A Macroscopic and Physically-Based Relationship Between Bike Speeds and Energy Expenditure During Commuting Trips

Giuseppe Cappelli[1,2], Sofia Nardoianni[1], Mauro D'Apuzzo[1(✉)], Heather Kaths[3], Vittorio Nicolosi[2], and Maria Teresa Iannattone[1]

[1] University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
{giuseppe.cappelli1,sofia.nardoianni,dapuzzo}@unicas.it,
cppgpp01@uniroma2.it,
mariateresa.iannattone@studentmail.unicas.it

[2] University of Rome "Tor Vergata", Via del Politecnico, 1, 00133 Rome, Italy
nicolosi@uniroma2.it

[3] Bergische Universität Wuppertal, Pauluskirchstraße 7, 42285 Wuppertal, Germany
kaths@uni-wuppertal.de

Abstract. As it emerges from the literature, bike speed is a trade-off between safety, travel times, and energy expenditure. In addition to that, infrastructure, terrain, and gender play also a key role. By assessing and correlating energy expenditure with cycling speed, it becomes possible to integrate terrain-related factors with individual human capabilities to gauge effort. This paper gathers terrain-related data from sixty-one (61) German cities and uses it to propose a relationship between energy expenditure and bike speed within a macroscopic, physically grounded framework. Furthermore, a Bike Mode Split (BMS) model is introduced to emphasize the role of energy expenditure in predicting cycling demand, as an application of this physically-based framework. Geographic data, Census data, and mode split data are collected from the main official German sources. The result shows that there is a linear relationship between bike speeds and energy expenditure, and also between energy expenditure and slope for conventional and electrical bike (c-bike, and e-bikes, respectively).

Keywords: Sustainable Mobility · Bike Speed · Energy Expenditure · e-bike · Modal Split

1 Introduction

When a road user decides to make a commuting trip, an activity or work (in technical terms) is performed. The energy required is provided by hydrolysis of the adenosine triphosphate (ATP), which allows muscle contraction within the human body. Only a fraction of this energy from ATP is implemented for working purposes: the other fraction is transformed in heat, and the magnitude depends on individual human body efficiency [1]. One way to measure the energy required to complete a task is the power

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that a commuter pushes on the pedals. This is due to the "power nature" of cycling: like rowing, cycling power output could be measured with strain gauges attached to elements subject to deformations (cranks, and pedals for instance) with the help of Hook's law [2].

De Geus et al. [3], in a field experiment, collect physiological data on different subjects to evaluate the energy expenditure required for commuting riders. Ten (10) men and eight (8) women were subjected to follow some protocols that employed maximal tests to collect power, perceived effort, heart rate, commuting speeds, travel times, and distances. In a so-defined and controlled framework, the main variables that could be used to retrieve energy expenditure are measured. But not always such types of methodologies could be implemented on a large scale, due to costs and not great attention paid to commuters.

The topography of the territory influences the reason why to cycle or not for commuting purposes, but it is less likely to influence recreational cyclists' attitudes. As it plays a fundamental role, hilliness and the effect of slope on cycling demand need to be studied in greater depth. In the last year, some studies have been conducted on route choice models for commuting purposes that considered slope as an important parameter [5, 6], but according to Meeder et al. [7] and Rodriguez and Joo [8], few studies account for topography in travel choice model.

Recently, new studies tended to overtake the problem of topography by introducing a more accurate variable, that is the energy expenditure: in the study of Cruz et al. [9], the authors try to quantify energy consumption, travel time, difficulty of each route, safety levels for cyclists in different alternative routes by using different sensors to assess the metabolic response of the human body during the activity. Although there are many ways to define the energy expenditure of physical activity, the metabolic equivalent of task (MET) can be seen as an index that gives information about the intensity of a particular activity [10], compared to a reference activity (resting or sitting): an activity of 3MET is three times more intense than resting (1MET, according to the original definition, is the resting metabolic rate during quite sitting [11]). As was highlighted in some studies [12], it is possible to foresee that the energy expenditure in flat cities is lower than in hilly cities, so the decision to use a bike for commuting is very related to the metabolic capabilities of the users, but also the choice to choose a specific route than another.

Another challenge is how it could be possible to evaluate speeds based on energy expenditure. According to Bigazzi and Figliozzi [13], speed choice compromises safety, travel times, and energy expenditure. As it emerges from the literature [14], bike speed is also influenced by infrastructure and topology, but also by gender: men cycle faster than women on conventional bikes. Evaluating and correlating energy expenditure with bike speed, can put together terrain-related aspects and human individual capabilities to make an effort.

According to Heinen et al. [15], the main determinants that influence the decisions to cycle or not could be categorized as the built environment, natural environment, socio-economic, psychological, and cost factors.

Among the natural environment determinants, landscape hilliness is considered in few studies [15], but according to Parking et al. [16], this variable could play an important role: a 10% increase in the hilliness proportion is associated with an 8.93% reduction in

proportion cycling commuting, but an increased hilliness of the route has a strong benefit on own health [17]. Moudon et al. [18] find that slopes do not have a negative effect, but their study mainly focuses on recreational cyclists who choose a route according to personal factors.

Despite the limited number of studies that take into account terrain-related parameters [19–21], it emerges from the current literature that this aspect is related to cycling demand, commuting, and route choices [22].

In this paper, terrain-related data on sixty-one (61) German cities are collected and used to evaluate a relationship between energy expenditure and bike speed in a macroscopic and physically based framework (and not on an individual basis). In addition to that, a Bike Mode Split (BMS) model in the German context is also provided to highlight the role of energy expenditure in forecasting cycling demand as a novelty aspect. The main research gap that this paper wants to highlight is the contribution of the energy expenditure parameters in defining cycling demand but also to find correlations between this parameter and cycling speed to improve cyclist behavioural models.

2 Method

In this section, the main steps of the proposed methodology are shown and explained as is possible to see in Fig. 1. The methodology starts with terrain-related data acquisition (described in Sect. 2.1), then the evaluation of power required during cycling, of the volume of oxygen during activity, and the e valuation of Energy Expenditure for c-bike and e-bike (Sect. 2.2), and finally the development of macroscopic speed model (see Sect. 4.1).

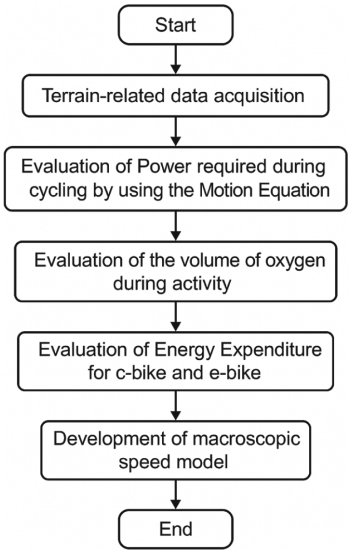

Fig. 1. Flow chart of the methodology proposed.

2.1 Terrain-Related Data Acquisition and Processing

The first step of this methodology includes terrain-related data acquisition and processing. With the help of Google Earth [23], used to collect and analyze terrain-related data, a digital terrain model (DTM) for each of the sixty-one (61) German cities is created to perform the following analysis.

Within this DTM, several nodes are placed in order to simulate the origin and the destination of the cycling commuting trip. This approach bypasses the need to define specific traffic zones, allowing for the simulation of random routes (see Fig. 2).

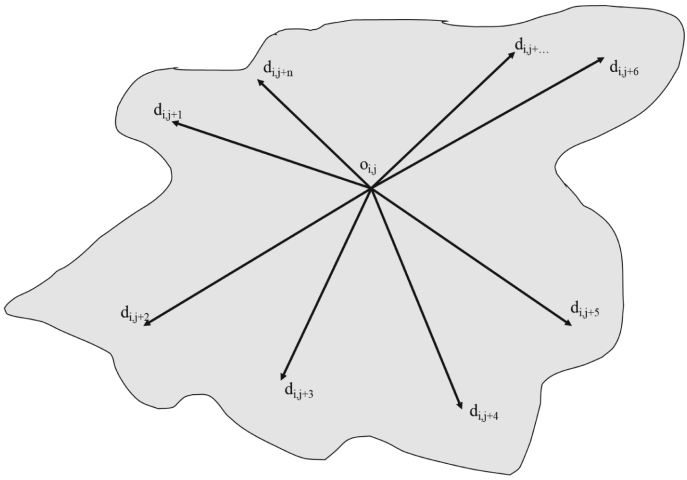

Fig. 2. Graphical representation of the methods to collect terrain-related data: the area in grey represents the city area within the municipal borders; $o_{i,j}$ is the origin of the simulated commuter trip, while $d_{i,j+1}$ to $d_{i,j+n}$ are the destinations of the trips. The slope is evaluated on each route connecting the origin and the destination.

2.2 Motion Equation and Energy Expenditure

Commuter cyclists, when making their trips, have to face three resistances: rolling, aerodynamic, and gravity resistance. This condition could be expressed through the motion equation below (Eq. 1) [24]:

$$W = \frac{C_b}{\eta_{bike}} \left\{ \sum mg \left[C_R + \frac{s}{100} + \frac{a}{g} \left(1 + \frac{m_w}{\sum m} \right) \right] + 0.5 C_D A \rho (C_b + C_w)^2 \right\} \quad (1)$$

Where:

- W: is the power expressed during cycling activity [W]
- C_b: bicycle speed [m/s]
- C_w: headwind [m/s]
- η_{bike}: mechanical efficiency

- m: mass of the cyclists, bike and accessories [kg]
- m_w: rotational mass of wheels and tires [kg]
- g: gravity acceleration [m/s^2]
- s: road gradient [%]
- a: acceleration [m/s^2]
- C_D: drag coefficient
- C_R: rolling resistance coefficient [dimensionless]
- A: frontal area of cyclist and bike [m^2]
- ρ: air density [kg/m^3]

From Eq. (1), the power expressed on pedals can be evaluated by knowing the road gradient that could be retrieved from the procedure in the previous section. For the other terms related to the equation, reference could be made to the current literature [25]. Equation (1) quantifies the external load that a commuter must face on a trip, but it is also essential to evaluate the internal load with terms to quantify aerobic activity. As suggested by Bigazzi e Figliozzi [13], aerobic activity can be quantified as the volume of oxygen utilized during a task. The authors suggest that this quantity could be evaluated as (Eq. 2):

$$VO_2 = a\frac{W}{m_b} + b \tag{2}$$

Where:

- VO_2 is the oxygen consumption during activity [mLO_2/min/kg]
- W is the power expressed during cycling activity [W]
- m_b is the mass of the cyclist [kg]
- a is a calibration coefficient equal to 10.8 in [13]
- b is a calibration coefficient equal to 7 in [13]

From Eq. (2) it is also possible to evaluate the Energy Expenditure, as expressed below (Eq. 3):

$$EE = \frac{VO_2}{c} \tag{3}$$

Where:

- EE is the energy expenditure during cycling activity [MET]
- VO_2 is the oxygen consumption during activity [mLO2/min/kg]
- c is an equivalent coefficient equal to 3.5

By combining Eqs. (1), (2), and (3), cyclist speed and Energy Expenditure could be related as follows (Eq. 4):

$$EE = \frac{a}{m_b * c}\left\{\frac{C_b}{\eta_{bike}}\left\{\sum mg\left[C_R + \frac{s}{100} + \frac{a}{g}\left(1 + \frac{m_w}{\sum m}\right)\right] + 0.5C_D A\rho(C_b + C_w)^2\right\}\right\} + \frac{b}{c} \tag{4}$$

Where:

- W: is the power expressed during cycling activity [W]

- C_b: bicycle speed [m/s]
- C_w: headwind [m/s]
- η_{bike}: mechanical efficiency
- m: mass of the cyclists, bike and accessories [kg]
- m_w: rotational mass of wheels and tires [kg]
- g: gravity acceleration [m/s^2]
- s: road gradient [%]
- a: acceleration [m/s^2]
- C_D: drag coefficient
- C_R: rolling resistance coefficient [dimensionless]
- A: frontal area of cyclist and bike [m^2]
- ρ: air density [kg/m^3]
- m_b is the mass of the cyclist [kg]
- a is a calibration coefficient equal to 10.8 in [13]
- b is a calibration coefficient equal to 7 in [13]

Equation (4) is valid for conventional bikes, but a similar relationship can be retrieved for e-bikes. As suggested by Liu et al. [25], if the objective is to evaluate power outputs for e-bikes, it is necessary to introduce the assistance ratio, which could be evaluated as follows:

$$AR = \begin{cases} 1.4 & if\ 0 \le C_b \le 10 \\ 1.4 - 0.1 * (C_b - 10) & if \quad C_b \ge 10 \end{cases} \tag{5}$$

Where:

- AR is the assistance ratio [dimensionless]
- C_b: bicycle speed [m/s]

The power output expressed on pedals without the assistance of an electric powertrain is expressed by Eq. (1): this contribution needs to be reduced by a coefficient as follows (see Eq. 6):

$$W = \frac{C_b}{(1+AR)\eta_{bike}} \left\{ \sum mg \left[C_R + \frac{s}{100} + \frac{a}{g} \left(1 + \frac{m_w}{\sum m} \right) \right] + 0.5 C_D A \rho (C_b + C_w)^2 \right\} \tag{6}$$

Where:

- W: is the power expressed during cycling activity [W]
- C_b: bicycle speed [m/s]
- C_w: headwind [m/s]
- η_{bike}: mechanical efficiency
- m: mass of the cyclists, bike and accessories [kg]
- m_w: rotational mass of wheels and tires [kg]
- g: gravity acceleration [m/s^2]
- s: road gradient [%]
- a: acceleration [m/s^2]
- C_D: drag coefficient

- C_R: rolling resistance coefficient [dimensionless]
- A: frontal area of cyclist and bike [m^2]
- ρ: air density [kg/m^3]
- *AR* is the assistance ratio [dimensionless]
- C_b: bicycle speed [m/s]

The Energy Expenditure for e-bikes can be evaluated as follows (Eq. 7):

$$EE = \frac{a}{m_b * c}\left\{\frac{C_b}{(1+AR)\eta_{bike}}\left\{\sum mg\left[C_R + \frac{s}{100} + \frac{a}{g}\left(1 + \frac{m_w}{\sum m}\right)\right] + 0.5C_D A\rho(C_b + C_w)^2\right\}\right\} + \frac{b}{c} \quad (7)$$

Where:

- W: is the power expressed during cycling activity [W]
- C_b: bicycle speed [m/s]
- C_w: headwind [m/s]
- η_{bike}: mechanical efficiency
- m: mass of the cyclists, bike and accessories [kg]
- m_w: rotational mass of wheels and tires [kg]
- g: gravity acceleration [m/s^2]
- s: road gradient [%]
- a: acceleration [m/s^2]
- C_D: drag coefficient
- C_R: rolling resistance coefficient [dimensionless]
- A: frontal area of cyclist and bike [m^2]
- ρ: air density [kg/m^3]
- *AR* is the assistance ratio [dimensionless]
- C_b: bicycle speed [m/s]
- m_b is the mass of the cyclist [kg]
- *a* is a calibration coefficient equal to 10.8 in [13]
- *b* is a calibration coefficient equal to 7 in [13]

3 Case Study

3.1 Description of the Sample

The analysis carried out in this paper started with the collection of the necessary data. Terrain-related data are needed to implement the methodology described in the previous section. In addition, a further application based on the aforementioned methodology is also proposed, that is, whether the Energy Expenditure parameter could be a good predictor in forecasting cycling demand at a macroscopic level.

The dataset contains sixty-one (61) German cities, each characterized by a population of more than 100,000 inhabitants. As shown in Table 1, socio-economic, traffic, and terrain-related variables of the cities analysed and considered in this study are proposed. Mean Slope is obtained by implementing the methodology described in the previous section, for the socio-economic variable to the German Census [26], while for the mode split data collection, references are made to the German National Survey Database [27].

Table 1. The main characteristics of the cities analyzed in this paper.

Categories	Minimum	Mean	Maximum
Population [−]	101,158	385857.92	3,677,472
Area [km^2]	54.40	190.23	891.30
GDP per capita [Euro]	27,745	56835.03	158,749
Bike mode split [−]	0.03	0.16	0.38
Pedestrian mode split [−]	0.09	0.23	0.35
Public transit mode split [−]	0.05	0.15	0.27
Car mode split [−]	0.21	0.46	0.7
Mean slope [%]	0.05	0.89	8.39

4 Results

4.1 Relationship Between Energy Expenditure and Bike Speeds

As shown in Eq. (4), the mass and the frontal area of the cyclist are very variable parameters and depend on the typology, age, and gender of the cyclist. In the macroscopic framework that characterizes this work, some parameters need to be defined *prior to performing the* analysis. Mean values of the parameters, according also to the evidence of the literature review, are selected [24].

As can be observed in the equation above, there are two unknown quantities: the first is energy expenditure, and the second one is bike speed. In field tests, oxygen consumption is measured by breathing face-mask [28], while cycling speed through GPS devices. When these two data are unavailable, measuring one quantity or the other is essential. For instance, in this paper, the speed is evaluated as expressed in Eq. (5), through a speed model (see Fig. 3) that is related to road slope [12], as the main assumption:

$$C_b = e \times s + f \tag{5}$$

Where:

- C_b is the average cycling speed [km/h]
- s is the slope [dimensionless]
- e and f are the calibration coefficients, equal to -1.1484 and 20.553, respectively.

From the evaluation of bike speeds with Eq. (5) and by the comparison with the related Energy Expenditure, it emerges that the relationship between the two variables is described below (Eq. 6):

$$C_b(EE) = g \times \mathrm{EE} + h \tag{6}$$

Where:

- C_b is the average cycling speed [m/s]
- EE is the Energy Expenditure [MET]

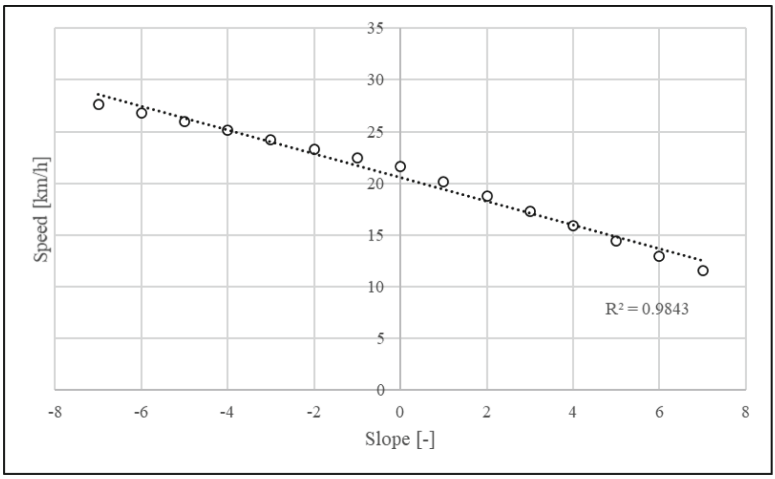

Fig. 3. Speed model from field data shown in the paper of Parking et al. [12]. The relationship between speed and slope is quite linear.

- g is the calibration coefficient (in this particular case of standard conditions equal to −0.0014) [dimensionless]
- h is the calibration coefficient (in this particular case of standard conditions equal to 5.7194) [dimensionless]

The graphical output of the relationship is shown in Fig. 4. By using the same equation described in the previous sections, relationships between terrain-related parameters and Energy Expenditure for conventional and electric bikes are also obtained (see Fig. 5 and Eq. 7):

$$EE = a \times \mathrm{s} + b \tag{7}$$

Where:

- EE is the Energy Expenditure [MET]
- s is the slope parameter [dimensionless]
- a is the calibration coefficient (in this particular case of standard conditions equal to 221.05 and 92.105, for c-bike and e-bike, respectively) [dimensionless]
- b is the calibration coefficient (in this particular case of standard conditions equal to 7.125 and 4.1354, for c-bike and e-bike, respectively) [dimensionless]

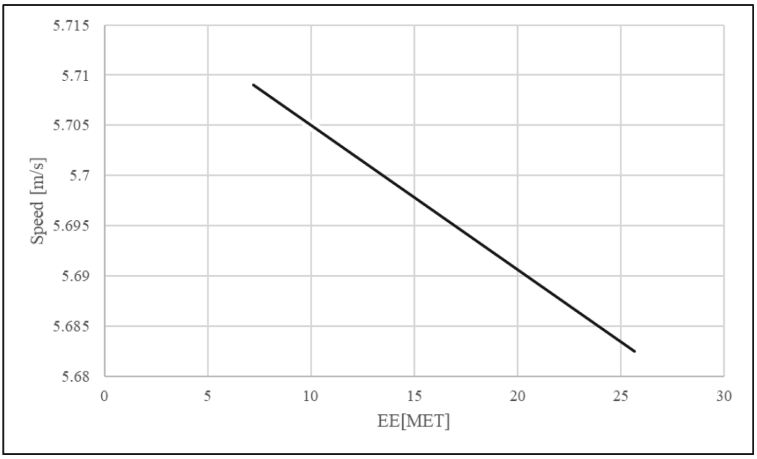

Fig. 4. Graphical representation of the relationship between bike speed and energy expenditure for conventional bikes, in standard condition as suggested by [24].

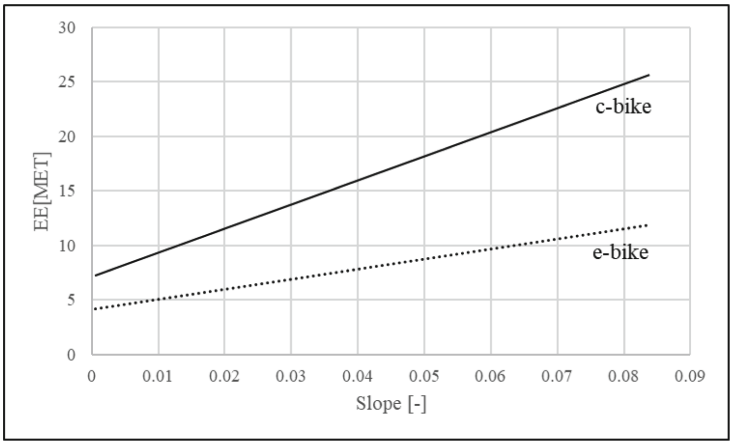

Fig. 5. Graphical representation of the relationship between terrain-related parameters and energy expenditure for conventional and electric bikes, in standard conditions as suggested by [24].

4.2 Some Applications: Energy Expenditure-Based Cycling Demand Model

According to some recent studies [19–21], there is a link between the terrain-related characteristics of an area and the commuting cycling demand, as well as between energy expenditure and cycling demand. The reason energy expenditure could be a better predictor relies on its structure: energy expenditure depends not only on terrain-related characteristics but also on human inner individual capabilities to make an effort. This ability is strictly related to the age and gender of individuals.

As shown in [21], energy expenditure, alongside other features in the Italian context, can predict with good accuracy cycling demand on a macroscopic level. As a further

application of this theoretical framework, the methodology in [20, 21] is replicated and proposed in this paper. In Fig. 6, the graphical relationship between energy expenditure and bike mode split (BMS) is shown: when the mean energy expenditure increases, the number of commuting trips made with the bike decreases.

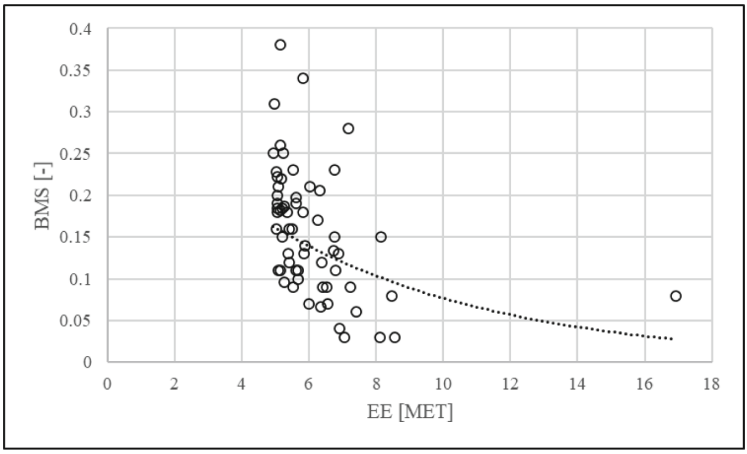

Fig. 6. Graphical representation of the relationship between energy expenditure (EE) and Bike Mode Split (BMS) for conventional, in standard conditions as suggested by [24].

As the first step of the methodology, the German cities analysed (it is worth remembering that cities with a population higher than 100,000 inhabitants are selected), are clustered into two sections: cities with a number of inhabitants lower than 500,000 and higher than 500,000. The two classes of cities allow to evaluate two different macroscopic models to forecast cycling demand. The general shape of the model can be described as follows (Eq. 8). The logarithm of bike demand is used is due to the not normal distribution of bike splits in the German context: the logarithms of these quantities follow a normal distribution.

$$\log(BMS) = a + b\frac{1}{EE} \tag{8}$$

Where:

- *BMS* is the bike mode split of the single city [dimensionless]
- *EE* is the Energy Expenditure [MET]
- a and b are the calibration coefficients [dimensionless]

The values of the calibration coefficients are shown in the Table 2 below.

In the Table 2, the two aforementioned modes are proposed. It is worth noting that the performances of the two models (expressed as adj-R^2), at first glance, seem not quite high, but it is essential to remember that only a single variable is used as a predictor of bike mode split. In addition, the p-value associated with the intercept and the Energy expenditure is very low, and that indicates the significance of the features used to define the model.

Table 2. A brief description of the two models proposed according to the dimensionality class identified: the estimate of the calibration coefficients, the p-values associated to the variables, and the adj-R^2 are reported.

Number of Inhabitants	Variable	Estimate	Std. Error	t-value	Pr(>|t|)	Adj-R^2
<500,000	a	−1.29569	0.08043	−16.109	$<2 \times 10^{-16}$	0.3902
	b	5.06158	0.90805	5.574	1.25×10^{-6}	
>500,000	a	−1.4059	0.1827	−7.694	5.59×10^{-6}	0.4311
	b	3.3504	1.0170	3.294	6.41×10^{-3}	

5 Conclusions

In the recent literature, several studies on the mode choice model tend to use all the possible explanatory variables to understand the utility of choosing a bike as a mode of transport or not. In this study, there is a need to study those variables that, according to the international literature review, influence the most bike commuting: energy expenditure is one of them.

Within a macroscopic and physically-based approach, the study wants to find reliable and accurate relationships between energy expenditure, speeds, and cycling demand in cities. Commuter cyclists encounter three types of resistance during their trips: rolling, aerodynamic, and gravitational resistance. These quantities can be represented by the motion equation.

The analysis presented in this paper began with gathering the necessary data. With the help of open-source tools, geographic data could be collected and processed and then utilized to simulate commuting trips within an area. Specifically, terrain-related information is crucial for applying the aforementioned methodology and evaluating the energy expenditure required to make a trip. Additionally, the paper proposes a further application based on this methodology: determining whether the Energy Expenditure parameter can effectively predict cycling demand at a macro level. As far as it is known, this variable is the first time that is used in simple regression models, and it is expected that it could be an important one also in more complex models, such as Discrete Choice Models.

In addition to that, relationships among energy expenditure for conventional and electric bikes, bike speeds, and slopes are shown alongside the whole methodology to retrieve the theme.

The contribution to the research field of this paper relies on two aspects. The first aspect regards bike speed models in which energy expenditure is the only independent variable. Energy expenditure depends on age, gender, and physical characteristics, which vary among people. This aspect highlights the need for further collection of field data on commuter cyclists to be able to calibrate more accurate bike speed models, which are useful, for instance, to forecast cyclists' behaviours and to improve microscopic models. In addition to that, Energy expenditure could also be implemented in Discrite Choice Models to study the reason behind e-bikes and c-bike are chosen. As a second

contribution, two bike demand models are calibrated by using as unique independent variable energy expenditure. Despite the not great performances of the model, almost 40% of the variance could be explained with only a single variable. The novelty aspect of this paper lies on defining a theoretical procedure to evaluate Energy Expenditure and highlight the importance of this variable in cycling commuting choices.

It is hoped that this methodology, rather than the proposed models, will be useful for new insights into research topics and for the development of behavioural models for cyclists which take into account, in a single variable, metabolic and individual aspects. From an urban planning perspective, these results could be useful to promote cycling in urban area in which terrain-related territory characteristics could be an obstacle to commuting cycling trip. In addition to that, these findings highlight how metabolic aspect should be considered when cycling paths and routes need to be designed and to make them more accessible for everyone. The accessibility of some points or areas in cities could also be evaluated, taking into account the energy expenditure to reach the destination.

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