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PEDELEC ON A HILLY CITY: A CASE STUDY IN COIMBRA

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Abstract *The pedelec is a basic type of electrically-assisted bicycle, designed to help cyclists overcome most slopes. This article presents a theoretical case study of a pedelec on the city of Coimbra, Portugal, which shows that even a low-end model provides enough power and autonomy for the daily transportation needs of a regular cyclist. It is only if battery wear is considered that a model of higher battery capacity is recommended, and even then only if the cyclist uses the pedelec very intensively. By overcoming what is arguably one of the greatest deterrents to cycling, the pedelec contributes towards materializing the concept of sustainable mobility. Overcoming the other major deterrent, safety concerns, is thus passed to the political decision makers, which will need to build and improve the urban infrastructures necessary for citizens to safely exercise their choice for this transport mode.*

1. INTRODUCTION

The 20th century has witnessed a sizeable increase in the flow of populations towards cities and their suburbs. Fueled by cheap automotive transport and favorable public policies, the subsequent urban sprawl ultimately led to inefficiencies related to traffic congestion and energy consumption, and environmental concerns. The recently signed Paris Agreement [1], perhaps the most symbolic and important of all measures concerning sustainability and climate change, shows that politicians are becoming ever more aware that the current state of affairs may not be sustainable in the long term. This awareness led transport policy makers to encourage a shift towards alternative, more sustainable travel modes.

The bicycle is a very efficient active travel mode that can be adopted in most cities, contributing to urban sustainability, given the associated environmental, economic and social advantages. Cycling, however, also has its deterrents. Among these, it is recognized that slopes play an important role in influencing the choice for this mode of travel [2] [3]. To overcome this limitation, and sipping from the winds of change, industry began offering consumers Electrically-Powered Assisted Cycles (EPAC), which aim to provide cyclists a normal, non-fatiguing ride on hilly cities. Regulatory authorities divided these vehicles into two standards: the pedelec and the e-bike. The pedelec is the basic electrically-assisted cycle, with maximum 250 W nominal electric power, as requested by EU regulation. The e-bike can have higher power, but requires some sort of driver's license. Both are active transport modes because they combine human power with electrical assistance for locomotion, although the e-bike can rely solely on battery power.

The aim of this study is to ascertain to what degree the most basic, and cheapest of these standards, the pedelec, can live up to expectations, i.e. comply with the demands posed by both high slopes and energy needs for assistance. For this purpose, the study determines whether the city is permeable to the pedelec, and whether its battery capacity is enough to allow for commuting trips and daily trips with multiple stops. This was done in the context of a real-life situation, the hilly, mid-sized city of Coimbra, Portugal (143 000 inhabitants in 2011), resorting to Geographic Information Systems (GIS) technology and following the methodology that is now described.

2. METHODOLOGY AND CASE STUDY

For purposes of this study, the lowest-end pedelec available on the Portuguese market was considered. This was the B'Twin Bebike 500 model, with 250 W nominal power and a battery capacity of 219 Wh (788 kJ). The combined efficiency of 'electric engine + mechanical parts' was taken to be 80%, translating to 200 W maximum assistance power passed to the wheels.

Performance and autonomy of this pedelec on Coimbra was assessed in a two-stage process, using the ESRI *ArcGIS* environment and its *network analyst* extension as the

main calculation tools. In the first stage, the streets network of Coimbra was programmed. More precisely, network arcs which require electric assistance for crossing were endowed with that energy, in both directions. Network turns were also parameterized, with a cost based on assistance energy for acceleration from rest to cruise speed added. In a second stage, city permeability to the pedelec and calculations for energy assistance needs were carried out and results analysed (an area is said to be 'permeable to transport mode X' if it allows trips between any two of its points using mode X). Service areas based on assistance energy for commuting trips to the city's main employers were derived. These service areas also allowed permeability to be checked. Results for assistance energy needs for 72 longer circuits with 5 to 8 stop-points were subsequently derived and analysed. No recharge points were considered: the cyclist can only recharge the bicycle at his residence.

2.1. Network programming

A GIS shapefile of the streets network of Coimbra was available from previous projects. This contained altimetric information in the form of average uphill/downhill slopes and distances of each network arc, in the From-To direction. Network programming started with rounding off slopes to integers (see below) and restricting network arcs with uphill slope higher than 10% and downhill slope higher than 12%, in the From-To (FT) direction. The uphill restriction follows manufacturer guidelines, whereas the downhill restriction is due to difficulties controlling downhill speed, which may force the cyclist to dismount its bicycle. In the To-From (TF) direction the restrictions applied the other way around: restrict if the FT uphill slope (which is downhill in the TF direction) is higher than 12% or if the FT downhill slope is higher than 10%. These restrictions may cause an arc to be non-traversable in the FT or TF direction, or both.

To calculate electric assistance energy needs, it was assumed that cyclists would try, as much as possible, to cycle the uphill slopes as if they were cycling in the flat. In other words, the human pedalling power was assumed to be the same as the pedalling power in the flat. Human average speeds for integer uphill slopes (this is the reason slopes were rounded off) were derived in the experimental study of [4] and are shown in table 1 below.

Table 1. Average unassisted cycling speed as a function of slope, according to [4].

Slope (%)	**0%**	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**
Speed (m/s)	6,01	5,61	5,21	4,81	4,41	4,01	3,61	3,21

The corresponding power balance (P) can be derived from the physics formula below:

$$P = \frac{v}{\eta_{\text{mech}}}\left[\sum mg\left(C_r + \frac{s}{100\%}\right) + \frac{1}{2}C_d A\rho v^2\right] \quad (1)$$

with v bicycle speed, η_{mech} the mechanical efficiency, m total mass (cyclist + bike), g gravitational acceleration, C_r the rolling resistance coefficient, s the slope (in %), C_d the

aerodynamic coefficient, A the frontal area (cyclist + bike), and ρ the air density. Assuming the values of [4] for formula parameters and an excess of 11 kg for the assistance devices (engine/battery, total man + machine: 106 kg), the human pedalling power for cycling at the statistical average of 6,01 m/s is, by (1), 156 W. It was thus assumed that the cyclist would always exert this pedalling power, regardless of uphill slope.

Electric assistance was considered to be zero for all downhill slopes and uphill slopes up to (but not including) 3%, as cyclists are known to be insensitive to slope up to this value. For 3-10% slopes, assistance begins to be necessary and it was assumed cyclists would maintain the speed they had when the incline reached 3%, which was taken to be the one indicated in table 1 above (4,81 m/s). At 3%, maintaining that speed requires, by (1) and along with the 156 W provided by the cyclist, an extra 97 W of electric assistance power. Since pedelecs allow for variable assistance levels, it was also assumed the cyclist would adjust assistance level to the power required to maintain speed at 4,81 m/s.

As slope rises, the assistance power required to sustain a 4,81 m/s speed increases as well. It is possible to keep a 4,81 m/s speed up to 5% slope. At this point the electric engine operates at full power (200 W at the wheel, 250 W nominal), so it is not possible to climb 6-10% slopes at 4,81 m/s while keeping human power stable at 156 W. Consequently, uphill speed for 6-10% decreases to what is possible to achieve for a combined 156 W + 200 W = 356 W. At 6% slope, for instance, speed decreases to 4,28 m/s and at 10% it goes down to 2,92 m/s.

The calculated speed and assistance power for 3-10% slopes was added to the streets network associated table using *ArcGIS* tool *field calculator*. The nominal assistance energy necessary to cross each arc was then added via the *field calculator* formula:

$$E = P\frac{l_{up}}{\eta v} \tag{2}$$

where E is the assistance energy required to cross the arc, P the assistance power, l_{up} the uphill length, η the efficiency (80%), and v the speed. This calculation was performed for both directions, leading to E_{FT} and E_{TF} fields in the associated table.

Finally, at intersections it was assumed that the cyclist would always stop when taking the left turn or going straight ahead, and stop about 50% of the time when turning right. It would then use full assistance, together with 120 W of human power [4], to accelerate back to the cruise speed on the flat of 6,01 m/s. This would require the battery to put 1490 J at the wheel, translating into network turn costs of 1860 J (recall η = 80%) for left turns and straight ahead, and 900 J was considered for right turns. Programming was completed with creation of a *network dataset*, with E_{FT} and E_{TF} as impedances, and turn costs.

2.2. Service areas for commuting and city permeability to the pedelec

With the network programmed, it was then possible to answer the first main question of this study: *Does a pedelec have enough autonomy to provide full assistance for a commuting trip in Coimbra, regardless of house and job locations?*

This is arguably the most important trip of a cyclist's day, so it is fundamental to know whether the pedelec can support it. For this purpose, service areas with respect to assistance energy were derived (*towards facility* and *away from facility*), with job location as the facility, energy breaks of 50 kJ, and polygon trimming of 25 m. Results for the most energy-demanding job location, the "Fórum Coimbra" shopping centre, located at a faraway hill-top, are shown in figure 1 below.

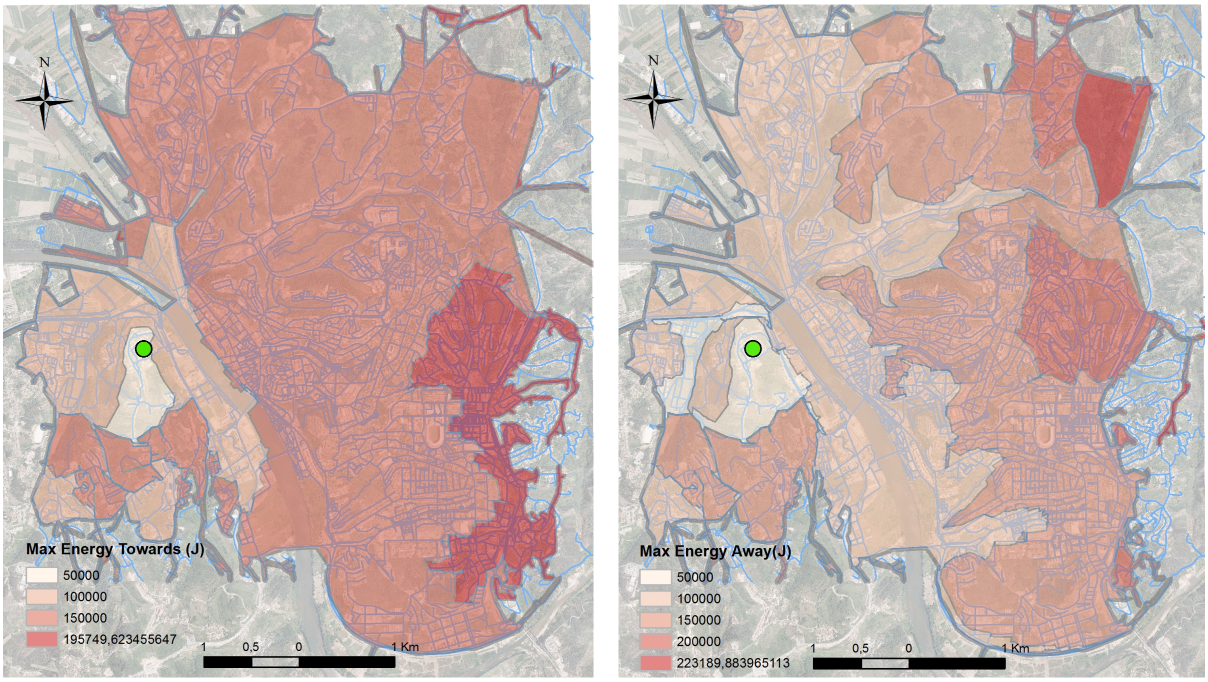

Figure 1. Assistance energy service areas to Fórum Coimbra, *towards* (left) and *away* (right).

The figure and its legend allow for two conclusions. First, it can be seen that most of the study area is fully cyclable with a pedelec. The city of Coimbra is thus permeable to this means of transport, except for some southwest and southeast areas with very high inclines. This is a vast improvement over the non-assisted bicycle, for which a permeability analysis [5] revealed a considerably smaller permeable area, furthermore divided into four disconnected zones. Second, the maximum assistance energy costs of 196 kJ (towards) and 223 kJ (away) sum up to a theoretical maximum of 419 kJ for commuting needs, which is far from the battery capacity of 788 kJ. The real round-trip maximum needs should be smaller than 419 kJ, as the geographical locations of the towards and away maxima do not coincide.

2.3. Daily circuits using the pedelec

Having ascertained that pedelec autonomy is sufficient for commuting trips, it was left to determine whether it could allow for more a demanding daily use, i.e.: *Does a pedelec have enough autonomy to provide full assistance for circuit trips that include stops at multiple locations and are representative of a busy day of a cyclist?*

To answer this question, 72 circuit trips were randomly generated and analysed, starting and ending at a residential area and going through in-between stops, for a total of 5-8 stop-points. Locations of urban facilities of Coimbra (available from previous projects) were added to the GIS and 12 types of circuits were considered (table 2 below), for which 6 samples were derived.

Table 2. Daily circuit types considered.

1.	Home–School–Workplace–Grocery store–Home
2.	Home–Primary healthcare–Grocery store–Bakery–Home
3.	Home–Post Office–Workplace–Bakery–Home
4.	Home–Workplace–Restaurant–Shopping center–Home
5.	Home–Pharmacy–Workplace–School–Grocery store–Bakery–Home
6.	Home–School–Post Office–Grocery store–Local government–School–Bakery–Home
7.	Home–School–Workplace–Sports place–School–Grocery store–Home
8.	Home–Church–Cultural association–Elderly care residence–Bakery–Home
9.	Home–School–Local government–Entertainment place–Park–Home
10.	Home–School–Workplace–School–Primary healthcare–Home
11.	Home–School–Workplace–Cultural association–Sports place–School–Shopping center–Home
12.	Home–Primary healthcare–Pharmacy–Police squad–Post Office–Grocery store–Home

The circuit trips were calculated in the *network analyst* using 3D length as impedance and energy as accumulation variable. Length was used instead of energy because cyclists tend to minimize travel distance, not energy assistance (doing the same for the service areas of section 3.2 would require a different approach). Results are shown in figure 2 histogram.

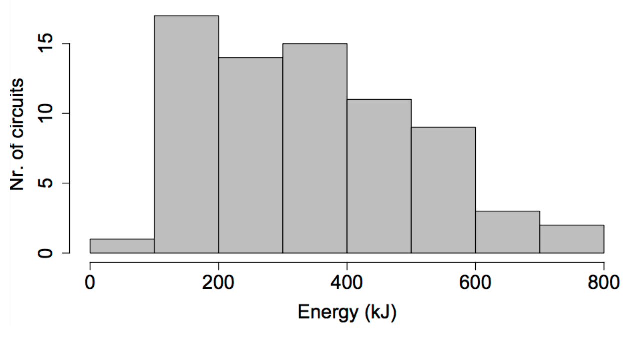

Figure 2. Pedelec assistance energy needs for 72 circuit trips in the city of Coimbra.

Only 5 out of 72 circuits required more than 600 kJ of assistance energy, and the most demanding circuit needed 758 kJ, still below battery capacity of 788 kJ. The pedelec can thus complete all the trips of a cyclist's busy day without draining out its battery

completely. One caveat that might emerge in the mid-long term is battery degradation. Batteries are known to lose storage capacity with time and use, a loss which can come to 20-30% after a few years. For the city of Coimbra and the pedelec model considered, this would jeopardize assistance for the subset of circuit trips over 600 kJ. It would thus be advisable for cyclists who use the pedelec very intensively to purchase a model of higher battery capacity.

In general, however, battery degradation is not expected to be a problem. Industrial production is continuously improving and 219 Wh batteries will soon be replaced by higher capacity ones. Currently it is already possible to acquire 300+ Wh batteries for just about the same price. It is also likely that in the future cities will have recharge points for assisted-cycles.

3. CONCLUSIONS AND FUTURE WORK

The pedelec emerges from this research as a viable active transport alternative for hilly cities. With adequate autonomy and power to overcome relief, one of the greatest deterrents for using the bicycle as main transport mode, it gives the ball back to politicians, who are responsible for providing cyclists with safe and comfortable pathways for exercising their choice for this mode. Investment on bike paths, bike lanes and adjustment of crossings is the natural next step to foster a more active and sustainable transport mode, from which all citizens would benefit.

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