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Introducing new criteria to support cycling navigation and infrastructure planning in flat and hilly cities

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Abstract

The main objective of this work is to quantify the energy consumption, travel time, difficulty of each route and also safety levels for cyclists in different alternative routes. For this study, cyclists ride a conventional bicycle equipped with a GNSS and the energy required is quantified with Bicycle Specific Power Methodology (BSP). Cyclists also wore an equipment to record the heart rate called Vital Jacket and a video camera to record road conflicts between cyclists and cars. The aforementioned methodology was applied to three different routes chosen in the Portuguese cities of Aveiro (flat terrain) and Porto (hilly). For the flat city, the average energy expenditure was 44, 5 Wh/km while for the hilly area the energy expenditure was 96,05 Wh/km. For each origin-destination pair by choosing an appropriate route it is possible to save about 28% energy in Aveiro and 35% in Porto. Regarding route comfort, the average number of car overtaking maneuvers to the bicycle was used as indicator, while road safety was based on historical data. The tradeoffs identified and variation magnitude of variables analyzed suggest the information provided would be useful for cyclists with heterogeneous profiles as well as to support management authorities in order to maximize the attractiveness of the various routes.

Keywords: On-road monitoring; bicycles; BSP; route optimization

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1. Introduction

The transportation sector faces increasingly demanding energy consumption and emissions standards representing 33,2% of the final energy consumption, with the road transportation sector being responsible in 2017 for 82% of that energy consumption (EIA, 2017). An alternative to reduce the impact of the transportation sector, especially regarding urban environment, is to reduce the demand for energy intensive modes of transportation and to promote alternatives that provide a less noisy, cheaper and more sustainable alternative than a day-to-day car commute. New information technologies and providing information on new variables related with road cycling can be an important tool for enhancing the use of bicycles, either through support systems at the policy level, or through the improvement and creation of bicycle sharing systems that effectively are attractive to citizens.

2. Literature review – current cycling navigation platforms

It is commonly acknowledged that cyclists select their route differently to drivers of private vehicles. Commuter cyclists have multiple criteria when choosing their route: the travel time and the suitability of a route including safety, traffic volumes, traffic speeds, presence of bicycle lanes, whether the terrain is flat or hilly (Ehrgott, Wang, Raith, & Van Houtte, 2012). Thus, bicycle route planners have emerged as a kind of extension of route planners for cars, although not always presenting the best solutions. In fact, the most interesting results obtained though bike route planners are based on more specific algorithms for the bicycle, but they are only incorporated in some cities where the use of this mode of transportation is more frequent. Although there are a number of bicycle route planning tools available, the modelling and way in which bicycle users choose their routes is rarely mentioned in the literature.

Table 1. Comparative synthesis of bike route planners on the market.

		Google Maps	Cycle Vancouver[1]	Bike Metro	Ride the City	Via Michelin	Bike	HSL HRT	Open Route Service	London Cycling Campaign
Characteristics	Alternative routes suggestion					o				o
	Return itinerary suggestion		o	o	o	o	o		o	o
	Adding intermediate points	o				o	o		o	
	Consider road slope	o	o	o				o	o	
	Open Source Technology		o				o		o	
	Smartphone version available	o	o		o	o				o
Inputs	Allows to add other information to the map (layers)	o	o		o		o	o	o	
	Accepts contributions or information to add to the map	o	o						o	
	Asks for feedback on the suggested route				o					o
Outputs	Best departure time									o
	Average speed		o				o	o		o
	Preferred route type		o				o	o	o	
	Type of pavement preferred						o	o		
	Slope tolerance level		o	o						
	Rider experience			o						
	Avoid areas or traffic lights						o		o	
	Distance	o	o	o	o	o	o	o	o	o
	Estimated travel time	o	o		o	o	o	o	o	o
	Turnaround list	o	o	o	o	o	o			o
	Altimetry profile		o	o			o	o	o	o
	Accumulated elevation		o	o	o					
	Calories consumed		o	o				o		o
	Meteorological forecast							o		
	Number of traffic lights									o
	Export route to Google Earth		o				o		o	o

([1] *http://cyclevancouver.ubc.ca*)

The selection of routes by the riders assumes beforehand that they behave all in the same way and that they only have a single objective of travel that is related to the minimization of the cost or time associated to the trip that they intend to make. In fact, route generators for bicycle users differ widely from the conventional route planners, since they integrate other variables when calculating tips costs for cyclists. Table 1 shows a comparative analysis of some the most important existing bike route planners. Although cycling navigation tools address a broad set of criteria, the authors did not identify collaborative tools focused on a multi-dimensional data structure analysis to support the decision making of cyclists and management authorities.

Regarding the decision making process, Pritchard (2018) has identified seven families of methods for studying Bicycle Route Choice—Such methods include GPS devices, smartphone applications, crowdsourcing, participant-recalled routes, accompanied journeys, egocentric cameras and virtual reality. Other works have focused on estimating the cyclist real physiological impacts (Duarte, Mendes, & Baptista, 2014) and developing a methodology to assess real-world operation patterns based on bicycle power (driving power distribution), Mendes, Duarte, & Baptista, 2015). Detailed information on route characteristics is not only useful to support cyclists in the route decision process, it also provides very relevant information for the level of planning and promote this transport mode. Demand is influenced by distinct sets of factors: the conventional bike share choice is most sensitive to measures of effort and comfort while the e-bike share choice is more sensitive to user heterogeneities (Campbell, Cherry, Ryerson, & Yang, 2016). While most of the studies focused on an analysis route choice behavior using different methods, to date the authors are not aware of applied research in the development of a collaborative platform to support cycling navigation based on important criteria (comfort, effort physical, travel time) and simultaneously constituting a tool to support the management and planning of cycling infrastructure.

3. Concept and Methodology

The main concept of the proposed approach can be seen in figure 1. The main purpose of this work is to assess in which extent the information generated in this study (Bicycle specific power, Energy expenditure, Safety and comfort and Travel time) may be relevant and effective for further integration into a collaborative sensing platform to be used both from and individual and management point of view. The methodology used to monitor the impact of the route choice was based on four main steps. i) empirical monitoring, ii) data analysis, iii) analysis of results and, iv) systemization of information for final users.

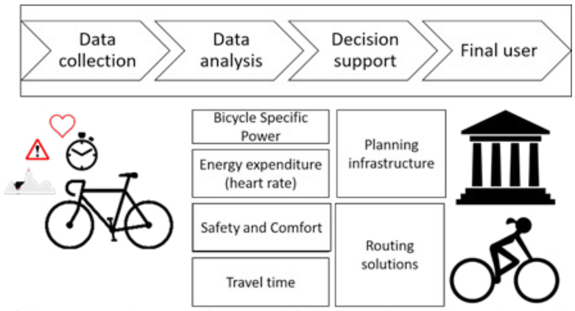


Fig. 1. Concept of the proposed approach to provide information to managing authorities and cyclists

3.1. Empirical monitoring

3.1.1. Prototype description

A conventional equipped aluminum bicycle (18 kg) was used to record three data sets: a video camera to record the traffic density and car overtaking's , an equipment for recording cyclist's heart rate called "Vital jacket" (Cunha et al., 2010) and a GNSS data logger data to record the dynamic profile of the trip (including location, altitude and speed). The Vital Jacket is intended to be a "heart wave monitor". This equipment can send clinical quality ECG and heart rate data through Bluetooth wireless connection. At the same time, all data is collected into an SD memory card that can be used for offline analysis (Cunha et al., 2010).

A video camera (Denver ACT-1015 MSD) was used to register and describe the traffic density on selected routes. All equipment have been synchronized and recorded data with 1 Hz resolution. The weight associated to the equipment is negligible and can be easily carried by a cyclist, as shown in Figure 2. Road experiments were performed during weekdays in similar periods of the day under dry weather conditions and temperature ranging between 18 and 22 Cº.

Fig. 2. Tested bicycle; Prototype components (GNSS, HR sensors, and video camera) used for the real time monitoring.

3.1.2. Study routes

12 routes connecting 6 origin-destination pairs were covered. In total 176 km of road experiments have allowed to gather about 13 hours of video equivalent to 48,240 data points on second by second heart rate (HR), bike position speed, acceleration, and road grade (see table 2).

Table 2. Route characterization in terms of route length, distance covered, and road grade

Route	City	OD	Route length (km)	Total Distance covered (km)	Average positive slope (rad)	Average negative slope (rad)
R1a	Aveiro	AB	2,82	25,38	0,047	-0,052
R1b	Aveiro	BA	2,79	25,11	0,05	-0,054
R2a	Aveiro	AB	2,2	19,8	0,066	-0,064
R2b	Aveiro	BA	2,24	20,16	0,055	-0,059
R3a	Aveiro	AB	2,83	25,47	0,06	-0,052
R3b	Aveiro	BA	2,81	25,29	0,056	-0,05
R4c	Oporto	CD	2,03	6,09	0,272	-0,342
R4d	Oporto	DC	1,51	4,53	0,161	-0,22
R5c	Oporto	CD	2,21	6,63	0,268	-0,249
R5d	Oporto	DC	1,67	5,01	0,178	-0,243
R6a	Oporto	DC	2,25	6,75	0,268	-0,285
R6b	Oporto	DC	1,89	5,67	0,239	-0,329

3.2. Data processing

3.2.1. Specific Power and Energy expenditure

Bicycle Specific Power methodology, a concept developed by Mendes, Duarte, & Baptiste, 2015 was employed to estimate energy consumption rates based on real world on-road data, according to eq.(1)

$$BSP = v \times [a \times (1+\varepsilon_i) + g \times sen(\theta) + g \times C_R] + \frac{1}{2} \times \rho_a \times C_D \times \frac{A}{m} \times v^3 \quad (1)$$

where v is speed (m/s), m is mass (bicycle and cyclist in kg), a is acceleration ($m.s^{-2}$), θ is road grade, ε_i is the effect of translational mass of powertrain rotating components (0.01), ρa is air density (1.2 kg/m^3), A is frontal area (0.50 m^2), g is the gravitational constant (9.81 m/s^2), Cr is the rolling coefficient (0.008 for bicycles and Cd is the aerodynamic coefficient (1.2). Using the respective coefficients, the BSP in (W/kg) is defined by Equation to conventional bikes:

$$BSP = v \times [1,01 \times a + 9,81 \times sen(\theta) + 0,078] + 0,00041 \times v^3 \quad (2)$$

Second by second, BSP values were categorized into modes in order to cover the full spectrum of bicycle operation. Table 3 presents the 10 modes used in this work and the respective range of power per mass previously defined by Duarte et.al (2014).

Table 3. Binning method for BSP (adapted from Duarte et al., 2014)

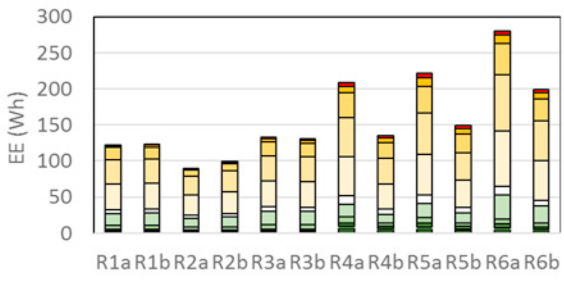
Descent, braking and stops		Rising, speed and deceleration	
BSP mode	Definition	BSP mode	Definition
0	BSP < -4	6	0 < BSP ≤ 1
1	-4 ≤ BSP < -3	7	1 < BSP ≤ 2
2	-3 ≤ BSP <-2	8	2 < BSP ≤ 3
3	-2 ≤ BSP < -1	9	3 < BSP ≤ 4
4	-1 ≤ BSP < 0	10	BSP >4
5	BSP = 0		

Heart rate (HR) data from different cyclists was matched with BPS modes distribution in order to estimate the human energy expenditure in different routes. An important step was to analyze the human energy expenditure (EE) associated to each BSP mode. i.e. the energy spent by the cyclist to drive the bicycle during each second. HR can be a useful explanatory variable to generate an accurate approximation of the energy consumed by human body during physical activity. Mendes et al (2014) developed an average equation based on three different models relating HR and Energy Expenditure (EE). This equation was used for the purpose of this study. For the purpose of demonstrating the methodology, the data of all cyclists were integrated into a single data set. However, further data from different demographic groups should be considered for achieving representative sample of the population. Empirical row data were filtered to remove outliers and errors from HR and GNSS data (e.g acceleration higher than $1m/s^2$).

$$EE = (9 \times 10^{-6}) \times HR^2 + 0.006 \times HR - 0.0449 \quad (3)$$

3.2.2. Safety and comfort data

To further support the decision-making process, other variables such as the traffic density (e.g. number of overtaking maneuvers by cars) were also considered. After the field work, the number of cars passed in the same direction along each route was estimated by video analysis in the laboratory. A low-cost distance sensor for counting and determine overtaking distance is being improved to automate this process.



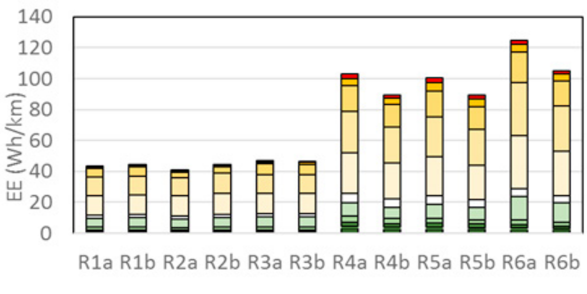


Fig. 3. (a) Total Energy expenditure and relative contribution of the time spent in each BSP mode; (b) Total Expenditure per km and relative contribution of the time spent in each BSP mode. Flat City Aveiro (R1, R2, R3) Hilly City (Porto R4, R5, R6).

The number of accidents on each route was processed in a geographic information system accident data with cyclists (2012-2017) and map matched with analyzed routes. All road accidents involving cyclists that results any level of injury (light and severe injuries) or fatalities were taken into consideration. However, the reported results revealed that all the crashes occurred in the analyzed routes refer to light injuries.

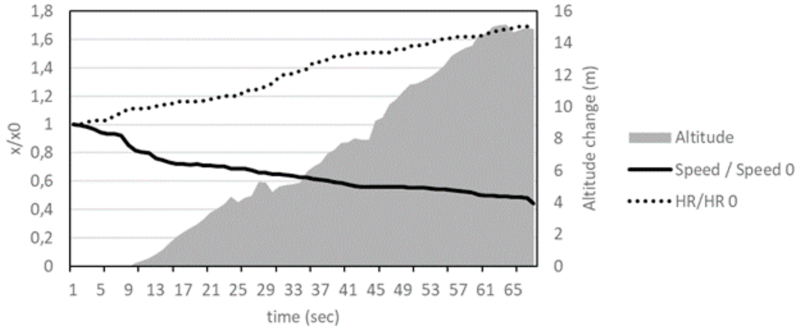


Fig. 4. Relative variation of HR and Speed over time during an ascending section with 180 m length.

4. Results

In a first phase, the results of the empirical monitoring of the routes are demonstrated. Subsequently, it is discussed how information can be disseminated to cyclists and used by management authorities.

4.1. Energy expenditure and BSP mode

Figure 3 demonstrates cumulative energy expenditure per BSP mode for the whole route and also normalized by distance. Despite all routes in the hilly City of Porto are shorter than in Aveiro, the average total energy expenditure per trip is considerable higher (170%). One may also see that the contribution of higher BSP modes for total energy expenditure is considerably higher in the hilly city routes. In terms of route comparison for the same OD pairs, figure 3a shows that is possible to save approximately 30% energy by choosing an appropriate route in the city of Aveiro and in the city of Porto. Figure 4 exemplifies the relevance of altitude change in terms of relative speed reduction and HR increase by crossing or a 180 meter ascending section.

Table 4 summarizes a set of important indicators for cyclists which were estimated based on the monitoring prototype and historical data. In addition to energy expenditure previously described, the 5-year accident history (ANSR 2018), the number of car overtaking's (from video sensors), the number of seconds spent on the higher VSP modes (3, 4, 5) (corresponding to situations of intense physical effort), travel time and distance are provided. Due to limited space, results are presented only for AB (flat) and CD (hilly) OD pairs.

The number of registered accidents with cyclists in both OD pairs is relatively low in both cities. A plausible explanation is the very low bicycling modal share in both cities Aveiro (2.7% (Way2go, 2012)) and Oporto (0,4% (INE, 2017)). Even considering the limited range of data, we can observe that the number of overtaking maneuvers by cars is not directly related to the number of accidents.

Table 4. Route data features gathered from road monitoring and historical accident data (2013-2017).

Route	Energy Expenditure (Wh)	5-year accidents (#)	Number of car overtaking (#)	High BSP modes (sec)	Travel time (sec)	Distance (km)
R1	122.64	4	132	13	668.7	2.76
R2	94.3	6	125	15	485.3	2.18
R3	131.52	6	55	16	640.7	2.84
R4	171.89	2	305	22	998	2.25
R5	185.82	2	290	25	1062	2.35
R6	239.74	3	120	20	1342	2.48

Therefore, we will consider this variable (overtaking) as a comfort indicator bearing in mind that drivers and cyclists perceive the road-sharing experience as life-threatening and experience anxiety, anger, and fear (Kaplan & Prato, 2016). A higher number of overtaking maneuvers can be also seen as an indicator of traffic volume and consequent pollution (Bahmankhah & Coelho, 2017). From table 4, one can observe the routes that have a greater energy expenditure (approximately 28% higher) in both cities compared to the routes where there is lower energy consumption), are also those routes where a smaller number of car bicycle overtaking is observed.

Fig. 5. Visual comparison of the relative variation of several criteria relevant to the cyclist's route choice.

4.2. Exploiting information to support route choice and infrastructure planning

In a traditional 4 step transport model, after the modal split the travelers decide which route is the one that minimize their cost. For a cyclist, the most relevant information may not be an absolute value as a single criterion (e.g. travel time in table 4), but rather the relative relation among multiple criteria associated to a set of alternatives available routes. Based on this assumption, figure 5 demonstrates how this information can be disseminated in a simple spider chart in which the best performing route for a specific criteria receives a score of 10 (shortest, fastest, lowest ration of high BSP modes, lowest energy expenditure, and car overtaking). The data length of a spoke is proportional to the magnitude of the variable for the data point relative to the maximum magnitude of the variable across all data points. As can be seen in figure 5 there is a common pattern regarding the route ranking in the different cities. R2 (Aveiro) and R4 Porto present the best indicators in terms of energy expenditure, distance and travel time, however they have a worse result in terms of comfort. These results are important to support the decision-making process of the route choice, but also to the level of urban planning and design of new infrastructures. From the point of view of the infrastructures manager who wants to promote the use of the bicycle, it is important to minimize these trade-offs, that is, to ensure that the best routes perform optimally on all the indicators to attract a heterogenic profile of cyclists i.e. those who value the travel time, and physical effort, as well as those that privilege safety and comfort. Figure 6 shows schematically how the decision maker can contribute to minimizing these trade-offs. Dedicated infrastructure such as cycle lanes and dedicated traffic signals can be implemented to improve safety, confront and travel time. In hilly cities e-bikes can be assigned to those routes with higher levels of physical effort demand or in longer routes.

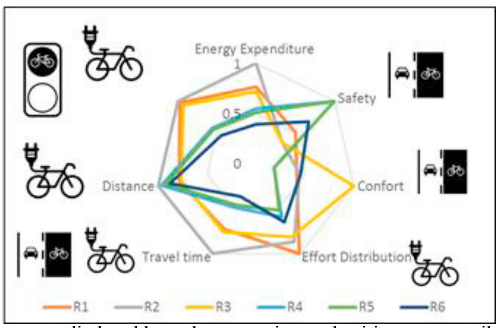


Fig. 6. Schematic representation of 6 routes studied and how the managing authorities can contribute to generate optimal routes.

5. Conclusions

In this work, routes in different cities were empirically monitored using an instrumented bicycle. The objectives were to: determine the relative relationship between several important factors considered by cyclists to select a route and assess in what extent they can be applied in a collaborative sensing cycling platform. The major conclusions are:

- For all the criteria there is a significant variability for the 3 routes connecting the same OD pair (greater than 20% for travel time, distance, safety history and comfort).
- In terms of energy expenditure and comfort indices, there is a significant difference (higher < 1.7) between the flat and hilly city (justifying the modal distribution rates of the bicycles in the two study areas 2.7% vs. 0, 4%)
- In terms of technical feasibility, GNSS information can be used to estimate traditional variables (travel distance, altitude profile) as the energy expenditure/physical effort result due to its strong relationship with heart rate and human energy expenditure. Current traffic information based on video processing should be replaced by low-cost distance sensors.
- The identified tradeoffs and magnitude variation suggest the information provided would be useful for both cyclists with heterogeneous profiles and managing authorities to maximize attractiveness of specific routes.

Other relevant data such as the number of intersections and the historical location of accidents and online traffic information (e.g., Google Maps) will be considered in the development of a navigation algorithm. In this study the data of different cyclists were aggregated into a single database. As the database is being fed by new users it will be possible to provide new indicators disaggregated by users with different profiles (age, gender, physical condition).

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