Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 147 (2016) 526 – 531

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

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.

Peer-review under responsibility of the organizing committee of ISEA 2016

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

---

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

---

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

Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.232

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:

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

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:

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

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, $c_{\mathrm{w}} \cdot A$ 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:

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

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