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What is slowing me down? Estimation of rolling resistances during cycling

Daniel Meyer[a,*], Gideon Kloss[a], Veit Senner[a]

[a] *Technical University of Munich (TUM), Sport Equipment and Materials, Boltzmannstrae 15, D-85748 Garching, Germany*

Abstract

In this paper, we present a method to estimate the current rolling resistance coefficient of a four-wheeled electric bicycle. We derived linear regression models between the velocity of the bicycle and the vibrations at the handlebars to be able to classify the current road surface and consequently the rolling resistance coefficient. To derive the models, we performed experiments on three different surfaces typical for cycling - asphalt, fine gravel and coarse gravel. A cyclist performed five test rides on each surface on different days at varying velocities. During the experiments power output at the pedals and velocity were measured. Additionally, vibrations at the handlebars were measured using a smartphone. Then, a curve consisting of the mathematical representation of rolling and air resistance was fitted to the experimental data and the rolling resistance coefficients of the surfaces and the effective frontal area of bicycle and cyclist were estimated. The magnitude of the vibrations at the handlebars was calculated for each test ride and each surface. From this data the linear regression models for each surface were derived using velocity as the predictor. Analyzing the data yielded rolling resistance coefficients of 0.01221, 0.01468 and 0.01832 for asphalt, fine gravel and coarse gravel, respectively, and showed significant difference. The magnitude of vibrations increases significantly with velocity and is higher for surfaces with higher rolling resistance. To validate the model the outdoor experiments were repeated with a similar prototype of a four-wheeled electric bicycle. The results can be used to classify the current surface and therefore estimate the rolling resistance coefficient. We believe that this system can help improve the estimation of the residual range of electric bicycles by providing more detailed information about the environment and consequently enhance their operating distance and the usage of the bicycle.

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Keywords: electric bicycles, cycling resistances, rolling resistance coefficient, road surface classification

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1. Introduction

An important issue for the usability of electric bicycles is their limited range, constrained by the capacity of the battery and the energy consumption of the motor. Especially when used for business purposes like cargo-bikes, the relationship between weight and operating distance is very important. As already known from electric vehicles, the total range is usually sufficient for daily mobility needs, but it mostly remains unused due to the range anxiety of users [1]. Providing accurate information about the residual range of an electric vehicle might help to overcome this problem and enhance the usage of the vehicle [1]. The residual range of an electric bicycle depends on three factors: the cyclists' fitness, bicycle characteristics and the environmental resistances. The environmental resistances during

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[*] Corresponding author. Tel.: +49-89-289-10351 ; fax: ++49-89-289-15389.
E-mail address: meyer@lfe.mw.tum.de

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cycling mostly consist of slope, air and rolling resistance [2,3]. Depending on the riding velocity the share of slope, wind and rolling resistances of the total riding resistances during steady state cycling is 10-20%, 56-96% and 10-20%, respectively [4]. Knowing these resistances in advance can help to better estimate the residual range of the electric bicycle. To calculate the necessary power output for cycling trips, several models have been used in the past [4–6]. However, to use these models accurate information about trip characteristics (e.g. road surface) is necessary. Whereas the resistances from slope can be estimated in advance using digital elevation models [7] or GPS information [8], the other resistances are often not available and subject to change. In this paper, we focus on the rolling resistance and present a method to estimate the current rolling resistance by classifying the current road surface. The system uses the cycling velocity and the vibrations at the handlebars to classify the road surface. The system can then be used to provide more detailed information about the environmental resistances and improve the estimation of the residual range of an electric bicycle and consequently enhance their operating distance and the usage of the bicycle. The outline of the paper is as follows: Section 2 describes the underlying methods of the study. Section 3 shows the results of the experiments while in section 4 the results are discussed. Section 5 concludes the paper.

2. Methods

2.1. System description

The main resistances which have to be overcome by a cyclist to maintain a certain velocity can be calculated by:

$$P_{res} = (F_{\text{slope}} + F_{\text{air}} + F_{\text{roll}}) \cdot v \tag{1}$$

where P_{res} is the total power from cycling resistances. The resistance forces in Eqn. (1) (F_{slope}, F_{air} and F_{roll}) are the slope, air and rolling resistance, respectively, and v is the cycling velocity. Resistances from bumps on the road can be neglected, because they are much smaller than the other resistances on most road surfaces. Resistances from acceleration can be neglected during cycling with a constant velocity [2]. The main resistance forces during cycling can then be calculated by the following equations:

$$\begin{aligned} F_{\text{slope}} &= m \cdot g \cdot \sin(\tan^{-1}(\Delta H)), \\ F_{\text{roll}} &= c_{\text{R}} \cdot m \cdot g \cdot \cos(\tan^{-1}(\Delta H)), \\ F_{\text{air}} &= 0.5 \cdot c_{\text{w}} \cdot A \cdot \rho_{\text{air}} \cdot (v - v_W)^2, \end{aligned} \tag{2}$$

where m is the combined mass of bicycle and cyclist, g is the acceleration of gravity, ΔH is the difference in altitude over the distance, c_{R} is the rolling resistance coefficient, $c_{\text{w}} \cdot A$ is the effective frontal area of the bicycle, ρ is the air density, and v_W is the wind speed.

Assuming level-road cycling ($\Delta H = 0$) and windless conditions ($v_W = 0$), Eqn. (1) can be rewritten to:

$$P_{\text{Air+Roll}} = 0.5 \cdot c_{\text{w}} \cdot A \cdot \rho_{\text{air}} \cdot v^3 + c_{\text{R}} \cdot m \cdot g \cdot v \tag{3}$$

Since the effective frontal area could not be determined separately by using, for instance, wind tunnel experiments, in the following both rolling resistance coefficient and effective frontal area of the bicycle were determined.

2.2. Subject and bicycle

A prototype of a four-wheeled electrically assisted bicycle (called QuadRad) was used in this study to collect the necessary data and to demonstrate the functionality of the system. It weighs 70 kg and has an integrated sensor system for measuring various parameters of the bicycle. The data is logged by a smartphone attached to the handlebar with a sampling frequency of 1 Hz. The sensors of the bicycle measure its velocity, the generated power of the electric motor and the power added by the cyclist by pedaling. In addition the acceleration in the three directions in space are measured by an accelerometer integrated in the smartphone. The subject participating in this study was 23 years old, had a weight of 75 kg and a height of 176 cm.

2.3. Test procedure

The rolling resistance coefficient (c_{R}) can be determined by various procedures [9,10]. In this paper, we used a method similar to the method of linear regression analysis [9]. The test procedure has been kept similar but a different analysis method was used to estimate the coefficients. For this method also the effective frontal area ($c_{\mathrm{w}} \cdot A$) has to be determined.

Rolling resistance itself depends on various factors like the road surface, tire tread, tire pressure and tire diameter. Friction losses in bearings and drive train are by definition not included in rolling resistance [2]. However, these losses occur during cycling and when measured in outdoor experiments contribute to the total resistances. Also, the test method yields results for the overall rolling resistance coefficient. Rolling coefficients for each tire separately might be different, because it is affected by load distribution and supported load [11].

For this study the subject tested three different tracks, each with a different type of surface typical for cycling (asphalt, fine gravel and coarse gravel, respectively). The tracks were chosen to have a certain minimum length so enough data could be collected during each test ride. The experiments were only executed at (almost) windless conditions. Also, the subject rode the test tracks in both directions to eliminate the effect of the remaining headwind as well as slope resistances from small inclinations (asphalt: 0.15%, fine gravel: 0.5%, coarse gravel: 0.31%). Each of the three tracks was tested five times on different days, resulting in a total amount of 15 data-sets. Tire pressure was set to 3 bar for each experiment.

One test ride on one track consisted of driving the track with five different velocities (5, 10, 15, 20, 25 km/h) in both directions - once from the starting point to the end and vice versa. The rider checked the current velocity via a tachometer which was mounted to the handlebars. The aim of the cyclist was to keep the velocity of the bicycle as close as possible to the predefined speed. Additionally, the cyclist focused on keeping the movements and posture of the upper body constant to keep the frontal area similar for each test ride.

2.4. Data preparation

The collected data was used to analyze three parameters. The first two parameters were the coefficient of rolling resistance (c_{R}) and the effective frontal area ($c_{\mathrm{w}} \cdot A$). To analyze these parameters, the velocity and corresponding total power (electric motor + cyclist) were plotted in Matlab and Eqn. (3) was fitted to the experimental data using a levenberg-marquardt algorithm [12]. The algorithm uses least-squares estimation to find the undefined variables of Eqn. (3) [13]. The air density was calculated on basis of appropriate weather data from a weather station in a 4 km range.

The third parameter calculated on basis of the collected data represents the vibrations that occurred at the handlebars during riding on the different surfaces. Therefore, the average absolute deviation of the accelerations in each direction in space was computed for each test ride. The formula to calculate the average absolute deviation for each direction is given by:

$$A_k = \frac{1}{n} \cdot \sum_{i=1}^{n} |a_{i,k}(t) - \overline{a}_k|, \text{with } k \in x, y, z \tag{4}$$

where A_k is the average absolute deviation in x, y and z direction respectively, $a_{i,k}(t)$ is the acceleration at each sampling point and $\overline{a}_k$ is the arithmetic mean of accelerations when the bicycle is stationary. n is the number of samples depending on the duration of the measurement and the used sampling frequency. In this study only negative deviations were considered because positive deviations sometimes exceeded the measurement range of the accelerometer. Then the magnitude of the average absolute deviations was calculated for each test ride using the following formula:

$$A_{x,y,z} = \sqrt{A_x^2 + A_y^2 + A_z^2}, \tag{5}$$

where $A_{x,y,z}$ is the magnitude and A_x, A_y and A_z are the average absolute deviations in the corresponding direction. This results in five different magnitudes for the five different velocities per data set. From this data, linear regression models can be calculated for each surface using the following equation:

$$y = \beta_0 + \beta_1 \cdot x \tag{6}$$

2.5. Statistical analysis

The computed coefficients of rolling resistance for the three different surfaces were statistically analyzed for differences using descriptive analysis of the confidence intervals as well as univariate ANOVA. Differences in magnitude between the various surfaces and velocities were tested using a bivariate ANOVA (mixed-model). Before computing the tests with SPSS the corresponding requirements for both ANOVA tests were checked.

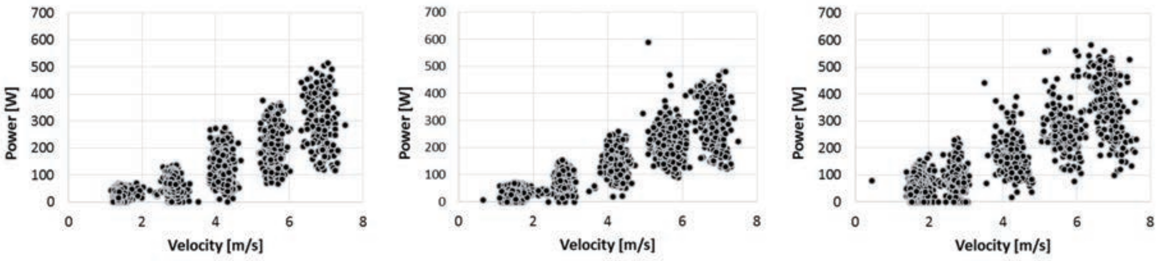

Fig. 1. Raw data for one test ride on asphalt (left), on fine gravel (middle) and on coarse gravel (right)

2.6. Classification

To automatically classify on which surface the cyclist is currently riding and consequently to estimate the current rolling resistance coefficient, the linear regression models are used. For the current velocity the corresponding magnitude for all three surfaces is calculated by Eqn. (6). Then, the euclidean distance between the measured magnitude and the calculated magnitude from the regression formulas can be determined by:

$$d_{surface}(A'_{x,y,z}, A_{x,y,z}) = \sqrt{(A'_{x,y,z} - A_{x,y,z})^2} \qquad (7)$$

where $d_{surface}$ is the euclidean distance of the magnitude for the specified surface, $A'_{x,y,z}$ is the calculated magnitude from the regression models and $A_{x,y,z}$ is the measured magnitude by the bicycle system. The lowest value of the three euclidean distances classifies the current surface and consequently determines the current rolling resistance coefficient.

3. Results

Figure 1 shows the raw data of velocity and propulsion power of one test ride for the three different surfaces. As can be seen, the variance in velocity and power increases with increasing velocity, since it becomes more difficult to keep the determined velocity constant. Fitting Eqn. (3) to the measured data for each test ride and calculating the mean value for each surface results in c_R values of 0.01221, 0.01468 and 0.01832 and c_w values of 0.84, 0.79 and 0.75 for asphalt, fine gravel and coarse gravel, respectively, and are shown by Tab. 1. Analysis of the 95% confidence intervals shows significant differences between the surfaces. ANOVA with post hoc test also shows significant differences in c_R between the different surfaces ($F(2, 12) = 15.93, p < .001$). Figure 2 shows the mean values and 95% confidence intervals of the rolling resistance coefficient as well as the resulting effective frontal area. The effective frontal area shows no significant difference between the tested surfaces neither when analyzing the 95% confidence intervals nor for the ANOVA ($F(2, 12) = 1.73, p > .05$), which shows the reliability of the test procedure.

Table 1. Mean coefficient of rolling resistance and effective frontal area with standard deviation (SD) and 95% confidence intervals (95% CI) for five test rides on three different surfaces estimated by fitting the mathematical representation of rolling and air resistance to experimental data.

	Asphalt	SD	95% CI	Fine gravel	SD	95% CI	Coarse gravel	SD	95% CI
c_R	0.01221	±0.00129	[0.011, 0.014]	0.01468	±0.00128	[0.013, 0.016]	0.01832	±0.00236	[0.015, 0.021]
$c_w A$	0.84	±0.10	[0.72, 0.96]	0.79	±0.06	[0.72, 0.86]	0.75	±0.07	[0.66, 0.83]

Figure 3 shows that the magnitude of vibrations depends on the current riding speed and is different for all three tested surfaces. Statistical analysis of the magnitude shows significant differences between velocities ($p < .001$) as well as between surfaces ($p < .001$). The dependency between velocity and magnitude can be described by a linear regression formula for each surface based on Eqn. 6 using the method of least squares. The resulting parameters β_0 and β_1 as well as the coefficient of determination for each surface are given by Tab. 2.

4. Discussion

The evaluation of the data shows a significant difference in rolling resistance coefficient and magnitude of accelerations for the three tested surfaces. However, other types of surfaces like sand or mud might show a different

Table 2. Results of the linear regression analysis for different surfaces.

	β_0	β_1	R^2
Asphalt	1.0554	0.3078	0.9965
Fine gravel	1.4667	1.0291	0.9801
Coarse gravel	2.0821	1.5313	0.9765

relationship between rolling resistance and magnitude. For calculating the riding resistances and coefficients only the rolling resistance and air resistance were considered. Slope resistance, resistances from moving parts and headwind were neglected in this study. Also, using a prototype of a four-wheeled electric bicycle leads to higher absolute values of rolling resistance coefficient as found in other studies [14,15]. As the characteristics of the tires (tread, pressure, diameter) affect the rolling resistance, they might as well affect the accelerations measured at the handlebars. Likewise, suspension will affect the accelerations as well. How these parameters affect the results has not been determined in this study and has to be considered for future work. For this study, sampling frequency of the data was determined by the integrated system at 1 Hz and thus the frequency spectrum of the vibrations was not evaluated, which might yield additional knowledge about the surfaces and improve the model. In [16] a sampling rate of 500 Hz was used. The effective values of the vibrations transported from the surface to the cyclist as well as the rolling resistance coefficient were measured and determined by analyzing the frequencies of the vibrations. The effective values increased linearly with velocity but did not necessarily increase with rolling resistance. Using a different measurement system to enable the analysis of both, absolute deviation and frequency of the vibrations, might enhance the validity of the method and improve the classification of the surfaces.

The tests performed for this paper were repeated with another prototype of the four-wheeled bicycle with a slightly different configuration (higher weight, larger frontal area, different tires) and another cyclist. These measurements took place on the same test tracks with the same test procedure. The calculated magnitudes for those tests show the same pattern as presented in this paper and increase with velocity as well as rolling resistance. However, absolute values of rolling resistance coefficient were higher due to the different bicycle type. Also, load distribution and supported load affect rolling resistance [11].

5. Conclusion

The aim of this paper was to find a method to classify the current road surface and consequently the current rolling resistance coefficient to provide additional information about environmental riding resistances. This information can be used to better estimate the residual range of electric bicycles and therefore increase their operational distance. The three tested surfaces have significantly different rolling resistance coefficients and magnitude of vibrations at the handlebars. The magnitude increases linearly with velocity and is higher for surfaces with higher rolling resistance coefficient. Linear regression models were derived to describe the relationship between cycling velocity and magnitude of the resulting accelerations at the handlebars for each surface. Using these models, the current surface can be classified by determining the euclidean distance between measured and calculated magnitude. The minimum distance represents the current road surface.

The results of this paper are valid for the tested surfaces and the used bicycle prototype but might be different for other types of surfaces and bicycles. In the next steps, experiments have to be conducted to enhance the current models and to transfer the results to conventional two-wheeled bicycles. Furthermore, to be able to classify the current surface

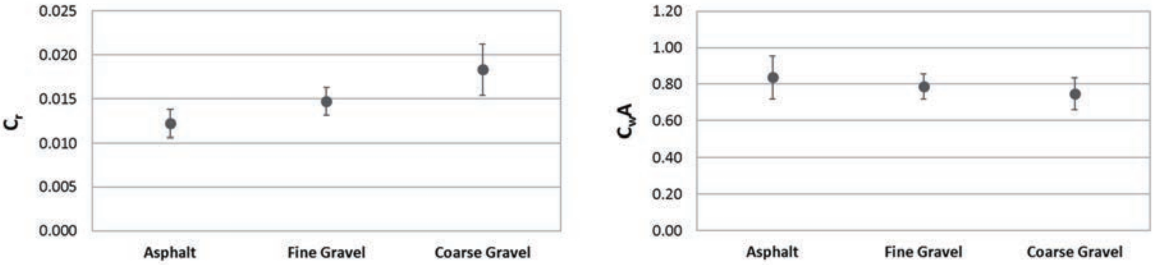

Fig. 2. Mean values with 95% confidence intervals of c_R (left) and $c_w \cdot A$ (right) for all three surfaces

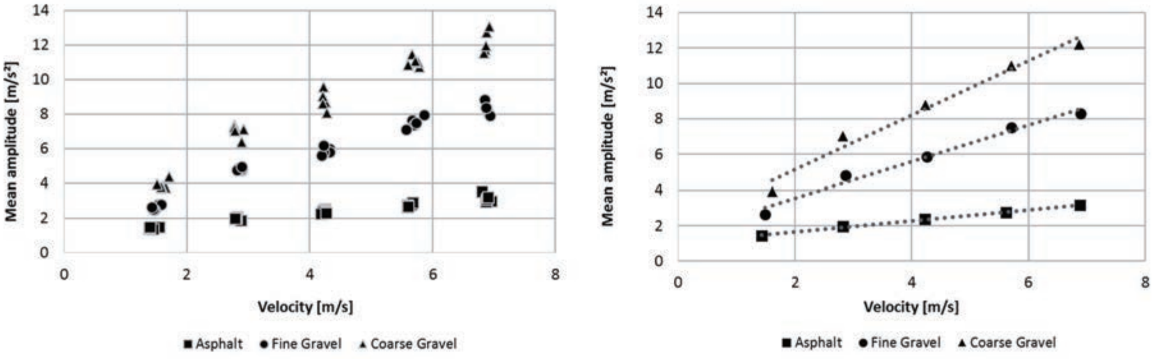

Fig. 3. Magnitudes of the average absolute deviations for every test ride and every surface (left) and results of the linear regression analysis (right)

while cycling, a method to extract and process measurement data in real-time has to be developed. Additionally, the system can be used to map the road surface of cycling paths and to provide this information to other cyclists, so that information about environmental resistances is available before starting a cycling trip.

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