill (1990) explored a rolling resistance measurement method with an eccentrically weighted oscillating wheel. The rolling resistance was calculated through the loss of energy when the tire oscillated backward and forward on a level surface. This method could measure small changes in rolling resistance between different types of bicycle racing tires.

Two-drum dynamometer

Kwarciak et al. (2009) tested the rolling resistance properties of different wheelchair tires with a two-drum dynamometer. Lower rolling resistance was found on pneumatic tires compared to solid tires. Increased inflation pressure and lower profile tread also lead to lower rolling resistance.

Handlebar push technique

Measurements of wheelchair rolling resistance on different floor surfaces have also been performed with a handlebar push technique (van der Woude et al., 2003).

2.3.5 Rolling resistance discussion

Rolling resistance is a complex phenomenon, which is affected by temperature and several aspects of the wheel, vehicle, and surface properties. On bare asphalt roads, the vehicle's mass and tire properties have the most effect on rolling resistance. Cars and trucks are heavy vehicles with wide tires, which experience large deformations. Energy loss in the form of hysteresis of the tire materials is therefore the dominant contributor to rolling resistance. Compared to cars and trucks, bicycles are light vehicles with narrow wheels. Bicycles have less vehicle mass and less tire material to deform, and hence, they are likely to experience less energy loss from visco-elastic hysteresis.

During winter, with snow- and ice-covered roads, a significant increase in rolling resistance is expected for both cars and bicycles. This increase happens partly due to energy loss from snow and ice deformation, partly from increased tire deformations from road surface irregularities, and because cold temperatures increase the energy loss from tire material hysteresis. While people use their cars as much or more in the winter than they do in the summer, many people are reluctant to use their bicycles in the winter. One reason may be that cycleways offer poor cycling conditions with high rolling resistances because winter maintenance operations are prioritized for the regular roads. Cyclists are also powering their bicycles with their bodies (partially in the case of an e-bike). A sudden increase, even marginally, in rolling resistance would be felt to a much larger degree than what a higher fuel consumption would for a driver of a car.

Bicycles are often equipped with narrow tires with high inflation pressure, which would increase the likelihood of snow and ice penetration. Lowering the inflation pressure or increasing the tire width, would increase the size of the contact patch and hence lower the pressure between the road surface and the tire. This would decrease the chances of deforming weak and semi-compact snow and ice and hence provide lower rolling resistance on these surfaces. However, it could also increase the rolling resistance on bare asphalt or compact snow or ice due to increased tire deformations.

Over the past eight years, an emergence of "fat bikes" (bicycles with 75-120 mm-wide tires) has been observed in the USA and other countries (Monz & Kulmatiski, 2016). Fat bikes have received increased popularity in winter conditions, probably due to their ability to roll over, rather than penetrating, soft surfaces.

Precise and reliable quantitative measurements of rolling resistance can help increase our knowledge about how rolling resistance is affected by different surface or vehicle parameters. Laboratory tests are valuable for comparisons of tire properties or possibly also slight changes in surface characteristics. However, to measure actual winter conditions, the method must be able to perform full-scale field testing. The trailer method and the coast-down method are potent methods in detecting differences in rolling resistance on different road surfaces. The trailer method isolates the effect of rolling resistance. However, the trailer must be heavy to generate realistic deflection on the test tire or equipped with much smaller tires than what is used on regular bicycles. The coast-down method does not isolate the rolling resistance but measures all resistive forces acting on the coasting vehicle. The method is simple and can be used with a regular vehicle. For flexible measurements of bicycle rolling resistance, the method introduced by Meyer et al. (2016) seems promising. This method estimates rolling resistance by measuring the bicycle propulsion power and comparing it to the resistive forces on the bicycle. In the study from 2016, the effect from wind, acceleration, and hill slope was eliminated and neglected. The elimination of these parameters led to limitations of the test method in terms of allowable wind conditions, velocity and that the test had to be performed both ways to eliminate the effect of the slope. By adding precise and reliable measurements of air speed, acceleration, and hill slope, the method by Meyer et al. (2016) would be able to measure rolling resistance regardless of wind conditions, hill slope, and change in velocity.

2.4 WINTER MAINTENANCE OF CYCLEWAYS

In Norway, winter maintenance of roads is performed using one out of three main strategies: bare road strategy, winter road strategy, or closed road strategy. The chosen strategy depends on the type of road, traffic amount, and local climate. The goal of a bare road strategy is always to keep the road surface free from snow and ice to ensure safe and efficient transportation. A bare road strategy usually allows the use of anti-icing chemicals to facilitate the mechanical removal of snow or prevent moisture from freezing on the road surface. The bare road strategy is mainly used on highways or other main roads or low-volume roads when the temperature fluctuates a lot around the freezing point. Furthermore, the goal of a winter road strategy is to offer an even road surface with sufficient skid resistance (friction) without using anti-icing chemicals. This strategy is often used on low-volume roads in periods with stable, cold winter weather. An even, compact snow layer can offer adequate driving conditions. However, depending on the temperature and amount of traffic, the snow layer can turn into a slippery layer of ice. Gritting or sanding is then needed to maintain a sufficient friction level. Anti-icing chemicals can be used as a last resort to remove unwanted ice and ruts. Finally, roads with a closed road winter maintenance strategy are closed during the winter. This is typical for roads going over mountain passes with harsh winter weather that usually get large amounts of snow, which also has alternative routes that are easier to maintain during the winter. Substantial efforts are often needed to re-open winter closed roads after the winter season.

NPRA specifies two standards for winter maintenance of pedestrian and bicycle areas: GsA and GsB. GsA is a bare road standard that allows the use of anti-icing chemicals. GsB is a winter road standard comprised of strict performance requirements concerning minimum friction level, loose snow depth, unevenness, and crossfall, which generally does not allow the use of anti-icing chemicals (NPRA, 2014). While GsA and GsB are usually assigned to high-priority cycleways, winter maintenance is constricted by the local municipality's guidelines on other less prioritized cycleways. For example, Trondheim municipality's guidelines for winter maintenance on cycleways specify the maximum amount of loose snow depth allowed before maintenance actions are taken and general instructions for sanding and using anti-icing chemicals (Trondheim Municipality, 2020). This municipal standard (MUN) does not have performance requirements and is a significantly "cheaper" standard than the GsB. In practice, this means that more snow may be present before an area is cleared.

Cycleways have only recently been maintained with a bare road winter maintenance strategy. Bare roads can often be obtained on roads with car traffic only by chemical treatment and snow plowing because the cars contribute to the snow removal just by driving there. Bicycles, however, do not contribute as much to the snow removal, and greater winter maintenance efforts are needed to obtain bare road surfaces. This is why more cycleways are now maintained using both snowplows, anti-icing chemicals, and snow brushes (Bergström, 2003).

3 RESEARCH METHODS

3.1 ROLLING RESISTANCE MEASUREMENT SETUP

A literature review of previously developed rolling resistance measurement methods was performed to answer the first research question: "Can rolling resistance on cycleways under winter conditions be quantified sufficiently accurate?". Rolling resistance has previously been determined outside of a laboratory using different approaches: an eccentrically weighted, oscillating pair of wheels (Hill, 1990), a handle push-bar technique (van der Woude et al., 2003), and a towed trailer method (Ronowski, 2016). Rolling resistance has also been determined with a vehicle by performing coast-down testing (Grappe et al., 1999; Sandberg et al., 2011; Tengattini & Bigazzi, 2018). In addition, rolling resistance has been estimated by measuring fuel consumption for trucks or cars or equivalently pedaling power for bicycles (Jonsson, 2007; Lim et al., 2011). Moreover, by utilizing multiple sensors to measure propulsive and resistive forces, the rolling resistance has been determined from the force equilibrium on a moving vehicle (Meyer et al., 2016).

In this project, the goal was to use rolling resistance measurements as a tool to describe the surface quality of cycleways during wintertime. It was assumed that the rolling resistance level correlated with people's perceived cycling comfort. To choose the most appropriate rolling resistance measurement concept for this purpose, six absolute requirements were determined:

1. The method must be small and light enough to be used safely on cycleways.
2. To evaluate cycleway stretches, the concept must have the ability to cover at least 100 meters.
3. The method must achieve accurate measurements on all sorts of cycleways, uphills or downhills, and in any type of weather, including snow, rain, and wind.
4. The concept must be accurate enough to significantly differentiate the rolling resistance levels on typical winter cycling conditions.

In addition to the absolute requirements, two desirable requirements were determined:

5. The rolling resistance measurement system should provide measurements of a magnitude equal to that encountered by actual cyclists.
6. The concept should be simple and easy to use to leave the opportunity open to use it as an operational winter maintenance tool in the future.

Considering the absolute requirements, the towed trailer method and the force equilibrium method stood out as appropriate measurement concepts. The towed trailer method had the advantage of offering a simple concept and potentially providing accurate measurements. However, it would need to be heavy to generate realistic tire deflection or be equipped with tires smaller than what is used on regular bicycles. The force equilibrium method had an advantage if used on a bicycle of providing rolling resistance values equal to that experienced by actual cyclists. Because the method is installed on a standard bicycle, it would also be flexible and usable for daily commutes. However, the downside of the force equilibrium method was that there was no proof that the method could give sufficiently accurate results on conditions that were not flat or when wind was present. Extensive development work would be required for the method to provide accurate measurements. After considering these factors, it was decided to develop a rolling resistance measurement device by utilizing the force equilibrium method on an instrumented bicycle.

Figure 3 illustrates the forces affecting the movement of a bicycle. In a force equilibrium, the propulsive and resistive forces are equal. Therefore, one can calculate rolling resistance force by measuring all the other forces acting on the moving bicycle.

For this project, measurements were not recorded during braking, and the forces from internal friction were assumed negligible. Therefore, the method needed sensors to measure the air drag (F_a), acceleration resistance (F_i), the component of the gravity force acting against the movement of the bicycle (F_g), and the bicycle propulsion (F_p).

A standard commuter bicycle (Breezer Radar Café) was the basis of the force equilibrium rolling resistance measurement method. The bicycle was equipped with a combined inclination and wind speed sensor (Aeropod), a GPS tracking device (Garmin Edge 130), and a pedaling power meter (Powertap G3). All sensors were commercially available "off the shelf", for a rapid prototyping process. It was assumed that continuous readings from these sensors while cycling would provide the information needed to estimate the rolling resistance accurately at any time. Figure 4 shows the instrumented bicycle and the measurement sensors. The readings from each sensor were combined in a Python script where the rolling resistance coefficient was calculated. Paper I provide a detailed description of the calculations. To get an idea about the potential of the method, a simple test was performed. The method was tested on a closed parking lot with four different tire inflation pressures. The results from the simple test showed that lower tire inflation pressures led to higher rolling resistances, as predicted from the rolling resistance theory.

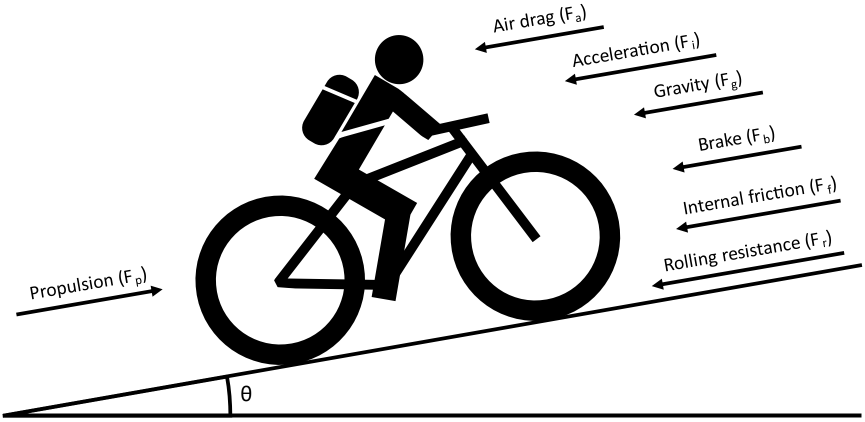


Figure 3: Schematic of the forces acting on a moving bicycle.

The next step was to calibrate the sensors to improve the measurement precision. A study of ten Powertap G3 hub power meters used by cyclists determined a mean pedaling power measurement accuracy of 0.9 ± 2.1% (Maier et al., 2017). In addition, the power meter was delivered with an integrated zero-offset procedure. This procedure was performed before each test ride to avoid sensor drifting or temperature effects. No further calibration of the power meter was deemed necessary. The combined inclination and windspeed sensor needed manual calibration as the mounting angle could affect the measurements. Therefore, the instrumented bicycle was brought to the wind tunnel at the aerodynamic laboratory at NTNU, where the wind speed sensor was calibrated. The air drag resistance was also determined in the wind tunnel. By accurately measuring the

Figure 4: The instrumented bicycle (C), with air speed and slope sensor (A), pedaling power sensor (B), and GPS device (D).

bicycle's and test cyclist's frontal area (A), the coefficient of air drag (C_d) was also determined. Out of curiosity and if the sensor needed to be calibrated later without an available aerodynamic laboratory, an outdoor calibration using the power meter was also performed. The outdoor windspeed sensor calibration was performed by investigating the increase in pedaling power for increasing cycling velocities. The calibration was performed on a level asphalt road stretch in no-wind conditions. The results from the wind tunnel testing and the outdoor calibration testing were the same. This showed that the method does not depend on a wind tunnel to be sufficiently calibrated. The inclination sensor was calibrated by cycling up a hill of known inclination. The GPS device was not calibrated, as its precision naturally varies depending on satellite reception.

After calibrating the sensors, the accuracy, and precision of the method needed to be verified. For this purpose, it was desired to test the method on a surface with a known rolling resistance. The first suggested solution was to compare the method measurements with a controlled coast-down test. A controlled coast-down test depends on a level surface and no wind. These conditions are most likely to be found indoors, but no suitable location for indoors coast-down testing was available. Cycling over a material (for example, a foam) with a known rolling resistance was also considered. However, it was soon determined that calculating the rolling resistance of a surface material based on the material properties would be too time-consuming. Finally, the method's accuracy was decided to be tested by performing rolling resistance measurements with and without a known added resistance. To add a known resistance to bicycle, a dynamo system was developed. The dynamo could deliver two levels of bicycle resistance. Figure 5 shows the dynamo system mounted to the instrumented bicycle. To evaluate the measurement accuracy, it was tested whether the method measured the correct amount of added dynamo resistance while operating in varying winds, slopes, and speeds. The dynamo verification testing showed that the instrumented bicycle was able to measure bicycle rolling resistance (C_{rr}) with a mean accuracy of 97.6% and a precision represented as the standard error of the mean, between ±0.005 (1 Hz, n = 9) and ±0.001 (1 Hz, n = 220).

Figure 5: The rolling resistance measurement bicycle equipped with a dynamo system used to verify the measurement accuracy.

3.2 CLASSIFYING BICYCLE WINTER CONDITIONS

To answer the second research question: "What is the rolling resistance level on typical winter conditions?", a framework for classifying winter conditions was needed. As mentioned in section 0, the effect of snow on rolling resistance depends on the snow depth and its mechanical properties (grain size and formation, density, temperature, and liquid water content) in addition to the speed of the vehicle. Measurements of the snow parameters require manual work and are pretty time-consuming, especially considering that, on a cycleway, these parameters often change within few meters. Trying to distinguish the effect of change in one of them seems more suitable inside a laboratory than in the field. Instead of performing detailed snow parameters measurements, a more pragmatic approach was chosen to describe the winter conditions in this study. Video of the road conditions was recorded while measuring the rolling resistance along the cycleways with the instrumented bicycle. Immediately after each test ride, the video recordings were visually analyzed, and the conditions were classified based on the video footage. The conditions were given a description based on snow type and loose snow depth. The road conditions were then classified based on loose snow depth and snow type. The loose snow depth was divided into four categories: no snow, less than 2 cm, between 2 and 5 cm, and more than 5 cm of snow. These snow depth classes were partly chosen because they are possible to differentiate visually. Another reason was that 2 cm is the maximum allowed loose snow depth on cycleways maintained with a GsB standard. More than 5 cm of loose snow was considered rare. Furthermore, it was assumed that few people would even try to cycle on cycleways with 5 cm or more of loose snow. The snow types were differentiated into ice, compact snow, loose snow, and slush. Table 2 in paper 2 shows an overview of the different winter conditions described in the study.

Air temperature and precipitation type, and amount before and during the test rides were also documented. In addition to being time-efficient, a visual description of the conditions was considered a good approach because the research project's goal was to improve winter maintenance. Winter maintenance is often performed based on how the conditions look visually. Winter maintenance personnel do not have time or resources to measure snow density and analyze the snow grain type and size.

In addition to snow depth and snow type, the conditions were classified based on perceived unevenness, steerability, and cycling comfort. One test cyclist performed all the test rides and evaluated the comfort parameters. Unevenness, steerability, and cycling comfort were given a score between 1 and 5, where 5 was very good, and 1 was very poor cycling conditions. Table 3 in paper II provides a detailed description of the evaluation of these parameters. The unevenness was evaluated based on the test cyclist's perceived discomfort due to vertical accelerations or bumpiness. Bumpy cycleways are often caused by soft, wet, and then refrozen tracked snow or ice. The steerability was evaluated based on how difficult it was for the cyclist to steer the bicycle in the desired direction. Poor steerability is often caused by soft, loose snow but also uneven or slippery surfaces. Finally, the cycling comfort was evaluated based on the cyclist's overall cycling comfort. It was a combination of perceived unevenness and steerability, but it could also be affected by reduced cycling efficiency due to poor cycling conditions. Other quantifiable parameters, like wheel shimmy, vibrations, and angular displacement (accelerometer), were also considered. However, these parameters would have needed individual measurement setups, which would have been a study on its own.

3.3 MEASUREMENTS OF BICYCLE ROLLING RESISTANCE ON WINTER CONDITIONS

After developing a reliable rolling resistance measurement method and a framework for classifying bicycle winter conditions, it was time to investigate how the winter conditions affect the rolling resistance level. It was desirable to measure rolling resistance on all sorts of winter conditions, including wet asphalt, compact snow, slush, uneven ice, deep loose snow, and snow contaminated by salt and dirt. It was also a desire to measure bicycle rolling resistance on cycleways with different maintenance standards.

The chosen test route started at the Department of Civil and Environmental Engineering at NTNU. It followed some stretches with the highest winter maintenance standard (GsA), some stretches maintained after GsB standard, and some stretches maintained after municipal guidelines. The test route followed some roads with mixed traffic, some with separate bicycle lanes, some separate pedestrian/cycleways. The route was 21 km long and had a total elevation gain/loss of 194 meters. Figure 6 shows the path and the different winter maintenance standards of the test route.

To collect rolling resistance measurements on a large variety of winter conditions, test cycling was scheduled according to weather events.

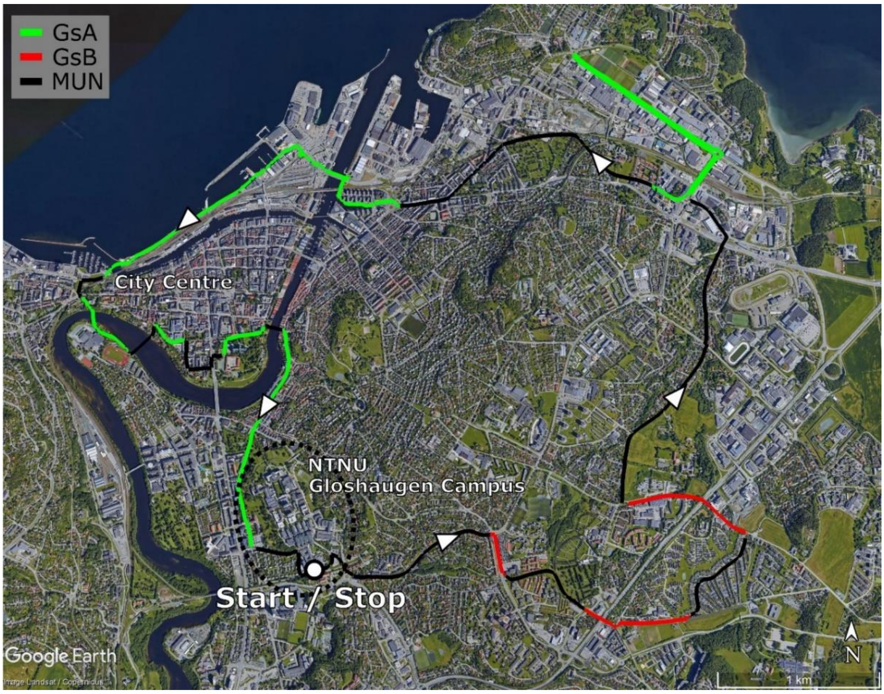


Figure 6: Satellite photo indicating the path and the winter maintenance standards for the rolling resistance test route.

3.4 VIDEO ANALYSES

The video recording of each test ride was analyzed immediately after it was performed. The videos were recorded using a steering bar-mounted smartphone. Based on visual analyses of the video recordings, the test ride was separated into sections with reasonably continuous conditions. The stretches were between 80 and 1520 meters long. Each stretch received a surface condition type, a loose snow depth grade, and a score of perceived unevenness, steerability, and cycling comfort. A Python script was used to merge rolling resistance measurement data and surface condition data and split the data into individual road stretches.

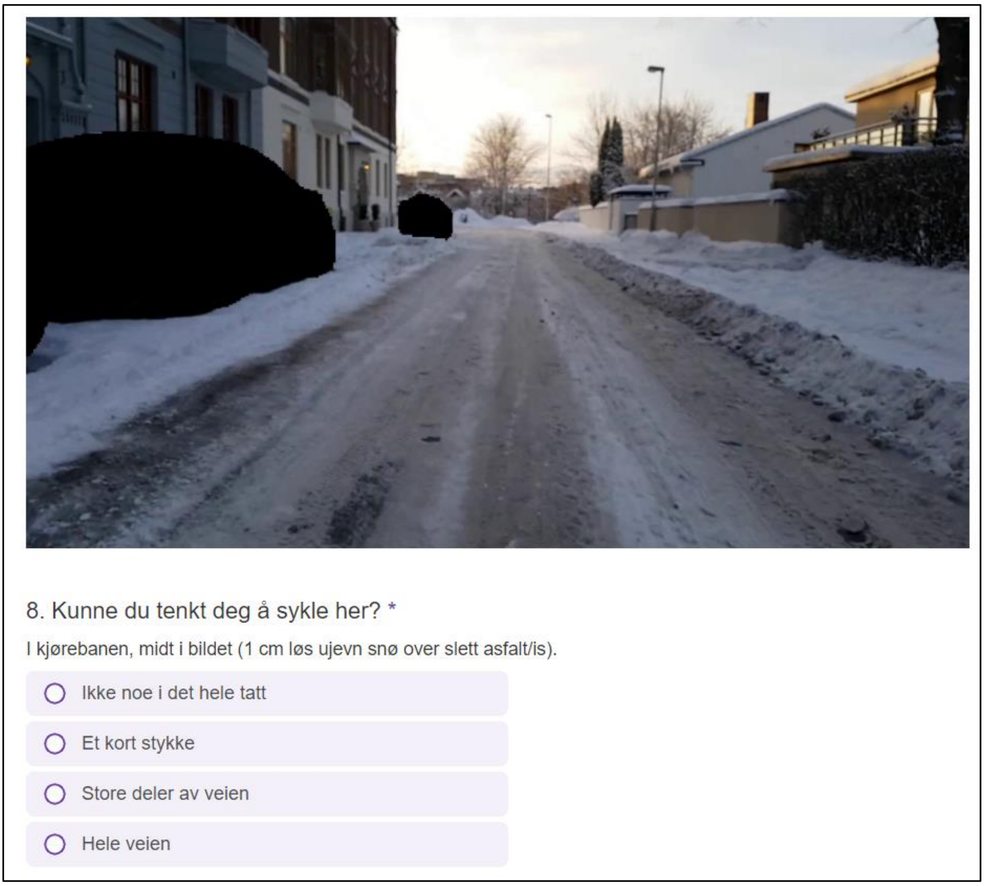
3.5 STATED PREFERENCES SURVEY

To answer the third research question: "How does the rolling resistance level affect winter cycling?", there was a need to involve actual cyclists. An early idea was to gather a sample of cyclists of different ages and cycling experience, ask them to cycle over test stretches with different, prepared winter conditions, offering a variety of rolling resistances. This study would provide a chance to analyze the correlation between cyclists' stated cycling comfort, cycling speed, and the rolling resistance level. However, collecting a large enough sample of cyclists and preparing different winter cycling conditions at the same time would have been a great challenge. Another approach was also suggested to indirectly analyze the effect of rolling resistance level on winter cycling. The idea was to define a short test track somewhere outside on campus or in the town square and ask random people to do a test ride. For each test ride, a dynamo would induce a resistance corresponding to a rolling resistance coefficient between 0.01 and 0.05. The participants would have to fill out an evaluation form following the test rides. A variety of this approach, which was also considered, was to have the participants cycling on a fixed bicycle roller and state their perceived comfort level on different levels of added rolling resistance. Data from either approach would provide data on the correlation between the rolling resistance level and cycling comfort. These data could, in time, be compared to the rolling resistance measurements on actual winter conditions, which had previously been performed. This comparison would connect people's perceived cycling comfort through the rolling resistance level to actual winter cycling conditions. With this connection, it would be possible to indicate how the rolling resistance level affects winter cycling.

During the process of choosing the best approach to analyze the correlation between rolling resistance and winter cycling, the Covid-19 pandemic introduced itself to Norway. It soon became apparent that planning an experiment that included close contact with many random people would lead to uncertainty. It was therefore decided that the study would be performed through an online survey. At this point, in April and May 2020, most people were in their home offices and would presumably be happy to spend some time on a survey about winter cycling. An online survey did also seem like a promising idea because we had already collected a large amount of video recordings of typical winter conditions, and we had also measured the rolling resistance on all the filmed road conditions.

Subsequently, the survey was developed. It was desirable to map socio-demographic information about the participants and their cycling habits throughout the year. The survey included questions about what bicycle type the participants usually used and whether they used studded tires when cycling during the winter. Those who answered that they did not cycle during the winter were asked to specify the main reason. The main part of the survey contained 37 photos of typical winter cycling conditions. The conditions in the photos varied from bare, dry asphalt to variations of slush, uneven icy conditions, compact snow, fresh light snow, to deep loose snow. The survey photos were snapshots from video recordings captured during previously performed rolling resistance measurements. For each photo, the participants were asked (translated from Norwegian): "Are you willing to cycle here?". They could choose between four alternatives: A) "Not at all", B) "A short stretch", C) "Large parts of the route", and D) "The whole route". Figure 7 shows a screenshot of the survey.

The respondents were mainly recruited through Facebook. Invitations to the survey were shared in several cycling-affiliated groups, in groups for environmental organizations, and Norwegian municipalities' Facebook-groups. The survey was also shared through the authors' private Facebook accounts and via e-mail and internal network channels to the Department of Civil and Environmental Engineering at NTNU and the Norwegian Public Roads Administration (NPRA).



8. Kunne du tenkt deg å sykle her? *

I kjørebanen, midt i bildet (1 cm løs ujevn snø over slett asfalt/is).

○ Ikke noe i det hele tatt
○ Et kort stykke
○ Store deler av veien
○ Hele veien

Figure 7: Screenshot of one of the questions in the online survey about winter cycling willingness.

4 RESULTS

4.1 ROLLING RESISTANCE MEASUREMENTS WITH AN INSTRUMENTED BICYCLE

Figure 8 shows the recorded measurements during a 2 km test round with the instrumented bicycle. The figure shows that the pedaling propulsion power, road slope, acceleration, and wind speed, are highly variable throughout the test. A natural consequence of these variations is that the estimated coefficient of rolling resistance (C_{rr}), which is calculated based on these independent variables, also varies. However, the variation in the calculated C_{rr} is much smaller than the variation in the independent variables.

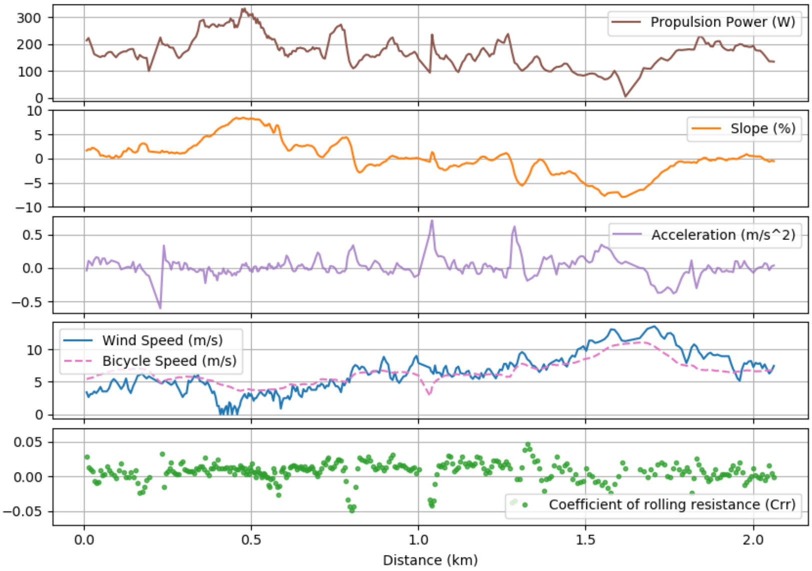


Figure 8: Natural variation of the variables and the estimated rolling resistance considered in the measurement method.

Due to the variation in the estimated rolling resistance, averaging over a stretch is needed to obtain precise results. Figure 9 (left) shows how the precision (represented by the standard error, SE) of the method increases with increasing sample sizes. As discussed in Paper I, a precision of $C_{rr} \pm 0.002$ should be adequate to determine whether a winter cycleway provides a C_{rr} above or below the suggested critical threshold at $C_{rr} = 0.035$. By utilizing the method presented in this study, a precision of ± 0.002 is achieved at 55 samples. A precision of ± 0.005 is achieved already at 9 collected samples and could also be good enough for some applications. Considering that the method has a sampling frequency of 1 Hz, 9 seconds of measuring would provide adequate precision. More than 55 seconds of measurements would provide excellent precision. Translated into measurement distance, this corresponds to 25 meters and 153 meters with a bicycle velocity of 10 km/h.

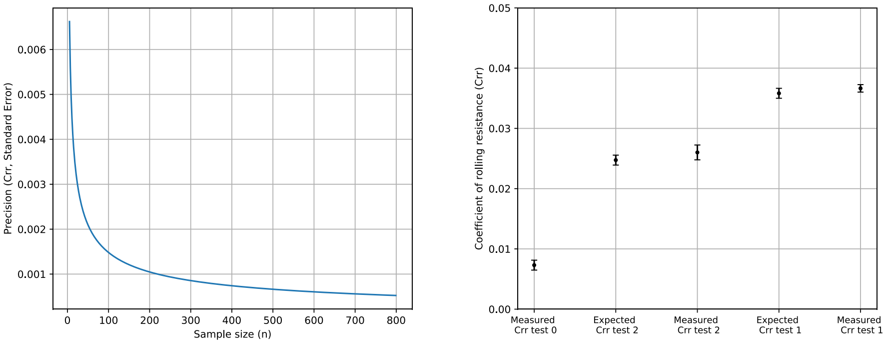


Figure 9: Precision (left) and accuracy (right) of the rolling resistance measurement method.

Figure 9 (right) illustrates the results of the accuracy testing of the method. Test 0 was done on a 2 km stretch without any additional load. The measured C_{rr} in test 0 was 0.0073 ± 0.0008 (SE). After test 0, the dynamo with two levels of known resistance was mounted to the instrumented bicycle. When the lowest known resistance was added, the C_{rr} was expected to rise to 0.0247 ± 0.0008. The measured level showed 0.0260 ± 0.0012. When the highest load was added, the C_{rr} was expected to rise to 0.0358 ± 0.0008, and it was measured to 0.0366 ± 0.0006. These results show that the method measures an increase in rolling resistance with a mean error of 3.7%.

4.2 BICYCLE ROLLING RESISTANCE LEVEL ON WINTER CONDITIONS

Figure 10 shows the measured rolling resistance for ten winter conditions typically encountered when cycling during the winter. The whiskers in the boxplot mark the center 90% of the measurements. Measurements outside this range are identified as outliers and have not been included in the plot. The box contains the interquartile range

(IQR), and the vertical lines illustrate the first 25%, 50% (median), and 75% of the measurements. The width of the notch in each box represents the 95% confidence interval of the median. The small triangles indicate the measurements' arithmetic mean. The rolling resistance increases with loose snow depths. There is a large spread in the measurement data, but there are significant differences between the average measured rolling resistance level on all ten surface conditions.

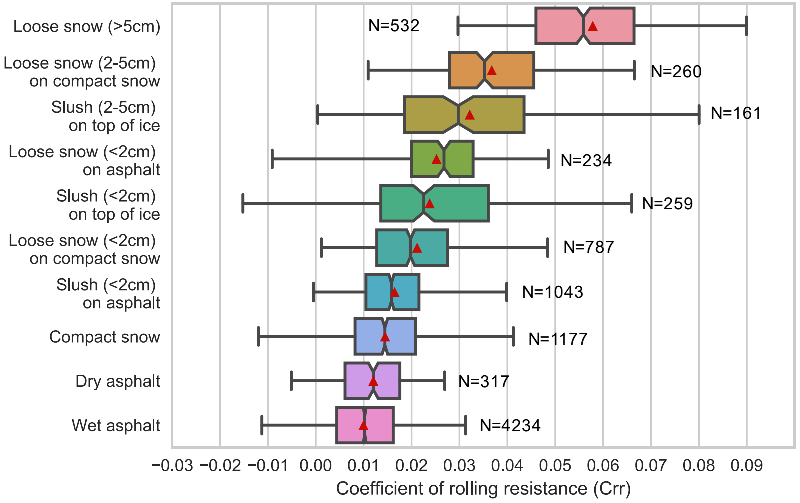
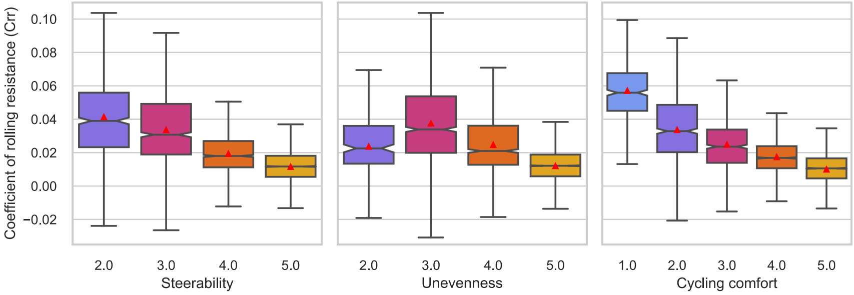


Figure 10: Rolling resistance measurements on ten winter conditions typically encountered during winter cycling. N = number of readings.

Figure 11 shows the relation between C_{rr} and steerability, unevenness, and cycling comfort. Grade 5 equals very good cycling conditions, and grade 1 equals very poor cycling conditions. When the rolling resistance was high, the steerability was perceived as poor. The two worst grades of steerability were registered at C_{rr} values higher than 0.03, which corresponds to conditions with compact snow or ice covered with more than 2-5 cm of slush or loose snow or conditions with more than 5 cm of loose snow. Increased rolling resistance also correlated with increased perceived unevenness. However, for the highest measured rolling resistances, i.e., conditions with significant amounts of slush or loose snow, the perceived unevenness was significantly reduced. The perceived overall cycling comfort was significantly reduced with increasing rolling resistance.



(a) (b) (c)

Figure 11: Correlation between bicycle rolling resistance and perceived steerability, unevenness, and cycling comfort.

Figure 12 shows how the measured bicycle rolling resistance level on cycleways maintained with GsA, GsB, and municipal (MUN) winter maintenance standards. The results show that GsA offered a significantly lower rolling resistance level than GsB and MUN. There was not a significant difference between the rolling resistance level measured on GsB and MUN.

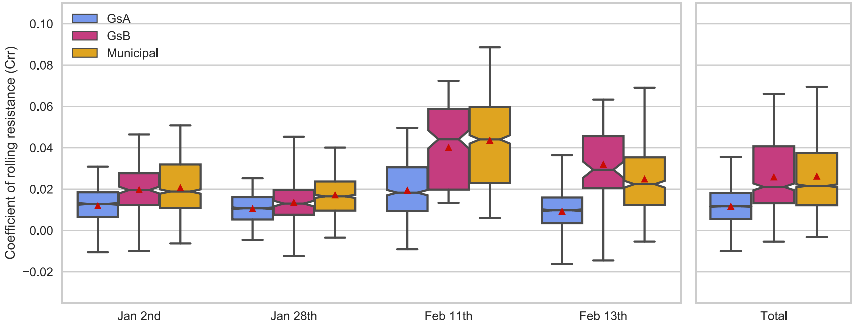


Figure 12: Measured rolling resistance level on cycleways maintained with three different winter maintenance standards: GsA, GsB, and municipal (MUN) standard.

4.3 STATED PREFERENCES SURVEY

The survey received 1318 individual responses. More males (71%) than females (29%) responded, and most were within 18 to 65 years of age. 92% were regular winter cyclists, 7% were summer-only cyclists, and 1% were not cyclists. Paper III describes the sample in more detail. The online survey results revealed that people's stated cycling willingness is reduced when the rolling resistance level increases. In Figure 13, the cycling willingness is represented by the cycling willingness index (CWI), which is the percentage of respondents answering that they would be willing to cycle "large parts of the route", or "all the way" on the conditions presented in photos of typical winter cycling conditions. The CWI was introduced in Paper III.

Figure 13 shows that the CWI decreases with increasing rolling resistance levels independent of age, gender, winter cycling experience, or bicycle type. Furthermore, the rate of reduced cycling willingness due to increased rolling resistance was affected by several factors. Male cyclists were less affected by conditions with increasing rolling resistance than female cyclists. Further, cyclists older than 65 years were more affected by increasing rolling resistances than younger cyclists. When it came to geographical location, cyclists residing in northern Norway were less affected by increasing rolling resistances than cyclists from Norway's eastern and middle parts. Cyclists from the western part of Norway had the most significant reduction in cycling willingness for increasing rolling resistances. The results also show that winter cycling habits have a significant impact on people’s winter cycling willingness. Experienced winter cyclists are far less affected by increasing rolling resistances than those who rarely or never cycle during the winter. Another interesting finding was that regular use of studded tires during winter cycling has a positive effect on winter cycling willingness. Furthermore, the results show that the use of e-bikes does not affect people’s willingness to cycle during the winter. Finally, the survey also revealed that the reasons for not cycling in the winter were low temperatures (29%), a lacked feeling of safety (27%), increased bicycle wear (17%), increased travel time (17%), and increased physical effort (10%).

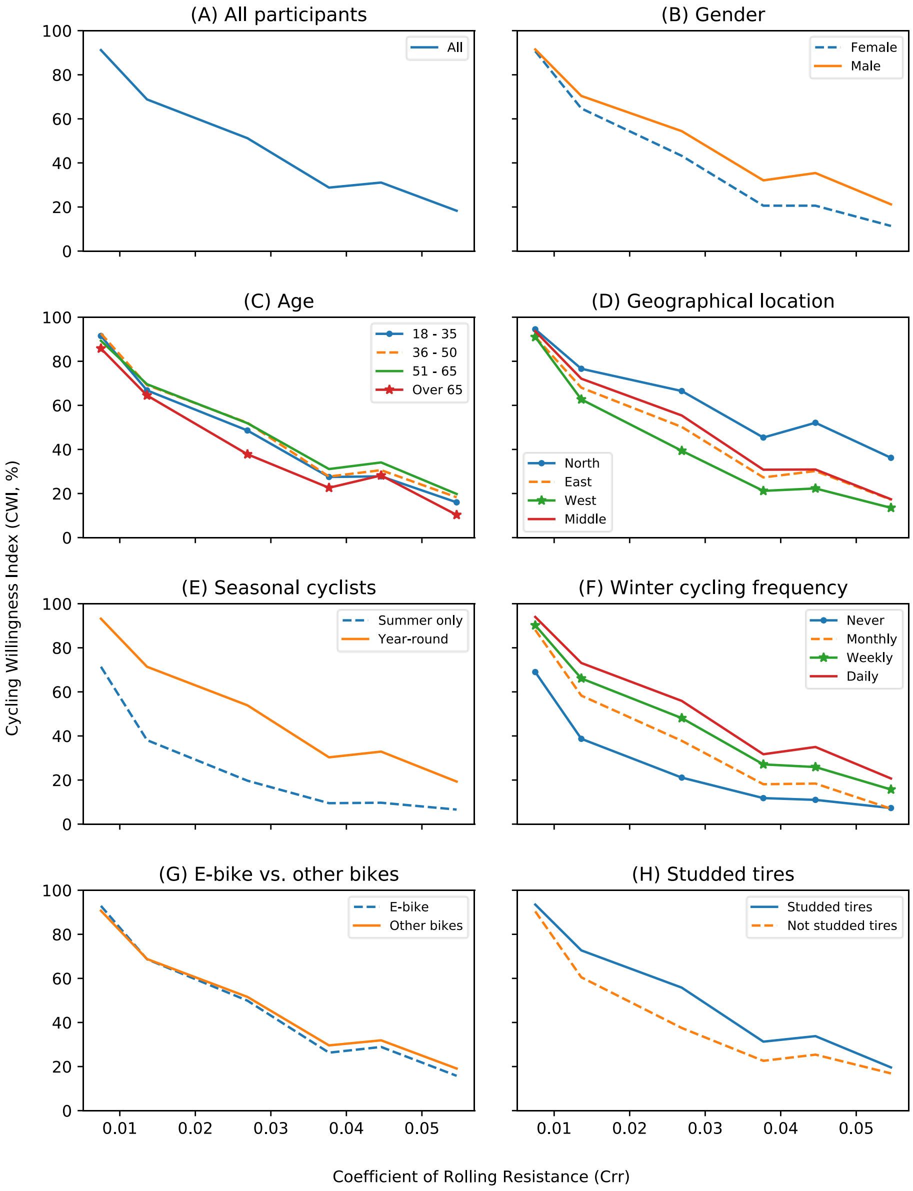


Figure 13: Results from the online survey showing correlations between reduced cycling willingness and increasing rolling resistance.

5 DISCUSSION

5.1 BICYCLE ROLLING RESISTANCE MEASUREMENT METHOD

The instrumented bicycle developed in this Ph.D. project proved through initial testing and field measurements that it could accurately determine the rolling resistance level on cycleways, regardless of weather and road surface conditions. Because the method determines the rolling resistance level based on air speed, slope, acceleration, and pedaling power, there is a natural variation in the measurements, and an average over a stretch is needed for a correct result. A C_{rr} measurement precision of ±0.005 is achieved with a measurement sample size of 9, or 25 meters of testing at a velocity of 10 km/h. Moreover, a sample size of 55 readings, corresponding to 153 meters of testing at a velocity of 10 km/h, is enough to achieve a precision of ± 0.002. Under winter conditions, rolling resistance directly relates to the depth, type, and configuration of snow and ice contaminations on the pavement.

Furthermore, the results from Paper II show that increasing amounts of snow and ice increase unevenness and reduce steerability and general cycling comfort, making cycleways less accessible. Therefore, rolling resistance measurements performed using the developed instrumented bicycle can be used to indirectly quantify the accessibility, or surface condition quality, of cycleways during wintertime.

The instrumented bicycle can potentially be used for other research purposes, such as determining rolling resistance properties for various bicycle tires or pavement surface materials. However, the current measurement frequency of 1 Hz requires 55 seconds for each measurement to reach a C_{rr} precision of ± 0.002. A higher level of precision and a shorter measurement duration are probably needed to identify significant differences in the rolling resistance between bicycle tires and pavement surface materials. One way of obtaining this is by increasing the sampling rate of the measurement sensors.

Several variables must be carefully controlled for the method to produce correct results. To obtain correct air drag measurements, the method requires the coefficient of drag times frontal area (C_dA) to be determined specifically for the person operating the instrumented bicycle. This can be done in an aerodynamic laboratory (wind tunnel).

Alternatively, the C_dA can be determined outside on a level road stretch in no-wind conditions, as described in Paper I. Furthermore, it is important to control the combined weight of the cyclist and bicycle, the cyclists' outfit and cycling position (due to air drag), to keep the air speed sensor at a constant angle, and to always control the bicycle tire inflation pressure. It is also important to ensure that the pedaling power sensor and GPS devices are calibrated. Controlling these variables is feasible in a research setting but probably not realistic in an operational setting. For the method to be used for controls of the performance in a winter maintenance contract, it should be more elegant, less time consuming, and with less room for error. For this use, the towed trailer method could be a better solution. The towed trailer method has potentially fewer variables that influence the result but may introduce issues regarding scaling the rolling resistance level to the level perceived by cyclists.

Theoretically, the instrumented bicycle could also be used to crowdsource a bicycle road conditions report service. A large portion of the bicycle fleet in an urban area could provide rolling resistance data to the service to inform other cyclists about the current conditions. However, it would probably be difficult considering the many variables and the large room for error. However, a crowdsourcing road conditions system could be useful if it provided alternative information that is easier to measure, like velocity, or accelerometer data (vibrations), recorded by, for example, smartphones. However, accelerometer data from smartphones would be highly dependent on the smartphone placement (pocket, backpack, or similar).

5.2 HOW CAN WINTER MAINTENANCE OPERATIONS INCREASE WINTER CYCLING?

The results from Paper III showed a clear correlation between increased rolling resistances and a reduction in people’s willingness to cycle during the winter. Furthermore, the results showed that the cycling willingness for e-bike users did not differ from those using standard bicycles, which was surprising because e-bikes reduce the cyclists' effort to overcome increasing rolling resistances. Moreover, what did significantly increase people’s willingness to cycle during the winter was the use of studded tires. The results also showed that summer-only cyclists’ reason for not cycling during the winter was that it is too cold (29%) and that they do not feel safe (27%). Only 10% stated that it was because it is too tiring. Paper II showed a correlation between increased rolling resistances and increased unevenness as well as reduced perceived steerability and overall cycling comfort. Therefore, it is reasonable to believe that the increased physical effort required for cycling in conditions with an increased rolling resistance is not the main reason people's cycling willingness drops during the winter. Conversely, it seems like it is mainly because increased rolling resistance levels correlate with increased unevenness and reduced steerability, leading to a reduced perceived safety and cycling comfort.

Figure 1 (section 3.2) shows that Norway, as a whole, experiences a drop in cycling during the winter of 50%, and in some cities, the drop is as high as 83%. This indicates a considerable potential in increasing winter cycling if one could recruit summer-only cyclists to cycle in the winter. Research has previously concluded that proper winter maintenance is essential to recruit summer cyclists to winter cycling (Bergström & Magnusson, 2003; Niska, 2010a; Svorstøl et al., 2017; Sørensen & Mosslemi, 2009). To recruit non-cyclists to cycle, there is often a need to reduce cultural or personal barriers such as a negative attitude towards cycling or work and family commitments (Gatersleben & Appleton, 2007). Paper III shows that the cycling willingness index (CWI), which indicates the percentage of respondents positive to cycle, increases from 38% at $C_{rr} \approx 0.014$ to 71% at $C_{rr} \approx 0.008$ for summer-only cyclists. For people already cycling once a month or more during the winter, the CWI increases from 71% at $C_{rr} \approx 0.014$, to 93% at $C_{rr} \approx 0.008$. This shows that by offering cycleways with a C_{rr} around 0.008 on stretches that used to offer conditions with a C_{rr} around 0.014, one could recruit about 30% of summer-only cyclists to winter cycling and possibly make about 20% of already winter cyclists cycle more often during the winter. Similarly, by reducing the C_{rr} on a cycleway from about 0.045 to about 0.027, a significantly larger reduction in rolling resistance, one could also expect a 20% cycling increase from winter cyclists, but only to recruit 10% of summer only cyclists. This indicates that smaller winter maintenance effort improvements that make cycleways accessible but are not perceived as safe and comfortable can increase the winter cycling frequency of already regular winter cyclists. However, to recruit summer cyclists to winter cycling, more comprehensive winter maintenance actions, leading to C_{rr} levels below 0.01, are required.

A C_{rr} lower than 0.01 is offered by road with bare or wet asphalt, asphalt with traces of slush, or even compact snow surfaces. These conditions require winter maintenance following a bare road standard that utilizes mechanical snow removal and chemical treatment to prevent surface freezing and facilitate mechanical removal of snow. However, 17% of the summer only cyclists stated that they do not cycle during the winter due to increased bicycle wear. Anti-icing chemicals accelerate corrosion and hence bicycle wear. Therefore, one would assume that increased use of anti-icing chemicals would scare some summer-only cyclists away from winter cycling, regardless of improved road conditions. A strict winter road maintenance strategy allowing a compact, even layer of snow or ice could also provide road conditions with $Crr < 0.01$, depending on stable winter conditions with little precipitation. Paper II presents a thorough analysis of the effect of various winter road conditions on the level of bicycle rolling resistance.

6 CONCLUSIONS

Rolling resistance impedes bicycles' movement and is affected by pavement surface contaminations, such as snow and ice. A new rolling resistance measurement method was developed to explore the effect of snow and ice contaminations on rolling resistance and the effect of rolling resistance on winter cycling.

The new measurement method consisted of an instrumented bicycle that measured resistive and propulsive forces and solved the force equilibrium on the moving bicycle to determine the rolling resistance level. Due to natural variations in the measured variables, averaging over a stretch was needed to obtain precise measurements. A sample size of 55 readings, or 153 meters of testing at a velocity of 10 km/h, was enough to achieve a coefficient of rolling resistance (C_{rr}) measurement precision of ± 0.002.

Several variables must be controlled for the method to obtain correct measurements. The most significant variables are the combined weight and frontal area of cyclist and bicycle, tire inflation pressure, and the wind speed sensor's angle. Controlling these variables is feasible in a research setting but probably not realistic in an operational setting. For the method to be used for controls of the performance in a winter maintenance contract, it should have fewer controllable variables, be less time-consuming, and leave less room for error.

The method was used to measure the bicycle rolling resistance level on various winter conditions. Significant differences in rolling resistance were found between ten typical types of winter conditions. The results showed that the bicycle rolling resistance level increases with increasing depths of deformable snow or ice. On conditions with loose snow deeper than 5 cm, the measured rolling resistance was almost six times higher than that measured on bare asphalt. The results also showed that increasing rolling resistance levels correlates with increased perceived unevenness and reduced perceived steerability and cycling comfort.

An online survey was conducted to explore the correlation between the rolling resistance level and people’s willingness to cycle during the winter. All 1318 respondents reported their willingness to cycle on 37 photos of winter cycling conditions. The conditions in the photos had various measured rolling resistance levels, but they were not presented to the respondents. The results showed a reduction in winter cycling willingness for increasing rolling resistance levels for all respondents. Furthermore, the use of e-bikes does not seem to increase winter cycling willingness but using studded tires does. Summer-only cyclists stated that they do not cycle during the winter primarily because of low temperatures and that they do not feel safe. These results indicate that the increased physical effort required for cycling in conditions with an increased rolling resistance is not the main reason people's cycling willingness drops during the winter. Conversely, it seems like it is mainly because increased rolling resistance levels correlate with increased unevenness and reduced steerability, leading to a reduced perceived safety and cycling comfort.

The decrease in winter cycling willingness was most rapid, going from very low to low rolling resistances and then flattening out with further increased rolling resistances. This effect was particularly evident for summer-only cyclists, while for already regular winter cyclists, the reduction in cycling willingness with increasing rolling resistances was more linear. This indicates that smaller winter maintenance effort improvements that make cycleways accessible but are not necessarily perceived as safe and comfortable can increase the winter cycling frequency of already regular winter cyclists. To recruit summer only cyclists to cycle also in the winter, the road conditions must offer low rolling resistance, preferably with Crr levels below 0.01, and the conditions must be perceived as safe and comfortable.

7 SUGGESTIONS FOR FURTHER WORK

There is still a need for quantifiable measurements of the rolling resistance level on cycleways in an operational winter maintenance setting. Future work should optimize the force equilibrium method or develop a towed trailer method for operational settings.

Future research can utilize the force equilibrium method to test how different types of bicycles, tires, and inflation pressures affect the rolling resistance on various winter conditions. This could help cyclists optimize their own winter cycling experiences and make more people comfortable cycling during the winter.

Unevenness and steerability affect cycling comfort. Future investigations should record quantifiable unevenness and steerability data and investigate how it correlates with various winter conditions. Unevenness and steerability could be quantified by measuring vibrations and angular displacement using steering bar-mounted accelerometers and gyroscopes.

A significantly large amount of summer cyclists stated that they do not cycle during the winter because they want to avoid wear and tear on their bicycles. Anti-icing chemicals accelerate corrosion and hence bicycle wear. Further efforts should investigate how winter maintenance can offer safe and comfortable cycling conditions with low rolling resistance without using corrosion accelerating de-icers.

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APPENDIX A – PAPER I

Fenre, Klein-Paste

Rolling Resistance Measurements on Cycleways Using an Instrumented Bicycle

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Rolling Resistance Measurements on Cycleways Using an Instrumented Bicycle

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ABSTRACT

Snow and ice on the roads often lead to increased rolling resistance which makes the roads less accessible and less attractive for cyclists. Introducing a minimum requirement for rolling resistance in winter maintenance of cycleways may increase the attractiveness of winter cycling. To control the rolling resistance level, an objective measurement method is needed. This article presents a new method for measuring rolling resistance for cyclists by using an instrumented bicycle. The new method utilizes measurements of pedaling power and resistive forces from gravitation, acceleration and air drag to estimate the rolling resistance. Test results show that the method can measure the coefficient of rolling resistance, C_{rr}, with a precision, represented as the standard error of the mean, between ± 0.005 (1Hz, n=9) to ± 0.001 (1Hz, n=220). The accuracy of the method was verified in a test with known rolling resistance and the results yielded a mean accuracy of 96.5%.

INTRODUCTION

During the winter, cycleways are often covered with snow, ice, ruts and irregularities, which leads to increased rolling resistance (Blaisdell, 1981; Lidström, 1979; Shoop, 2001; van Es, 1999). This makes cycling less efficient and less comfortable (Descornet, 1990; Hölzel, Höchtl, & Senner, 2012). Many regions experience a drop in the bicycle transportation share during the winter (Amiri & Sadeghpour, 2015; Bergström & Magnusson, 2003; Nordström et al., 2014). Inclement road conditions have been identified to be a barrier to winter cycling (Nahal & Mitra, 2018; Spencer, Watts, Vivanco, & Flynn, 2013). In Norway, the percentage of trips made by bicycle drops from 8% in the summer to 1% in the winter (Vågane, Brechan, & Hjorthol, 2011). Cycling in general has received increased appreciation as an efficient, healthy and sustainable mode of transportation (Grous, 2011; Teschke, Reynolds, Ries, Gouge, & Winters, 2012). In Norway, politicians have decided that all increase in passenger traffic in urban areas should be covered by public transportation, walking, and cycling. More specifically, the Norwegian goal is to increase the year-round bicycle transportation share in the whole country from today's 5% up to 8% by 2023. In urban areas, the goal is to reach a bicycle share of 20% (Lunke & Grue, 2018). To reach these goals, an increase in the bicycle transportation share during the winter is needed, and the barriers to winter cycling must be reduced.

Improved winter maintenance of the cycleways may reduce the barriers to winter cycling. A Swedish study concluded that improved winter maintenance of bicycle facilities in urban areas may increase the number of bicycle trips during winter by 18% and at the same time decrease the number of car trips by 6% (Bergström & Magnusson, 2003).

An important ingredient in the quest to improve winter maintenance of cycleways is objective evaluation of the road conditions (Hamilton & Hyman, 2006). In many countries, including Norway, winter maintenance services are performed by private contractors. To control whether the maintenance contracts are fulfilled according to the requirements, a standardized assessment of the current state of the pavement is needed. This can also be useful for comparison of service levels across regions or time periods (Xu et al., 2017). In Norway, the current state of the pavement is often evaluated based on the performance requirements in the levels of service (LOS) developed by the Norwegian Public Roads Administration (NPRA). NPRA have developed two LOSs for winter maintenance of bicycle road networks. These LOSs have minimum performance requirements for friction, loose snow depth, unevenness and crossfall (NPRA, 2014).

Friction is used as a performance criterion in most winter maintenance contracts in the Nordic countries. The most important factor to reduce the number of single bicycle accidents is a sufficiently high level of friction (Niska, 2010). The number of people who choose to bicycle in the winter, however, or the attractiveness of the bicycle infrastructure, is not solely dependent on friction. Winter-cyclists often use studded tires and feel safe even on slippery roads (Grann, 2016). Cyclists are attracted to accessible roads, and an effective measure to increase accessibility is snow removal (Svorstøl, Ellis, & Varhelyi, 2017). Snow removal, however, is expensive and it often involves use of anti-icing chemicals that are detrimental to vehicles and the surrounding environment (Fay & Shi, 2012; Fay, Volkening, Gallaway, & Shi, 2008). It would be advantageous to achieve accessible cycleways without complete snow removal and without the use of anti-icing chemicals. Depending on the physical properties of the snow and the evenness of the surface, snow-covered roads sometimes offer a high level of attractiveness and accessibility. There seems to be a lack of knowledge on how the requirements for loose snow depth and unevenness correlate with the actual accessibility experienced by cyclists. This knowledge is needed in order to optimize and streamline winter maintenance of bicycle roads.

Rolling resistance is a parameter that is affected by, among other factors, loose snow depth, snow density and unevenness. The rolling resistance level is also a measure on the accessibility of the road. A bicycle-based rolling resistance measurement device could cover relatively long stretches of the bicycle network and provide objective measurements of the rolling resistance experienced by cyclists.

In Oulu, Finland, new bicycle road winter maintenance contracts include a set of possible road inspection methods. The operators are rewarded for monthly- or every second week-road inspections by bicycle. One or two persons should conduct the inspections and one or two kilometers should be covered each time. During the maintenance year, 50% of the bicycle lanes must be inspected by bicycle (Pirinen, Maenpaa, Hautaniemi, & Rankka, 2018). Quantitative measurements of rolling resistance would increase the quality of the results and analyses of such inspections. This would facilitate improved winter maintenance on bicycle roads in cold climates and possibly increase the bicycle transportation share during winter. There seems to be a lack of earlier attempts to measure rolling resistance for bicycles in winter conditions, but several studies have investigated the contribution of snow to the rolling resistance of trucks, aircraft and tracked vehicles (Blaisdell, 1981; Lidström, 1979; Shoop, 2001; van Es, 1999). Non-winter specific methods for measuring rolling resistance for bicycles however, have been explored. Hill (1990) explored a rolling resistance measurement method with an eccentrically weighted pair of wheels. The rolling resistance was calculated through the loss of energy when the tire oscillated backward and forwards on a level surface. This method could measure small changes in rolling resistance between different types of bicycle racing tires. The influence of tire pressure and vertical load on rolling resistance was identified by using a coast-down method on a level indoors surface (Grappe et al., 1999). Coast-down rolling resistance testing for bicycles was also later tested outside, however, wind, slope and riding surface led to inconsistent measurement precision (Tengattini &

Bigazzi, 2018). Coast-down testing has also been performed to investigate the effect of normal force, tire inflation pressure and wheel diameter on the rolling resistance of bicycles (Warnich & Steyn, 2014). Wilson, Papadopoulos, and Whitt (2004) suggested that a rear-hub power measurement device could be used to measure rolling resistance for bicycles, if the effect of air drag, hillslope and acceleration were accounted for. In a study by Meyer, Kloss, and Senner (2016), the rolling resistance of a four-wheeled electric bicycle was estimated by measuring the combined motor/pedaling force and the resistive forces acting on the bicycle. In this study, the test variables were controlled to avoid contributions from air velocity, acceleration and slope. Estimation of rolling resistance by measuring the pedaling force has also earlier been performed in Boulder, Colorado, USA. This study concluded that commercially available power meters are sensitive enough to detect changes in rolling resistances associated with substantial changes in tire pressure (Lim et al., 2011).

In this study, a new method based on the experiments by Lim et al. (2011) and Meyer et al. (2016) for estimating rolling resistance for bicycles has been developed and tested. The new method estimates rolling resistance based on pedaling force, air velocity, acceleration, and slope. By taking these variables into account, evaluation of rolling resistance can be performed in all wind conditions, in all types of road slopes and at varying velocities.

METHOD

The rolling resistance was estimated by solving the force equilibrium on a moving bicycle. When the cyclist pedals, the propulsion force (F_p) acts in the direction of the motion of the bicycle. The gravity force (F_g) acts in the direction of the motion of the bicycle in descents and against it in ascents. The air drag force (F_a) usually acts in the opposite direction of the motion of the bicycle, except in cases of a heavy tailwind. Due to the mass of the bicycle and cyclist, the inertia force (F_i) acts in the opposite direction of the acceleration of the bicycle. The rolling resistance force (F_r) between the wheels and the road surface always acts against the motion of the bicycle. This is also the case for the internal friction forces (F_f) in the drivetrain and wheel bearings. Finally, braking forces (F_b) also act in the opposite direction of the motion of the bicycle. Therefore, the rolling resistance can be found by solving the force equilibrium:

$$F_p = F_r + F_g + F_a + F_i + F_f + F_b \tag{1}$$

Figure 1 illustrates the force equilibrium in equation (1). As the test bicycle in this study was brand new and had high-quality wheels, the internal friction from the wheel bearings was neglected. The propulsion force measurement was located directly between the rear wheel

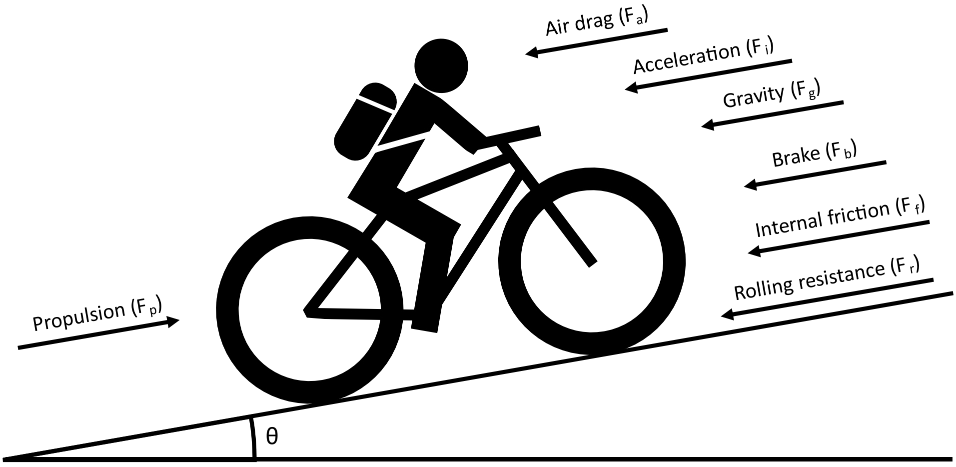

Fig. 1. Forces acting on a moving bicycle.

sprockets and the hub of the rear wheel. The measurement was therefore unaffected by internal friction, and the internal friction force from the drivetrain was neglected. Measurements were only included while the pedaling cadence (rounds per minute, RPM) was above zero. It was assumed that braking occurs mainly while the pedaling cadence is equal to zero, and hence the force from braking resistance was neglected. The rolling resistance was therefore estimated

using the following simplified force equilibrium:

$$F_r = F_p - \left(F_g + F_a + F_i\right) \tag{2}$$

All variables affecting the elements of the force equilibrium were measured at a rate of 1 Hz using commercially available components. The propulsion power, P_p (W), was measured with a rear-wheel-hub bicycle power meter (*Powertap G3*). The propulsion force (N) is therefore expressed as:

$$F_p = \frac{P_p}{v_b} \tag{3}$$

Where v_b (m/s) is the velocity of the bicycle, measured with a bicycle GPS device (*Garmin EDGE 130*) and a hub mounted gyroscope (Wahoo speed) in cases of lacking GPS signals. The road slope, s (%) was measured with a handlebar-mounted sensor (*Velocomp Aeropod)*, utilizing a 6-axis accelerometer and a barometric pressure sensor. GPS data was used to calibrate the altitude measurements. The resistive force due to gravity is therefore expressed as:

$$F_g = m\text{g} * \sin\left(\arctan\left(\frac{s}{100}\right)\right) \tag{4}$$

Where m (kg) is the combined mass of the bicycle and rider and g (m/s^2) is the gravitational acceleration constant.

The handlebar-mounted sensor (*Velocomp Aeropod*) utilizes a differential pressure sensor (Pitot tube) to measure air velocity, v_{air} (m/s) in the opposite direction of the motion of the bicycle. Air density, ρ_{air} (kg/m^3) is estimated based on temperature and barometric pressure. Hence, the resistive force due to air drag is expressed as:

$$F_a = \frac{1}{2}\rho_{air} * C_d A(v_{air}) * {v_{air}}^2 \tag{5}$$

Where the combined coefficient of drag and the frontal area of the bicycle and rider, C_dA (m^2) was determined experimentally in the wind tunnel at the fluid mechanics laboratory at The Norwegian University of Science and Technology (NTNU) in Trondheim (Oggiano, Spurkland, Sætran, & Bardal, 2016). The C_dA depends on the air velocity due to turbulence effects. For comparison, the C_dA was also determined in a simpler field experiment by measuring the increase in propulsion force for increased air velocities at a close to flat course with a constant rolling resistance. Both approaches for determining the C_dA are described in more detail in section 2.1.

The inertia forces due to acceleration were determined based on the measurements of v_b:

$$F_i = \left(m + \frac{Iw_f + Iw_r}{{r_w}^2}\right) * \frac{\mathrm{d}v_b}{\mathrm{dt}} \tag{6}$$

Where Iw_f and Iw_r (kg*m^2) are the rotational inertias of the front wheel and the rear wheel, respectively, and r_w (m) is the wheel radius. The rotational inertias of the wheels were calculated based on the weight and the approximate average radius of the wheel components (rim, tire, tube, spokes and nipples, hub and brake disk).

Previous research has found a nearly linear relationship between rolling resistance and wheel load due to increased bending and shearing of the tire or deformation of the surface (Baldissera & Delprete, 2016; Clark, 1978; Gent & Walter, 2006; Gillespie, 1992). To be able to compare rolling resistance between wheel loads, a dimensionless coefficient, C_{rr}, is commonly used to represent the rolling resistance characteristics between a wheel and a road surface:

$$C_{rr} = \frac{F_r}{F_N} \tag{8}$$

Where F_N is the wheel load. In this study, the wheel load, or the combined load of the bicycle and rider was measured before each test ride and varied between 834 N and 874 N.

All sensors were mounted on a *Breezer Radar Café* hybrid bicycle, equipped with 42mm wide 29-inch diameter studded tires (*Schwalbe Marathon Winter Plus*). The tire inflation pressure during testing was set at 2 bar (200 kPa) in 20°C.

Aerodynamic Drag

The accuracy and precision of the handlebar mounted air velocity measurement device were tested in the wind tunnel located in the fluid mechanics laboratory at NTNU on December 20th, 2018. The bicycle and cyclist were fixed on a stationary bicycle roller in the wind tunnel. The handlebar-mounted air velocity measurement device was pointing directly in the opposite direction of the air flow inside the tunnel. The air temperature inside the wind tunnel increased from 22.6°C to 23.9°C during the experiment. The air velocity, v_{air}, inside the wind tunnel increased in five steps from 2.8 m/s up to 13.8 m/s. The stepwise air velocities reported from the wind tunnel instrumentation was compared to the air velocities measured by the handlebar-mounted device.

During the same session, the combined drag coefficient times frontal area, C_dA, of the test bicycle and cyclist was determined. A force transducer measured the horizontal drag force from the bicycle and cyclist, F_a (N), while the air velocity increased. During testing, the cyclist kept a constant normal position on the bicycle and was pedaling with an average cadence of 61 RPM to mimic real conditions. The C_dA was calculated for each air velocity-step with the following equation:

$$C_dA = \frac{2F_a}{\rho_{air} * {v_{air}}^2} \tag{9}$$

Where the air density, ρ_{air}, was estimated based on the barometric pressure and temperature in the tunnel. The air velocity was controlled and measured by the default instrumentation in the wind tunnel.

A photo analysis software (*Digimizer*) was used to determine the frontal area, *A*, of the bicycle and the rider in a normal pedaling position.

In addition to the wind tunnel experiment, the C_dA was determined in a simpler field experiment. On February 11th, 2020, the bicycle with measurement sensors was brought to a 400-meter-long, SSE-facing, straight, approximately flat, stretch of road with a dry asphalt surface next to Lerkendal stadium in Trondheim. The average air temperature was 3.1°C. The average wind speed was 2.2 m/s, coming from south west with wind gusts up to 5.5 m/s. The road surface provided a constant rolling resistance along the stretch. The cyclist assumed the normal cycling position (the same position as in the wind tunnel) and rode the stretch five times at five different velocities: 10, 15, 20, 25 and 30 km/h.

The rate of change in air drag force (ΔF_a) with respect to air velocity was then isolated from the force equilibrium on the bicycle:

$$\Delta F_a = \Delta\left(F_p - F_g - F_i - F_r\right) \tag{10}$$

$$\Delta F_a = C_d A * \rho_{air} * v_{air} \tag{11}$$

Where ΔF_r is zero due to the constant rolling resistance. The C_dA was then estimated with the following equation:

$$C_d A = \frac{\Delta F_a}{\rho_{air} * v_{air}} \tag{12}$$

Where ΔF_a was found by fitting a second-degree polynomial to the measured F_a vs v_{air} data.

Precision and Accuracy

The accuracy and precision of the rolling resistance measurement method were tested on a test course with and without known additional rolling resistances. The course had a moist asphalt surface, and the rolling resistance was assumed constant. The rolling resistance on the course was measured in three separate runs. Test 0 was performed with no additional rolling resistance. Figure 2 shows the measured variables and the estimated C_{rr} during test 0.

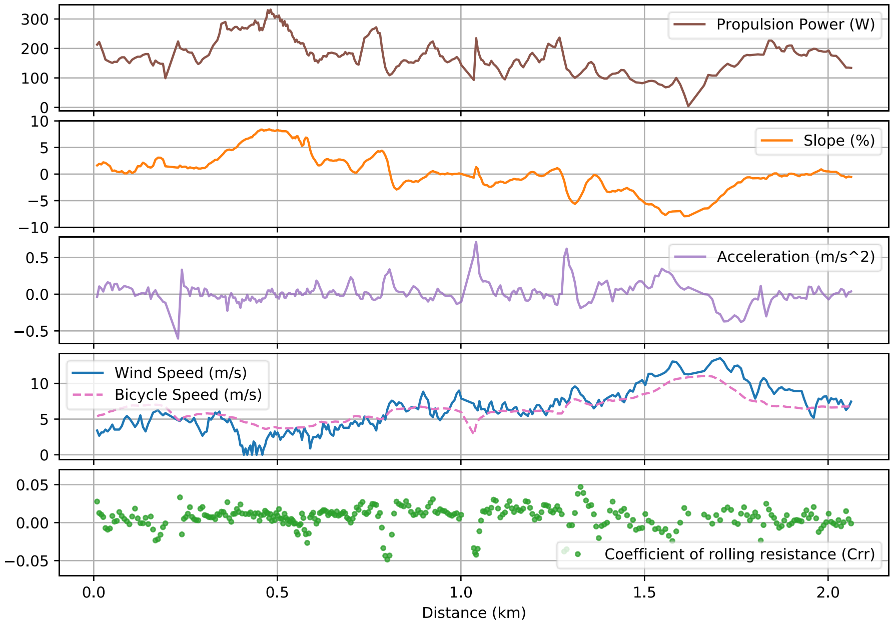

Fig. 2. Measured variables and estimated C_{rr} during test 0.

The precision of the method was determined based on the standard error of the mean (SEM), of the measured rolling resistance in test 0 ($C_{rr,\,m,\,0}$):

$$\text{Precision (SEM)} = \frac{\text{Std}\left(C_{rr,m,0}\right)}{\sqrt{n}} \tag{13}$$

Where Std ($C_{rr,\,m,\,0}$) represents the standard deviation of $C_{rr,\,m,\,0}$, and n represents the number of measurement samples. From (13) we see that the precision increases with increased sample sizes.

Tests 1 and 2 were performed with a high and a low known additional rolling resistance from a dynamo. The expected C_{rr} in test 1 and 2 ($C_{rr,\,exp,\,1,\,2}$) was therefore the measured rolling resistance in test 0, plus the added rolling resistance from the dynamo ($C_{rr,\,dyn,\,1,\,2}$):

$$C_{rr,exp,1,2} = C_{rr,m,0} + C_{rr,dyn,1,2} \tag{14}$$

The accuracy of the method was determined based on the difference between the measured C_{rr} ($C_{rr,\,m,\,1,\,2}$) and the expected C_{rr} ($C_{rr,\,exp,\,1,\,2}$) in test 1 and test 2, measured in a course with changing velocities, slopes and winds:

$$\text{Accuracy}_{1,2}\ (\%) = \frac{\left|C_{rr,m,1,2} - C_{rr,exp,1,2}\right|}{C_{rr,m,1,2}} * 100 \tag{15}$$

During preliminary testing, it was discovered that the dynamo resistance decreased somewhat during testing, possibly an effect of increased temperature. To minimize the temperature-increase during test runs, the dynamo was run at a high speed until it was almost too hot to touch, before the test runs were performed. In addition, to account for any loss in dynamo resistance during test runs, the dynamo resistance was measured immediately before and after each test run with a deceleration test.

The testing was performed close to NTNU Gløshaugen Campus on March 2nd, 2020. The average air temperature was -1.3°C. The average wind speed was 5.7 m/s, coming from north east, with wind gusts up to 9.9 m/s. The length of the test course was 2.1 kilometers. The test course included a straight, flat section, an up-/downhill with a slope up to 9% and some gentle turns. Half of the course was surrounded by a large football stadium, a large hotel and a large open training ground, while the rest of the course was surrounded by residential houses and mixed vegetation. Figure 3 shows a Google Earth photo, elevation (m) plot and slope (%) plot of the test course.

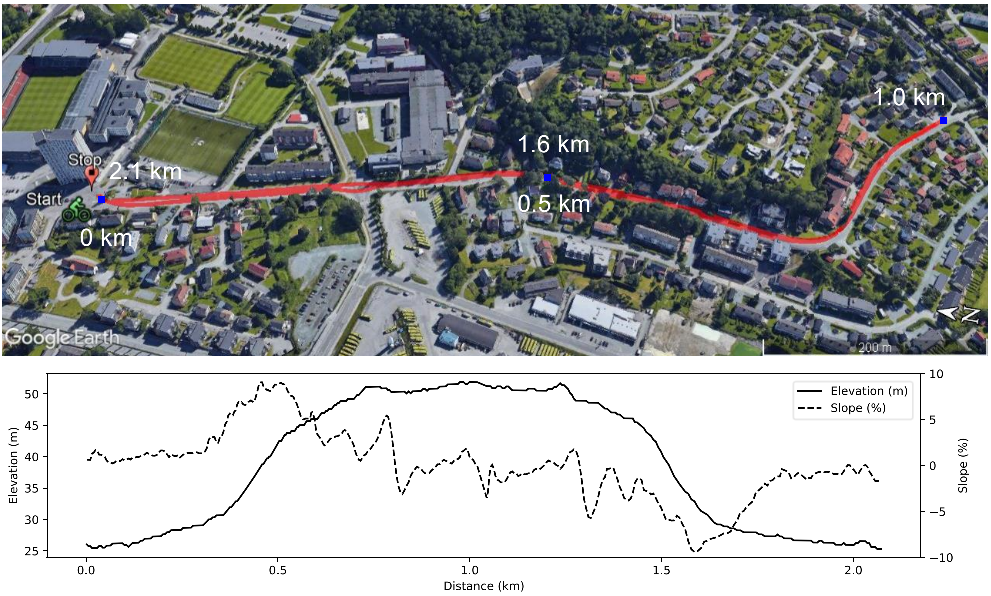

Fig.3. Google Earth photo, elevation (m) plot and slope (%) plot of the test course.

Dynamo design and resistance testing

The additional rolling resistance was added to the bicycle in the form of a dynamo (*Crouzet Brushed DC Motor 89850008*), which was connected to a resistor of 0.3 ohms. Controlled torque testing revealed that the resistance from the dynamo increased with increased rotational speeds. The dynamo was mounted to a hinged arm and pressed to the top of the rear bicycle tire with an adjustment bolt. Two spacers controlled the pressure from the adjustment bolt. Figure 4 shows how the dynamo was mounted to the bicycle. Two dynamo axle wheels

with diameters of 30mm and 40mm were used between the bicycle tire and the dynamo. The different diameters made it possible to utilize two different ranges of rotational speeds in the dynamo at the same range in bicycle velocity, hence utilizing two different ranges of resistance.

Fig. 4. Dynamo mounted to the bicycle for added rolling resistance.

The exact rolling resistance added to the bicycle by the dynamo was measured by deceleration testing. The bicycle was tilted forwards to allow the rear wheel to rotate freely with no ground contact, and the rotational velocity of the rear wheel was accelerated up to approximately 8 m/s. The rotation of the wheel was then slowed down by the dynamo, and the change in rotational velocity of the wheel was measured with a hub mounted gyroscope (*Gulf Coast Data concepts, HAM-IMU*) until the wheel stopped rotating. Five deceleration tests were conducted for both dynamo resistances, immediately before and after each test run. An exponential function was fitted to the angular velocity test data, and the function for the rate of change in angular velocity was calculated. The resistive force from the dynamo as a function of angular velocity was then calculated using the following formula:

$$F_{dyn}(\omega) = \frac{Iw_r}{r_w}\frac{\mathrm{d}\omega}{\mathrm{dt}} \tag{16}$$

Where F_{dyn} (N) is the rolling resistance force from the dynamo, ω (rad/s) is the angular velocity of the bicycle wheel and Iw_r (kg*m^2) is the rotational inertia of the rear bicycle wheel. F_{dyn} was considered as a part of the total rolling resistance between the bicycle and the road surface. The C_{rr} contribution from the dynamo, $C_{rr,\,dyn}$, to the total C_{rr} was therefore:

$$C_{rr,dyn} = \frac{F_{dyn}}{F_N} \tag{17}$$

Where F_N was the total load from the bicycle and cyclist. The exact C_{rr} contribution from the dynamo was based on the average bicycle velocity during the test runs.

RESULTS

Aerodynamic Drag

The wind tunnel testing showed that the handlebar-mounted air velocity sensor measured the headwind air velocities in the wind tunnel from 0 m/s to 13.5 m/s with a standard error of the mean (SEM) of 0.28 m/s ± 0.07. The air velocity measurements from the sensor were therefore adjusted for the identified error. The precision of the air velocity measurements was ± 0.06 m/s (SEM).

The results from the wind tunnel testing showed that the C_dA decreased for increasing air velocities. The maximum measured value for C_dA was 0.670 at an air velocity of 2.7 m/s. The minimum measured value for C_dA was 0.605 at an air velocity of 13.5 m/s. A 4th degree polynomial function was fitted the measured C_dA for each air velocity step to with a perfect correlation, shown in figure 5 (left).

The frontal area, *A*, of the bicycle and cyclist was measured with a photo analysis software (*Digimizer*) to be 0.501 m^2. The value of the corresponding drag coefficient, C_d, was therefore between 1.338 – 1.208, for air velocities between 2.7 m/s to 13.5 m/s.

The field experiment for determining C_dA resulted in a second-degree polynomial correlation between air drag force and air velocity, shown in figure 5 (right). The calculated C_dA based on the rate of change in F_{air} with respect to v_{air} was 0.648 ± 0.014 (SE).

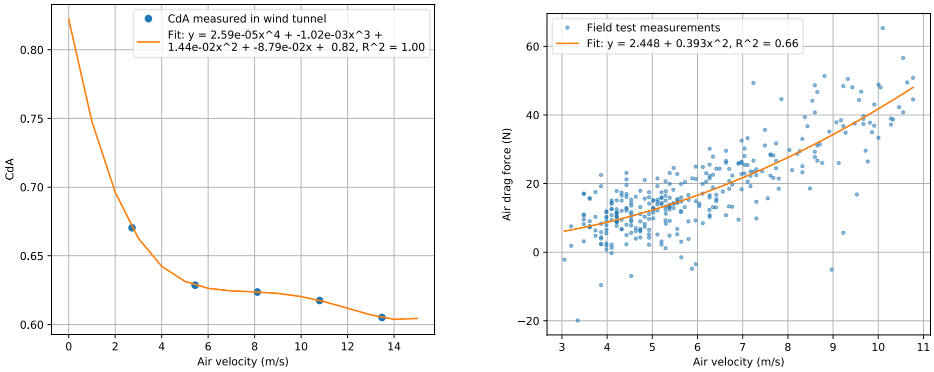

Fig. 5. C_dA measured in wind tunnel (left). Correlation between air drag force and air velocity used to estimate C_dA (right).

Precision and Accuracy

Test 1 was performed with the dynamo axle wheel with the smallest diameter and hence the highest dynamo speeds and the highest dynamo resistance. Test 2 was performed with the smallest dynamo resistance. Figure 6 (left) shows the results from the dynamo deceleration tests before and after test 1 and 2. The dynamo resistance was significantly higher before than after the tests, and the reduction was significantly higher for test 1 than for test 2. For test 1 the reduction in dynamo resistance was 37.7%. For test 2 the reduction was 13.3%. The reduction in dynamo resistance was assumed close to constant during the test runs, and the mean of the before and after test results were used to estimate the expected rolling resistances in tests 1 and 2. Figure 6 (right) shows the expected added $C_{rr,\,dyn}$ in tests 1 and 2 with respect to bicycle velocity.

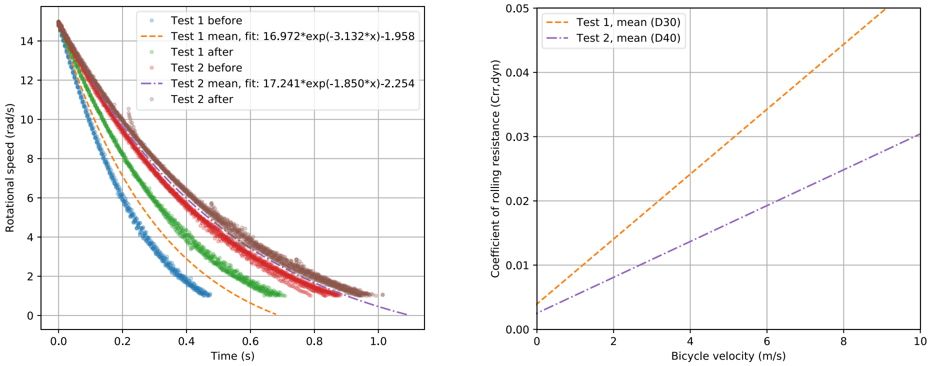

Fig. 6. Dynamo deceleration test (left). Expected added $C_{rr,\,dyn}$ for test 1 and test 2 (right).

Figure 7 (left) shows, starting from the left, the measured C_{rr} in test 0 (0.0073 ± 0.0008 (SE)). The expected C_{rr} in test 1 was 0.0358 ± 0.0008, based on an average test run velocity of 4.93 m/s. The measured C_{rr} in test 1 was 0.0366 ± 0.0006. The expected C_{rr} in test 2 was 0.0247 ± 0.0008, based on an average test run velocity of 5.42 m/s. The measured C_{rr} in test 2 was 0.0260 ± 0.0012. The expected C_{rr} values in test 1 and 2 were found by combining the measured C_{rr} in test 0 and the added $C_{rr,\,dyn}$. The accuracy of the mean of the measured C_{rr} in test 1 and 2 was 97.8% and 95.1%, respectively. The mean accuracy of the C_{rr} measurement method was 96.5%.

In test 0, without any added rolling resistance, the mean of the measured C_{rr} on the test course was 0.0073. The precision was ± 0.0008 (SE). Figure 7 (right) illustrates how the precision of the method increases with increased sample sizes.

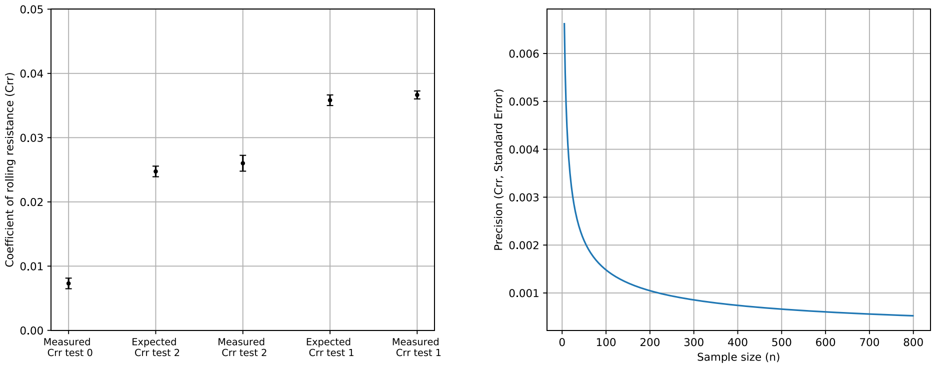

Fig. 7. Results from accuracy testing (left). C_{rr} measurement precision versus sample size (right).

DISCUSSION

Aerodynamic Drag

Previous research has documented C_dA values from wind tunnel testing of competitive cyclists in upright positions range from 0.270 – 0.521 with a mean of 0.355, measured in air velocities between 8.9 m/s and 18 m/s. Previously reported values of the isolated coefficient of drag (C_d), found by accounting for the frontal area, range from 0.600 – 1.33 with a mean of 0.878, measured in air velocities between 8.2 and 21.0 m/s (Crouch, Burton, LaBry, & Blair, 2017). The values found in the wind tunnel in this study seems reasonable and was probably higher than those previously reported because of lower air velocities, the non-racing bicycle utilized in this study and that the cyclist wore more loose-fitting clothes compared to the competitive cyclists. The negative correlation between C_d and air velocity is probably due to turbulence effects (Crouch et al., 2017). The 4th degree polynomial fitted to the C_dA values found in the wind tunnel may give too large C_dA values at low air velocities. This is not considered to be a problem, because the contribution of air drag at low air velocities is relatively small.

The C_dA value obtained from the field test matches the values from the wind tunnel testing very well. By determining the C_dA with a field test like this, the C_dA value is constant for all air velocities. This may decrease the accuracy of the method. However, the accuracy of the method by utilizing the C_dA found in the field test is 95.4% compared to 96.5% by using the C_dA value function found in the wind tunnel. Therefore, it seems like a C_dA determined in a field test at different air speeds is accurate enough to achieve a high level of accuracy with this method. A C_dA determined in a wind tunnel will probably offer a slightly higher accuracy but may not be worth the extra necessary resources.

Precision and Accuracy

The method detected an increase in C_{rr} corresponding to the expected increase $C_{rr,\,dyn}$, added by the dynamo with a mean accuracy of 96.5%. This result indicates that the method is capable of correctly measuring the current rolling resistance on the tested road surface even with changing wind, slope and acceleration.

The reduction in dynamo resistance was significantly higher during test 1 than it was during test 2. The dynamo was noticeably warmer after test 2 than before test 1. The relatively low reduction during test 2 may therefore indicate that more pre-heating of the dynamo would have reduced the relatively large reduction during test 1. However, taking into consideration that the reduction in dynamo resistance continued during test 2, the reduction during both tests probably followed a negative exponential function. Still, the assumption of constant reduction in dynamo resistance during both tests is probably very close to the truth.

The precision of the method, or the standard error of the mean of the measured C_{rr}, was ± 0.0008, based on 322 samples. To obtain accurate and precise measurements, averaging over a stretch is needed. The longer the stretch, the more precise becomes the mean of the measured rolling resistance. Given that the rolling resistance is constant within the stretch, a precision of 0.005 is obtained with 8 samples, and a precision of 0.001 is obtained with 220 samples.

There is no available research on the specific effect of rolling resistance on route choice for bicycle commuters. However, there are some investigations on the effect of hill slope. Three independent studies from large parts of England and Wales, Zurich, Switzerland and Portland, Oregon, USA, agrees that on average, commuting cyclists avoid riding up hills that have a 3% or steeper slope (Broach, Dill, & Gliebe, 2012; Menghini, Carrasco, Schüssler, & Axhausen, 2010; Parkin, Wardman, & Page, 2008). These studies are based on paved roads with non-winter conditions. The power needed to climb a hill with a 3% slope, corresponds to the power needed to travel at a constant speed on a flat road with a C_{rr} of 0.03. By adding the average C_{rr} for a well maintained road bicycle on a paved surface, 0.005 (Wilson et al., 2004), the threshold for a tolerable C_{rr} for bicycle commuters would be 0.035. A precision of ± 0.002 should be enough to determine whether a winter bicycle road provides a C_{rr} above or below the possible critical C_{rr} threshold of 0.035. By utilizing the method presented in this study, a precision of ± 0.002 is achieved at 55 samples. A precision of ± 0.005 is achieved already at 9 collected samples and could also be good enough for some applications. Considering that the method has a sampling frequency of 1 Hz, 9 seconds of measuring would provide adequate precision. More than 55 seconds of measurements would provide excellent precision. Translated into measurement distance this corresponds to 25 meters and 153 meters with a bicycle velocity of 10 km/h.

General Discussion

In the case of Oulu, Finland, where the bicycle inspection should cover one or two kilometers of bicycle roads, this method would be well suited and offer a very high grade of precision. The method could be used to determine an overall C_{rr} level of the tested route and to point out areas of especially high or low levels of C_{rr}. This method would prevent the inspection evaluation to be affected by the physical shape and cycling ability of the controller.

The data in this study were collected on a homogeneous asphalt surface. During winter, the conditions are often much less homogeneous and measurements of C_{rr} would include larger natural variations. The mean of the measured C_{rr} will still give a realistic quantification of the rolling resistance on the tested road stretch.

Preliminary results from testing the method in winter conditions shows clear differences between the rolling resistance measured on snow-covered cycleways, compared to bare-asphalt cycleways. Figure 8 shows an example of the difference between the measured rolling resistance on a wet asphalt-cycleway compared to the same cycleway covered in slush.

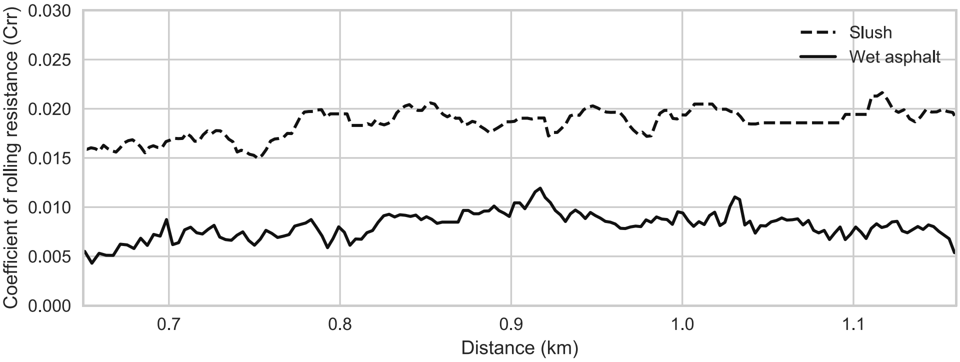

Fig. 8. Preliminary rolling resistance measurements from the same stretch of road with both wet asphalt and slush conditions.

As mentioned earlier, the bicycle in this study was equipped with 42mm wide, 29-inch diameter, studded tires with a 2-bar inflation pressure. The rolling resistance is highly dependent on tire properties. Compared to standard studded bicycle tires, fat-tire bikes will for example probably experience higher rolling resistance on smooth asphalt surfaces and hard, compact snow surfaces due to increased tire rubber deformations and abrasion between tire and road surface. On softer snow surfaces however, fat bikes will probably experience a lower rolling resistance due to a larger contact area, lower contact pressure, and hence less deformation of the snow. A calibration would therefore be important when comparing results across measurement devices.

The research on rolling resistance in winter conditions is limited and there is a need for further investigations. Earlier investigations on rolling resistance in snow have been restricted to unprocessed, dry snow. On winter roads, however, the snow is usually processed in some way, for example compressed or made uneven by traffic, partly melted and re-frozen, mixed with dirt or salt or a combination of these. The presented method can assist in the exploration of the science of rolling resistance on winter conditions. For research specific purposes, the measurement sampling frequency should be higher to allow for a shorter winter-road condition test specimen. A sampling frequency of 10 Hz or 100 Hz would allow for a C_{rr} measurement precision of ± 0.001 on 61-meter or 6.1-meter long test stretches, respectively, given a test velocity of 10 km/h.

CONCLUSIONS

Improved methods for performance evaluation of winter maintenance on bicycle roads may increase the quality of the winter maintenance as well as increase the number of cyclists during winter. Rolling resistance is a useful performance metric that describes the quality of the road conditions and is affected by many important parameters such as snow depth, snow type, and road unevenness. This study has presented a new bicycle rolling resistance measurement method. The method is based on solving the force equilibrium on a moving bicycle. The method is versatile and can perform measurements in all road slopes, wind speeds, and velocities. The method can estimate the C_{rr} on a tire/road surface system with a 96.5% accuracy. A C_{rr} measurement precision of 0.005 is achieved with a measurement sample size of 9 or 25 meters of testing at a velocity of 10 km/h. Based on hill steepness route choices for bicycle commuters, there is a proposed limit at a C_{rr} of 0.035 where people avoid cycling or tries to find alternative routes. To effectively determine whether a bicycle road provide a level of C_{rr} less than 0.035, a precision of ± 0.002 would be adequate. A sample size of 55, or 153 meters of testing at a velocity of 10 km/h is enough to achieve a precision of 0.002. Road condition inspections by bicycle have already been successfully introduced in the city of Oulu, Finland. By adding a quantitative measurement on the road conditions in the form of a coefficient of rolling resistance, these road conditions inspections will become even more important.

The method is already applied on a study on the rolling resistance for bicycles in winter conditions, which will be published elsewhere.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS

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APPENDIX B – PAPER II

Fenre, Klein-Paste

Bicycle rolling resistance under winter conditions

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Bicycle rolling resistance under winter conditions

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Abstract

In many cold regions of the world, the percentage of trips made by bicycle drops drastically during the winter months. To facilitate increased bicycle usage during the winter, we studied the effect of typical winter conditions on bicycle rolling resistance and cycling comfort. An instrumented bicycle was used to measure bicycle rolling resistance under various winter conditions on streets and cycleways in Trondheim, Norway. The rolling resistance was estimated by first measuring propulsive and resistive forces on a moving bicycle and then solving the force equilibrium. Simultaneously, the test cyclist subjectively evaluated the level of cycling comfort, and video recordings were made to document the conditions. Data were collected on 103 road sections, including three levels of service (maintenance standards). The results showed that rolling resistance increased significantly in accordance with increasing loose snow depths. Dry and wet snow leads to a higher rolling resistance than slush does at the same depth. Similarly, increased rolling resistance correlates with reduced cycling comfort. Rolling resistance coefficients (C_{rr}) higher than 0.025 noticeably reduce cycling comfort. The road sections that were maintained with a bare road winter maintenance strategy (using anti-icing chemicals, brushing and/or plowing) provided significantly lower rolling resistance and higher levels of cycling comfort than the sections maintained with a winter road strategy (only plowing and sanding). This study shows that rolling resistance measurements may be used to estimate winter cycling comfort indirectly. Therefore, rolling resistance may be useful for improving winter maintenance operations and controls. Better winter maintenance is essential for increasing bicycle usage in the winter.

Keywords: winter cycling; bicycle rolling resistance; winter maintenance; cycling comfort

Introduction

As a means of transportation in urban areas, cycling has received increased attention for its benefits in terms of public health and economics (Fishman et al., 2015; Gössling et al., 2019; Teschke et al., 2012). A higher rate of cycling also reduces the use of private cars, thereby reducing pollution and congestion (Gössling et al., 2016; Koska & Rudolph, 2016). Cycling also shows excellent potential as pandemic-resilient transportation (De Vos, 2020; Litman, 2020).

Due to cycling's acknowledged benefits, several governments are facilitating increased bicycle usage, especially in urban areas (BMVI, 2012; NMoT, 2016-2017). In Norway, the official goal is to increase the nationwide bicycle share rate from its current level of 5% to 8% by 2023. The term “bicycle share” is the percentage of total trips made by bicycle, and the largest metropolitan areas’ goal is to reach a bicycle share rate of 20% (Lunke & Grue, 2018). One challenge to achieving these goals is cold winters, which have led to a significant drop in the bicycle share rate (Flynn et al., 2012; Nahal & Mitra, 2018). In Norway, the bicycle share rate drops to only 2% in December, January, and February, falling from 7% in May through August (Ellis et al., 2016). Cold temperatures, increased precipitation, reduced visibility, and inclement road conditions have been identified as "barriers" to winter cycling (Bergström & Magnusson, 2003; Brandenburg et al., 2007; Godavarthy & Rahim Taleqani, 2017; Nahal & Mitra, 2018; Spencer et al., 2013). Thus, in order to increase the bicycle share rate, the number of barriers to winter cycling must be reduced.

During the winter, inclement road conditions are usually caused by snow and ice covering the road surface. The presence of snow and ice on the surface leads to reduced friction. Rekilä and Klein-Paste (2016) measured bicycle braking friction under winter conditions. Reduced friction leads to reduced safety for cyclists (Niska, 2010; Sørensen & Mosslemi, 2009). Moreover, snow and ice on the roads often lead to bumps, ruts and other irregularities, which induces vibrations for bicycles and cyclists alike. Cyclists tend to avoid roads with irregular surfaces because these vibrations make the cycling experience less comfortable (Bíl et al., 2015).

Another interesting parameter in cycling is rolling resistance, which acts in opposition to the cycling direction. Rolling resistance is a complex phenomenon that occurs because of deformations in the rolling tire or the traction surface or because of contaminations between the tire and the road surface (Mitschke & Wallentowitz, 2004). These deformations or contaminations cause the vertical reaction of the ground, acting on the wheel, to offset in front of the wheel's center. This vertical reaction offset creates a rolling resistance moment acting against the wheel's driving torque. However, for mathematical descriptions, rolling resistance is commonly expressed as a force (Andersen et al., 2015; Volskaia et al., 2018). The rolling resistance force is equal to the force needed to push (or tow) a wheel (or a vehicle) forward at a constant speed on a level surface, with zero air resistance. A higher level of rolling resistance may extend the duration of cyclists’ regular routes, increase their energy expenditure, making them sweat more and/or cause them to have a less comfortable ride. The presence of snow and ice on the surface leads to increased rolling resistance. Depending on the liquid water content of the snow and contact pressure between the snow and tire, increased rolling resistance occurs when the snow is either compressed under the tire or squeezed to the side of the tire (Lidström, 1979; Shoop et al., 2006; van Es, 1999). The presence of bumps, ruts and irregularities on the road surface also leads to increased rolling resistance (Andersen et al., 2015; Descornet, 1990).

The effect of snow on a bicycle’s rolling resistance depends on its depth, density and mechanical properties in addition to vehicle speed (Lidström, 1979). The most significant properties affecting snow's mechanical characteristics are grain size and formation, density, temperature and liquid water content (Pytka, 2010). Further, variations in wind, temperature, rain, time (sintering) and humidity continuously transform snow's characteristics. It is therefore challenging to determine the characteristics of snow at any given time. Hence, models for predicting rolling resistance are often simplified and based solely on parameters that are easily measured, such as snow depth and density, rather than the mechanical properties of the snow layer itself (Shoop, 2001). Besides, existing models of rolling resistance in snow have been restricted to unprocessed, dry snow. On actual winter roads, the snow is usually processed in some way, having been compressed or made uneven by traffic, partially melted and re-frozen, mixed with dirt or anti-icing chemicals, or a combination of these factors. Models for predicting rolling resistance under winter conditions are therefore not well-suited to obtaining useful information for winter cyclists. So in order to understand the real effect of snow and ice on bicycle rolling resistance, field measurements must be performed under actual winter conditions. Field measurements of bicycle rolling resistance have previously been performed by measuring deceleration over a stretch (coast-down testing) (Steyn & Warnich, 2014; Tengattini & Bigazzi, 2018), and by measuring pedaling power versus speed relationship (Fenre & Klein-Paste, 2021; Lim et al., 2011; Meyer et al., 2016). However, none of these tests have been performed under actual winter conditions.

The winter conditions cyclists encounter depends on weather events and performed winter maintenance operations. The Norwegian Public Roads Administration (NPRA) specifies two standards for winter maintenance of bicycle roads: GsA and GsB. GsA is a bare road standard that allows the use of anti-icing chemicals. GsB is a winter road standard comprised of strict performance requirements with respect to minimum friction level, loose snow depth, unevenness and crossfall, which generally does not allow the use of anti-icing chemicals (NPRA, 2014). While GsA and GsB are usually assigned to high-priority cycleways, winter maintenance is constricted by the local municipality's guidelines on other less prioritized cycleways. Trondheim municipality's guidelines for winter maintenance on cycleways specifies the maximum amount of loose snow depth allowed before maintenance actions are taken, as well as general instructions for sanding and using anti-icing chemicals (Trondheim Municipality, 2020). This municipal standard (MUN) does not have performance requirements and is a significantly "cheaper" standard than the GsB. In practice, this means that more snow may be present before an area is cleared.

In this study, we measured rolling resistance under various winter conditions. Appreciating the complexity of factors determining whether a person is likely to use a bicycle for transportation or not, we simultaneously recorded the cyclists' subjective feelings of unevenness, steerability and overall cycling comfort. Secondly, since a local municipality's chosen maintenance standard determines winter cycling conditions, we documented the maintenance standard on the investigated roads.

This article wants to answer the following research questions: (1) How do typical winter conditions affect bicycle rolling resistance? (2) Are there any correlations between bicycle rolling resistance and cyclists' perceptions of steerability, unevenness, and general cycling comfort? (3) What would be a realistic maximum allowable bicycle rolling resistance level? (4) How do different winter maintenance strategies affect bicycle rolling resistance?

Method

Rolling resistance was estimated using the method described and tested in Fenre and Klein-Paste (2021), a method which uses an instrumented bicycle equipped with sensors to measure pedaling power and pedaling cadence (*Powertap G3 hub*), road slope and airspeed (*Velocomp Aeropod*), and bicycle speed and acceleration (*Garmin Edge 130*) to estimate the rolling resistance rate. This rate was found by using the force equilibrium on the moving bicycle:

$$F_p = F_r + F_g + F_a + F_i + F_f + F_b \tag{1}$$

…where F_p represents the propulsion force, F_r is the rolling resistance force and F_g is the component of the gravity force acting in the opposite direction of the movement of the bicycle. F_a is the air drag force, F_i is the inertia force due to acceleration, F_f is the internal friction force (mainly caused by friction in the drive chain, and, to some extent, the wheel bearings) and F_b is the braking force. Figure 1 shows a schematic of the forces considered.

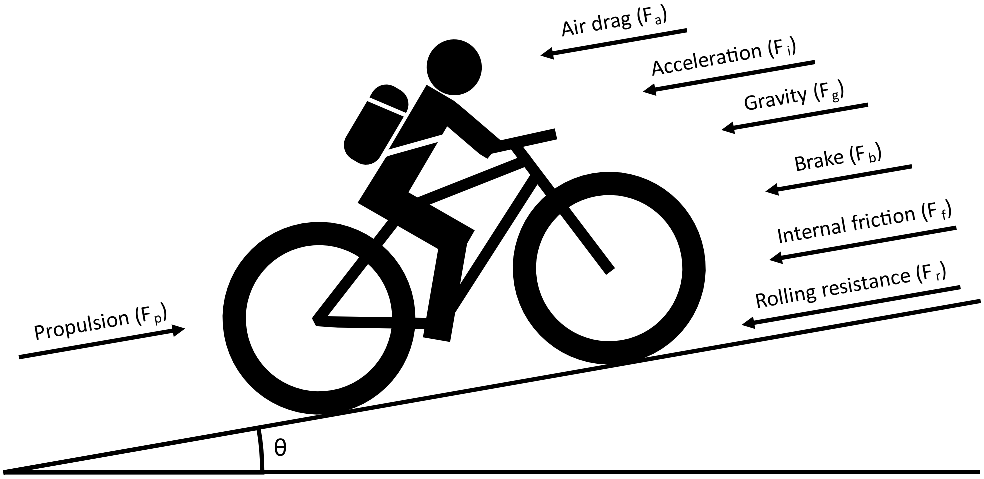


Figure 1: Schematic of the forces considered in the rolling resistance measurement method

The propulsion force was measured between the rear wheel sprockets and rear wheel hub; thus, internal friction resistance from the drivetrain did not affect the force equilibrium. Because the bicycle was new, the drivetrain friction loss was assumed to be negligible, and the resulting internal friction force was neglected in the force equilibrium. Measurements were only included when the pedaling cadence was higher than zero. It was assumed that braking only occurs either while the cyclist is not pedaling or the pedaling cadence is zero. The braking force was therefore set at zero in the force equilibrium. By removing the internal friction force and braking force, the force equilibrium equating the rolling resistance force is shown here:

$$F_r = F_p - \left(F_g + F_a + F_i\right) \tag{2}$$

The component of the gravity force acting in the opposite direction of the movement of the bicycle was calculated as a function of road slope, s, the combined mass of the bicycle and rider, m, and the gravitational acceleration, g:

$$F_g = m\text{g} * \sin\left(\arctan\left(\frac{s}{100}\right)\right) \tag{3}$$

The air drag force was calculated as a function of air density, ρ_{air}, the air-drag coefficient, C_d, frontal area, A, and airspeed, v_{air}:

$$F_a = \frac{1}{2}\rho_{air} * C_d A(v_{air}) * {v_{air}}^2 \tag{4}$$

…where C_dA was determined in a wind tunnel test at NTNU. The C_dA value was also confirmed in a separate outdoor test.

The inertia force was calculated as a function of the combined mass of the bicycle and cyclist, m, the rotational inertia of the front (Iw_f) and rear (Iw_r) bicycle wheel, the wheel radius, r_w, and the rate of change in bicycle velocity, v_b, i.e., the bicycle acceleration:

$$F_i = \left(m + \frac{Iw_f + Iw_r}{{r_w}^2}\right) * \frac{\mathrm{d}v_b}{\mathrm{d}t} \tag{6}$$

Rolling resistance is highly dependent on the wheel load (Baldissera & Delprete, 2016; Clark, 1978; Gent & Walter, 2006; Gillespie, 1992). Due to this fact, it is commonly represented as the ratio between the rolling resistance force and wheel load, or the coefficient of rolling resistance, C_{rr}:

$$C_{rr} = \frac{F_r}{F_N} \tag{8}$$

Figure 2 shows the bicycle with instruments and measurement sensors.

Figure 2: Airspeed, air density, and road slope sensor (A) Pedaling power sensor (B) Instrumented bicycle under winter conditions (C) GPS tracking device (D)

The method estimates the C_{rr} on a given road surface based on measurements of 4 variables (propulsion force, road slope, airspeed and bicycle speed). It is therefore necessary to determine an average over a stretch of road in order to obtain a precise estimation of the C_{rr}. Increased sample sizes improve the method's precision, i.e., the standard error of the mean (SEM) of the estimated C_{rr}. Upon completion of verification testing on bare asphalt, the method precision was found to be ± 0.005, ± 0.002, and ± 0.001 for sample sizes of 9, 55, and 220, respectively. The C_{rr} on hard, smooth pavements for bicycles with high-quality racing tires may be as low as 0.002 and as high as 0.008 for utility tires at low pressure (Wilson et al., 2004). On soft ground, such as sand or snow, the C_{rr} is 10 – 100 times higher (Michelin, 2003). A C_{rr} measurement precision of ± 0.003 (24 samples) should therefore be adequate to differentiate the rolling resistance under different types of winter conditions.

The measurement frequency is 1 Hz. A handlebar-mounted smartphone makes video recordings of the test rides and tracks the route via GPS. Before any field measurements were collected, information about air temperatures and precipitation levels over the previous 24 hours was recorded from the Norwegian Meteorological Institute (NMI, 2019).

The test bicycle was a *Breezer Radar Café*, equipped with 29" *Schwalbe Marathon Winter Plus*, 42mm wide, studded winter tires. Figure 3 shows a photo of the tire tread. The tire inflation pressure was set at 2 bar (200 kPa) and checked at the beginning of every test round. This was the lowest recommended level of inflation pressure for this tire. The maximum recommended pressure was 5 bar. The low pressure was chosen to increase the contact area and reduce contact pressure and deformation of soft ground, such as compacted snow. This would not only reduce rolling resistance on soft surfaces but also increase it on hard surfaces due to increased tire deformations. In very soft snow conditions, such as slush, the tire will disperse the snow to the sides and gain contact with the asphalt surface regardless of the inflation pressure. In this case, an increased inflation pressure will, in addition to less tire deformation, give the tire a narrower contact area, leading to less snow dispersion and lower rolling resistance. All measurements were conducted using the same bicycle and cyclist. The test cyclist was a 28-year-old male, active cyclist. To ensure that the C_dA and combined bicycle/rider mass were kept constant, the same outer clothes were always worn, and the cyclist tried to sit in the same position on the bicycle during each ride.

Figure 3: Tread of the tire used in the experiments (Schwable Marathon Winter Plus)

Field measurements

The bicycle rolling resistance measurements were performed using an instrumented bicycle during the winter of 2019 in Trondheim, Norway. It was desirable to measure rolling resistance on as many different types of winter conditions as possible; therefore, the test route included sections that were maintained through applying three different maintenance standards: GsA, GsB, and MUN. The test cyclist was aware of the maintenance standards along the route, but not whether maintenance was performed as planned on the test days. The length of the test route was 20.3 km, and the route was traveled on four separate days. The sections of the test route were always cycled in the same sequence. Figure 4 shows a map of the test route. The measurements were taken under cold, stable winter conditions both during and after a snowfall, and under soft conditions when the snow melted after a cold period. Detailed information about the climatic conditions during field measurements is shown in Table 1.

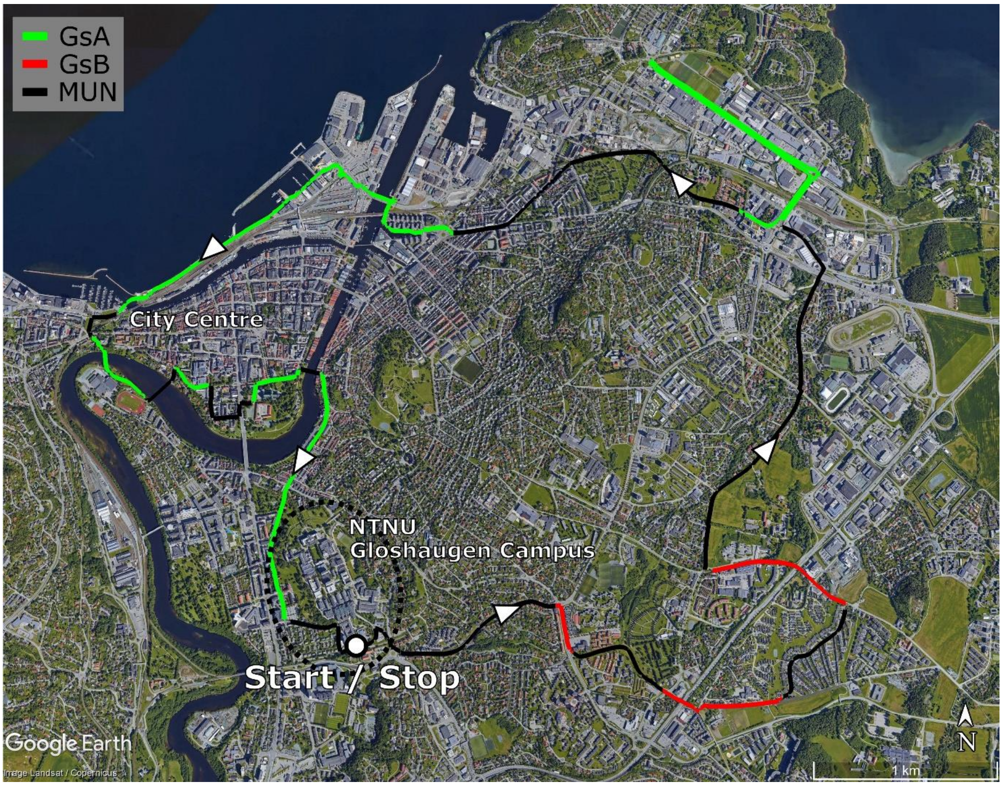


Figure 4: Map of the test route indicating the locations of the different winter maintenance standards

Table 1: Climatic details from the field measurements

Day	Date	Time of day	T_{air} (°C)		Precipitation	
			During test	24 h prior to test Min - Max (Mean)	During test	24 h prior to test (mm, Cumulative)
Wed	Jan 02, 2019	08:39 – 10:01	0.1	-1.2 to 3.8 (0.9)	Rain	5.9 (rain)
Mon	Jan 28, 2019	07:58 – 09:05	-3.7	-6.9 to -3.7 (-5.6)	-	-
Mon	Feb 11, 2019	08:03 – 09:28	-1.8	-3.6 to 1.4 (-0.7)	Snow	4.2 (snow)
Wed	Feb 13, 2019	10:33 – 11:55	4.4	-0.1 to 4.9 (2.2)	Rain	9.0 (snow) + 7.3 (rain)

Each test route was split into 38 or 39 sections on which the road conditions were reasonably constant. The surface conditions on each stretch were visually determined according to the classification provided in Table 2. Because the uncertainty of the estimated C_{rr} decreases with larger sample sizes, sections containing less than 24 samples were removed from the results. When there is a sample size of 24 observations on a smooth, bare asphalt road, the estimated C_{rr} has a precision (standard error of the mean (SEM)) close to ± 0.003 (Fenre & Klein-Paste, 2021). During the rolling resistance measurements, the unevenness, steerability and cycling comfort were rated subjectively by the cyclist on a scale from 1 to 5, where 5 indicated optimal cycling conditions and 1 very poor conditions. Table 3 provides a detailed description of this scale.

Table 2: Photos, description and location of typical winter cycling conditions

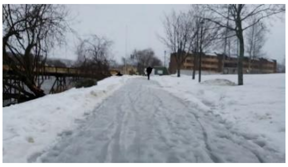
Classification	Description	Typical areas	Example photo
Wet asphalt	Moist or wet asphalt. In generally good condition with few cracks and potholes.	High-priority cycleways and roads.	
Dry asphalt	Dry asphalt in mostly good condition.	High-priority cycleways and roads. The asphalt usually dried during long periods of cold and dry weather.	
Compact snow	Sections with a solid layer of compact snow. Seemingly compacted by snowplows, cars, bicycles, and pedestrians. Probably also affected by thaw-freeze cycles.	Typically found in high-priority cycleways or side streets outside the city center.	
Slush (<2 cm) on asphalt	Asphalt sections with a continuous, or close to continuous, layer of less than 2 cm of slush.	Bicycle lanes separated from other traffic by pavement markings and sprayed with slush from the adjacent traffic.	
Loose snow (<2 cm) on compact snow and Loose snow (2 – 5cm) on compact snow	A layer of compacted snow (compacted by traffic or previous plowing) with a layer of loose snow on top.	Separate pedestrian areas or cycleways and side streets.	
Slush (<2 cm) on top of ice	Typically, compacted snow that had turned to ice with a layer of slush on top. The underlying ice was often bumpy. The temperatures were usually well above the freezing point.	Typical areas were isolated pedestrian areas or cycleways and side streets.	
Loose snow (<2 cm) on asphalt	Occurred during or after a snowfall. The loose snow was fresh and light.	Usually on lower-priority pedestrian areas that were normally kept free from snow and ice.	
Loose snow (> 5cm)	Areas with no visible or tangibile hard surface below the deep loose snow. Varied from fresh untouched snow to loose snow with tracks appearing to have been created by pedestrians and bicycles. Clearly challenging bicycle and walking conditions.	Short stretches of lower-prioritized cycleways and side streets.	

Table 3: Detailed description of the scale used to evaluate unevenness, steerability and cycling comfort

Score	Unevenness	Steerability	Cycling comfort
5	Smooth, hard, road surface.	Good steerability; comparable to smooth pavement.	Very good cycling comfort. Comparable to smooth pavement.
4	Small, visible irregularities in the road surface that are barely felt when cycling.	Slightly reduced steerability. Requires more attention but still easy to steer.	Visible snow, ice or gravel on the road, but feels almost like a bare surface.
3	Uneven surface with noticeable vertical vibrations.	Medium steerability. Some sudden steering deflections that need to be counteracted.	Visible and tangible snow, ice or gravel on the road, but no noticeable reduction in cycling efficiency.
2	Very uneven surface; unpleasantly large vertical vibrations	Challenging to keep going straight because of snow or ice tracks. Front wheel may slide when trying to change direction.	Speed is clearly reduced, and cycling is a lot more physically demanding.
1	Severe unevenness; challenging to keep cycling	Very difficult to keep the bicycle steady. Constantly balancing and turning from side to side to prevent falling.	Particularly challenging to keep the bicycle stable as the speed is very low.

Video recordings of each test ride were analyzed to separate, classify and judge the sections correctly. The same cyclist evaluated the unevenness, steerability and cycling comfort for all test rides. The purpose of evaluating the cycling comfort was to provide a more detailed description of the road conditions and an indication of the cycling experience's overall quality.

Results

Data were collected on a total of 103 road sections, the length of which varied between 80 m and 1520 m. Figure 5 presents the measured rolling resistance on the ten different types of surface conditions. The whiskers in the boxplot mark the center 90% of the measurements. Measurements outside this range are identified as outliers and have not been included in the plot. The box contains the interquartile range (IQR), and the vertical lines illustrate the first 25%, 50% (median) and 75% of the measurements. The width of the notch in each box represents the 95% confidence interval of the median. The small triangles indicate the measurements' arithmetic mean.

The coefficient for rolling resistance, C_{rr}, was lowest on wet asphalt (0.010), while it was more than five times higher on loose snow (> 5cm) (0.056). The average C_{rr} for all conditions except loose snow (> 5cm) lies between 0.010 – 0.035. Increasing depths of loose snow and slush lead to increased rolling resistance. Each section's road conditions had natural variations, which in turn caused variations in C_{rr}. This fluctuation led to measurement outliers and at times a skewed measurement distribution, which most often occurred under conditions having the highest estimated C_{rr}. The standard deviation (SD) range for the estimated C_{rr} for all road condition groups was 0.014 – 0.027. The uncertainty range of the average C_{rr} (SEM) for each group varied between 0.0003 – 0.0019.

There is no overlap among the majority of the 95% confidence intervals (width of the notches) in the medians for each road condition group. While the measured C_{rr} for groups with non-overlapping confidence intervals is statistically different, these intervals did overlap between "Loose snow (< 2cm) on compact snow" and "Slush (<2 cm) on top of ice" and between "Loose snow (<2 cm) on top of asphalt" and "Slush (2-5cm) on top of ice". A Mann-Whitney test confirmed that there was also a statistical difference between the estimated C_{rr} for these groups.

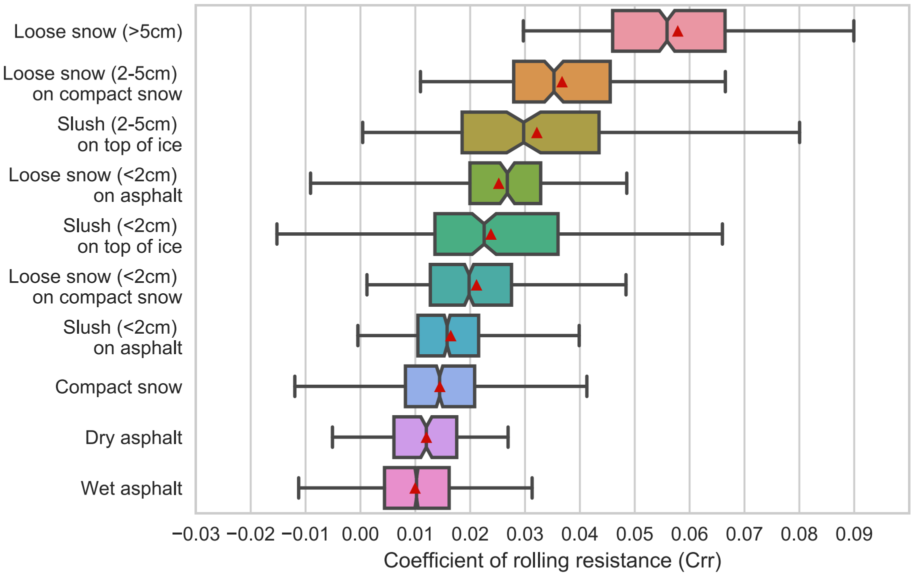


Figure 5: Distribution of the measured C_{rr} for each road condition group

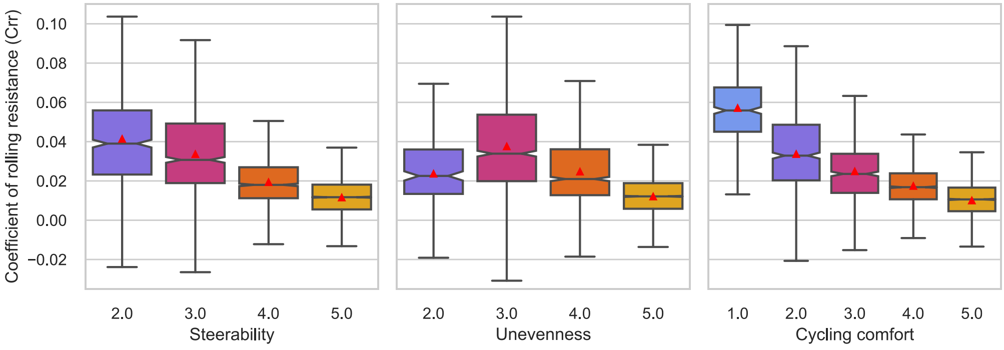
Table 4 shows detailed information from each road condition group, including estimated median, standard deviation (SD) and standard error of the mean (SEM) of the C_{rr}. Table 4 also shows the variation and mean of unevenness, steerability and cycling comfort.

Table 4: Median, standard deviation (SD) and standard error of the mean (SEM) of the estimated C_{rr} for all groups in addition to section and sample count (N), mean air temperature (T_{air}), unevenness (U), steerability (S) and cycling comfort (C)

Road condition	*Count*		C_{rr}			T_{air} (°C)	U^*	S^*	C^*
	Sections	N	Median	SD	SEM	Mean	Min – Max (Mean)		
Wet asphalt	37	4234	0.010	0.017	0.0003	1.3	5 – 5 (5.0)	5 – 5 (5.0)	5 – 5 (5.0)
Dry asphalt	5	317	0.012	0.014	0.0008	-3.5	5 – 5 (5.0)	5 – 5 (5.0)	5 – 5 (5.0)
Compact snow	17	1177	0.014	0.020	0.0006	-1.1	3 – 5 (4.6)	3 – 5 (4.3)	3 – 5 (4.0)
Slush (<2 cm) on asphalt	10	1043	0.016	0.016	0.0005	0.0	5 – 5 (5.0)	5 – 5 (5.0)	4 – 5 (4.2)
Loose snow (<2 cm) on compact snow	14	787	0.020	0.018	0.0006	-1.4	3 – 5 (3.7)	2 – 4 (3.5)	2 – 4 (3.4)
Loose snow (2-5 cm) on compact snow	3	260	0.035	0.021	0.0013	0.4	3 – 4 (3.6)	3 – 4 (3.4)	2 – 3 (2.7)
Slush (<2 cm) on top of ice	4	259	0.023	0.027	0.0017	5.0	2 – 3 (2.1)	2 – 4 (2.9)	2 – 4 (2.3)
Slush (2-5 cm) on top of ice	3	161	0.030	0.024	0.0019	5.0	3 – 3 (3.0)	2 – 2 (2.0)	1 – 2 (1.7)
Loose snow (<2 cm) on asphalt	3	234	0.027	0.021	0.0014	-0.8	5 – 5 (5.0)	4 – 5 (4.8)	4 – 4 (4.0)
Loose snow (>5 cm)	7	532	0.056	0.027	0.0012	-1.0	3 – 4 (3.3)	2 – 3 (2.6)	1 – 3 (1.4)

**5 = very good -> 1 = very poor.*

Figure 6 shows the measured C_{rr} shown in contrast to the subjectively perceived steerability, unevenness and cycling comfort. Analyses of the results show a clear correlation between reduced steerability and increased C_{rr}, thereby demonstrating that the conditions which cause more difficulties for steering also cause increased rolling resistance. Further, there seems to be a correlation between increased unevenness and increased C_{rr}. However, a threshold was reached at unevenness score = 3, where an even lower (worse) unevenness score led to lower (improved) rolling resistance. There was a clear correlation between a decrease in cycling comfort and an increase in rolling resistance.



(b) (c) (a)

Figure 6: Correlation between estimated C_{rr} and subjective perception of cycling comfort, steerability and unevenness (5 = very good -> 1 = very poor)

Figure 7 shows the measured C_{rr} on cycleways with GsA, GsB, and municipal (MUN) winter maintenance standards for each individual test day and the four test days combined. The field measurements showed a significantly lower C_{rr} on the roads with winter maintenance standard GsA than what was found on roads with GsB and MUN. Although there was no significant difference between the estimated C_{rr} on GsB and MUN, there was a clear difference in the conditions that occurred on the roads having distinctive winter maintenance standards. For example, on GsA the road conditions were dominated by wet asphalt and combined asphalt and slush. There were also dry asphalt patches and ones covered with fresh snow in addition to less frequent stretches of compact snow and compact snow combined with less than 2 cm of loose snow. In contrast, no bare asphalt was observed on GsB: on the contrary, these stretches were dominated by compact snow and a certain amount of deep, loose snow (> 5cm). Loose snow (<2 cm) on compact snow and combined ice and slush (2-5cm) were also observed. Moreover, while all types of road conditions were observed on MUN stretches, compact snow, combined compact/loose snow (< 2cm) and loose snow (> 5cm) were the most prevalent. Table 5 shows the share and number of measurement samples from each road condition group and how these road conditions are distributed over the different winter maintenance standards.

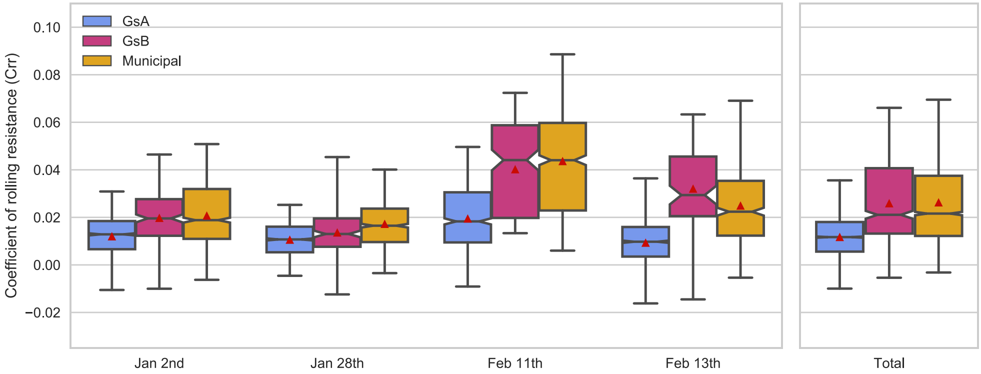


Figure 7: Estimated C_{rr} on bicycle areas with GsA (bare road), GsB (winter road), and Municipal winter maintenance standard for four different dates during winter 2019

Table 5: Distribution of road conditions over three different winter maintenance standards: GsA, GsB, and municipal standard. N = number of samples

	Road conditions	GsA		GsB		Municipal		Total	
		N	%	N	%	N	%	N	%
1	Wet asphalt	3908	70.7	0	0	326	11.4	4234	47.0
2	Dry asphalt	292	5.3	0	0	25	0.9	317	3.5
3	Compact snow	88	1.6	388	62.5	701	24.5	1177	13.1
4	Slush (<2 cm) on asphalt	1015	18.4	0	0	28	1.0	1043	11.6
5	Loose snow (< 2cm) on compact snow	51	0.9	79	12.7	657	22.9	787	8.7
6	Loose snow (< 2cm) on compact snow	0	0	0	0	260	9.1	260	2.9
7	Slush (<2 cm) on top of ice	0	0	0	0	259	9.0	259	2.9
8	Slush (2-5cm) on top of ice	0	0	36	5.8	125	4.4	161	1.8
9	Loose snow (<2 cm) on top of asphalt	173	3.1	0	0	61	2.2	234	2.6
10	Loose snow (>5cm)	0	0	118	19.0	414	14.5	532	5.9

Discussion

The rolling resistance measurements taken from an instrumented bicycle under winter conditions yielded median C_{rr} values between 0.010 and 0.056. To place these numbers in perspective, C_{rr} = 0.01 is equivalent to the resistance felt on a flat road, while C_{rr} = 0.056 feels like a 4.6% uphill slope. This range of resistance is noticed by any bicycle commuter, irrespective of their fitness level. The C_{rr} for bicycles with high-quality racing tires on hard road surfaces can be as low as 0.002 and as high as 0.008 for utility tires at low inflation pressure (Wilson et al., 2004). The average C_{rr} on wet and dry asphalt found in this study lay between 0.010 to 0.012. This seems like a relatively high reading; a probable reason for this was the low air and pavement temperatures, each around 0°C, which led to decreased elasticity in the tire rubber. In addition, at only 2 Bar, the inflation pressure was low, a situation which caused larger deformations in the tire, in turn increasing the effect of low tire elasticity. The most important reason for the seemingly high C_{rr} on bare asphalt was probably the fact that the tires had steel studs for increased traction on icy surfaces. The studs improve safety and maneuverability on ice. However, when there is no ice or snow on the road surface for the studs to penetrate, they are instead pushed into the tire, causing more tire rubber deformations. Also, the energy loss from tire slippage on bare asphalt is probably higher for studded tires than for regular tires, leading to a larger measured Crr. Further, the C_{rr} was significantly lower on wet asphalt compared to dry asphalt. This can be explained by the surface water acting as a lubricating agent, reducing both slippage friction - and abrasion in tire studs and pavement alike.

The average C_{rr} on compact snow was 0.014, a reading only slightly higher than that found on asphalt. This was expected because even though the surface is relatively hard, a cyclist expends a certain amount of pedaling energy on deforming compact snow. The low C_{rr} shows that compact snow is not only an efficient surface for winter cycling, but it is also available without the use of anti-icing chemicals. A smooth layer of compact snow is, however, dependent on having consistently cold winter conditions.

The rolling resistance increased along with snow depth. This increment concurs with the literature: in snow with similar density and strength, increased snow depths lead to higher levels of rolling resistance due to a larger volume of deformable snow (Lidström, 1979; van Es, 1999). Compared to loose snow (dry or wet), increasing depths of slush led to a smaller rise in C_{rr}. When a maximum of 2 cm of slush lay on top of asphalt, this only led to a C_{rr} of 0.016, or a relative rise of 60% compared to wet asphalt. The same depth of dry or wet snow on top of asphalt led to a C_{rr} of 0.027, causing a 170% higher rolling resistance than wet asphalt. Larger depths of slush and snow indicated the same finding: between 2-5cm of slush on top of ice yielded a C_{rr} of 0.030, whereas 2-5cm of dry or wet snow on top of compact snow led to a C_{rr} of 0.035. Slush has a higher liquid water content than dry or wet snow, giving it a significantly higher density, meaning that more mass must be compacted/displaced to move slush than the same volume of snow, suggesting a higher rolling resistance increase. However, the high level of water content also lubricates the bonds between the snow crystals, which makes the slush behave more like a liquid than a deformable solid. Therefore, the slush is easily squeezed out to the tires' sides rather than compressed under the tire like dry snow. Giudici et al. (2019) discovered that this squeeze-out effect is dominant in snow having a liquid water content level higher than 10% by weight. This fact can explain why slush offers less additional rolling resistance than dry or wet snow despite its higher density level.

In addition to snow type and depth, we also found correlations between perceived steerability and rolling resistance, as seen in Figure 6a. Table 4 shows that deep slush on top of ice and deep loose snow caused the worst steerability. This correlation was expected because, in addition to increased rolling resistance, loose snow (dry, wet or slush) causes increased steering resistance. Energy is needed to displace or compress snow in order to change the front wheel's direction in loose snow. Steering can also be problematic in very wet snow because it offers a low level of friction, even with studded tires. So in compacted, wet snow, the front wheel can slip when the cyclist initiates a turn. When cycling uphill, this can also allow the rear wheel to spin, significantly increasing the energy output and therefore the rolling resistance.

Figure 6b shows that the correlation between increased unevenness and rising rolling resistance was clear for the three "best" grades of unevenness (3, 4, and 5). For the “worst” given grade of unevenness (2), the rolling resistance decreased to about the same level as for unevenness grade 4. Surfaces comprised of the worst grade of unevenness (1) were nearly impossible to cycle on; hence, the number of collected samples on these surfaces was too low to achieve statistically reliable data. The power lost when cycling over bumps is determined by the amplitude and frequency of the bicycle's and cyclist's vertical displacement. At amplitudes less than 60mm and frequencies lower than 6 Hz, the power loss has been found to be less than 2.7W, corresponding to an increase in C_{rr} of 0.0012 (at 10km/h and a combined bicycle and cyclist mass of 84 kg). Higher frequencies and amplitudes quickly increase this power loss by several magnitudes (Pradko & Lee, 1966). Most human limbs and organs have frequencies between 0.5 and 10 Hz, and this is also the frequency spectrum that causes most human discomfort (Clevenson et al., 1978; Griffin, 1990). While higher frequencies cause higher power loss, they may also be more comfortable, a correlation that may explain why the largest rolling resistance did not coincide with the worst perceived unevenness in this study. However, at levels below $C_{rr} = 0.02$, the correlation between unevenness and rolling resistance is clear.

Figure 6c showed that decreased cycling comfort correlates with increased rolling resistance. This finding was expected based on the observed correlations between rolling resistance and loose snow depths, unevenness, and steerability. These are all winter condition components that increase rolling resistance and reduce cycling comfort. By ensuring that the rolling resistance level stays within an acceptable range, we can indirectly ensure that unevenness, steerability, and general cycling comfort remain tolerable. Therefore, we can use rolling resistance as a universal, quantitative parameter to describe both the physical efficiency of the road surface and the available level of cycling comfort.

Due to the length (over 20 km) and variable conditions over the test course, one could expect that the cyclist felt tired towards the end of the route and that this affected the perceived cycling comfort and the cycling speed. However, the statistical analyses showed no correlation between the cycling comfort parameters or speed and distance traveled.

Transportation policymakers are interested in understanding how the increased rolling resistance due to winter conditions affects bicycle transportation statistics. Although there is currently no available information describing this correlation, the rolling resistance adds to the same force balance as the slope resistance (equation 1). We may therefore assume that we can use earlier studies on the effect of slopes and hilliness to predict consequences. Previous results from route choice investigations for cyclists in Portland, Oregon, and Zurich, Switzerland, indicate that cyclists generally avoid routes with slopes steeper than around 3% (Broach et al., 2012; Menghini et al., 2010). Further, an analysis of British travel habits showed that a 10% increase in the *hilliness* proportion was associated with an 9% reduction in proportion cycling for commuting to work. The hilliness factor is a measurement for the proportion of 1 km squares in a district with a mean slope of 3% or greater (Parkin et al., 2008). By converting the hill slope resistance from a 3% slope to rolling resistance from inclement surface conditions, the results from these studies suggest that cyclists generally avoid routes when more than 10% of the route has a C_{rr} greater than 0.04. Indeed, the average estimated rolling resistance on most sections in this study (92%) lay below the suggested 3% slope, or equivalent to $C_{rr} = 0.04$ resistance threshold. Considering the findings in this study, it seems like a realistic critical rolling resistance for winter cycling should be lower than $C_{rr} = 0.04$. The average C_{rr} on stretches considered to have a medium level of cycling comfort (subjective cycling comfort score = 3) was 0.024. Therefore, a Crr around 0.025 seems like a more realistic threshold where most people would choose either a different route or not cycling at all. The threshold for rolling resistance caused by snow and ice is also likely lower than that caused by climbing hills because snow and ice also often contribute to increased bumpiness and steering challenges.

The field measurements show that implementing a winter road strategy (GsB) results in a significantly higher rolling resistance (average $C_{rr} = 0.021$) than cycleways maintained with a bare road strategy (GsA) (average $C_{rr} = 0.012$). This is not surprising, because without the use of anti-icing chemicals (GsB), there is more snow and ice on the road, leading in turn to increased rolling resistance. The most dominant road conditions on GsA roads were wet asphalt (70.7%) and asphalt with less than 2 cm of slush (18.4%). On the tested GsA roads, 96.9% of all stretches had an average C_{rr} below the previously discussed critical C_{rr} threshold of 0.025. On GsB roads, compact snow (62.5%) was the most dominant road condition. There was, however, also a considerable amount of deep, loose snow (> 5cm) (19%) and compact snow combined with loose snow (< 2cm) (12.7%). In total, 75.2% of the tested GsB roads had stretches with average C_{rr} levels below 0.025. On the roads with municipal standards, the conditions varied more among all types of conditions, and 86.8% of these stretches had average C_{rr} values below 0.025. These numbers confirm that the increased effort of a higher service level does result in an increased fraction of sections that are favorable for cycling.

In this study, the correlation between rolling resistance and cycling comfort was only assessed using one test cyclist. A larger number of cyclists' perceptions should be evaluated to find a more reliable and tolerable rolling resistance threshold. It is also important to appreciate the fact that the test runs were performed on only four different days; moreover, coincidences may have led to the differences between the conditions on the stretches with different winter maintenance strategies. Nonetheless, looking at the total values in Figure 7, we can see that the measured C_{rr} on GsA roads is significantly lower than that measured on GsB and MUN; however, between GsB and MUN there is no significant difference in the measured rolling resistance. More data (several days of measurements taken during a winter season) is needed to determine the actual difference in performance between GsB and MUN, which could be a topic for further study.

Conclusions

A hybrid bicycle with 42 mm wide and 29-inch diameter tires inflated to 2 Bar was used to measure the rolling resistance on different winter road conditions. The rolling resistance was estimated by measuring propulsive and resistive forces and solving the force equilibrium on the moving bicycle. The average coefficient of rolling resistance (Crr) varied between 0.010 – 0.056. A Crr of 0.010 is equivalent to the resistance felt on a flat road, while Crr = 0.056 feels like a 4.6% uphill slope. The rolling resistance was slightly lower on wet asphalt (Crr = 0.010) compared to dry asphalt (Crr = 0.012). A smooth, compact snow surface yielded a Crr of 0.014. Increasing snow depths led to a higher rise in rolling resistance than rising depths of slush. Increased rolling resistance was caused by two factors: the presence of loose snow and uneven surfaces.

The measured rolling resistance was found to correlate with the subjective overall feeling of cycling comfort. High levels of rolling resistance were also found to correlate with reduced steerability and increased unevenness. This finding means that the method offers an objectively measured parameter that can indirectly indicate levels of cycling comfort under winter conditions. Objectively measured performance parameters are preferred when road owners outsource winter maintenance services to contractors.

A rolling resistance of Crr = 0.025 seems to be a reasonable threshold to indicate whether or not the conditions are satisfactory for bicycle commuters. However, as this statement is based on the subjective perception of one person, more data is needed to confirm or adjust this criterion.

Winter maintenance of cycleways using a high standard such as the bare road strategy (GsA) keeps the rolling resistance at a tolerable level, even during heavy snowfalls. Further, while a winter road strategy with strict performance criteria (GsB) keeps the rolling resistance tolerable during stable winter weather, GsB roads offered rolling resistance worse or much worse than the tolerable threshold during and after heavy snowfalls.

Finally, while it may not be practically feasible for most cities to undertake frequent rolling resistance control rides using an instrumented bicycle like the one employed in this study, this type of bicycle is a powerful research tool that can be applied to classify several winter cycling conditions through utilizing rolling resistance data, written descriptions and high-definition video recordings. All of these factors may be useful for both evaluating different maintenance standards or methods and labelling images used in machine learning algorithms.

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Data Availability

All data and code that support the findings of this study are freely available as an online Mendeley dataset (Fenre & Klein-Paste, 2020).

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APPENDIX C – PAPER III

Fenre, Klein-Paste

The effect of rolling resistance on people's willingness to cycle during wintertime

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The effect of rolling resistance on people's willingness to cycle during wintertime

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Abstract

Harsh winters reduce utilitarian cycling in many cities. Using an online survey, we examined how increasing rolling resistance due to snow and ice affect people's cycling willingness. The respondents (N = 1318) reported their willingness to cycle on various winter cycling conditions presented in photos. The answers were compared to the rolling resistance levels on the presented conditions, measured in a previous study. Respondents' cycling willingness dropped from 91.2% at very low to 18.3% at very high rolling resistances. The cyclist's age, gender, local climate, winter cycling experience and studded tire use affected the cycling willingness significantly. Electric bike usage did not affect cycling willingness. "Summer-only" cyclists did not cycle during the winter due to low temperatures (29%), lacked feeling of safety (27%), bicycle wear (17%), increased travel time (17%) and increased physical effort (10%). Hence, lower rolling resistance and increased use of studded tires can increase the cycling frequency of existing winter cyclists. To recruit new winter cyclists, the surface conditions should not only offer a low rolling resistance but should also be perceived as safe and comfortable.

Keywords: Sustainable transportation; winter cycling; cycling willingness; rolling resistance; winter maintenance.

1. Introduction

The number of both recreational and utilitarian bicycle trips often drops significantly during the winter months. This is especially the case in the Nordic countries (Aalto-Setälä et al., 2017; Bergström & Magnusson, 2003; Ellis et al., 2016; Nordström et al., 2014) and some parts of Northern America with harsh winters (Amiri & Sadeghpour, 2015; Flynn et al., 2012; Orvin, 2020; Sears et al., 2012). Fournier et al. (2017) found that in areas with harsh winters (in the northern hemisphere), the seasonal bicycle usage can be estimated with a sinusoidal model peaking on July 1 and being at the minimum on January 1. The most prominent "barriers" to winter cycling have been identified to be cold temperatures, increased precipitation, darkness and inclement road conditions (Bergström & Magnusson, 2003; Brandenburg et al., 2007; Godavarthy & Rahim Taleqani, 2017; Nahal & Mitra, 2018; Spencer et al., 2013).

There is a widespread political desire to increase bicycle usage throughout the year because it can relieve the pressure on overcrowded metros and buses (Sun & Zacharias, 2017). More cycling also leads to benefits in terms of public health, travel-time reliability, cost-effectiveness, reduced congestion and pandemic resilience (Blondiau et al., 2016; Fishman et al., 2015; Koska & Rudolph, 2016; Litman, 2020; Teschke et al., 2012). Due to the acknowledged benefits, several governments have set official goals for increased cycling. The current Norwegian National Transport Plan (2018-2029) states that walking and cycling should cover 40-60% of all passenger traffic increases in urban areas (NMTC, 2018). Finland's new energy and climate strategy include an official national goal to increase the number of trips made by bicycle or foot to 30% by 2030 (Huttunen, 2017). Sweden published a national strategy dedicated to more and safer cycling and invested 100 million SEK in promoting cycling in a 2016-2017 initiative (SMEI, 2017). Malone (2020) analyzed cycling policies that have been deployed in several European cities in a report produced for EU city planners, decision-makers and citizens. The report underlines that a successful cycling policy can only be achieved by an organization with knowledge and cycling data. Malone indicates that municipalities should build this knowledge by developing relationships with engineering firms, schools, cycling associations and consultants.

The goal of deploying cycling policies is to increase cycling by inducing changes in the factors determining people's cycling habits, i.e., cycling determinants. Previous research has documented these factors thoroughly. Pucher and Buehler (2012) summarize the majority of academic research on how to increase cycling in cities and make it safer for all society segments. Heinen et al. (2010) present a comprehensive review of the academic literature on the dominant factors affecting people's decision to cycle or not. To summarize, the cycling determinants can be divided into four main categories, namely the natural environment (weather and topography), the built environment (infrastructure and land-use mix), temporal factors (calendar-events and time of day), and other (individual and cultural) factors. An et al. (2019); Butterworth and Pojani (2018); Schneider (2013); Willis et al. (2015) have later written complementary overviews on this topic.

To increase cycling, one can induce changes in the cycling determinants to either recruit new cyclists or increase current cyclists' cycling frequency. To recruit new cyclists, there is often a need to reduce cultural or personal barriers such as a negative attitude towards cycling or work and family commitments. Occasional cyclists are often reluctant to increase their cycling frequency due to flexibility and practical matters, for example, if they need to transport cargo during the day (Gatersleben & Appleton, 2007). Moreover, to encourage summer cyclists to cycle more during the winter, proper winter maintenance, especially snow removal, is essential (Bergström & Magnusson, 2003; Niska, 2010; Svorstøl et al., 2017; Sørensen & Mosslemi, 2009). However, to evaluate the cost-benefit of improved winter maintenance, there is still a need for more knowledge about the actual effect of improved winter maintenance (Veisten et al., 2019).

The purpose of winter maintenance is to improve the road surface conditions. During the winter, snow and ice on the roads often reduce skid resistance and steerability and increase cycling resistance and unevenness. Quantifiable surface quality measurements are important to evaluate the effect of winter maintenance performances on infrastructure winter resilience (Xu et al., 2017). Friction measurements have been used to quantify the skid resistance, and an adequate friction level is essential for cycling safety (Niska, 2010; Niska et al., 2014).

Another quantifiable measure of the surface conditions is rolling resistance. The rolling resistance increase with increasing loose snow depths and unevenness (Descornet, 1990; Fenre & Klein-Paste, (under review); Lidström, 1979; van Es, 1999). The rolling resistance is also highly dependent on the bicycle properties, i.e., tire rubber properties, inflation pressure and contact area (Clark & Dodge, 1979; Gent & Walter, 2006). Previous research has found a nearly linear relationship between wheel load, i.e., the average contact pressure times the contact area between the wheel and the road surface, and rolling resistance force (Baldissera & Delprete, 2016; Clark, 1978; Gent & Walter, 2006; Gillespie, 1992). The coefficient of rolling resistance, C_{rr}, has therefore been established to compare rolling resistances for different wheel loads:

$$C_{rr} = \frac{F_r}{F_N}$$

where F_r is the rolling resistance force and F_N is the wheel load.

Fenre and Klein-Paste (2021) developed a new method for estimating bicycle rolling resistance on cycleways by measuring propulsive and resistive forces on a moving bicycle. This method considers pedaling power, air drag forces, inertial forces, and gravity forces. The method is suitable for rolling resistance measurements at variable speeds, variable weather conditions, and any road gradient. This method was utilized to investigate how bicycle rolling resistance is affected by typical winter conditions on cycleways. These investigations found a strong correlation between the rolling resistance level and snow type, loose snow depth, and unevenness (Fenre & Klein-Paste, (under review)). Moreover, there seems to be knowledge gap about how the rolling resistance level correlates to people's willingness to cycle. This knowledge can help determine how various winter maintenance actions affect the urban infrastructure resilience during wintertime.

In this study, we used an online survey to collect data about people's willingness to cycle on various winter cycling conditions shown in photos. We compared the cycling willingness results to rolling resistance measurements of the same conditions collected in a previous study (Fenre & Klein-Paste, (under review)) and investigated how people's stated willingness to cycle is affected by the rolling resistance level.

2. Method

2.1 Data collection

The data in this study was collected during May 2020 through an online survey. The participants were mostly recruited through Facebook. Invitations to the survey were shared in several cycling-affiliated groups, in groups for environmental organizations and Norwegian municipalities' Facebook-groups. The survey was also shared through the authors' private Facebook accounts and via e-mail and internal network channels to the Department of Civil and Environmental Engineering at NTNU and the Norwegian Public Roads Administration (NPRA).

The survey included socio-demographic questions to map the participant's age, gender and location (county). The participants' ages were sorted into six age groups: under 18, 18 to 35, 36 to 50, 51 to 65 over 65 years old. The participants' locations were sorted by the Norwegian main geographical regions: North, Middle, West, East and South. As most utilitarian cycling occurs in urban areas, we chose to collect climate data from the largest cities in each region as reference points to analyze the effect of climate on cycling. Figure 1 shows Norway's location in Europe, the Norwegian geographical regions and the largest cities in each region. Table 1 shows climatic data for these cities during the winters (October - March) of 2010 – 2020.

There were also questions mapping how often the participants cycle during the summer (April - September) and how often they cycle during the winter (October - March). Those respondents who answered that they cycle during the winter (the winter cyclists) were asked what type of bicycle they usually use when cycling during the winter. The winter cyclists were also asked whether they normally use studded tires when cycling during the winter. Those who answered that they cycle during the summer but not during the winter (summer only cyclists) were asked to specify the reason for not cycling during the winter. For this question, there were five alternatives: 1) it takes too much time; 2) It is too cold; 3) I do not feel safe; 4) It is too tiring; 5) I want to avoid wear and tear on my bicycle. This question was asked to investigate how and to what extent improved winter maintenance may affect summer only cyclists.

Figure 1: Map illustrating Norway's location in Europe, the main Norwegian geographical regions and their largest cities.

Table 1: Mean annual snowfall, snow days (days with snow precipitation) and mean temperature from October to March for the years 2010–2020 for the largest cities in each of Norway's main geographical regions (The Norwegian Meteorological Institute, 2020).

Region	City	Mean annual snowfall (cm)	Mean annual snow days	Mean temperature (°C)					
				Oct	Nov	Dec	Jan	Feb	Mar
South	Kristiansand	74.6	11.3	8.3	4.0	1.1	-0.8	-0.2	2.7
	Arendal	103.9	15.5	9.5	5.4	2.9	0.7	0.6	3.0
East	Fredrikstad	60.7	13.2	8.9	4.5	1.6	-1.1	-0.7	2.2
	Oslo	115.4	23.4	6.8	2.2	-1.3	-3.3	-2.0	1.8
	Hamar	101.7	25.1	5.2	0.1	-4.5	-6.9	-5.1	-0.8
Middle	Trondheim	130.7	26.1	6.0	1.7	-0.6	-2.2	-1.0	1.0
	Steinkjer	142.8	29.6	5.6	1.7	-1.0	-3.1	-1.9	0.4
West	Stavanger	28.8	5.4	9.2	5.8	3.7	1.9	2.0	3.8
	Bergen	76.7	11.3	9.0	5.3	3.4	1.8	2.3	4.0
	Ålesund	76.3	10.1	8.4	5.4	3.8	2.8	2.8	4.4
North	Bodø	147.0	27.7	6.0	2.9	1.0	-1.3	-0.8	0.3
	Tromsø	275.2	44.9	3.5	0.5	-1.4	-3.7	-3.3	-2.0
	Alta	189.3	48.8	2.7	-2.3	-4.5	-8.1	-7.2	-3.7

The survey's main part contained 37 photos of winter cycling surface conditions collected in January and February of 2019. The photos were collected during rolling resistance measurements on winter conditions using a bicycle steering bar-mounted camera. The photos show various road conditions, including wet asphalt, slush, compact snow, ice, loose snow, and dirt and salt-contaminated snow. For clarification, a short description of the road conditions was provided for each photo. For each photo, the participants were asked: Are you willing to cycle here? They could choose one out of four alternative answers: A: Not at all; B: A short stretch; C: Large parts of the route; D: The whole route. The survey did not reveal to the participants the rolling resistance levels on the conditions in the photos. Eight road stretches were shown twice or thrice during the survey, with very similar photos (taken a few meters apart). Respondents who submitted completely different answers on very similar photos were identified as inconsistent and removed from the results.

The survey photos were snapshots from video recordings captured during an earlier study where rolling resistance was measured on various winter cycling conditions. The rolling resistance was estimated using an instrumented bicycle that measured propulsive and resistive forces acting on the moving bicycle. The instrumented bicycle had sensors measuring pedaling power, airspeed, velocity and road gradient. The rolling resistance was found by solving the force equilibrium on the moving bicycle. The rolling resistance measurement method is described in detail in Fenre and Klein-Paste ((under review)). Thus, each survey photo had a corresponding rolling resistance level. In the survey, the photos were shown in a random rolling resistance order. The full survey, answers, photos and rolling resistance data are available as an online dataset (Fenre & Klein-Paste, 2020a).

2.2 Data analyses

In the data analyses, the survey data was combined with the rolling resistance data. The cycling willingness answers were sorted after rolling resistance levels on the conditions in the photos and placed into six rolling resistance level ranges going from $C_{rr} = 0.00$ to $C_{rr} = 0.06$. Table 2 shows the mean and standard deviation of the measured rolling resistance in each group, as well as three example photos of the road conditions in each group. Exploratory data analyses were used to discover differences in cycling willingness for different rolling resistance groups between different participant groups. To test whether the differences observed in the exploratory analyses were significant between the answers from different age, location and cycling frequency groups, we utilized a Kruskal-Wallis one-way analysis of variance test. The Kruskal-Wallis test is a nonparametric method for testing whether samples originate from the same distribution (Kruskal & Wallis, 1952). If the Kruskal-Wallis test indicated that the distribution of some groups significantly differed from the others, a Dunn's post hoc test for multiple comparisons of mean rank sums was performed to identify which groups differed from each other (Dunn, 1964). A Mann-Whitney u-test was used to find significant differences between opposite groups: female or male, electric bike (e-bike) or not and studded tires or not. The Mann-Whitney u-test is a nonparametric test of the null hypothesis that, for randomly selected values x and y from two populations, the probability of x being greater than y is equal to the probability of y being greater than x (Mann & Whitney, 1947). The statistical tests were performed with a significance level, $\alpha = 0.05$. To limit the relative size difference between the groups in the statistical analyses, groups with less than N=40 respondents were excluded.

Table 2: Example photos of road conditions providing six ranges of bicycle rolling resistance. Mean measured rolling resistance and ± standard deviation in parentheses.

C_{rr} level 1: $0.00 < C_{rr} \leq 0.01$ (0.0075 ± 0.0019). N = 4

C_{rr} level 2: $0.01 < C_{rr} \leq 0.02$ (0.0136 ± 0.0022). N = 8

C_{rr} level 3: $0.02 < C_{rr} \leq 0.03$ (0.0269 ± 0.0024). N = 9

C_{rr} level 4: $0.03 < C_{rr} \leq 0.04$ (0.0377 ± 0.0017). N = 7

C_{rr} level 5: $0.04 < C_{rr} \leq 0.05$ (0.0446 ± 0.0038). N = 5

C_{rr} level 6: $0.05 < C_{rr} \leq 0.06$ (0.0546 ± 0.0018). N = 5

3. Results

The survey received a total of 1318 complete responses. 30 responses were filtered out due to inconsistency. The respondents reside all over the country with a predominance of people from the eastern and middle part. The survey had more male (79%) than female (31%) respondents. The largest part of respondents was in the age group from 36 to 50 years old (45%). The age groups from 18 to 35 (24%) and 51 to 65 years old (30%) and were also well represented. The age groups 66 to 75 and more than 75 years old were combined and represented 2% (N=31) of the respondents. The respondents younger than 18 were excluded from the statistical analyses due to a small sample size (N=9).

7% of the respondents answered that they were "summer only" cyclists. Only 1% (N=19) were not cyclists at all. 92% responded that they are winter cyclists, meaning that they use a bicycle for utilitarian purposes more than once per month during the winter. 76% stated that they cycle several times per week during the winter. Out of the winter cyclists, 26% answered that they mostly use e-bike when cycling in the winter months. This is more than the e-bike share rate for Norway as a whole (15%) (Norwegian Public Roads Administration (NPRA), 2019). 89% of the winter cyclists responded that they normally use studded tires during the winter months.

Among the "summer only" and "not at all" cyclists, the reasons for not cycling during the winter were: "It is too cold" (29%), "I feel unsafe" (27%), "I want to avoid wear and tear on my bicycle" (17%), "It takes too long" (17%) and "It is too tiring" (10%).

To analyze the respondent's stated willingness to cycle on the survey photos' conditions, we introduce the *cycling willingness index* (CWI). CWI is defined as the percentage of respondents answering: "Large parts of the route" or "The whole route" to the question "Are you willing to cycle here?".

Figure 2 shows CWI plotted against the coefficient of rolling resistance for different respondent groups. Table 3 contains the tabular data for Figure 2. The figure shows a clear reduction in CWI as the rolling resistance increases. Figure 2A shows that overall, the CWI increases from 25% at $C_{rr} \approx 0.049$ to 50% at $C_{rr} \approx 0.027$ to 75% at $C_{rr} \approx 0.012$ and up to 90% at $C_{rr} \approx 0.008$. A general trend among all respondents is that the reduction of CWI for increasing rolling resistances is rapid at first before the reduction gradually slows down and eventually seems to flatten out at large rolling resistances.

Figure 2B shows that male cyclists are less affected by increasing rolling resistance levels than female cyclists. Figure 2C shows that the age group over 65 years old is marginally, yet significantly, more affected by increasing rolling resistance than the rest of the respondents. Figure 2D shows that the CWI of people living in northern Norway is significantly less affected by increasing rolling resistance than people living in the rest of the country. Increasing rolling resistance levels affect the CWI of people living in the middle and the eastern part of Norway significantly more. Those most affected are the people living in western Norway. There were not enough respondents from the southern part of Norway (N=19) to find any significant results for this group. Figure 2E shows that year-round cyclists show a significantly higher CWI than summer only cyclists for all rolling resistance values. The most considerable difference in CWI is found at C_{rr} values between 0.02 and 0.03. Figure 2F shows that people's winter cycling frequency affects their CWI. The cycling willingness is largest for those cycling daily during the winter and decreases gradually for the weekly, monthly, and never winter cyclists. Figure 2G shows that CWI of e-bike users are equally affected by increasing C_{rr} levels as the other bicycle type users. Figure 2H shows that cyclists who use studded tires are significantly less affected by increasing rolling resistances than cyclists who do not use studded tires during the winter. The difference is largest at medium-large C_{rr} values (between 0.02 and 0.03).

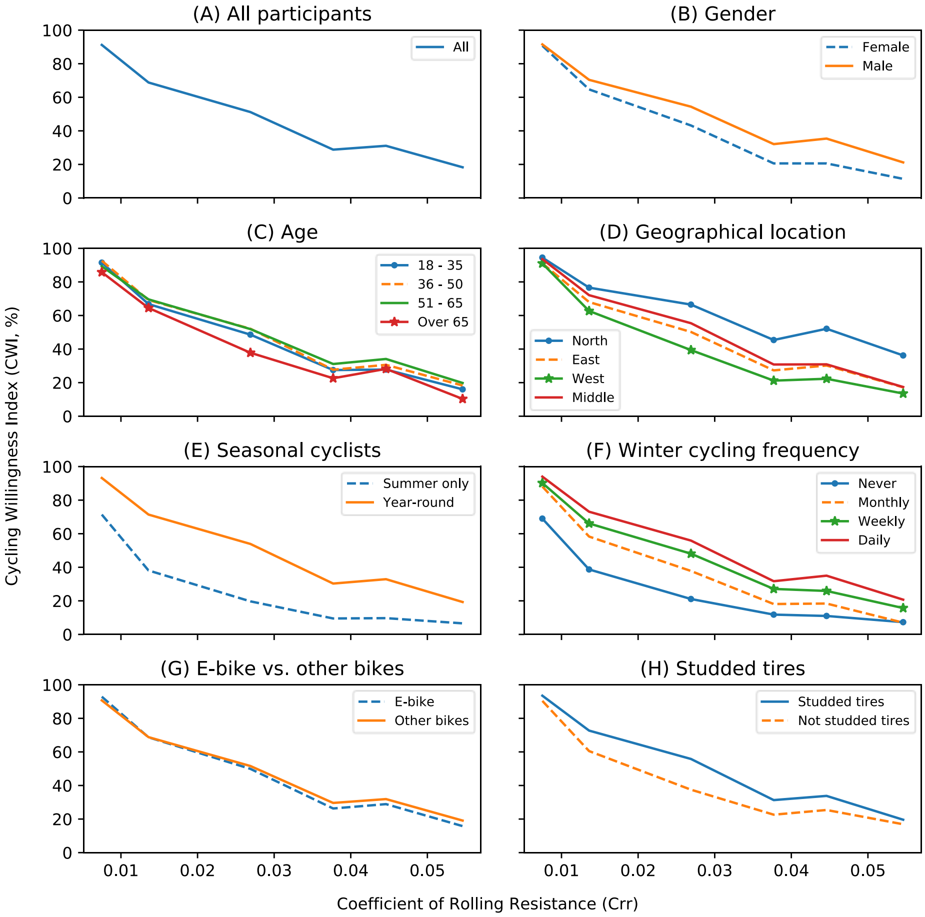

Figure 2: Correlation between the cycling willingness index (CWI) and bicycle rolling resistance.

Table 3: Cycling willingness index (CWI) for the different coefficient of rolling resistance (C_{rr}) ranges. P-value representing the difference between answer distribution for opposite groups. Post-hoc indicates significant differences between answer distribution for multiple groups.

C_{rr} level	C_{rr} range	All respondents (1318)	Gender		p-value	E-bike		p-value	Studded tires		p-value
			Female (379)	Male (938)		Yes (311)	No (900)		Yes (1084)	No (127)	
1	0.00-0.01	91.2%	90.7%	91.5%	0.298	92.9%	90.7%	0.029	93.5%	90.4%	0.011
2	0.01-0.02	68.8%	64.7%	70.4%	0.000	68.7%	68.8%	0.344	72.7%	60.5%	0.000
3	0.02-0.03	51.2%	43.2%	54.4%	0.000	49.9%	51.6%	0.354	55.8%	37.5%	0.000
4	0.03-0.04	28.8%	20.6%	32.1%	0.000	26.3%	29.6%	0.000	31.3%	22.6%	0.000
5	0.04-0.05	31.1%	20.6%	35.4%	0.000	28.9%	31.9%	0.014	33.8%	25.4%	0.000
6	0.05-0.06	18.3%	11.4%	21.2%	0.000	15.8%	19.1%	0.072	19.6%	16.9%	0.000

		Season specific cyclists			P-value
		Not cyclists (19)*	Summer only (88)	Year-round (1211)	
1	0.00-0.01	~~57.9%~~	71.4%	93.2%	0.000
2	0.01-0.02	~~41.4%~~	38.1%	71.4%	0.000
3	0.02-0.03	~~27.3%~~	19.7%	53.9%	0.000
4	0.03-0.04	~~22.8%~~	9.5%	30.3%	0.000
5	0.04-0.05	~~17.1%~~	9.7%	32.9%	0.000
6	0.05-0.06	~~10.5%~~	6.6%	19.3%	0.000

		Winter cycling frequency				Post-hoc
		N (Never) (107)	M (Monthly) (72)	W (Weekly) (139)	D (Daily) (1000)	
1	0.00-0.01	69.0%	88.1%	90.2%	94.0%	N < M, W < D
2	0.01-0.02	38.7%	58.3%	66.1%	73.1%	N < M < W < D
3	0.02-0.03	21.1%	37.8%	48.1%	55.9%	N < M < W < D
4	0.03-0.04	11.8%	18.1%	27.1%	31.7%	N < M < W < D
5	0.04-0.05	11.0%	18.4%	25.9%	35.0%	N < M < W < D
6	0.05-0.06	7.3%	7.0%	15.7%	20.7%	N < M < W < D

		Location					Post-hoc
		S (South) (19)*	N (North) (47)	E (East) (723)	W (West) (147)	M (Middle) (274)	
1	0.00-0.01	~~83.2%~~	94.5%	91.1%	91.0%	93.6%	E, W, M, N
2	0.01-0.02	~~65.4%~~	76.6%	68.0%	62.7%	72.1%	W < E < M < N
3	0.02-0.03	~~58.4%~~	66.5%	50.2%	39.4%	55.4%	W < E < M < N
4	0.03-0.04	~~33.3%~~	45.4%	27.3%	21.2%	30.8%	W < E < M < N
5	0.04-0.05	~~42.1%~~	52.1%	30.2%	22.3%	30.9%	W < E, M < N
6	0.05-0.06	~~14.7%~~	36.2%	17.2%	13.5%	17.4%	W < E, M < N

		Age					Post-hoc
		A (18-) (9)*	B (18-35) (317)	C (36-50) (591)	D (51-65) (423)	E (66+) (31)	
1	0.00-0.01	~~91.1%~~	91.5%	92.6%	89.3%	85.8%	B, C, D, E
2	0.01-0.02	~~71.4%~~	66.8%	69.2%	69.6%	64.5%	B, C, D, E
3	0.02-0.03	~~50.5%~~	48.6%	52.1%	51.9%	37.8%	E < B < C, D
4	0.03-0.04	~~42.6%~~	27.5%	27.7%	31.1%	22.6%	E < B < C < D
5	0.04-0.05	~~41.7%~~	27.8%	30.6%	34.1%	28.2%	E < B < C, D
6	0.05-0.06	~~33.3%~~	16.0%	18.3%	19.8%	10.3%	E < B < C, D

**Groups with N<30: not included in statistical analyses. P-value < 0.05 indicates significant differences between groups.*

4. Discussion

The first main finding in this study is that the willingness to cycle during the winter, represented with the cycling willingness index (CWI), decreases significantly with increasing rolling resistances for all respondent groups. This indicates that proper winter maintenance is indeed a key factor in promoting winter cycling, as it is the only way road owners can lower the rolling resistance. Well performed winter maintenance will promote winter cycling in all groups, from the cautious, only cycling sporadically during the summer cyclists to the risk-taking, well equipped, enthusiastic winter cyclists. By reducing the C_{rr} from ~ 0.027 to ~ 0.008, one can expect the CWI to increase from 50% to 90%. This reduction in C_{rr} can for example be obtained by going from a cycleway with less than 2 cm of loose snow on top of a compact snow layer to a cycleway with wet asphalt, completely free from snow (Fenre & Klein-Paste, (under review)).

Moreover, the results from this study show that male cyclists are less affected by increasing rolling resistances than female cyclists. This finding correlates with several previous studies. Amiri and Sadeghpour (2015) and (Heesch et al., 2012) found that there are generally more male than female cyclists and that men cycle longer distances than women. Men have also generally been more risk-taking than women. However, this gap seems to grow smaller over time (Abbott-Chapman et al., 2007; Byrnes et al., 1999). Research has also found that men consider cycling more acceptable than women (Parkin et al., 2007).

Figure 2D shows that the CWI of respondents living in northern Norway is less affected by increasing rolling resistances than people from the rest of the country. Table 1 shows that northern Norway has been the part of the country with the coldest and snowiest winters. The CWI of people living in western Norway, the region with the warmest and least snowy winters, is most affected by increasing rolling resistances. Therefore, this result indicates that people who are used to harsh winters are less sensitive to increased rolling resistance. This is also reflected in Figure 2E and 2F, which shows that frequent winter cyclists are less affected by increasing rolling resistances than less frequent winter cyclists.

When it comes to age, those older than 65 are more affected by increasing rolling resistances than the rest of the respondents. This is probably not only because it is heavier to cycle with increased rolling resistance, but that the older cyclists are more aware of the risks and perceive conditions that have a higher rolling resistance as "less safe". The age group between 18 and 35 is significantly less affected by increasing rolling resistances than those older than 65. Simultaneously, they are significantly more affected than the respondents between the age of 36 and 65. This agrees with the analyses by Parkin et al. (2007), who found that young people and older people consider the risk of cycling in cities to be higher than those in the age band 35 to 44 years. Why the cyclists aged between 35-65 in this study are least affected by increasing rolling resistances can also be explained by the differences in CWI for people living in different climatic regions, indicating that cyclists with a vast winter cycling experience are less affected by increased rolling resistances due to snow and ice. However, risk aversion seems to reduce cycling willingness built from cycling experience with age.

Figure 2G shows that the CWI of e-bike users and users of other bicycle types are equally affected by increasing rolling resistances. This came as a surprise to the authors because e-bikes reduce the cyclists' effort to overcome increasing rolling resistances. Therefore, we expected that e-bike users' willingness to cycle would be less reduced by increased rolling resistance than cyclists on standard bikes. This contradictory finding suggests that the increased effort needed to overcome larger rolling resistances due to snow and ice is not the main reason why cyclists are less willing to cycle on cycleways with elevated C_{rr} levels.

This is also reflected in the observation that only 10% of the summer only cyclists stated that "because it is too tiring" was the reason why they did not cycle during the winter. The main reasons for not cycling during the winter was that "it is too cold" (29%) and "I feel unsafe" (27%). Fenre and Klein-Paste ((under review)) found that an increased rolling resistance during winter cycling was accompanied by reduced steerability and increased unevenness. The reduction in willingness to cycle appears therefore directly related to reduced steerability and increased unevenness (which is close to equal for all bicycle types), rather than that it is harder to cycle. Reduced steerability and increased unevenness will often lead to a reduced feeling of safety when cycling.

Opposed to e-bike users, cyclists using studded tires during winter show a significantly larger CWI than other cyclists for increasing C_{rr} values. Studded tires improve traction on slippery surfaces and facilitate safe cycling. This finding also supports the theory that it is not the need for an increased physical effort that is the main barrier to cycling on cycleways covered in snow and ice, but the reduced feeling of safety. Knowing this, promoting widespread use of studded tires seems to be more effective than promoting e-bike usage when seeking to increase the number of bicycle trips during the winter.

Figure 2 shows that the reduction in CWI is significantly larger, going from very low to low coefficients of rolling resistance (C_{rr} level 1 → C_{rr} level 2) than it is going from large to very large C_{rr} (C_{rr} level 4 → C_{rr} level 6). This means that there are most gains at the lower end of the C_{rr} range, and one should perform winter maintenance at a very high level to increase winter cycling significantly. Figure 2E and 2F show that to recruit 50% of the "summer-only" respondents in this study, the rolling resistance level must at most be as low as ~ 0.011. This rolling resistance level is only offered by snow-free asphalt roads or, in some cases, a smooth, compact snow layer.

Despite the finding that extra physical effort is not the most crucial factor affecting cycling willingness, it seems that rolling resistance measurements can be a suited parameter to quantify the surface conditions. Crr measurements can describe the conditions in a measurable manner that directly relates to peoples' willingness to cycle. It is important to remember that the measurement equipment properties, e.g., the bicycle used to collect Crr measurements, affect the results. Therefore, a comparison of C_{rr} data collected with other measurement equipment than that used to collect the data in this study requires instrument calibration.

5. Conclusions

This study investigated the correlation between people's stated willingness to cycle on different winter cycling conditions shown in photos and the rolling resistance level measured on the same conditions.

The stated cycling willingness drops significantly with increasing bicycle rolling resistance. The cycling willingness index (CWI), indicating the percentage of people being positive to cycle on the shown conditions, dropped from 91.2% at coefficients of rolling resistance (Crr) lower than 0.01 to 18.3% at a Crr larger than 0.05. The CWI dropped rapidly from very low (< 0.01) to low (0.01-0.02) rolling resistances, whereas from high (0.03-0.04) to very high (> 0.05) rolling resistances, the CWI dropped at a slower rate. All frequent and occasional winter cyclists had a high CWI on very low rolling resistances.

How rapidly the CWI drop due to increasing rolling resistances depends on the cyclists' age and gender, the winter climate they are familiar with, their winter cycling experience and habits, and whether they use studded tires when cycling during the winter.

Surprisingly, e-bike users are no less affected by increasing rolling resistances due to snow and ice than users of standard bicycles. This finding indicates that cycling willingness is more governed by the feeling of safety rather than the physical effort needed to overcome an increased rolling resistance. Increased rolling resistance under winter conditions is accompanied by reduced steerability and increased unevenness, leading to a reduced feeling of safety when cycling.

To increase the number of winter cyclists, continuous, long-term efforts are required because the winter cycling experience makes cycling willingness robust to increasing rolling resistances from snow and ice on the roads. Smaller efforts may keep or increase the winter cycling frequency of existing winter cyclists.

The use of studded tires has a significant positive effect on people's cycling willingness under winter conditions.

This study's findings show that bicycle rolling resistance measurements are well-suited for quantifying the surface quality on cycleways under winter conditions. The rolling resistance level can be used to estimate the cycling willingness index for different user groups, and the bicycle-infrastructure winter-resilience.

By comparing the results from this study to the cost of maintaining different rolling resistance levels on cycleways during winter, we could come one step closer to evaluate the cost-benefit of improved winter maintenance on cycleways.

Abbreviations

C_{rr}	Coefficient of rolling resistance
CWI	Cycling willingness index

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Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not Applicable

Availability of data and materials

The datasets generated and/or analyzed during the current study are available in the Mendeley Data repository, http://dx.doi.org/10.17632/h3rc7973fx.1 (Fenre & Klein-Paste, 2020b)

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All authors participated in designing the study. MDF collected and analyzed the rolling resistance data and the data from the online survey and was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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APPENDIX D – ADDITIONAL PAPER

Fenre, Klein-Paste

A torque-based method for measuring bicycle braking friction

Presented at Transportation Research Board Annual Meeting (TRB), Washington DC, January 18, 2019

A torque-based method for measuring bicycle braking friction

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ABSTRACT

Friction measurement devices (FMDs) are important tools for quality control on new pavements, condition monitoring in pavement management systems and operational use during winter maintenance. Several FMDs measure the friction experienced by cars, trucks, and aircraft. However, pedestrians and cyclists does not perceive the same friction as heavy road vehicles. Being able to measure the friction perceived by cyclists could aid in improving winter maintenance on walking- and cycling areas and facilitate for year-round bicycling and walking in urban areas. We developed and tested a bicycle braking friction measurement device in a laboratory. The method utilized torque balance on a braking bicycle wheel to measure the friction perceived by a cyclist on different pavement conditions. We measured friction values for slip rates continuously from 0.0 (freely rolling tire) to 1.0 (locked, sliding tire). The results showed mean maximum coefficients of friction of 0.07, 0.14, 0.33 and 0.35 on snow covered ice, ice, sandpaper (P240) and plywood, respectively. The standard deviation varied from 0.007 to 0.027. The method provided slip curves from the experiments that showed that maximum friction occurred at slip rates between 0.1 and 0.6. We obtained few to no friction measurements for slip rates from 0.7/0.8 to 1.0, due to limited resolution of the angular velocity measurement of the braking wheel. The method is simple, and we hope to install it on a bicycle or another field measurement device to aid in winter maintenance operations and facilitate for bicycling and walking in urban areas in winter conditions.

Keywords: Bicycles; friction; measurements; winter; maintenance

INTRODUCTION

There is an increased focus on using walking and cycling as transportation modes in urban areas. Walking and cycling is healthy, efficient, and is sometimes faster than other modes of transportation (1, 2). Accordingly, the Norwegian National Transport Plan of 2014-2023 and 2018-2029 (3, 4) states that public transport, walking and cycling should cover all growth in passenger transport in urban areas. Therefore, the Norwegian Public Roads Administration (NPRA) initiated a new research program, running from 2017 to 2021, named “Bevegelse” (Norwegian for “motion”). The goal of the project is to get more people in urban areas walking and cycling all year round. To reach this goal, one important step is to facilitate for year-round bicycling and walking by improving winter maintenance operations of walking- and cycleways. The use of friction indicators can improve winter maintenance operations and mobility on walking- and cycleways (5).

Tire-pavement friction, also known as skid resistance, is important for both design, construction and maintenance of roads and airfields because vehicles need a certain amount of tire-pavement friction for propulsion (traction), retardation and directional control. Full scale evaluation of available friction for cars and trucks is typically by measuring retardation or braking distance during braking tests (6). For in-service aircraft, wheel braking friction can be determined when the anti-skid system gets activated by modelling the retardation forces during the landing (7). Rather than measuring the available friction for a whole vehicle, it is more common to measure the friction on a test tire using a friction measurement device (FMD). There is an available overview of the main types of FMDs that have been, or are currently in use and these include locked wheel testers, fixed slip devices, variable slip devices and side force devices (8). FMDs are important tools for construction and maintenance of roads. Several areas rely on a trustworthy source of information regarding the current state of the pavement, such as quality control on new pavements, condition monitoring in pavement management systems and operational use during winter maintenance.

One issue with FMDs is that their response is system dependent (9). Kinetic friction is a property that describes the force acting between two surfaces that slide against one another. When measuring friction, the result is not only dependent on the properties of the road surface. Other factors that affect the friction are the properties of the surface of the wheel, the ambient environment and any interfacial media that may occur between the surfaces, such as water, snow or ice. The response of the FMDs is dependent on this complex interaction, called a tribosystem. Due to the system dependence, harmonization efforts between different FMDs have turned out to be difficult on bare pavements (10, 11) and likely even more difficult on snow/ice covered pavements due to the complex nature of these pavement surfaces.

In Norway, measurements from the same devices that measures the available friction for cars, defines the friction requirements on bicycle and walking areas (12). However, the majority of the FMDs, such as the Saab Friction Tester (SFT) (13) are developed to assess the available friction levels for cars, trucks or aircraft. Measurement of the available friction for vulnerable road users such as pedestrians, bicyclists and wheel chair users has received much less attention. This is problematic because bicyclists or pedestrians do not perceive the same friction as cars due to the different tribosystems. Considering the issue with harmonization, and the increased focus on using walking and cycling as transportation modes, there is an increased need for developing methods that can describe the available friction for soft road users.

There are a few already existing methods for estimating friction for soft road users. One is the British Pendulum Tester (14), used in the ASTM E303 standard to assess the slipperiness of floor tiles. In Finland, a portable slip simulator proved to be able to measure differences in footwear slip friction in winter conditions (17). Another method measured bicycle-braking friction on snow/ice with studded bicycle tires using: 1) initial speed and stopping length and 2) an acceleration sensor (16). There is also the portable friction tester (PFT), which is a fixed slip portable friction tester. It was originally used to measure friction on road markings, but has also been used for testing friction on cycleways (15).

TABLE 1 Friction values for selected road conditions measured with SFT (13), PFT (15) and with bicycle using: 1) an accelerometer and 2) initial speed and stopping distance (16).

	SFT	**PFT**	**Bicycle (Accelerometer)**	**Bicycle (Stopping Distance)**
Road condition	**Location 1**	**Location 2**	**Location 3**	**Location 3**
Dry, bare ground	0.8-1.0	0.76-1.00	-	-
Packed snow	0.20-0.30	0.14-0.44	0.31-0.46	0.29-0.44
Thin ice	0.15-0.30	-	-	-
Thick, uneven ice	-	0.20-0.49	-	-
Loose snow on thin ice	0.15-0.25	-	-	-
Slush on thin ice	-	0.22-0.36	-	-
Wet, thin ice	0.05-0.10	-	-	-
Loose snow	-	0.19-0.37	-	-
Coarse snow on ice	-	-	0.36-0.45	-

The British pendulum and the Finnish slip-friction tester, measures the friction perceived by walking pedestrians. They did not measure bicycle friction. The bicycle-braking method measured the perceived braking friction for a studded tire bicycle. They found the method to be easy and inexpensive. They found the bicycle braking friction to be at least as high as the friction measured by a standard FMD on the same location. However, they experienced problems with large result variations due to challenges with determining the starting point of braking and the initial speed measurement. The measurement with the accelerometer faced challenges with sensor alignment and lack of slip control. The PFT can perform measurements even on narrow sections without compromising the safety of cyclists. However, it is unknown how the values measured with the PFT compares to the friction experienced by cyclists and values measured with the standard FMD's such as the SFT.

Table 1 shows published friction values on different winter road conditions using four different measurement techniques at three different locations. The differences in measured friction for "Packed snow", varies from 0.14 to 0.46. Considering the Quality Classification of Winter Maintenance by the Finnish National Road Administration (FinnRA), where friction values between 0.00 – 0.15 are “poor” and values between 0.45 – 1.00 are “excellent”, the variation of measured friction on “Packed snow” is significant (18). Based on the mentioned issues with previous bicycle friction measurements, this research area is in need of more exploration.

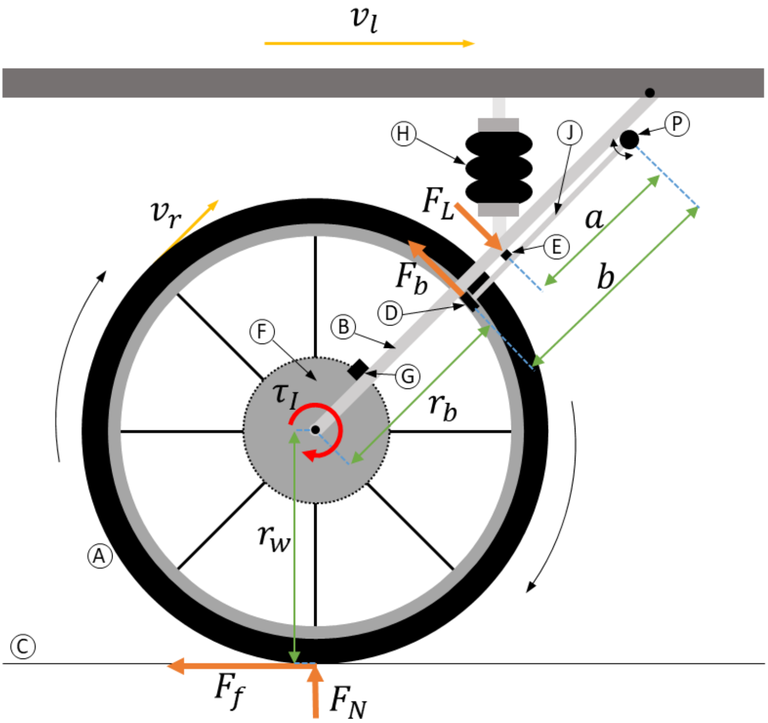

FIGURE 1 Sketch of the experimental setup.

In this study, we explored a new method to measure the available friction for a bicycle tire. Rather than attempting to measure braking friction at a fixed slip rate, we measured the braking force of a braking bicycle wheel at all slip rates from 0 to 1. By knowing the rotational inertia of the wheel and the rate of deceleration of the wheel, we calculated the breaking friction coefficient.

We used the method in the indoor linear friction track LARS (19), but the principle has potential to be mounted on a normal bicycle or wagon with a bicycle wheel for outdoor measurements. Our hope is that such a method can aid in improving winter maintenance and facilitate for year round bicycling and walking in urban areas.

METHOD

The laboratory used to conduct the experiments contains a friction track, LARS, with an impregnated plywood surface, measuring a length of eight meters, built in a stiff aluminium frame. Bolts fix the aluminium frame to a solid concrete foundation. A 46 kW electrical motor drives a belt that can transport a trolley over the test track, along a pair of carbon steel railings. The trolley carries the test equipment and can be accelerated up to a maximum linear velocity (v_l) of 10 m/s and hold this velocity for 2 meters at the middle of the track before slowing down and stopping. The laboratory room has a cooling system that can control the air temperature down to - 25°C ± 1°C. The temperature control allows us to imitate winter conditions on the test track, for example by freezing water to a compact ice layer, or adding a layer of fresh snow from our snow machine, *Lumi* (19).

To get our friction measurements, we used a standard bicycle wheel (marked as (A) in figure 1), mounted to a special fork (B) and placed on the test surface in the lab (C). After accelerating the wheel up to a constant speed of 7 m/s (v_l), the brake (D) automatically triggered and slowed the rotational speed of the wheel (v_r) down to zero while v_l was kept constant. Whilst braking, we measured the force exerted from the wheel to the brake i.e. the brake force (F_b) using a load cell (E). With a fine toothed disk (F) and a tachometer (G) we optically measured the angular velocity (ω) of the wheel at 150 pulses per revolution. A sensor in the friction track motor measured the velocity of the trolley, which is equivalent to the linear velocity of the wheel (v_l). Before each test series, we activated the air bellow (H) to induce normal force (F_N) thrust from the tire to the surface. In order to measure the normal force at the correct bellow stroke length we deflated the tire and placed a weight scale under the wheel. Before testing, we reflated the tire to the correct pressure. With a manometer, we surveilled the bellow pressure to make sure it kept constant during each test series.

The brake force measurement depends on several factors. The first is the friction force (F_f) between the test surface and the wheel. The friction force is the parameter we are interested in measuring in this study, and the parameter that tells us something about the friction of the tribosystem we are testing. The second is the rotational inertial torque (τ_I) from the wheel, which is dependent on the rate of angular acceleration of the wheel ($\dot{\omega}$) (negative during deceleration) and the rotational inertia of the wheel (I). The load cell measuring the brake force is placed on a lever arm (J) and we utilize the torque balance about the pivot point P on the lever arm and about the center of the wheel to find F_b from the force measured by the load cell (F_L). The formula for F_f is therefore:

$$F_f = \frac{F_L r_b a}{r_w b} + \frac{I\dot{\omega}}{r_w} \tag{1}$$

Where (r_w) is, as seen in figure 1, the deflected radius of the wheel, (r_b) is the average radius of the position of the brake pads, (a) is the distance from the pivot point (P) to the load cell and (b) is the average distance from P to the center of the brake pads. The coefficient of friction (μ) is defined as the friction force divided by the normal force. µ is then:

$$\mu = \frac{F_f}{F_N} = \frac{F_L r_b a}{F_N r_w b} + \frac{I\dot{\omega}}{F_N r_w} \tag{2}$$

We found the wheel’s rotational inertia by measuring the swinging period of the wheel swinging at the end of a pendulum. With the swinging period, we calculated the rotational inertia of the wheel about the axis of rotation of the pendulum. By utilizing Steiner's theorem for parallel axes (20), the rotational inertia about the axis of rotation of the pendulum can be transformed into the rotational inertia about the rotational axis of the wheel.

The period (T) of small oscillations in the pendulum is:

$$T = \frac{2\pi}{\omega_0} = 2\pi\sqrt{\frac{I_p}{mgr_p}} \tag{3}$$

Where m is the mass of the wheel, g is the gravitational force, r_p is the radius of the mass center of the pendulum and ω_0 is the angular frequency of the pendulum. The rotational inertia of the pendulum about the axis of rotation of the pendulum (I_p) is then:

$$I_p = T^2\frac{mgr}{4\pi^2} \tag{4}$$

The parallel axis theorem states that:

$$I = I_p - mr_p^2 \tag{5}$$

Where I is the rotational inertia of the pendulum about the rotational axis of the wheel. Hence, we can calculate I like this:

$$I = mgr_p\frac{T^2}{4\pi^2} - mr_p^2 \tag{6}$$

We measured the period to be $T = 3.316$ seconds by averaging the swinging period over 50 swings. Consequently, we found the rotational inertia of the wheel to be $I = 0.1383\ kgm^2$.

We performed test runs on four different surfaces: ice, snow covered ice, plywood and sandpaper (P240). Table 2 shows a list of the test surfaces and the measured results. The ramp up length (acceleration and retardation phase) was 1.5 meters. We stopped the wheel after seven meters to keep the last meter as a safety buffer. Hence, four meters of a constant speed of 7 m/s where available for collecting results.

The bicycle tire used was a *Schwable Marathon Plus 28"* hybrid tire. The tire air pressure was 350 kPa. The normal force was set to 375N, to resemble the weight on the back wheel of a bike ridden by a person weighing 65 kg, assuming close to a 60/40 weight ratio between the back wheel and the front wheel.

RESULTS

We performed 10 – 15 successful test runs on each of the four different surfaces. Figure 2 shows how the measurements for a single test on the ice surface typically looked like. The graph illustrates how the wheel speed and the trolley speed i.e. the rotational speed and the linear speed of the wheel, respectively, accelerated up to 7 m/s within just over 0.4 seconds. At a little over 0.6 seconds, the wheel speed decreased steadily down to 3 m/s and then rapidly down to zero, indicating the trigger-point of the brake. At the same time, the brake force increased rapidly to a maximum, before dropping and stabilizing when the wheel speed reached zero, indicating a locked, sliding wheel. During braking of the wheel, the graph shows that the trolley kept going at a constant speed, before slowing down after 1.1 seconds.

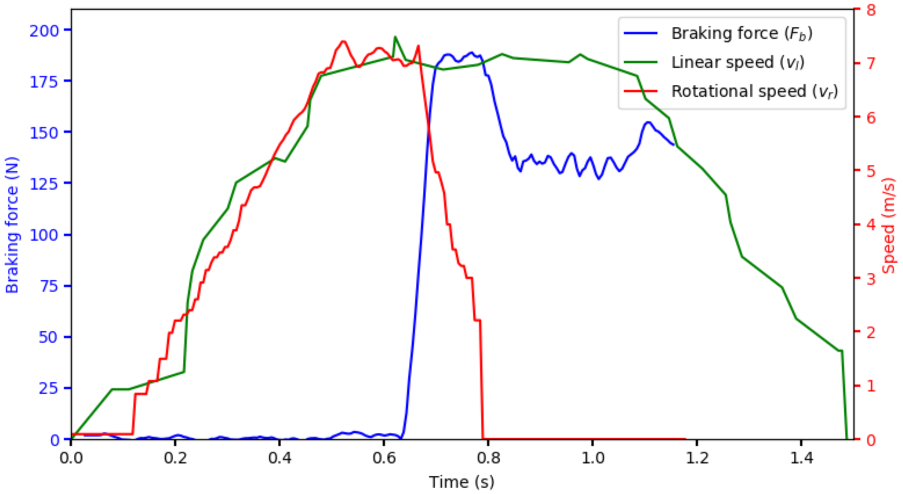

FIGURE 2 A typical test run. We accelerated the trolley up to 7 m/s within approximately 0.5 seconds. Then the brake triggered, and the rotational speed gradually decreased while the braking force initially increased and then stabilized as the rotational speed of the wheel reached zero and wheel started to slide.

Table 2 lists minimum, maximum, mean and standard deviation values for measured peak friction coefficient (μ_p) and the corresponding slip rates for each test surface. We measured the highest friction for the plywood and sandpaper surfaces, with a mean peak friction coefficient ($\bar{\mu}_\mathrm{p}$) of 0.35 and 0.33, respectively. On ice, $\bar{\mu}_\mathrm{p}$ was 0.14. On the snow covered ice surface, $\bar{\mu}_\mathrm{p}$ was 0.07. The standard deviation (*SD*) of μ_p was 0.027 for sandpaper, 0.013 for plywood, 0.007 for snow covered ice and 0.006 for the ice surface.

Figure 3 shows how the measured friction distributes over the slip rates. We see that plywood and sandpaper, in addition to the snow covered ice surface, provides maximum friction at a slip rate between 0.2 and 0.3. Ice provides maximum friction at a slip rate between 0.1 and 0.2. The density of data points decreases along the slip rate axis. At slip rates close to zero the density of data points is high, but between slip rates from 0.6/0.8 up to 1.0, there are few to no data points. At the slip rate of 1.0, the density of measurements is again high.

We fitted curves to the data using a semi-empirical tire-road interaction formula (21), also known as the *Magic Formula*. The coefficients of determination, r-squared, were 0.681, 0.465, 0.927 and 0.881 for ice, snow covered ice, plywood and sandpaper, respectively. For plywood and sandpaper, the fit was best after a slip rate of 0.1. For ice, the best fit is for slip rates in the range 0.0 – 0.5. For the snow covered ice surface, the highest data points spread is at slip rate 1.0.

For sandpaper, we see that after maximum friction is reached, the friction coefficient stabilizes at the maximum level as the slip rate moves towards 1. For plywood, ice and snow covered ice, the friction level drops after reaching the maximum level before moving towards an asymptote as the slip rate moves towards 1.0.

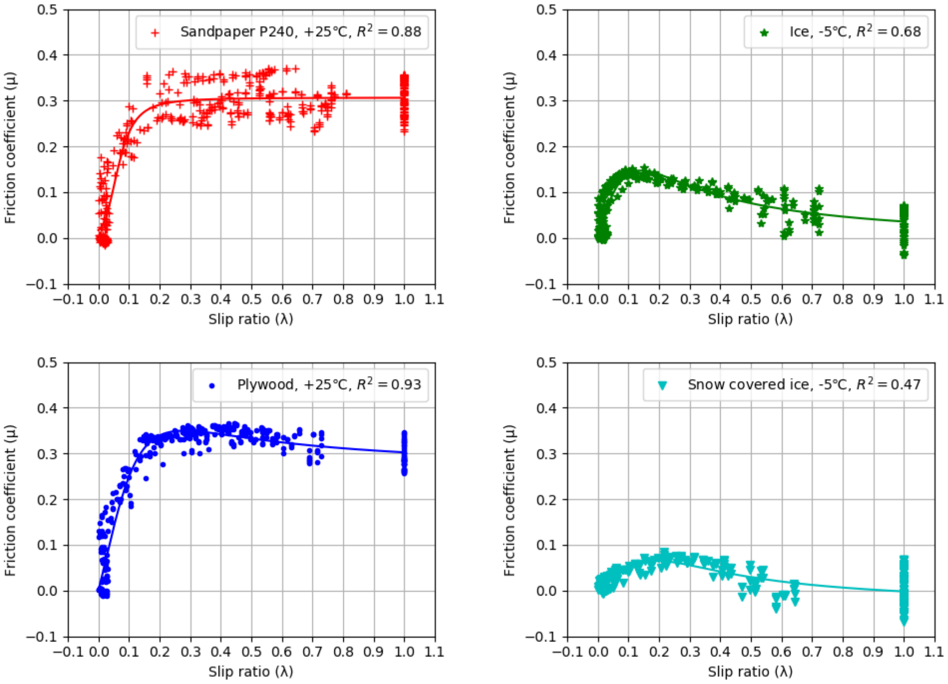

FIGURE 3 Coefficient of friction versus slip rate.

TABLE 2 Measured maximum friction values (μ_m) and the corresponding slip rates (λ) for each test surface.

Surface	Air temperature	Test runs	μ_p			λ @ μ_p
			Min - max	**Mean**	**Std. dev.**	**Min – max**
Ice	- 5°C	11	0.13 - 0.15	0.14	0.007	0.10 - 0.15
Snow covered ice	- 5°C	10	0.06 - 0.08	0.07	0.006	0.20 - 0.30
Plywood	+ 25°C	13	0.32 - 0.36	0.35	0.013	0.30 - 0.45
Sandpaper P240	+ 25°C	15	0.29 - 0.38	0.33	0.027	0.20 - 0.60

DISCUSSION

We have shown that it is possible to measure a slip curve and the peak friction coefficient for a bicycle tire. The results show that the density of data points decrease as the slip rate increases and that there are almost no friction values for slip rates above 0.7/0.8 up to 1.0. An explanation for this could be the measurement frequency of the angular velocity of the wheel. The frequency is proportional to the angular velocity and negative proportional to the slip rate, as long as the center of the wheel moves at a constant speed. When the slip rate is close to 1.0, the wheel is rotating so slowly, or decelerates so quickly, that the tachometer may not register a pulse by the time the brake-force load cell registers a new friction force measurement. The system then interprets the angular velocity as zero, and places the friction measurement coincident to a slip rate of 1.0 even though it could have been e.g. 0.8 or 0.9. Figure 2 illustrates this where the rotational velocity of the wheel suddenly drops to zero at around 0.8 seconds. The solution for this shortcoming is to increase frequency of the angular velocity of the wheel. Increasing the number of pulses per revolution would accomplish this. Alternatively, using a gyroscope to achieve a constant measurement frequency independent of the angular velocity could be a better solution. However, maximum friction is typically obtained at slip rates of about 0.15 – 0.25, depending on the tire stiffness, and interfacial medium on the pavement (22). In this study, we found maximum friction at slip rates between 0.10 and 0.60. Consequently, as far as finding the maximum available friction for a system is concerned, a high density of friction values for slip rates up to 0.7/0.8 and for slip rates at 1.0 seems to be adequate. Still, obtaining a high density of friction values for all slip ratios is important to improve the general knowledge around friction phenomena.

Compared to the friction values from earlier studies listed in table 1 and to the Finnish Quality Classification of Winter Maintenance (18), the friction values obtained in this study were relatively low. A reason for this is the differences in the tribosystems between the different measurement methods. The bicycle wheel has a smaller contact area against the pavement than most of the other FMDs and less space for the tire to adhere to the pavement surface. In addition to a lower normal force, this may lead to lower friction. If we compare the sandpaper (P240) surface to a bare asphalt surface, the sandpaper does not have the macroscopic varieties, holes and impurities, as does the asphalt. However, the sandpaper has a rough micro texture, rougher than asphalt. Consequently, while the friction mechanisms occurring between a rubber tire and asphalt are deformation of the tire rubber, adhesive forces between rubber and asphalt and tire wear, on sandpaper it is mostly tire wear and smaller magnitudes of adhesion and tire rubber deformation.

This suggests that bicycles without studded tires experience a lower friction than that measured by standard FMDs. Before the experiments of this study, due to previous testing, the tire thread showed clear signs of wear, which may also have contributed to lower friction values.

Based on the calculated standard deviations for peak friction coefficient, the repeatability of this method is promising. For the surfaces with low friction and low surface roughness, the result variation was exceptionally low at low slip rates. At higher slip rates, the results seem to vary a bit more. This is likely a consequence of the discussed angular velocity measurement problem at low angular velocities. Vibrations in the system due to high acceleration may also affect the force measurement signal. Moreover, these system weaknesses could also explain the negative friction values measured at ice and snow covered ice. The sandpaper surface provided the highest result variation, probably due to an increased magnitude in vibrations in the system when braking on this rough surface. Road surfaces in winter conditions are often uneven and bumpy. Hence, system vibrations is a challenge that will probably be more noticeable when attempting to use this method for outdoor field measurements.

Based on the presented results, the explored method can distinguish between small differences in friction between a bicycle tire and its braking surface.

We could implement this method to the field either by instrumenting a bicycle or by using a FMD with a bicycle wheel. With an instrumented bicycle, the measurements would be exactly as perceived by cyclists. Ideally, many users in different parts of a city would use the instrumented bicycle. In addition, the bicycles could send reports about the pavement conditions on their route in real time. A live information service open to the public, covering large parts of urban areas could then be possible. Users could then check information about their planned bicycle ride and decide whether varying conditions means they should change their route or not. Moreover, the reports from the live information service could help maintenance personnel decide whether they need to perform maintenance procedures or not. If we would install the explored method on a FMD trailer on a winter maintenance vehicle, the operator would get instant feedback on the maintenance procedures. Measurements would be close to what is perceived by cyclists, but not as close as if measured by a real bicycle. The operators can cover large areas with few units and inform the public about the conditions. By using a FMD trailer, updates about the pavement conditions would only be available after maintenance procedures. Sometimes, conditions change considerably between maintenance procedures. The information about the conditions may then be inaccurate. Consequently, in order to inform the public and the operators about the current pavement conditions, the best way to put the explored method out in the field seems to instrument a large number of bicycles that together, cover large parts of an urban area. However, also placing FMD-trailers on maintenance vehicles could be a good solution for operators to receive instant feedback on maintenance procedures.

To summarize, continuous bicycle measurements, or frequent controls with FMDs, can help the operators with their decision-making routines, and facilitate for satisfactory transport conditions on cycleways year-round. The benefit of utilizing this method is that we measure the friction values at all slip rates, which assures us that we find the maximum available friction for the system. In addition, by using a regular bicycle wheel and tire, we measure the perceived friction for a cyclist.

CONCLUSIONS

The explored method measured braking force and utilized torque balance on a bicycle wheel to measure braking friction on four different surfaces in the lab. The method provided friction values for slip rates from 0.0 to 1.0, but inaccurate measurements of the angular velocity of the braking wheel led to few or no friction values for slip rates between 0.6-0.8 and 1.0. However, the shape of the obtained slip curves indicates that maximum friction occurs at slip rates between 0.1 and 0.6 for all the tested surfaces. The repeatability of the method was very good for the surfaces providing low friction i.e. plywood, ice and snow covered ice. On sandpaper, the results varied most, probably due to system vibrations. Compared to previous studies, the measured friction values were relatively low, probably due to smaller contact area and normal force. This suggests that bicyclists perceive lower friction values than cars, trucks or aircraft on the same surface conditions. The method proves to measure the friction perceived by a bicyclist and we hope to transfer it to a bicycle or other field measurement device in the future. In the field, this method can aid winter maintenance personnel in decision-making processes or inform the public about current friction conditions.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: 2. Author, 1. Author; data collection: 1. Author; analysis and interpretation of results: 1. Author, 2. Author; draft manuscript preparation: 1. Author, 2. Author. Both authors reviewed the results and approved the final version of the manuscript.

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