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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.

1. 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 and 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 and 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 and 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 and Magnusson, 2003; Brandenburg et al., 2007; Godavarthy and Rahim Taleqani, 2017; Nahal and 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 and 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).

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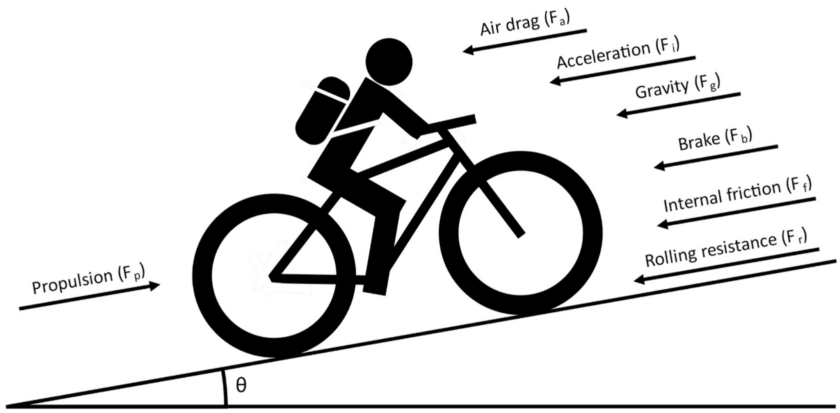


Fig. 1. Schematic of the forces considered in the rolling resistance measurement method.

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 and 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 and Warnich, 2014; Tengattini and Bigazzi, 2018), and

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

Fig. 3. Tread of the tire used in the experiments (Schwable Marathon Winter Plus).

by measuring pedaling power versus speed relationship (Fenre and 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?

2. 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:

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

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. Fig. 1 shows a schematic of the forces considered.

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:

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

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:

$$F_g = mg^*sin\left(arctan\left(\frac{s}{100}\right)\right)\# \quad (3)$$

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}:

$$F_a = \frac{1}{2}\rho_{air}{}^*C_dA(v_{air})^*v_{air}{}^2\# \quad (4)$$

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:

$$F_i = \left(m + \frac{Iw_f + Iw_r}{r_w{}^2}\right)^*\frac{dv_b}{dt}\# \quad (5)$$

Rolling resistance is highly dependent on the wheel load (Baldissera and Delprete, 2016; Clark, 1978; Gent and Walter, 2006; Gillespie, 1992). Due to this fact, it is commonly represented as the ratio between

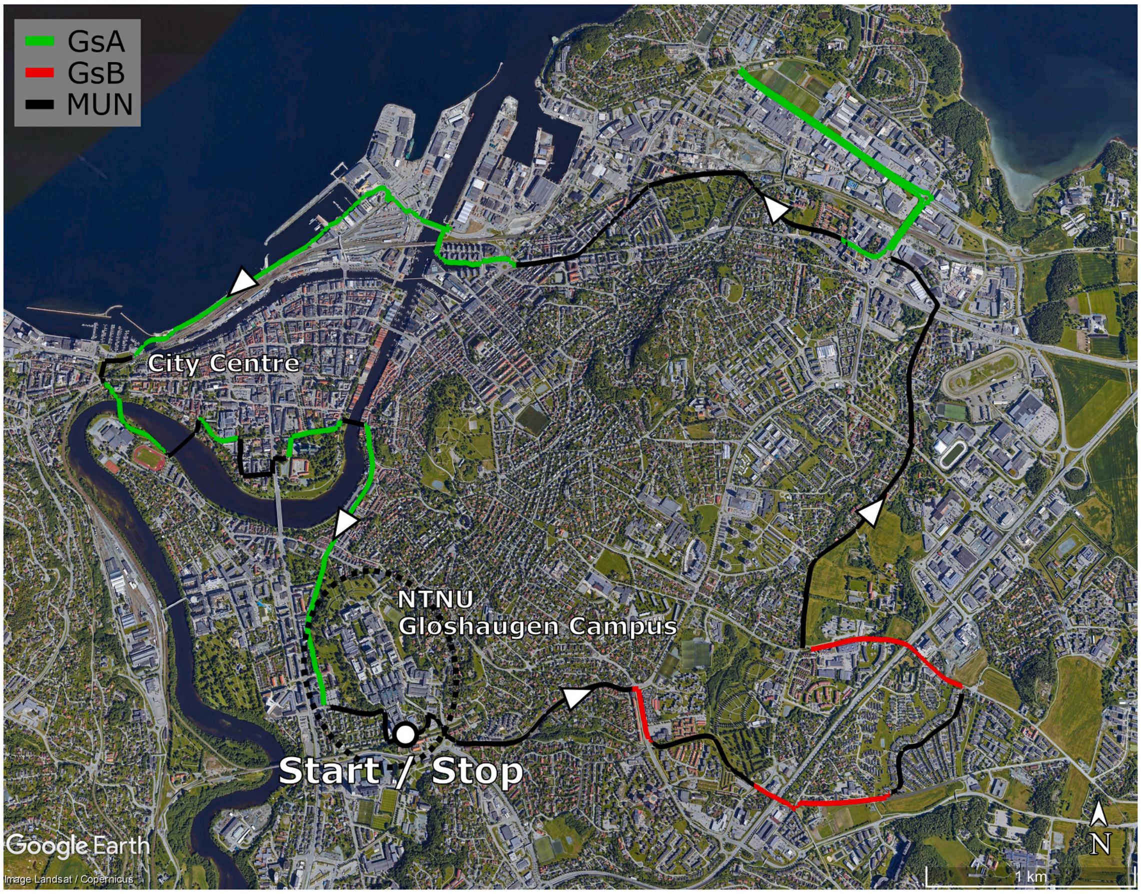


Fig. 4. Map of the test route indicating the locations of the different winter maintenance standards.

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)

the rolling resistance force and wheel load, or the coefficient of rolling resistance, C_{rr}:

$$C_{rr} = \frac{F_r}{F_N} \# \tag{6}$$

Fig. 2 shows the bicycle with instruments and measurement sensors.

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 h was recorded from the Norwegian Meteorological Institute (NMI, 2019).

The test bicycle was a *Breezer Radar Café*, equipped with 29" *Schwalbe Marathon Winter Plus,* 42 mm wide, studded winter tires. Fig. 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

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

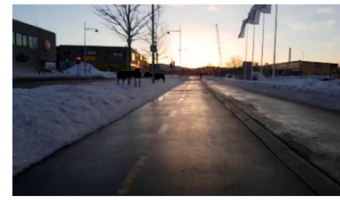
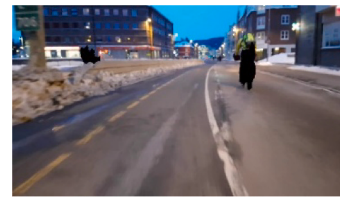
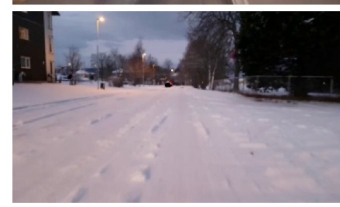
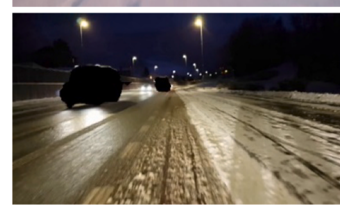
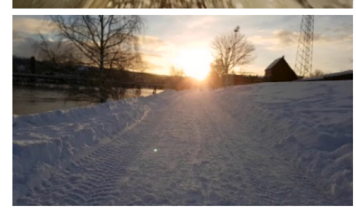
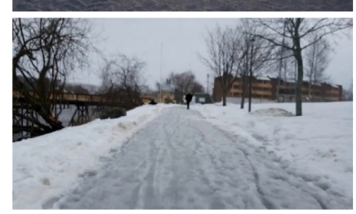
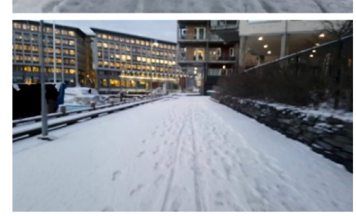
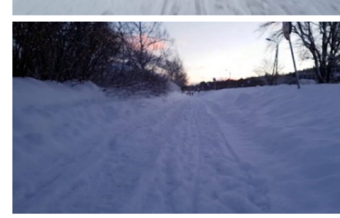
Classification	Description	Typical areas	Example photo
Wet asphalt	Moist or wet asphalt. In generally good condition with few cracks and potholes.	High-priority cycleways and roads.	
Dry asphalt	Dry asphalt in mostly good condition.	High-priority cycleways and roads. The asphalt usually dried during 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 (2–5 cm) 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 (>5 cm)	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.

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.

2.1. 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. Fig. 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.

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 and 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.

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.

3. Results

Data were collected on a total of 103 road sections, the length of which varied between 80 m and 1520 m. Fig. 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

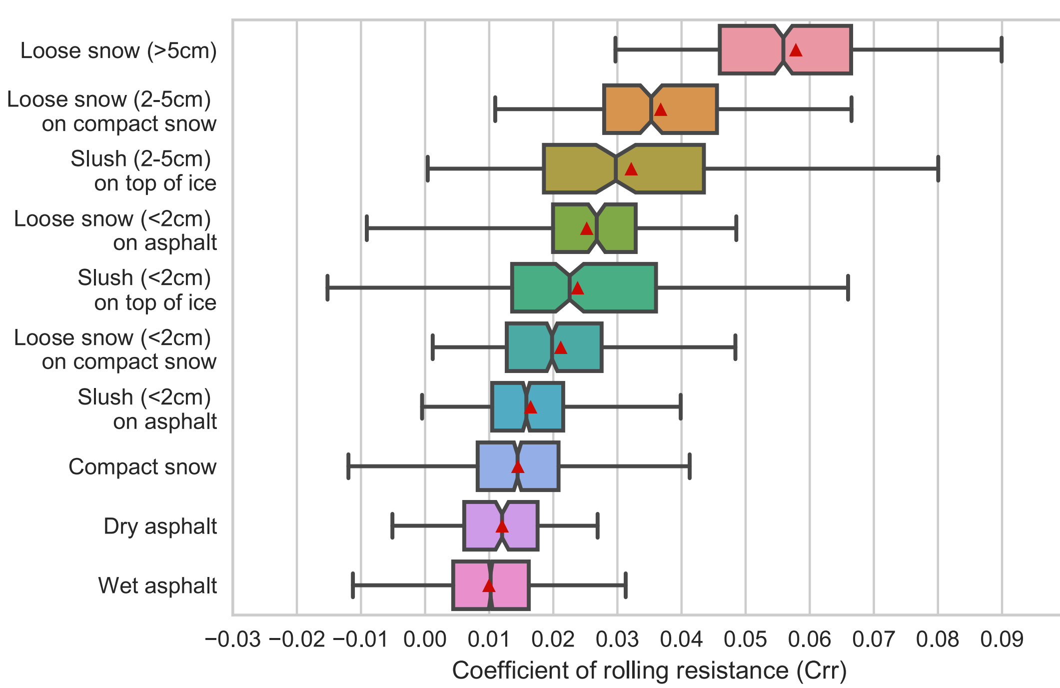


Fig. 5. Distribution of the measured C_{rr} for each road condition group.

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.

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 (>5 cm) (0.056). The average C_{rr} for all conditions except loose snow (>5 cm) lies between 0.010 and 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 and 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.

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.

Fig. 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.

Fig. 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 (>5 cm). Loose snow (<2 cm) on compact snow and combined ice and slush (2-5 cm) were also observed. Moreover, while all types of road conditions were observed on MUN stretches, compact snow, combined compact/loose snow (<2 cm) and loose snow (>5 cm) were the most prevalent. Table 5 shows the share and number of measurement samples from each road condition group and how these road

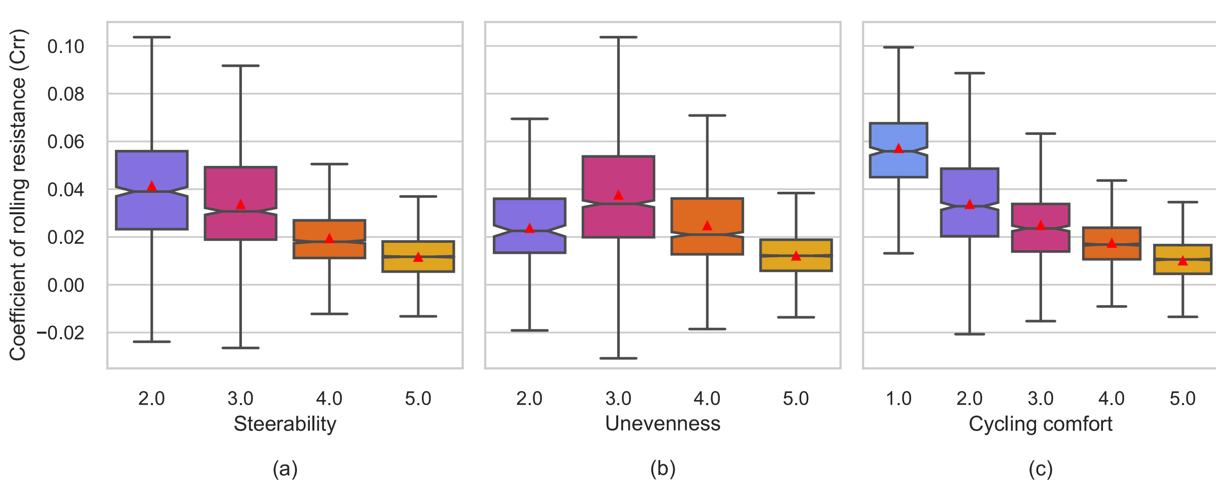


Fig. 6. Correlation between estimated C_{rr} and subjective perception of cycling comfort, steerability and unevenness (5 = very good - > 1 = very poor).

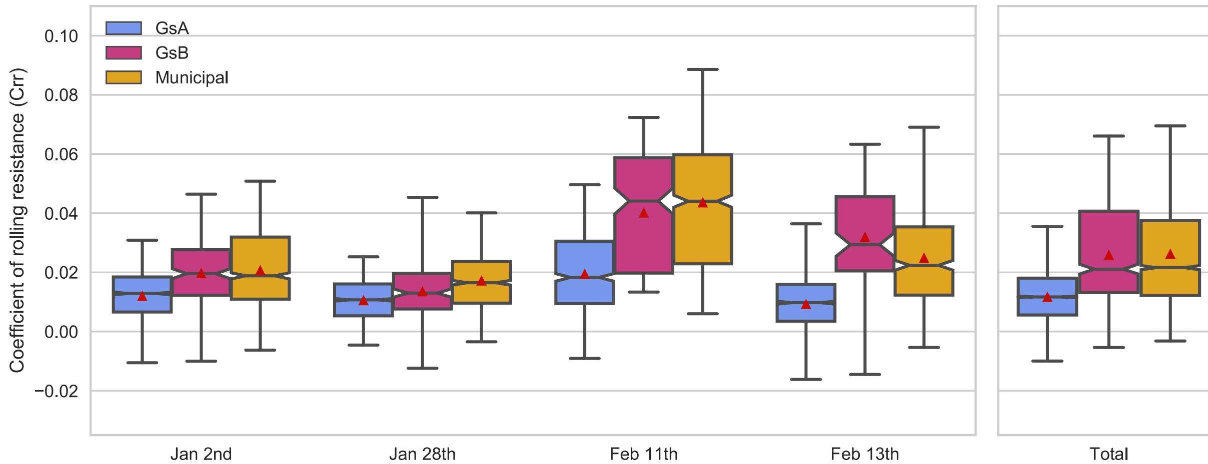


Fig. 7. Estimated C_{rr} on bicycle areas with GsA (bare road), GsB (winter road), and Municipal winter maintenance standard for four different dates during winter 2019.

conditions are distributed over the different winter maintenance standards.

4. 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 and 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 and 5 cm of slush on top of ice yielded a C_{rr} of 0.030, whereas 2-5 cm 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 Fig. 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.

Fig. 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 60 mm and frequencies lower than 6 Hz, the power loss has been found to be less than 2.7 W, corresponding to an increase in C_{rr} of 0.0012 (at 10 km/h and a combined bicycle and cyclist mass of 84 kg). Higher frequencies and amplitudes quickly increase this power loss by several magnitudes (Pradko and 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

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

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 (<2 cm) on compact snow	51	0.9	79	12.7	657	22.9	787	8.7
6	Loose snow (<2 cm) 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 (2-5 cm) 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 (>5 cm)	0	0	118	19.0	414	14.5	532	5.9

N = number of samples.

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.

Fig. 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 (Eq. (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 (> 5 cm) (19%) and compact snow combined with loose snow (< 2 cm) (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 Fig. 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.

5. Conclusions

A hybrid bicycle with 42 mm wide and 29-in. 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 and 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.

Data availability

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

CRediT authorship contribution statement

Mathis Dahl Fenre: Conceptualization, Methodology, Software, 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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