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Quantifying the benefits of switching to an e-bike: a multi-criteria calculation tool

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Summary

E-bikes are often mentioned as interesting commuter vehicles for distances up to 30 km, yet individual perceived barriers such as high purchase costs and the fear for longer commuting times, often overrule societal motivators such as CO_2 reduction and health benefits. Quantifying the benefits in a multi-criteria calculation tool can replace perception by facts and convince more individual commuters to make the switch from car to e-bike, contributing to active, cleaner mobility. The paper illustrates the outcome for four personae, based on realistic Belgian commuters and shows that switching to an e-bike is beneficial for three out of four criteria.

Keywords: bicycle, cost, emissions, ICE, BEV

1 Introduction

In Belgium, the e-bike has become a popular mode of transport. Already now, more than half of all bicycles sold in Belgium are electric and, within this category, the speed pedelec (SP) gains popularity each year. Belgium is a small country with a population living close to work (83% of workers has a commute distance of less than 30 km [1]). E-bikes, i.e. pedelecs and SPs, have the potential to get commuters out of their car and to commute actively.

Switching from a car to an e-bike is for many a big step, with high purchase costs and perceived time loss as main barriers to switch to a more active way of transport such as SPs [2]. These perceived barriers still weigh heavier than the obvious health benefits and the lower CO_2-emissions of commuting with an e-bike. This raises the question: Is it possible to quantify those costs and benefits in an easy-to-understand way to reach the general public?

Several sources already identify the financial costs related to owning a car [1]–[5]. [6] even looks at the cost for society of several car types and states that the cost for society for battery electric vehicles (BEVs) will become more favorable as purchase prices evolve to similar prices as for internal combustion engine vehicles (ICEVs). Total cost of ownership (TCO) studies for pedelecs are less prevalent in literature [7]–[11], and scientific publications on the TCO for SPs are, to the best of the authors' knowledge, not existing. However communication on TCO can help the general public to switch commuting vehicle as [12] states: "*... providing information on total cost of ownership increases the probability that small/mid-sized car consumers express a preference to acquire a conventional hybrid, plug-in hybrid, or a battery-electric vehicle.*".

With regards to the CO_2 emissions, studies on the environmental impact of ICEVs and BEVs [13]–[15] and studies on pedelecs [9], [16]–[21] are available, but only [9] estimates the impact of SPs. The potential time savings [22]–[24] and health benefits [25]–[28] of riding an e-bike are also documented, however, few publications combine these different topics in one study and include SPs. [9] studies the potential of light electric vehicles, which includes e-bikes and reports on the costs, emissions and time savings, [29] reports on the impact a shift away from thermal vehicles would have on mobility, economic and energy aspects in Brussels and [30] makes an assessment of urban transport with the criteria of travel time, cost, CO_2 emissions and external costs for the case of Munich. However no study, to the best of the authors' knowledge, fully reports on the costs, emissions, time savings and health benefits a switch from a car to a pedelec or SP would bring.

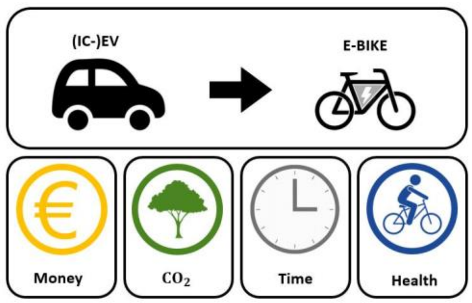

Figure 1: Visualisation of multi-criteria calculation tool

To that end, this paper proposes a multi-criteria calculation tool that quantifies the impact of switching to an e-bike in four criteria: money, CO_2 emissions, time and health.

Based on a limited number of input questions, the calculation tool is designed to answer following research questions: How much does an e-bike cost compared to an ICEV or BEV? How much CO_2-emissions would a switch to an e-bike save annually, looking at the total life cycle, compared to ICEVs or BEVs? To what extent is time gain possible with an e-bike, considering regular traffic jams which lower your overall travel speed? What would be the impact on a person's physical health when cycling to work on a daily basis instead of going by car?

2 Methodology & calculations

The tool uses different approaches for each criterion. The output-accuracy is determined by the detail provided by the user. Many in-depth questions increases the accuracy, but decreases the willingness of the respondents to use the tool. Therefore, the user is asked a minimum of 11 questions, in attempt to not comprise too much on depth. Following sections will elaborate on the approach for each criterion. In each section, the calculation will be made up for a generic pedelec, SP, petrol ICEV and BEV of the city car segment. The final section elaborates on the development of personae to assess the actual impact of switching to an e-bike.

2.1 Boundaries & general assumptions

First, it is important to determine the papers' boundaries for reproducibility reasons. The scope of this study limits itself to Belgium and will discuss the values for each criterion for following vehicles: pedelecs, SPs, ICEVs and BEVs. Costs calculations are done for the duration of ownership, which [6], [8], [31] state to be eight years for both an e-bike, an ICEV and a BEV. The accessories are assumed a similar ownership lifetime. For the analysis, an ICEV and a BEV of a city car segment are considered, based on [6], [32]. For the e-bikes, only the commute distance is taken as input. Distances travelled outside the commute are based on literature (15 km/week for pedelecs [33], 20 km/week for SPs [22]). The total distance is calculated by asking the single commute distance and the frequency of commute. It is assumed that there are 220 working days in a year, and a year is made up of

52 weeks. Neither the costs of potential accidents, potential fees nor fines or the societal cost of the vehicles are taken into account. Only the resale value for the cars is taken into account. A real discount rate of -0.5% was used [34] in following formula to calculate the value of money in present time:

$$PV = At * \frac{1}{(1+r)^t} \quad (1)$$

With PV = present value, At = one-time cost at time t, r = real discount rate and t = time expressed in years.

For the CO_2-emissions calculations, only the production process and usage are taken into account, the end-of-life is not. The time savings are calculated with speed values based on literature and the input of users, but are not linked to the exact trajectory of the user. The activity hours are calculated on the basis of the commute time, independently of the number of hours of activity already carried out by the user.

2.2 Monetary savings over ownership

To determine the monetary savings a switch from car to e-bike would bring, all costs related to these vehicles over their respective ownership need to be determined. As mentioned in the introduction, TCO studies on ICEVs and BEVs are available in literature [1]–[6] and are available as calculators [32], [35], however similar TCO studies for pedelecs and SPs are scarce [7], [9]–[11] or non-existent respectively. Therefore, a market study of current purchase prices of e-bikes, an analysis of the energy consumption of an e-bike, a survey of Flemish bicycle dealers with regards to maintenance costs and ownership, and desktop research into legal benefits and leasing options were conducted to identify the purchase costs, operational costs and non-operational costs. To obtain the total cost of ownership, the sum of all present values of costs over the whole period of ownership must be taken. The cost per kilometre is then calculated by dividing the total cost with the total amount of kilometres driven during the time of ownership.

2.2.1 Purchase costs

The purchase costs are the costs involved in either buying or leasing an e-bike. When considering the former, the purchase costs consist of the initial **purchase price** of the e-bike (charging adaptor included) and necessary **accessories** (i.e. a bike bag, rain clothes, … for a total of € 100) [8] and in case of the SP, the price of an **obligatory helmet** (€ 50) [36] and a **license plate**. The cost of a license plate in Belgium is € 30 [37]. For the latter, only the accessories (and helmet in case of the SP) are taken into account, as the other costs are assimilated into the monthly leasing price. The purchase price of a pedelec (€ 2050) is based on literature [8], as for the SP (€ 5650) is based on a market study of 131 models of 17 different brands [36]. The purchase costs for ICEVs and EVs are taken from literature [6], [32].

2.2.2 Operational costs

The operational costs are the costs that are made for the vehicle to operate. In the case of e-bikes, this is the **electricity cost**. The annual cost is determined by the price of electricity ($0.30\ €/kWh$) [38], but also the driving efficiency of the e-bike (pedelec: $10\ Wh/km$, SP: $19\ Wh/km$) [39] and the distance travelled during that year. For the ICEVs and EVs, the values are based on literature [6].

$$Operational\ costs\ [€] = \frac{Price\ of\ electricity}{1000} \left[\frac{€}{Wh}\right] * \eta_{e-bike} \left[\frac{Wh}{km}\right] * distance_{\frac{total}{year}}\ [km] \quad (2)$$

2.2.3 Non-operational costs

Non-operational costs are the remaining costs that need to be considered. These can be split up into**: bicycle allowance, insurance costs, leasing costs and maintenance costs**. The bicycle allowance is a tax-free allowance paid by the employer to the employee per kilometre travelled by (electric) bicycle [40]. The current maximum amount is 0.24 €/km [41]. With regards to insurance costs, a civil liability insurance for a (speed) pedelec is not obligatory, but is advisable for a SP [42]. 84 € per year is taken as an average [36]. The cost of an omnium insurance for the pedelec is 3% of the purchase cost and 4% of the purchase cost of the speed pedelec. For ICEVs, taxes and insurance (omnium and obligatory civil liability insurance) and for BEVs, premiums are taken into account, based on literature [6].

When the (speed) pedelec is acquired with a leasing formula, the insurance is included in the leasing costs. The leasing cost is a monthly amount paid by the employee. After a period of three years, the consumer can buy the vehicle by paying 16% of the original acquisition price. The monthly amount during those first three years varies dependent on the original purchase price and the formula used by the leasing company. In this paper, the formula used by bike-leasing company o2o [43] (acquired through personal communication) is used to calculate the monthly leasing price:

$$Leasing\ \ price_{per\ \ month}[€] = 55.15 + \frac{(purchase\ \ price - 4000) * 5.1992}{500} + \frac{accessories\ \ price * 1.332}{1000} \tag{3}$$

The leasing price per year is the leasing price per month multiplied by 13.92 due to the way Belgian salaries are paid out: employees get a holiday bonus (92% of a monthly salary) around May and a 13th month worth of salary at the end of the year.

$$Leasing\ \ price_{per\ \ year} = 13.92 * leasing\ \ price_{per\ \ month} \tag{4}$$

At the end of the three-year leasing contract, the user of the e-bike gets the option to purchase the e-bike for 16% of the acquisition price. This paper will assume that the user will buy the e-bike at the end of the contract.

Determining maintenance costs for e-bikes is more difficult than for (IC)EVs. Maintenance frequency and costs are not well monitored nor documented as is the case for the car industry. Maintenance on (IC)EVs is typical carried out by professionals and is periodical, where small maintenance on e-bikes and bikes in general can be performed by the owner and the frequency is highly dependent on the use, road conditions and care of the users. Therefore a survey of bicycle dealers was carried out [36], with a response of 36 Flemish dealers, which identified following aspects as the biggest contributors to maintenance costs: standard check-up (i.e. tightening loose parts, greasing, checking chain or belt tension, software update and replacing brake pads), replacement of parts (drive train, inner and outer tires and/or bearings) and the replacement of the battery. The frequency of standard check-ups and replacements of parts is determined by the driven kilometres, while the battery replacement is determined by the charging cycles. Table 1 gives an overview of different maintenance costs, frequency of occurrence and the cost linked to the replacement, which is the cost of the product and the working hours.

Table 1: Maintenance costs

Maintenance	Frequency of occurrence	Cost
Standard check-up	3000 km	€ 120
Drive train: belt	17 500 km	€ 285
Drive train: chain/cassette	4000 km/6000 km	€ 45/€ 100
Tires	9 000 km	€ 170
Bearings	15 000 km	€ 90
Battery	500 cycles	€ 579

The eventual frequency of occurrence in the time of ownership will depend on total amount of kilometres travelled. Table 1 shows a difference in frequency of occurrence for the replacement of the drivetrain between a belt or a chain. The costs of accidents are not included in this paper, due to limited accident numbers for Belgium with regards to e-bikes [44].

2.3 CO_2 savings

The potential CO_2-emission reduction related to a switch from car to e-bike is based on literature [9], [13]–[21]. With regards to the e-bike, a distinction was made between the CO_2 generated during the **production** of the vehicle and the CO_2-emissions for **usage** i.e. the energy mix of the country where the e-bike is charged, the distance travelled and the energy consumption per kilometre travelled.

The CO_2 generated from the production of the e-bike is split up in the assembly of the e-bike (184 kg CO_2 eq.) and the production of the Li-ion battery (143 kg CO_2 eq./kWh), as the number of times the battery is replaced will also be taken into account. The numbers originate from personal communication with Bosch e-Bike Benelux and represent an e-bike with a 500 Wh battery. These numbers are also in large part validated by [17].

$$CO_{2_{Production\ e\text{-}bike}}[kg] = CO_{2_{assembly\ e\text{-}bike}}[kg] + \frac{kgCO_2}{kWh_{Li-ionbattery}}\left[\frac{kg}{kWh}\right] * Battery_{capacity}\ [kWh] * \left(N_{replace} + 1\right) \quad (5)$$

The CO_2-emissions caused by the commute is calculated by use of the energy consumption and the energy mix in the country where the charging happens (for Belgium: 0.2 $kgCO_2$/kWh [13]). The energy consumption of an e-bike is determined by dividing the battery capacity (on average 500 Wh [36]) by the maximum distance that can be travelled with one battery. The distances (pedelec: 50 km, SP: 27 km) were obtained with the help of the Bosch eBike Range Assistant [24] with the inputs mentioned in Appendix A.

$$\frac{CO_2\ Emissions}{km_{Usage\ e-bike}}\left[\frac{kg}{km}\right] = Energy\ mix_{country}\left[\frac{kgCO_2}{kWh}\right] * Energy\ consumption_{e-bike}\left[\frac{kWh}{km}\right] \quad (6)$$

$$Energy\ consumption_{e-bike}\left[\frac{kWh}{km}\right] = Battery\ capacity\ [kWh]/Distance_{1\ full\ battery}[km] \quad (7)$$

The total amount of CO_2-emissions over the time of ownership is then calculated by summing the outcome of formula 5 with the outcome of formula 7 multiplied by the total number of kilometres travelled over the total ownership time for the user case.

$$Total\ ownership\ CO_2\ emission\ [kgCO_2] = CO_{2_{Production\ e-bike}} + \frac{CO_2\ Emissions}{km_{Usage\ e-bike}} * \ time_{ownership} * distance_{total/year} \quad (8)$$

2.4 Time savings

The time savings are determined by calculating the time that will be spent on a single commute on an e-bike. The user can compare the calculated time with their current commute time. To determine the duration of the daily single commute, the distance of the commute is divided by the average speed during this single commute. As the speed of an e-bike varies considerably in an urban versus a non-urban environment [22], [23], the user is asked to indicate what percentage of the commute is done in the urban environment close to the start and end of the trip (durations y_1 and y_2). Within this urban environment a 'city' speed (pedelec: 20.6 km/h [23], SP: 28.2 km/h [22]) will be taken as average speed, outside the urban environment a cruising speed (pedelec: 22.2 km/h [23], SP: 34.2 km/h [22]) is taken as average speed. The total average speed is then the sum of those percentages multiplied with their respective speeds. When the user lives or works outside an urban environment (i.e. rural), 5 % is assumed for the *y* value, when the user lives or works in an urban environment 15 % is assumed for *y*.[1]

$$Speed_{average}[km/h] = x\ \% * speed_{cruising} + (y_1 + y_2)\ \% * speed_{city} \quad (9)$$

With the average speed and the commute distance, the time spent on a single commute can easily be calculated as follows:

[1] For example: Living and working in urban environment results in 30% of commute riding at city speed. Living in a rural area, working in urban environment results in 20% of commute at city speed.

$$time_{commute}(h) = \frac{distance_{commute}}{speed_{average}} \quad (10)$$

2.5 Activity

Changing from a sedentary way of transport such as the car, to a more active way of transport such as a bike or e-bike, will have an impact on a person's physical health. [45] recommends 150 minutes of moderate to vigorous physical activity (MVPA) each week to be in a normal health condition, above a certain age it is best to perform more than 210 minutes of MVPA. Activities with a Metabolic Equivalent Task (MET) value of above 3 are considered MVPA and both cycling and electric cycling have a MET above 3 [46]. Driving a car is not considered as MVPA as sitting has a MET value of 1 [47].

Only the extra hours of MVPA per week that will be achieved by taking an e-bike to work are calculated in this criteria with following formula:

$$\#h_{MVPA\_extra/week} = \ 2 * n_{days,commute} * frequency_{commute} * time_{commute} \quad (11)$$

2.6 Personae

To capture the variability in outcomes for the four criteria, which depend on the input given by the user, four different personae are set up as shown in Table 2. Persona 1 is an average Belgian commuter [48], who drives an ICEV for 22.9 km per trip on daily basis, who will purchase an e-bike with 0.24 €/km bicycle allowance. Persona 2 only differs from persona 1 in the frequency of commuting, four times a week in accordance with a new trend since the Covid-19 pandemic, being one day working from home, and a bicycle allowance of 0.15 €/km. Persona 3 both works and lives in an urban environment, but in different cities. Persona 3 has a good train connection and will bike to work occasionally and has a commute distance of 30 km. Persona 4 lives 10 km from work and has bicycle allowance of 0.24 €/km. All personae buy either a pedelec or a SP.

Table 2: Different personae

	Persona 1	Persona 2	Persona 3	Persona 4
Home	Rural	Rural	City	Rural
Work	City	City	City	Rural
# km commute	22.9	22.9	30	10
Commuting frequency	100%	80%	40%	100%
Bicycle allowance	0.24 €/km	0.15 €/km	0.24 €/km	0.24 €/km

3 Results & Discussion

This paper presents a multi-criteria calculation tool which quantifies the impact of a switch from a car to e-bike in four criteria. To lower the entry barriers for using the tool, the necessary input is limited and can be adjusted by the user within certain boundaries. This section will first describe the results for each persona and then compare the cost and $kgCO_2$ values for the four vehicles more in depth.

Table 3: Criteria results for each persona buying an e-bike

Criterion		**Persona 1**		**Persona 2**		**Persona 3**		**Persona 4**	
		pedelec	SP	pedelec	SP	pedelec	SP	pedelec	SP
Cost	[€/km]	- 0.08	0.01	0.03	0.012	-0.04	0.09	-0.01	00.12
CO_2	[$kgCO_2$/km]	0.0074	0.0114	0.0076	0.0121	0.0087	0.0129	0.0099	0.0138
Time	[min]	63	42	63	42	83	56	27	18
Fitness	[min/week]	628	416	502	333	331	224	272	179

Table 3 shows for each persona what the values are for each criterion when they either buy a pedelec or buy a SP. The negative values in the 'Cost' criterion indicate that the persona can earn money, this is due to the bicycle allowance. Persona 1, 3 and 4 only earn money per kilometre travelled when choosing for a pedelec. When looking at both Table 2 and Table 3, it is clear that it is more beneficial to commute frequently and greater distances in terms of costs, CO_2 and fitness, especially if the person receives the maximum bicycle allowance (i.e. 0.24 €/km). However larger commute distances have an effect on the time travelled, which most likely has an effect on the willingness to travel that distance daily.

All personae in Table 3 were set-up as if they would buy an e-bike. However, a scenario where the personae lease their e-bike for the first three years and then purchase the vehicle at 16% of the original purchase price, is also possible. [49] shows that leasing in Flanders even represents 30% of the newly acquired SPs in 2020. Table 4 presents the cost per kilometre values for each persona if they would either purchase or lease an e-bike.

Table 4: Costs results for each persona buying versus leasing e-bike

Cost [€/km]	**Persona 1**		**Persona 2**		**Persona 3**		**Persona 4**	
	Ped.	SP	Ped.	SP	Ped.	SP	Ped.	SP
Purchase	- 0.08	0.01	0.03	0.12	- 0.04	0.09	- 0.01	0.12
Leasing	-0.10	-0.03	0.00	0.07	-0.07	0.02	-0.06	0.02

Because the high purchase price of the e-bike can be avoided at the beginning of the use and the lease amount is partly absorbed by the gross salary, a lease option is, according to the calculations, more advantageous than buying an e-bike for all personae.

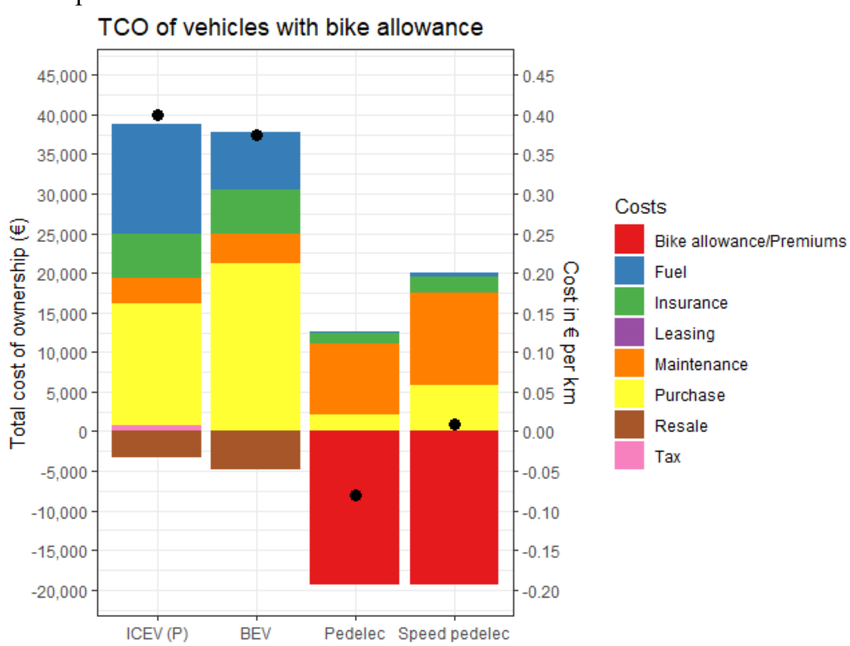

Figure 2: TCO and €/km for BEVs, petrol ICEVs, pedelecs & speed pedelecs

To put the values of the cost criteria in perspective, **Fout! Verwijzingsbron niet gevonden.** shows the total cost of ownership and the cost per kilometre for four different vehicles (petrol ICEV[2], BEV[2], pedelec, SP) in the case of persona 1. The total cost of ownership is split up in to eight different categories similar to [6] and in accordance with the assumptions described in section 2.1. In **Fout! Verwijzingsbron niet gevonden.**, it can be seen that the TCO is largest for the petrol ICEV (€ 35 463), mainly due to the high fuel cost (0.2 €/l) [50]. In second, the petrol

[2] The petrol ICEV considered is a Renault Twingo Intens 0.9 TCe 90 EDC, the BEV considered is a Renault Twingo R80 Zen [32].

ICEV (€ 32 984), with the largest cost factor being the purchase cost. For both the pedelec (€12 672[3]) and the SP (€20 047[3]), the largest cost is the maintenance.
This is mainly attributable to the assumptions that were made when estimating the maintenance costs. The figures that bicycle mechanics reported, were estimations on when a component should be replaced to ensure optimal performance. In the scenario of this study, the components would always be replaced in time before potential and/or destructive damage occurs. Consequently, the e-bike will also be in fairly optimal condition at the end of the ownership period. In reality, with actual users, it may take longer for maintenance to take place, which would lower the overall TCO and thus the cost per kilometre. The cost per kilometre for the petrol ICEV is 0.40 €/km, for the BEV it is 0.375 €/km. For the pedelec, with(-out) bicycle allowance, it is -0.08 €/km (0.14 €/km). For the SP, with(-out) bicycle allowance, it is 0.01 €/km (0.22 €/km). So the average Belgian, can, by switching from a petrol ICEV to a pedelec, earn 0.48 €/km. When switching to a SP, the average Belgian can earn 0.39 €/km. Note that in **Fout! Verwijzingsbron niet gevonden.** the TCOs for the ICEV and BEV are calculated with the TCO calculator of Flemish government [32] and the total distance travelled is 88 000 km for the cars, 88 928 km for the SP and 86 848 km for the pedelec.

To now put the values for CO_2 emissions for persona 1 in perspective, the emission values of the pedelec and SP are compared to emission values of a BEV and petrol ICEV in Figure 3.

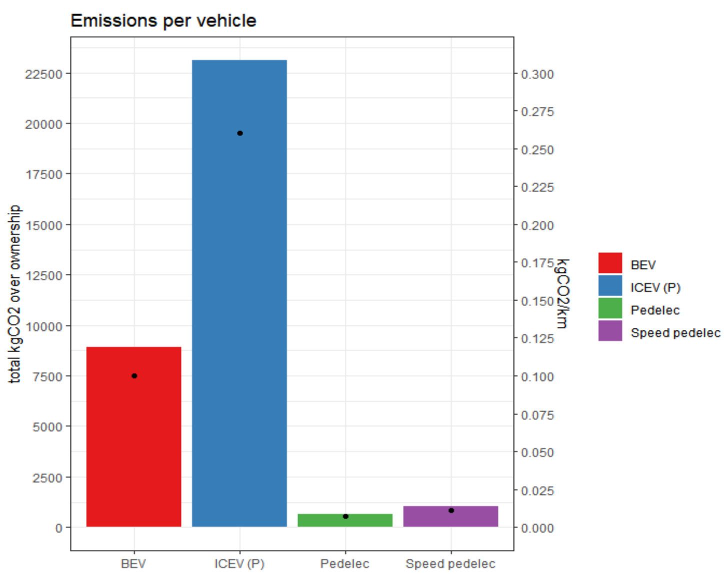

Figure 3: Total CO2 emissions over ownership and kgCO2/ km for four vehicles

Figure 3 shows the total amount of CO_2 emissions (bars) over the ownership of the vehicle with the production of the vehicle included and the $kgCO_2$/km for each vehicle (dots) for persona 1.The petrol ICEV in this case has the highest value, with a total of 23.121 ton CO_2/km over a period of eight years, the result of the multiplication of 0.26 $kgCO_2$ eq./km acquired from [29][4] and the distance travelled by persona 1 in eight years (88 928 km). The BEV has the second highest value with 8.893 ton CO_2/km and 0.1 $kgCO_2$/km [29]. The SP has a smaller $kgCO_2$/km value, being 0.0114 $kgCO_2$/km and a total CO_2 emissions over the period of eight years and 88 928 km of 1013.8 $kgCO_2$. The pedelec has the smallest value with a total of 642.7 $kgCO_2$ emitted in 8 years of ownership. This was calculated with 0.0074 $kgCO_2$/km and the distance travelled in eight years with a pedelec (86 848 km). Based on these calculations, it can be concluded that pedelecs emit over 13 times less CO_2 emissions

[3] This is a TCO without the bicycle allowance. With bicycle allowance the pedelec has a TCO of -6674 € and the speed pedelec 701 €.

[4] In [29], the assumption is that the vehicles have an average life span of 14.1 years and a total of 14 856 annual kilometres.

than BEVs and 36 times less than ICEVs and SPs emit over 8 times less CO_2 emissions than BEVs and 22 times less than ICEVs. When the average Belgian would switch from a petrol ICEV to a BEV, the person would save 0.16 $kgCO_2$ per kilometre, but a switch from a petrol ICEV to an e-bike would save at least 0.24 $kgCO_2$ per kilometre.

The time values give the users of the calculator an indication of what the commuting time would be if they were to switch to an e-bike. It is evident from the speeds mentioned in section 5 and the numbers provided in Table 3, that the commuting times of the pedelec are higher than those of the SP. No comparison has been made with commuting times by car, as they are fickle due to traffic jams and the user is best suited to estimate their own commuting time by car. Nonetheless, literature does show that e-bikes are more predictable [22], [51]. Finally, Table 3 shows the extra minutes MVPA per week the personae would have by taking an e-bike to work. All personae pass the advisable limit of 150 minutes MVPA per week and only persona 4, if the person would switch to a SP, would not exceed the 210 minutes MVPA, a threshold to stay in good health.

Conclusions

To help clarify what a switch from a car to an e-bike would mean for a user in terms of benefits, this study developed a multi-criteria calculation tool with following criteria: money saving, CO_2 emissions savings, time savings and fitness benefits. All assumptions, formulas and appropriate key figures used are described in the methodology. The results are discussed on the basis of four personae, of which the first is an average Belgian commuter. The costs savings and CO_2 emissions savings are discussed in more depth by comparing those values with values from literature for a petrol ICEV and BEV of a city car segment.

The results show that a switch to an e-bike is beneficial for all four personae for the criteria of costs, emissions and fitness. The benefits in terms of time can only be determined by the user, but the values given are reasonable estimations of travel time, with high predictability. An average Belgian could save 0.48 €/km and 0.24 $kgCO_2$/km if they would switch from a petrol ICEV to a pedelec.

To conclude, the multiple available inputs and different criteria make the calculation tool complex to report on as there are a variety of dimensions to variate on. A full and in-depth study with sensitivity analysis on, for example, larger e-bike prices and battery cycles is however out of scope for this manuscript and will be taken up in further publications. The development of an online fully customisable version of the calculator could be an important step towards further convincing the general public of switching to cheaper and most importantly more sustainable active transport.

Limitations

Many assumptions were made to assemble this calculator for all criteria. Some aspects of the ownership are not included in the TCO, such as the cost of accidents, the resale value, the real behaviour of users related to maintenance, but also the cost for society, the monetary benefit of exercise, the loss of functionality and the cost of noise reduction. In terms of CO_2 emissions, the end-of-life was not taken into account. Also other emissions, for example NOx emissions are not taken into account. For the time savings, the estimation of the commute time can be more exact, by taking the exact route of the user as input and match the on-road time with speeds achieved on the chosen paths. Multimodality was also not included. Finally the mental health effects of riding with an e-bike and the determination of the MET of SP riding were not included. These are aspects on which future research will focus.

Acknowledgments

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References

[1] Q. De Clerck *et al.*, “How Total is a Total Cost of Ownership ?,” 2016, vol. 8, pp. 742–753.

[2] P. Lebeau and C. Macharis, “How to Improve the Total Cost of Ownership of Electric Vehicles : An Analysis of the Light Commercial Vehicle Segment,” *World Electr. Veh. J.*, vol. 10, no. December, p. 16, 2019.

[3] E. A. Gilmore and L. B. Lave, “Comparing resale prices and total cost of ownership for gasoline , hybrid and diesel passenger cars and trucks,” *Transp. Policy*, vol. 27, pp. 200–208, 2013.

[4] P. Letmathe and M. Suares, “A consumer-oriented total cost of ownership model for different vehicle types in Germany,” *Transp. Res. Part D*, vol. 57, no. October 2017, pp. 314–335, 2020.

[5] D. Huber, Q. De Clerck, C. De Cauwer, N. Sapountzoglou, T. Coosemans, and M. Messagie, “Vehicle to Grid Impacts on the Total Cost of Ownership for Electric Vehicle Drivers,” *34th Int. Electr. Veh. Symp. Exhib.*, pp. 1–12, 2021.

[6] Q. De Clerck, T. van Lier, M. Messagie, C. Macharis, J. Van Mierlo, and L. Vanhaverbeke, “Total Cost for Society: A persona-based analysis of electric and conventional vehicles,” *Transp. Res. Part D Transp. Environ.*, vol. 64, no. February, pp. 90–110, 2018.

[7] X. Yan and J. He, “Electric bicycle cost calculation models and analysis based on the social perspective in China,” pp. 20193–20205, 2018.

[8] B. Van Zeebroeck, W. Baert, I. Caers, and R. Marchal, “No . 4 Fietsbeleid brengt op,” 2018.

[9] G. Stevens, B. Rotthier, A. Roetynck, T. Coosemans, and J. Cappelle, “Het potentieel van lichte elektrische voertuigen in Vlaanderen,” 2017.

[10] S. Gössling and A. S. Choi, “Transport transitions in Copenhagen : Comparing the cost of cars and bicycles,” *Ecol. Econ.*, vol. 113, pp. 106–113, 2015.

[11] E. Salmeron-Manzano and F. Manzano-Agugliaro, “The Electric Bicycle: Worldwide Research Trends,” *Energies*, vol. 11, no. 1894, pp. 1–16, 2018.

[12] J. Dumortier *et al.*, “Effects of providing total cost of ownership information on consumers ’ intent to purchase a hybrid or plug-in electric vehicle,” *Transp. Res. Part A*, vol. 72, pp. 71–86, 2015.

[13] M. Messagie, “Life Cycle Analysis of the Climate Impact of Electric Vehicles,” 2017.

[14] J. Van Mierlo, M. Messagie, and S. Rangaraju, “Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment,” *Transp. Res. Procedia*, vol. 25, pp. 3435–3445, 2017.

[15] M. Messagie, F. Boureima, T. Coosemans, C. Macharis, and J. Van Mierlo, “A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels,” *Energies*, vol. 7, no. March, pp. 1467–1482, 2014.

[16] M. Machedon-Pisu and P. N. Borza, “Are personal electric vehicles sustainable? A hybrid E-bike case study,” *Sustain.*, vol. 12, no. 1, pp. 1–24, 2020.

[17] S. Mellino, A. Petrillo, V. Cigolotti, C. Autorino, E. Jannelli, and S. Ulgiati, “A Life Cycle Assessment of lithium battery and hydrogen-FC powered electric bicycles: Searching for cleaner solutions to urban mobility,” *Int. J. Hydrogen Energy*, vol. 42, no. 3, pp. 1830–1840, 2017.

[18] A. Fyhri and C. Weber, “TØI-rapport 1498/2016 Aslak Fyhri Hanne Beate Sundfør Christian Weber,” 2016.

[19] C. Brand *et al.*, “The climate change mitigation impacts of active travel: Evidence from a longitudinal panel study in seven European cities,” *Glob. Environ. Chang.*, vol. 67, 2021.

[20] P. Astegiano, F. Fermi, and A. Martino, “Investigating the impact of e-bikes on modal share and greenhouse emissions: A system dynamic approach,” *Transp. Res. Procedia*, vol. 37, no. September 2018, pp. 163–170, 2019.

[21] I. Philips, J. Anable, and T. Chatterton, "E-bikes and their capability to reduce car CO2 emissions," *Transp. Policy*, vol. 116, no. November 2021, pp. 11–23, 2022.

[22] B. Herteleer, N. Van den Steen, L. Vanhaverbeke, and J. Cappelle, "Analysis of initial speed pedelec usage for commuting purposes in Flanders," *Transp. Res. Interdiscip. Perspect.*, vol. 14, no. April 2020, p. 100589, 2022.

[23] D. Twisk, A. Stelling, P. Van Gent, J. De Groot, and W. Vlakveld, "Speed characteristics of speed pedelecs, pedelecs and conventional bicycles in naturalistic urban and rural traffic conditions," *Accid. Anal. Prev.*, vol. 150, no. November 2020, p. 105940, 2021.

[24] Bosch eBike Systems, "eBike range calculator for Bosch drive systems - Bosch eBike Systems," 2021. [Online]. Available: ttps://www.bosch-ebike.com/en/service/range-assistant. [Accessed: 10-May-2021].

[25] H. B. Sundfør and A. Fyhri, "A push for public health : the effect of e-bikes on physical activity levels," *Biomed Cent.*, pp. 1–12, 2017.

[26] S. M. Gojanovic, Boris, Welker, JOris, Iglesias, Katia, Daucourt Chantal, Gremion Gerald, Unit, "Electric Bicycles as a New Active Transportation Modality to Promote Health ´," *Appl. Sci.*, no. 18, pp. 2204–2210, 2011.

[27] B. De Geus and I. Hendriksen, "Cycling for transport, physical activity and health: What about pedelecs?," *Cycl. Futur. From Res. into Pract.*, no. January, pp. 17–32, 2015.

[28] K. Shaaban, "Why Don ' t People Ride Bicycles in High-Income Developing Countries , and Can Bike-Sharing Be the Solution ? The Case of Qatar," pp. 1–18, 2020.

[29] Q. De Clerk, N. Hooftman, K. Mommens, J. Nuyttens, and L. Vanhaverbeke, "Etude d'impact sur la mobilité, sur les aspects economiques et sociaux et sur l'energie et roadmap vers une sortie des vehicules thermiques," 2020.

[30] D. Schröder and F. Gotzler, "Comprehensive spatial and cost assessment of urban transport options in Munich," *J. Urban Mobil.*, vol. 1, no. August, p. 100007, 2021.

[31] I. Hendriksen and R. van Gijlswijk, "Fietsen is groen , gezond en voordelig Fietsen is groen , gezond en voordelig," 2010.

[32] Departement Mobiliteit & Openbare Werken, "Vergelijk milieuvriendelijke en conventionele wagens," 2021. [Online]. Available: https://mow.vlaanderen.be/tco/.

[33] G. Vandamme, "Motivatie-onderzoek van de Vlaamse e-fietser omtrent het gebruik of de aankoop van de elektrische fiets," 2017.

[34] ECB, "Official interest rates." [Online]. Available: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/key_ecb_interest_rates/html/index.en.html. [Accessed: 16-Dec-2020].

[35] MOBI-VUB, "TCO Mobi," 2022. [Online]. Available: tco-mobi.be.

[36] A. Declerck, "Total Cost of Ownership van speed pedelecs," 2021.

[37] FOD Mobiliteit, "Kentekenplaat voor bromfietsen." [Online]. Available: https://mobilit.belgium.be/nl/wegverkeer/inschrijving_van_voertuigen/kentekenplaten/bromfietsen. [Accessed: 29-Mar-2021].

[38] Statistics Explained, "Electricity price statistics." [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics. [Accessed: 09-May-2021].

[39] B. Uytterhaegen, "Analyse van de geschiktheid van speed pedelecs voor woon-werkverkeer," KU Leuven Technologycampus Ghent, BE, 2019.

[40] FOD Finance, "Fietsvergoeding." [Online]. Available: https://financien.belgium.be/nl/particulieren/vervoer/aftrek_vervoersonkosten/woon-werkverkeer/fiets#q5. [Accessed: 26-Apr-2022].

[41] BikeForm, “Fietsvergoeding: wat kan en wat mag?” [Online]. Available: https://www.bikeform.be/nl/financieel-en-fiscaal/fietsvergoeding-wat-kan-en-wat-mag. [Accessed: 16-Dec-2020].

[42] FOD Economy, “Compulsory insurance for e-bikes,” 2020. [Online]. Available: https://economie.fgov.be/en/themes/consumer-protection/insurance/car/civil-liability/vehicles-subject-insurance/compulsory-insurance-e-bikes. [Accessed: 26-Apr-2022].

[43] o2o, “o2o Homepage.” [Online]. Available: https://www.o2o.be/nl/. [Accessed: 26-Apr-2022].

[44] TRL, “Study on market development and related road safety risks for L-category vehicles and new personal mobility devices,” 2021.

[45] J. M. Nagata *et al.*, “Physical Activity and Hypertension From Young Adulthood to Middle Age,” *Am. J. Prev. Med.*, vol. 60, no. 6, pp. 757–765, 2021.

[46] B. C. Langford, C. R. Cherry, D. R. Bassett, E. C. Fitzhugh, and N. Dhakal, “Comparing physical activity of pedal-assist electric bikes with walking and conventional bicycles,” *J. Transp. Heal.*, vol. 6, no. May, pp. 463–473, 2017.

[47] B. de Geus *et al.*, “Utilitarian Cycling in Belgium: A Cross-Sectional Study in a Sample of Regular Cyclists,” *J. Phys. Act. Heal.*, vol. 11, no. 5, pp. 884–894, 2014.

[48] D. Janssens, R. Paul, and G. Wets, “Onderzoek verplaatsingsgedrag Vlaanderen 5.5 Tabellenrapport,” 2020.

[49] TRAXIO, “De Belgische fietsmarkt in 2020,” 2021.

[50] GlobalPetrolPrices.com, “Global Petrol Prices Belgium,” 2022. .

[51] N. Van den Steen, B. Herteleer, J. Cappelle, and L. Vanhaverbeke, “Motivations and Barriers for Using Speed Pedelecs for Daily Commuting,” *World Electr. Veh. J.*, vol. 10, no. 4, p. 87, Dec. 2019.

Appendix A

Inputs used for the Bosch eBike Range Assistant [24]:

For the pedelec:

- Average speed: 22 km/h [23]
- Riding mode: Turbo
- Effort: 3 stripes
- Rider: 100kg - 60 rpm
- eBike: Active Line - City bike
- Hybrid bike tires
- Environment: some inclines - road with poor quality - light breezes - winter
- Starting up middle

For the SP:

- Average speed: 32 km/h [22], [23]
- Riding mode: Turbo
- Effort: 3 stripes
- Rider: 100kg - 60 rpm
- eBike: Performance Line Speed - City bike
- Hybrid bike tires
- Environment: some inclines - road with poor quality - light breezes - winter
- Starting up middle

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