# 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:

$$F_p = F_r + F_g + F_a + F_i + F_f + F_b \quad (1)$$

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 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:

**Fig. 1.** Forces acting on a moving bicycle.

$$F_r = F_p - \left(F_g + F_a + F_i\right) \quad (2)$$

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:

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

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, $\rho_{air}$ (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, $\rho_{air}$, 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 *CdA* 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 ($\Delta F_a$) 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 $\Delta F_r$ is zero due to the constant rolling resistance. The *CdA* was then estimated with the following equation:

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

Where $\Delta F_a$ 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, $\omega$ (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 $\mathrm{C_{rr}}$ 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.

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