

Human-powered vehicles as a way to abate transport-related greenhouse gas emissions, Part 1:
Assessing modal shift impact through comparative Life Cycle Assessment — An

Original

Human-powered vehicles as a way to abate transport-related greenhouse gas emissions, Part 1: Assessing modal shift impact through comparative Life Cycle Assessment — An Italian case study / Di Gesù, A., Gastaldi, C., Delprete, C.. - In: TRANSPORTATION ENGINEERING. - ISSN 2666-691X. - 22:(2025). [10.1016/j.treng.2025.100401]

Availability:

This version is available at: 11583/3005356 since: 2025-11-23T21:12:19Z

Publisher:

Elsevier

Published

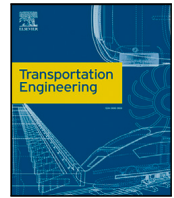
DOI:10.1016/j.treng.2025.100401

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



Full length article

Human-powered vehicles as a way to abate transport-related greenhouse gas emissions, Part 1: Assessing modal shift impact through comparative Life Cycle Assessment — An Italian case study

Alessandro Di Gesù¹, Chiara Gastaldi^{1*}, Cristiana Delprete¹*Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*

ARTICLE INFO

Keywords:

Velomobile
Human-powered mobility
Modal shift
Greenhouse gas emission reduction
Comparative Life Cycle Assessment
Future scenario
Survey
Simulation

ABSTRACT

This study delves into the pressing issue of surging Greenhouse Gas (GHG) emissions within the European Union (EU) transport sector. With a particular focus on the significant environmental impact of road transportation, the paper advocates for a transition toward more sustainable alternatives. It specifically explores the potential of velomobiles, enclosed human-powered vehicles (HPVs), as a viable solution. A survey of more than 1200 individuals in Italy, with most respondents based in the Piedmont region, provides insights into commuting patterns across ten modes of transportation and attitudes toward the adoption of velomobiles. Survey results on the willingness to adopt velomobiles are used to project future mobility patterns within the population surveyed. Rather than merely reiterating the environmental benefits of cycling, the study offers an original contribution by integrating behavioural insights with environmental modelling to assess the realistic potential for a modal shift. Particular attention is given to identifying which transportation modes velomobiles are likely to replace, providing a nuanced understanding of their role in future sustainable mobility systems. The subsequent comparative Life Cycle Assessment (LCA) reveals GHG emission reductions with the most realistic scenarios indicating a 20% to 30% decrease in Well-To-Wheel emissions. Despite the conservative assumptions adopted, the study yields promising results. A final analysis, limited to velomobiles and cars, shows that expanding the system boundaries could lead to even greater savings, as the modal shift could extend the life of the car and help avoid the purchase of a second one in the long term. Velomobiles, with their potential to drive modal shifts, emerge as effective tools in reducing emissions. While recognizing regional variations, the study suggests encouraging outcomes for velomobile adoption in Italy and emphasizes the pivotal role of modal shifts in achieving sustainable transportation objectives.

1. Introduction

1.1. Transport emissions in the EU are on the rise

With the Green Deal, the EU has set the aim of 90% reduction in transport-related greenhouse gas (GHG) emissions by 2050, compared to 1990 levels [1]. However, we are falling considerably short of that objective. In 2021, European Union's GHG emissions from the transportation sector exceeded 1990 levels by over 18%, as reported by the European Environment Agency [2]. Even with the lockdowns imposed during the pandemic, in 2020 the emissions were still 8% higher than the 1990 reference values. This situation is of significant concern since, as far back as 2009 [3] and 2013 [4], studies were already highlighting criticalities in the carbon budget. And finally, in 2021 the International Council on Clean Transportation [5] suggested that the transport sector

alone could consume the carbon budget allocated by the EU for the 1.5 °C global warming goal.

1.2. Past and present attempts to solve the problem

Eurostat data reveals that among the various modes of transportation, road transportation is by far the most impactful in terms of total GHG emissions [6,7]. Therefore, a substantial decrease in its emissions is crucial to achieve the Green Deal goals. Reducing emissions associated with mobility represents a complex challenge that must be addressed on multiple, interconnected fronts. These include transforming mobility habits, work patterns, and supply chain logistics; improving the efficiency of existing vehicles; and investing in sustainable transport infrastructures [8]. Each of these dimensions plays

* Corresponding author.

E-mail address: chiara.gastaldi@polito.it (C. Gastaldi).

Nomenclature

$APER$	Average personal annual GHG emission reduction, (measured in kg)
$C_{El,j}$	Electric energy consumption of battery electric vehicles, plug-in hybrid vehicles and human-powered electrically-assisted vehicles during trip j , (measured in J)
$C_{H,j}$	Metabolic energy consumed by a person riding various vehicles during trip j , (measured in J)
$C_{ICEs,j}$	Mass of fuel s (diesel, gasoline, CNG, LPG) consumed by vehicles with an internal combustion engine (ICE), full hybrid and mild hybrid included, during trip j , (measured in kg)
D_j	Frequency of trip j , (measured in days/year)
E	Total CO ₂ equivalent emissions generated in one year by all the trips accounted by the MoSToVIt survey, (measured in kg)
E_j	Total CO ₂ equivalent emissions generated in one year by trip j , (measured in kg)
$E_{H,j}$	CO ₂ equivalent emissions due to the caloric expenditure during trip j , (measured in kg)
$E_{V,j}$	CO ₂ equivalent emissions due to the use of vehicles with an engine (be it ICE, electric or hybrid) during trip j , (measured in kg)
EF_{diet}	Emission factor of the diet, (measured in kg/kcal)
EF_{El}	Emission factor of electricity in Italy, (measured in kg/Wh)
EF_s	Emission factor of fuel s , (measured in kg/kg)
$MSIP$	Modal shift index potential, (measured in trip/trip)
$MR_{i,j}$	Metabolic rate during trip j on vehicle i , (measured in W)
$ER\%$	Emission reduction percentage, (measured in kg/kg)
$e_{i,j}$	Specific electric energy consumption of vehicle i during trip j in real driving conditions, (measured in Wh/km)
$f_{s,i,j}$	Specific fuel consumption of chemical composition s with vehicle i during trip j under real driving conditions, (measured in kg/km)
$flag_{i,j}$	Is either 0 or 1 and is used in the script to correct the result when a vehicle is not used ($\dot{x}_{i,j}$ should be null), since $\dot{x}_{i,j}$ is artificially changed to 1 m/s in order to perform the division without returning an infinite value
$h_{i,j}$	Specific consumption of chemical energy related to the metabolic rate of a human riding vehicle i during trip j , (measured in J/km)
$k_{1,s}$	Conversion coefficient of fuel s that transforms the tank-to-wheel emissions in well-to-wheel emissions, (measured in kg/kg)
k_2	Conversion factor from m to km, (1/1000 km/m)

k_3	Conversion factor from J to Wh, (1/3600 Wh/J)
k_4	Conversion factor from J to kcal, (1/4186 kcal/J)
m	Angular coefficient of the linear interpolation between mechanical power and metabolic rate, (measured in W/W)
q	Vertical intercept of the linear interpolation between mechanical power and metabolic rate, (measured in W)
t_j	Type of trip j (urban, mixed, or rural; with or without motorway)
$v_{i,j}$	Vehicle of type i (walk, alternative HPVs, electric kick-scooter, bicycle, moped/motorbike, bus, metro, tram, train, car/van, velomobile) with specific characteristics during trip j
x	Distance, position, (measured in m)
\dot{x}	Speed, (measured in m/s)
$\dot{x}_{i,j}$	Average speed of vehicle i during trip j , (measured in m/s)

a crucial role in lowering the environmental footprint of transport systems. Within this complex context, when it comes to vehicle design, the authors see two major strategies to try and reduce the sector emission. Historically, one of the ways that has been adopted to try to reduce transport emissions has been the promotion and enforcement of regulations on direct emissions of vehicles (e.g., through the EURO label of road vehicles in Europe). However, this approach has not been enough. Even though ICEs efficiencies have been improved, transport-related CO₂ emissions have been raising in the past two decades. This can be explained by both:

1. A counterbalancing effect caused by the increase in the weight and size of cars, as indicated by [9];
2. A rise in the number of individuals opting for car usage [10].

Electric vehicles (EVs) may not be the ideal solution for reducing CO₂ emissions because they come with a higher embedded carbon footprint, mainly attributed to battery production. Since achieving 100% renewable electricity generation is expected to take a considerable amount of time, this carbon offset remains significant. Depending on the size of the vehicle and on its usage, the break-even point, i.e. where an EV becomes more environmentally friendly than its ICE counterpart, may never be attained [11]. It is essential to note that the problem cannot be solely addressed through more efficient engines. Additional regulations on vehicle design, such as limits on weight and aerodynamic drag coefficients, are required to complement these efforts, as highlighted in [9].

Conversely, encouraging a shift to more environmentally friendly transportation options is considerably more effective as it addresses the issue at its root. The first category of these “green alternatives” is “active mobility”, including modes of transport such as walking and human-powered vehicles (HPVs). Mobility on HPVs (e.g., cycling) is not only more efficient than walking but also frequently the quickest means of urban transportation. In addition, unlike ICE vehicles, HPVs generate neither direct relevant GHGs nor local pollutants (e.g., nitrogen compounds and particulate matter) during the use. Moreover, given their substantially lower embedded carbon footprint compared to EVs, HPVs should be considered the preferred mode of transportation for short-medium distances; however, this is not always the case. In the past few years, an increasing amount of research has been conducted

on electric micromobility, including e-kick scooters, e-bikes, and e-mopeds. A recent study [12] revealed that micromobility modes might lead to an increase in GHG emissions. This increase was observed in all shared micromobility modes analysed in the study. The primary reasons for this increase were the indirect impacts related to fleet rebalancing and the transportation of discharged swapped batteries. However, the more significant issue was that these modes tended to encourage a shift from less polluting modes of transportation, such as walking, rather than from cars. While these electric vehicles could theoretically reduce GHG emissions when used as an alternative to cars, the actual modal shift worked against this potential reduction. This demonstrates that mapping mobility habits of individuals and assessing which means of transportation may be substituted by the new mobility alternative is a vital step to ensure that the proposed modal shift has the desired effects in terms of emission reduction.

Another vital step when introducing a new alternative, is to identify the characteristics that make the current mainstream solution the preferred choice. Cars are not going to be replaced unless a valid competitive alternative arises for their drivers. Local legislation and city redesign can play a fundamental role in reducing the attractiveness of cars: higher ownership costs and parking fees, along with narrower car lanes, lower speed limits, and traffic-restricted zones have been proven to be effective (the most exemplary and best-known case is that of Dutch cities). These kinds of measures revolve around the concept of walkable cities or “15-minutes cities”, which aim to discourage the use of cars in favour of active mobility. A global survey by IPSOS (Institut Public de Sondage d’Opinion Secteur) [13] shows that this is the desire of the majority of people, “*In most countries surveyed, a solid majority of citizens are in favour of giving bicycles priority over automobiles in new infrastructure projects*” given that “*most adults across 28 countries consider cycling plays an important role in the reduction of carbon emissions (on average, 86% do so) and in the reduction of traffic (80%)*”. So, we can expect more and more cities to gradually become more walkable and cyclable, but it cannot be expected to be a sudden change. Additionally, for out-of-town travel, where longer distances and higher speed limits are the norm, cars often have an advantage in terms of cruising speed compared to traditional HPVs. Furthermore, depending on the quality of the infrastructures, HPVs may be perceived as dangerous to be ridden [13]. While the latter issue could be, technically, easily countered by the construction of dedicated cycling infrastructures, the lower speed tends to be an insurmountable wall for many people who need to commute tens of kilometres every day. There is, however, a class of HPVs called *velomobile* which offers the potential to contrast both of these issues.

1.3. Velomobiles and future possibilities

Velomobiles are HPVs fully enclosed in aerodynamic and structural shells that offer protection from the weather and from injury in case of an accident. Thanks to their aerodynamic shapes, many commercial velomobiles make it possible for the average person to maintain 40 km/h on flat ground for long periods of time. Fit individuals can reach speeds of over 80 km/h in sprints and maintain an average speed of more than 60 km/h for an hour, or over 55 km/h for six hours, covering a total distance of 340 km during a race [14]. Data recorded on open road also validate the extraordinary performances of these vehicles, with people travelling of 545 km over a 13 h timespan (11 h pedalling, averaging 49 km/h), and covering 1100 km over a 2-days ride [15]. To provide these performances, commercial velomobiles are typically designed with an average height of less than 1 m, and are therefore deemed as dangerous in a urban setting due to the presence of other vehicles. Nonetheless, as shown in the second part of the present work [16], taller velomobiles with efficient aerodynamics can also be developed. Because of their high cruising speed, the weather protection, the impact protection, and other appealing features (e.g., some have

a large luggage compartment), velomobiles have been deemed as the missing link between cars and bicycles.

According to Van De Walle [17], velomobiles could play a major role in the future of transportation, particularly within what he named the “non-evoliner” framework (see Fig. 1). In this scenario, velomobiles are not viewed as a mere evolution of bicycles (the “evoliner” view), but rather as a distinct alternative to cars for a much broader audience. Almost 20 years have passed since Van De Walle’s proposal and, at present, it appears that the original evoliner paradigm is gradually shifting toward a more non-linear, inclusive view of transport options. As a proof, one can consider the growth in sales of electrically assisted bicycles (e-bikes) in recent years in European countries [18–20]. E-bikes have gained popularity in urban areas as people recognize their potential and practicality. These electric bikes are no longer limited to cycling enthusiasts, and individuals from diverse backgrounds are now adopting them. Furthermore, an increasing number of companies have incorporated e-bikes and e-cargo bikes into their home delivery services over the past few years [21]. At the same time, there is a shifting perception among “cyclist”, referring here to individuals who primarily ride bikes for recreational purposes, as opposed to the “casual rider” or the “commuter”. Fewer and fewer “cyclist” regard e-bikes as “cheating” because the boundaries that define “what a bicycle really is” are changing. Considering this evolving cultural landscape, velomobiles hold significant potential to become an appealing mode of transportation in the near future. Nevertheless, to accurately assess the environmental performance of this technology, it is essential to take into account its expected modal shift with each of the other present modes of transportation.

1.4. A focus on mobility in Italy

At the European scale, transport-related GHG emissions have increased markedly since 1990, rising from 672 Mt to 833 Mt in 2019 (+24%), confirming the sector’s growing contribution to overall emissions. In contrast, Italy has experienced a general decline in total GHG emissions (from 521 to 417 Mt), while transport emissions have remained nearly stable. However, this stability is the result of two opposite trends: decreasing emissions from freight transport and increasing emissions from passenger cars (from 56 to 62 Mt, or up to 67 Mt in 2019 [22]). This trend highlights the persistent challenge of decarbonizing passenger mobility and justifies the focus of this study on promoting low-impact, human-powered transport alternatives.

In Italy, according to ISFORT (Italian Higher Institute for Education and Research in Transportation) [23], urban trips make up 70.6% of the total number of journeys but contribute to only 31.7% of the overall passenger-kilometres travelled. On the other hand, mid-range trips (below 50 km) represent 47.8% of the total passenger km, while long trips (over 50 km) account for the remaining 20.5%, even though they only cover 2% of the total trips. Furthermore, ISFORT’s data reveal that, even though cycling in Italian cities has been gradually increasing, walking levels have dropped below those of 2019 following the end of the pandemic. As mentioned earlier, the development of walkable cities cannot be expected to happen suddenly, and Italy appears to be addressing this issue at a gradual pace. In fact, according to ISFORT’s report, the expansion of bike paths and pedestrian zones does not seem to be extensive enough to drive substantial growth in micromobility within urban areas.

More importantly, though, there has also been a rise of trips by car from 2010 to 2021 for both mid-range trips (from 84.4% to 87.0%) and long trips (from 71.6% to 79.8%). It is evident that this issue is particularly significant outside of urban areas. This poses a considerable challenge for countries with lower levels of urbanization. In this context, Italy has approximately 65% of its population residing in towns/suburbs and rural areas (47.7% and 17.1% respectively), while only 35.2% of the population lives in cities [24]. Concerning the Italian Piedmont region, the focus of the present study, 25.4% of the

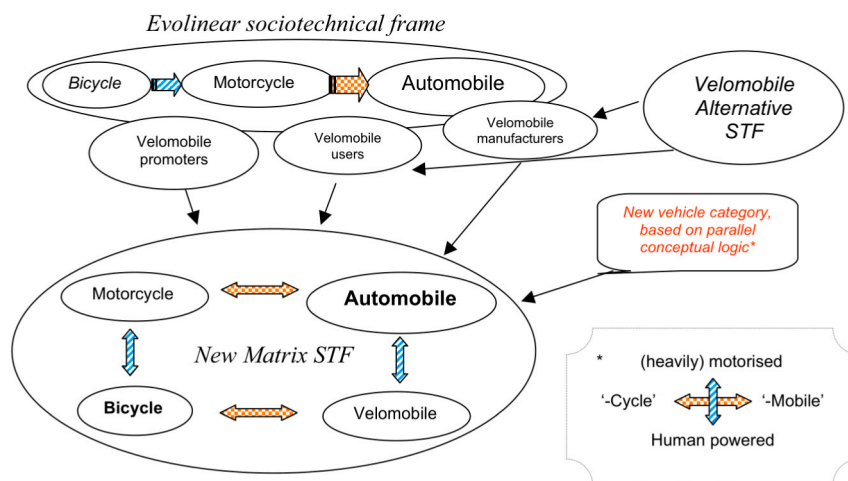


Fig. 1. Evoliner vs. non-evoliner paradigm, from [17].

population lives in cities, 45.8% in towns and 28.8% in rural areas [25]. These statistics align with the EU average, where 38.9% of people live in cities, 35.9% in towns and suburbs, and 25.2% in rural areas. Therefore, an analysis of travel habits among Italians, with a focus on the Piedmontese population, could lead to valuable results that could hopefully be extended to other European populations.

1.5. Structure of this paper

In this introduction, the general panorama of the transport-related GHG emissions has been analysed, and the velomobile has been proposed as a good candidate for a car “alternative”. Additionally, the necessity of a real case study to assess the actual GHG reduction potential of this technology was discussed. For this reason, Section 2 presents the survey which this study is based upon. Subsequently, the GHG reduction during the use phase of vehicles is calculated with a comparative LCA following a Well-To-Wheel approach, taking into account the modal shift declared in the survey. Later, out of the 11 modes of transportation analysed, the LCA’s boundaries of cars and velomobiles are expanded with a Cradle-To-Gate approach that includes the production phase of the vehicles to better assess the potential of the declared modal shift. The survey and the LCA model are both detailed in Section 2, while the analysis and discussion of the results are presented in Section 3. To this date, to the best of the authors’ knowledge, no study has attempted to quantify the environmental performance of velomobiles by analysing their potential modal shift through a survey.

2. Methodology

2.1. Survey

This study is based on the results gathered from the MoSToVIt survey (acronym of “Modal Shift To Velomobiles in Italy”) which was distributed online in Italy. The survey was open to compilation from April 13th to June 8th 2023, and received 1291 answers. The first part of the survey was used to gather general information on the population sample, which will be discussed later in the paper (see Section 3.2). Participants were asked to specify their age, province of residence, employment among 4 classes (i.e., (i) student, (ii) worker, (iii) working student, (iv) homemaker/retired/unemployed). Based on the employment class, each participant was then asked to describe one or more routine trips. Students and workers were queried about the typical frequency of their trips to school/working place, encompassing both the number of days per week and the weeks per year. This information was essential to exclude from their annual trips the days

when workers worked from home (an increasingly common practice in Italy) and students studied from home, which could significantly impact their travel patterns. In the second part, students and workers who reported travelling to school or work at least once per week were asked to provide detailed information about their trips. This included:

1. The province of destination, if different from that of their residence;
2. The type of trip, categorized as (i) urban, (ii) mixed urban and rural without a motorway, (iii) mixed urban and rural with a motorway, (iv) rural without a motorway, and (v) rural with a motorway;
3. The distance travelled with each mode of transportation, which included (i) walking, (ii) alternative HPVs (e.g., skateboard, rollerblades, non-electric kick-scooter), (iii) electric kick-scooter /hoverboard, (iv) bicycle, (v) moped and motorbike, (vi) bus, (vii) metro, (viii) tram, (ix) train, (x) car and van.

For each mode of transportation used, respondents were asked to provide specific details, such as the occupancy rate of the vehicle. Additional questions varied depending on the type of vehicle involved. For example, for cars, respondents were asked about the type of engine, the size of the vehicle, and the time needed to find a parking spot. If the trip included a portion on a motorway, respondents were required to specify the distance travelled on the motorway. This information was essential to refine calculation of fuel consumption, as explained in Sections 2.2.4 and 2.2.5. Respondents using cars/vans and mopeds/motorbikes also had the option to report their self-declared fuel consumption for the vehicle during the trip. These values were later verified, and any unreasonable data was excluded. Additionally, respondents could customize their return trip details by unchecking the box labelled “the return trip coincides with the outward one that was just compiled”, which would otherwise auto-populate the return trip information. The third part was optional and allowed the respondents to specify an additional routine trip (e.g., going to the grocery store). Finally, in the fourth part of the survey, the authors presented their research activity and the idea of using a velomobile for routine trips. The respondents were first asked to rate 27 customer needs/characteristics that the ideal velomobile should possess in order to define the basis for the actual design of the velomobile. This analysis is beyond the scope of the present paper, but it will be cited once more in Section 2.2.9 because of its implications on the modal shift assessment. More detailed information can be found in [16]. The second goal of this fourth part was to assess the respondents’ interest in using the velomobile in substitution to one or more of their current modes of transport, which is the key element of this paper. A clarifying example is reported in Fig. 2. This illustration depicts

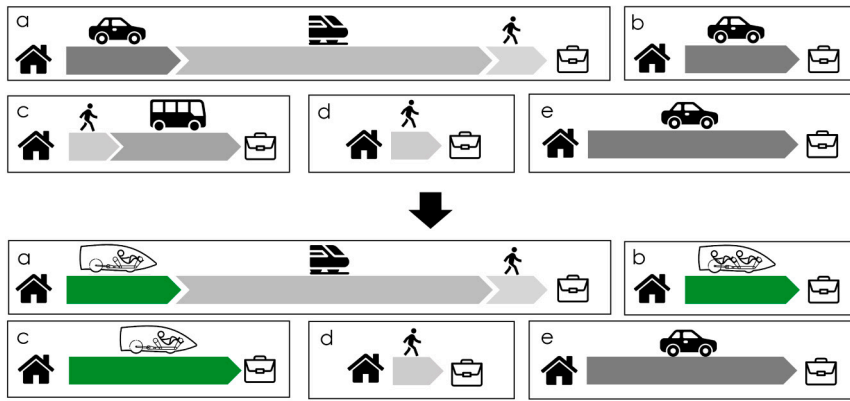


Fig. 2. Graphical representation of the commuting modes of five respondents to the MoSToVIt survey: current situation in the upper portion of the figure, potential modal shift in the lower portion of the figure.

five individuals and their modes of commuting. The first individual (Fig. 2a) currently employs three transportation modes for their daily commute: a car for the initial segment from home to the station, the train for the middle part of the trip, and walking from the train station to the office. Said individual is planning to replace the car with the velomobile for the first part of the commute, representing a partial substitution. In contrast, the second and third individuals (Fig. 2b-c) declare the willingness to use the velomobile for the full trip. In case b, the velomobile will replace only one mode of transport (the car), while case c represents a more comprehensive substitution, replacing both walking and bus with the velomobile. Finally, the last two individuals in the example (Fig. 2d-e) have no immediate intention of incorporating the velomobile into their commutes. One will continue to walk to work, while the other will persist in using the car.

2.2. LCA - model overview

This paper employs a LCA approach to assess the potential environmental impacts resulting from the widespread adoption of velomobiles within the current transportation market. Specifically, the study focuses on quantifying the effects on Global Warming Potential (GWP), which is often referred to as a carbon footprint (CF) calculation, following a Well-To-Wheel approach.

The reliability of LCA results hinges on the use of accurate data and an appropriate model. Consequently, the LCA methodology mandates the explicit definition of three key components before conducting calculations:

1. Goal and scope;
2. Functional unit;
3. Boundaries of the system.

Additionally, the study should disclose the datasets used for each part of the system. These preparatory steps serve two essential purposes:

1. Reproducibility of the calculation;
2. Comparison within findings of different studies.

The subsequent subsections in this paper provide detailed information on these critical aspects of the LCA methodology, ensuring transparency and facilitating an informed understanding of the study's methodology.

2.2.1. Goal and scope

This study intends to evaluate the reduction in GHG emissions during the use phase of vehicles, including the upstream pathways of production of fuels according to the Well-To-Wheel mindset, considering the routine trips reported in the MoSToVIt survey and taking into account the intended modal shift of the respondents from their present modes of transportation to the velomobile that the authors are designing.

2.2.2. Functional unit

The functional unit was defined as the cumulative distance travelled over the course of a year's worth of routine trips, taking into account the actual trip conditions reported by the respondents in the MoSToVIt survey.

2.2.3. System boundaries

The velomobile is still in the early stages of the design process, but it is already possible to estimate with a good degree of confidence the emissions generated during its use phase [16]. On the other hand, it is far too early to give a good estimate of:

1. The emissions that will be generated during its production, due to an incomplete design of the vehicle, and to the programmed use of non-standard materials that will need a dedicated LCA study. Plus, being the overall mass of the vehicle still unknown, even an attributional method proportional to mass related to a known proxy would not be possible. Therefore, the analysis performed in Section 3.4 was kept outside of the general study, as a simple hint toward possible new horizons for this study.
2. The credits that will be gained from both the reuse of parts, and from the recycling of materials during the end-of-life (EOL) of the velomobile.

For these reasons, in order to perform a comparison with the emissions of other modes of transport, the calculations were carried out considering only the use phase of the vehicles, with a Well-To-Wheel approach. Fig. 3 shows the full boundaries of the system and the sources of the data used. Note that also food was taken into account, as it is the "fuel" for HPVs.

2.2.4. Life cycle inventory (LCI)

In preparation to the LCI calculation, the survey data were filtered and any contradictory or unrealistic entries were deleted. After this operation, the survey dataset was left with 1247 entries. The calculation of the LCI was then performed processing these data with a MATLAB[®] script developed by the authors. The software acquires the data and returns for each trip: the mass of combusted fuels $C_{ICE_{s,j}}$ (Eq. (1)), the electric energy used C_{El_j} (Eq. (2)), and the caloric expenditure due to the integral of the metabolic rate¹ (Eq. (3)):

$$C_{ICE_{s,j}} = \sum_{i=1}^{11} x_{i,j} \cdot k_2 \cdot f_{s_{i,j}}(v_{ij}, t_j) \quad (1)$$

¹ The metabolic rate is the power consumed by a human to keep the body functioning, and is dependent on the activity that is being carried out (e.g., resting, walking, running).

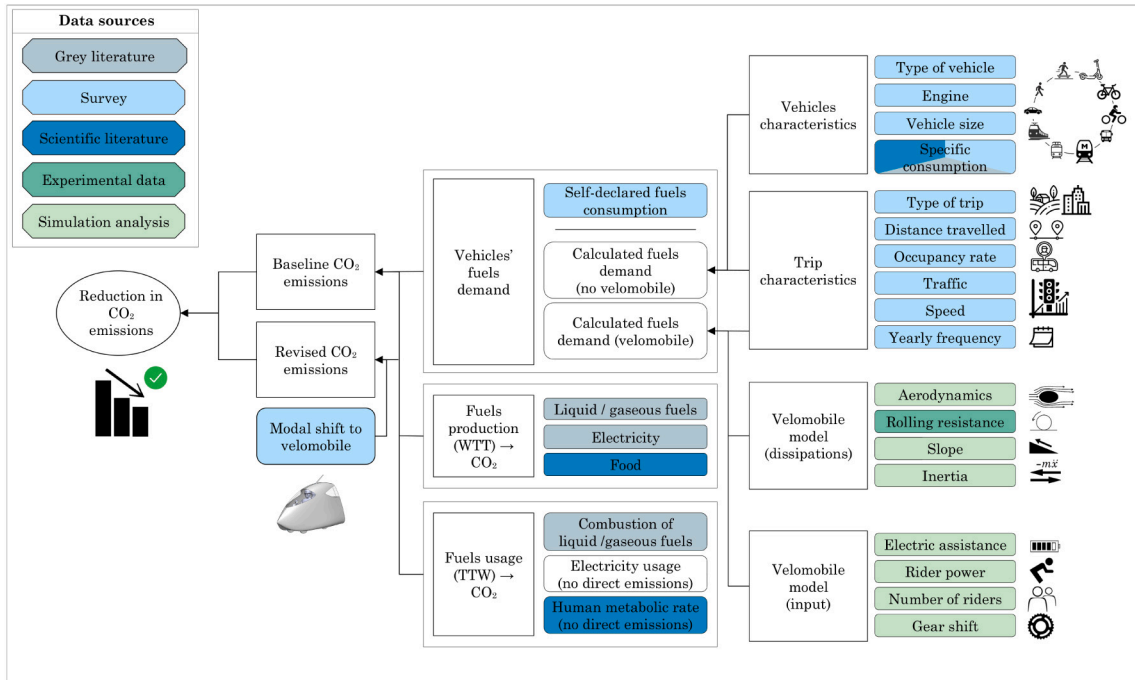


Fig. 3. Graphical representation of the system boundaries of the model, including different data sources.

$$C_{El_j} = \sum_{i=1}^{11} x_{i,j} \cdot k_2 \cdot e_{i,j} (v_{i,j}, t_j) \quad (2)$$

$$C_{H_j} = \sum_{i=1}^{11} x_{i,j} \cdot k_2 \cdot h_{i,j} (v_{i,j}, t_j) \quad (3)$$

The structure of the three equations is similar: the distance x_{ij} travelled with mode of transport i during trip j is multiplied by a conversion factor k_2 and by the appropriate specific consumption (fuel $f_{s_{i,j}}$, electric $e_{i,j}$ and human metabolic rate $h_{i,j}$). Depending on the mode of transport i , all or only some of the specific consumption may need to be accounted for, as detailed in Table 1. The specific consumption values depend on the type of trip t_j and on the type of vehicle $v_{i,j}$, as summarized in Table 2 for $f_{s_{i,j}}$ and $e_{i,j}$. These will be discussed more in detail in the next Section 2.2.5, while further clarifications on the calorific expenditure calculation are detailed in Section 2.2.7. Appendix A shows all the types of vehicles and their sub-classes considered in the model.

Equations from (1) to (3) are applied to the data coming from the second part of the MoSToVIt survey to build a *baseline reference model* of the current situation. Then, after assessing the willingness of participants to perform a modal shift and monitoring the “customer needs” of the velomobile, a new *revised value* of the consumption is calculated using the same three equations. These results are the starting point for the Life Cycle Impact Assessment (LCIA) that will be discussed in Section 2.2.8. The LCIA makes use of different possible scenarios, fully described in Section 2.2.9.

2.2.5. Model of consumption for conventional modes of transport (and data sources)

For the definition of the specific fuels consumption ($f_{s_{i,j}}$, $e_{i,j}$, and $h_{i,j}$) of all modes of transportation, the authors made use of both scientific and grey literature. This section discusses the fuels demand of traditional modes of transportation (see Fig. 3).

Note that the study aims to evaluate only the emissions related to the population of the MoSToVIt survey (Section 2.2.1). For this reason, the vehicles’ consumption was always referred to one person, dividing the vehicles’ specific consumption by the occupancy rate declared

Table 1

Types of specific consumption accounted for each mode of transportation (“–” for not accounted, and “x” for accounted). When the specific consumption $f_{s_{i,j}}$ and $e_{i,j}$ are not accounted for, their respective value in Eqs. (1) and (2) is zero.

Mode of transport i	$f_{s_{i,j}}$	$e_{i,j}$	$h_{i,j}$
1: walking	–	–	x
2: alternative HPVs	–	–	x
3: electric kick-scooter	–	x	x
4: bicycle	–	x	x
5: moped and motorbike	x	x	x
6: bus	x	–	x
7: metro	–	x	x
8: tram	–	x	x
9: train	–	x	x
10: car and van	x	x	x
11: velomobile	–	x	x

in the survey. For public transit, where many people can simultaneously board a single vehicle, the occupancy rate was estimated. The MoSToVIt respondents were asked to estimate the crowdedness of the vehicle as a percentage, and the calculations were performed taking into account the data retrieved on the manuals of the GTT² fleet [26] in order to assume a realistic value of the occupancy rate. More details can be found in Appendix A.

2.2.5.1. ICE cars consumption. It is widely acknowledged that actual fuel consumption on open roads is typically higher than the figures declared by manufacturers. Additionally, the standardized New European Driving Cycle (NEDC) and the Worldwide harmonized Light vehicles Test Procedure (WLTP) provide an average consumption value that may not accurately represent various scenarios (e.g., a purely urban

² GTT (Gruppo Torinese Trasporti) is a public corporation in charge of the Turin tram and metro services along with the majority of the public bus transit (for both urban and extra-urban trips) in the Piedmontese provinces of Alessandria, Asti, Cuneo and Turin. It also serves 3 railway lines in the province of Turin.

Table 2

Dependency (“–” for independent, and “x” for dependent) of $f_{s_{i,j}}$ and $e_{i,j}$ from the vehicle’s ($v_{i,j}$) and of the trip’s ($t_{i,j}$) characteristics, for each mode of transportation, for one person. When the specific consumption $f_{s_{i,j}}$ and $e_{i,j}$ are completely independent, their respective value in Eqs. (1) and (2) are constant, but not necessarily null. In fact, electric kick-scooters account for $e_{i,j}$ (see Table 1). The terminology “type of trip” is used as defined in Section 2.1 (urban, rural or mixed trip with or without motorway).

Mode of transport i	$v_{i,j}$		$t_{i,j}$	
	Engine type	Vehicle size	Type of trip	Occupancy rate
1: walking	–	–	–	–
2: alternative HPVs	–	–	–	–
3: electric kick-scooter	–	–	–	–
4: bicycle	x	–	–	–
5: moped and motorbike	x	–	x	x
6: bus	x	–	x	x
7: metro	–	–	–	x
8: tram	–	–	–	x
9: train	–	–	–	x
10: car and van	x	x	x	x
11: velomobile	–	–	x	x

trip with high congestion). Therefore, the authors opted to utilize data from tests conducted in real driving conditions. The monthly magazine *alVolante*, which reports numerous real car performances, served as the source for this purpose. Their primary measuring apparatus [27] consists of three flowmeters, alongside a GPS for determining the vehicle’s speed. The tests are conducted on fixed itineraries with uniform pace and traffic conditions, covering:

1. Urban roads;
2. Rural roads;
3. Motorways.

In cases of mixed trips, where the MoSToVIt survey accounted for both urban and rural segments (see Section 2.1), the average value between urban and rural consumption was utilized, assuming a 50/50 ratio between the two. To avoid potential complications and inaccuracies, the survey did not delve into more precise information, as this might have discouraged participants from completing the survey or led to subjective interpretations of trip categorizations. Additionally, since the “size of the vehicle” is a key determinant for specific consumption (see Table 2), the authors selected from *alVolante* reports the most popular cars in Italy for each size. Refer to Appendix A for the complete dataset used in the calculations. The special case of dual fuel (LPG+gasoline) cars was modelled assuming 10% usage of gasoline and 90% usage of LPG. This ratio was set as a reasonable average value between two more extreme scenarios of 25% gasoline vs. 75% LPG and 5% gasoline vs. 95% LPG. The choice of 10% gasoline as the middle ground was based on the fact that the emissions’ total difference between these more extreme scenarios was only 5%. Lastly, since for diesel, gasoline and LPG the specific consumption $f_{s_{i,j}}$ is usually expressed in l/km, this was also the unit of measurement used for the self-declared consumption in the survey. These values were then converted in kg/km using the density reference values reported in the EMEP/EEA air pollutant emission inventory guidebook [28].

2.2.5.2. Hybrid cars consumption. On mild hybrid (MH) and full hybrid (FH) cars, the battery cannot be charged connecting the vehicle to an electric outlet. The battery is charged by the ICE motor and by the energy recovered during light brakes. Therefore, as for ICE cars, their direct GHG emissions only depend on the consumption of the ICE motor. Once again, the specific consumption of these vehicles was set using data from *alVolante*.

On the other hand, plug-in hybrids (PHs) have two independent power sources. For these cars, *alVolante* determines the ICE consumption independently, assuming that the rider would use the ICE motor only with a fully discharged electric battery. As done already for ICE cars, the authors selected the most popular cars in Italy for each car

size. For hybrid cars (which are a relative new technology, not so widespread in Italy) the popularity was based on the sales from 2020 to 2022 in Italy [29–31].

2.2.5.3. Electric cars consumption. Since *alVolante* does not provide much data on electric cars, the authors chose to use data from *ev-database.org* [32]. This website provides data for specific consumption in both:

1. Cold weather (“worst-case” based on -10 °C and use of heating);
2. Mild weather (“best-case” based on 23 °C and no use of A/C).

For the model used in this paper, the averages between these two set of values were used. Unlike the tests done by *alVolante*, which provided the consumption for motorway trips at 130 km/h, *ev-database*’s motorway speed was set to 110 km/h. For this reason, the results may not be strictly comparable. Nonetheless, this is an acceptable approximation, since electric cars were only used in 1% of the MoSToVIt survey trips.

2.2.5.4. Mopeds and motorbikes consumption. For these vehicles, the determination of the fuel consumption was based on results from the web [33], online forums and private interviews. These results may not be as accurate as those for ICE cars, but are absolutely reasonable (Appendix A for all the details). Besides, as for electric cars, approximate results are acceptable for this class, since their usage concerns only about 3,5% of the survey population.

2.2.5.5. Buses, metro, trams and trains consumption. Since 91% of the survey population declared to travel in Piedmont (more on this in Section 3.2), the authors decided to use real consumption data of the GTT fleet for these four modes of transport. A surprisingly complete analysis on this topic can be found in a very detailed Master’s thesis [34], conducted in 2019 in collaboration with GTT, which wanted to evaluate its energetic audit of year 2018. Therefore, all primary data were used, and also the trips of the vehicles to the warehouse were accounted for. For these reasons, the quality of these data is expected to be very high.

2.2.5.6. E-kick scooters and e-bikes. For these modes, data acquisition relied on a dataset provided in additional sources of a scientific article that scanned for products in market portals, technical magazines, product tests, and the web pages of vehicle manufacturers [35]. The dataset was filtered to include only models of e-kick scooters with a nominal power up to 500 W and e-bikes up to 250 W. This filtering was done because, above these power outputs, these vehicles are not currently legally admitted on public roads in Italy.

2.2.6. Model of the velomobile consumption (and data sources)

For the calculation of the velomobile’s electric consumption, the authors developed a specific model detailed in the second part of

the present study [16]. Various configurations were simulated, and all the results are provided in the Appendix A. For consistency with the rest of the model presented in this paper, average consumption values for urban and rural trips were utilized. Specifically, the electric consumption and average speed considered referred to simulations where:

- the ground is flat or with a slight slope (in the range of $\pm 2\%$), and
- the maximum power output of the rider is 100 W.

Furthermore, all the simulations were run with a relative low mechanical efficiency (93%) and no energy recovery of the electric motor.

2.2.7. Model of human caloric expenditure (and data sources)

Since this study aims to account for all the relevant sources of GHG emissions related to the use phase of its vehicles, the metabolic rate is included in the model. As hinted in Section 2.2.3, the metabolic rate is certainly relevant for HPVs, but it should also be accounted for non-HPVs for a fair comparison. Eq. (4) shows that the relation between the human consumption $h_{i,j}$ is inversely proportional to the travelling speed $\dot{x}_{i,j}$. Therefore, for a car driver jammed in the traffic (i.e. with a very low $\dot{x}_{i,j}$ at the denominator), even with a relatively low metabolic rate MR , the $h_{i,j}$ value may be not negligible. Quantitative examples are reported in Table 4, where it is also possible to see the impact of the human consumption in term of CO_{2eq} under the assumption that all the calories expended during the trip are replenished by eating (more details on this in Sections 2.2.8 and 2.2.9). When a vehicle $v_{i,j}$ is not used during trip j , the travelled distance $x_{i,j}$ is null, and so is the average speed $\dot{x}_{i,j}$. In these cases, in order to perform the division in Eq. (4) without returning an infinite value of $h_{i,j}$, the value of $\dot{x}_{i,j}$ is artificially set to 1 m/s in the algorithm, and $flag_{i,j}$ is set to 0. In all the other cases, $flag_{i,j}$ is set to 1.

$$h_{i,j}(v_{ij}, t_j) = \frac{MR_{i,j}(v_{ij}, t_j)}{\dot{x}_{i,j}} \cdot \frac{flag_{i,j}}{k_2} \quad (4)$$

Naturally, the value of the metabolic rate MR is dependent on the activity that is being performed. This means that active modes of transportation (fully or partially human-powered) have a higher value of h when travelling at the same speed of other vehicles. Table 3 shows the MR coefficients that were used in the model. The main source that was used for this matter is fairly complete [36], but it does not provide a sufficiently large spectrum of scenarios related to the use of HPVs. Cycling is cited, but a single value of MR is given, only representative of cycling speeds in the 13–18 km/h range. When comparing these speeds with values found in literature [17], or using a few online calculators [37,38] based on published scientific literature [39,40], or yet with the results given by the model described in [16], it is clear that this range of speed is related to a human power output of no more than 60 W. Therefore, to be able to make a fair comparison later with the velomobile calculations (which are performed with 100 W of mechanical power output for each rider) a clear and complete review of efficiency in cycling was used [41]. In that paper, Ettema and Lorås reported graphical data and suggested a strong linear correlation between the metabolic rate and the mechanical power output (which they referred to as EP , External power), as in Eq. (5). After an analysis of the graphs, we set the coefficients to $m = 3.8955 \text{ W/W}$ and $q = 232 \text{ W}$.

$$MR = m \cdot EP + q \quad (5)$$

This is a basic approach that works quite well for the calculation of the caloric expenditure. However, as clarified in the following two sub-subsections, this formula should be used carefully when assessing the GHG emissions related to the caloric expenditure. Particular care should be taken especially when the aim, as in this paper, is to assess the effect of the modal shift (more on this in Section 2.2.9.2). Also, due to the variability in human metabolism and people's build, the actual MR may vary from the values reported in Table 3. Nonetheless, these data should give a fairly good representation of the average human caloric expenditure.

Table 3

Metabolic rate values used in the model. Alternative HPVs were treated as bicycles due to the lack of more representative data.

Activity	MR	Associated mode of transportation	Source
Sitting (at rest)	120 W	Bus, metro, train, tram	[36]
Sitting (high level of attention)	210 W	Car, moto e-kick-scooter	[36]
Walking	280 W	walk	[36]
Cycling, mechanical power 100 W	622 W	Alternative HPVs, bicycle, velomobile	[41]

2.2.8. Impact assessment

As for the LCI, also the LCIA was modelled with a MATLAB[®] script. The conversion to annual CO_{2eq} emissions E of the quantities calculated in the last step of the LCI was performed with the system of Eqs. (6).

$$\begin{cases} E = \sum_{j=1}^{1247} E_j \\ E_j = D_j \cdot (E_{V,j} + E_{H,j}) \\ E_{V,j} = \sum_{s=1}^4 (C_{ICE_{s,j}} \cdot k_{1,s} \cdot EF_s) + (C_{El_j} \cdot k_3 \cdot EF_{El}) \\ E_{H,j} = C_{H_j} \cdot k_4 \cdot EF_{diet} \end{cases} \quad (6)$$

For each fuel s used in ICE vehicles, the reaction of complete combustion was considered, in accordance with the *Atmospheric Emission Inventory Guidebook 1.A.3.b.i-iv* guidelines [28]. On the other hand, emissions of CH_4 and N_2O from secondary processes (i.e., combustion of lubricant oil and addition of carbon-containing additives in the exhaust) were not accounted for, as preliminary calculations showed that they could be neglected (i.e., the fuel combustion generates the vast majority of the CO_{2eq} emissions). The coefficients $k_{1,s}$ which allow to transform the Tank-To-Wheel emissions in Well-To-Wheel emissions, were assessed with the *JEC report for automotive fuels and powertrains in the European context* [42].

The values of electric and caloric consumptions vary depending on the scenarios. The exact values were set according to the procedures reported in Section 2.2.9 Eq. (7) was used in substitution to the 4th equation of system (6) when different dietary habits were assumed, depending on the type vehicle considered (see Section 2.2.9 for its implications).

$$\begin{aligned} E_{H,j} &= \sum_{i=1}^{11} (C_{H_{i,j}} \cdot k_4 \cdot EF_{diet_{i,j}}) \\ &= \sum_{i=1}^{11} (x_{i,j} \cdot k_2 \cdot h_{i,j}(v_{ij}, t_j) \cdot k_4 \cdot EF_{diet_{i,j}}) \end{aligned} \quad (7)$$

For non-docked shared modes of micromobility (i.e. bicycles, e-bicycles, e-kick scooters and e-mopeds) additional emissions were introduced to account for the *fleet rebalance* studied in a recent paper [12].

For each scenario, the results are calculated both with the baseline and the revised values. Then, by performing the subtraction of these two results, it is possible to define the saved emissions thanks to the modal shift. Finally, dividing this result by the population size n_{pop} , one gets the “Average Personal (annual GHG) Emission Reduction” ($APER$), as in Eq. (8).

$$APER = \frac{E_{baseline} - E_{revised}}{n_{pop}} \quad (8)$$

The authors also defined the “Emission Reduction %” ($ER\%$) to represent MoStoVIt's normalized saved GHG emissions after substitution with respect to the baseline GHG emissions (Eq. (9)).

$$ER\% = 1 - \frac{E_{revised}}{E_{baseline}} \quad (9)$$

Table 4

Relevance of the caloric consumption on the Well-To-Wheel impact, assuming typical conditions for all vehicles. Calculations performed under “full replenishment” hypothesis, as by scenario Sc_1 detailed in 2.2.9.2.

Vehicle boarded by the passenger	Condition	$\frac{MR}{W}$	\dot{x}_{avg}		$\frac{h}{cal/(p \text{ km})}$	$\frac{E_H}{g/(p \text{ km})}$	$\frac{E_{motor/d}}{g/(p \text{ km})}$	$\frac{E_{TOT}}{g/(p \text{ km})}$	$\frac{E_H}{E_{TOT}}$
			/(km/h)	/(m/s)					
Diesel car	Jammed in traffic	120	8	2.222	12.9	18–66	185	203–251	9%–26%
Diesel car	Urban average	120	20	5.556	5.2	7–26	160	167–186	4%–14%
Diesel car	Rural average	120	45	12.500	2.3	3–11	136	139–148	2%–8%
Diesel car	Free-flow motorway	120	130	36.111	0.8	1–4	199	200–203	1%–2%
Motorbike	Jammed in traffic	210	8	2.222	22.6	32–115	130	162–245	20%–47%
Motorbike	Urban average	210	23	6.389	7.9	11–40	120	131–160	8%–25%
e-kick scooter	Urban average	210	20	5.556	9.0	13–46	4	17–50	76%–92%
e-kick scooter (docked sharing)	Urban average	210	20	5.556	9.0	13–46	4+32 ^a	49–82	26%–56%
Bicycle EP = 100 W	Urban average	622	18	5.000	29.7	42–152	0	42–152	100%
Bicycle EP = 150 W	Urban average	816	20	5.556	35.1	49–179	0	49–179	100%
Bicycle EP = 150 W	Rural average	816	25	6.944	28.1	39–143	0	40–143	100%
e-velomobile EP = 100 W	Urban average	622	16	4.444	33.4	47–170	3	50–173	94%–98%
e-velomobile EP = 100 W	Rural average	622	31	8.611	17.2	24–88	2	26–90	92%–98%
e-velomobile EP = 200 W	Urban average	1011	17	4.722	51.2	72–261	2	72–261	97%–99%
e-velomobile EP = 200 W	Rural average	1011	37	10.278	23.5	33–120	1	33–120	97%–99%
Walk	Average pace	280	4	1.111	60.2	84–307	0	84–307	100%
Bus	Urban	120	18	5.000	5.7	8–29	22	30–51	27%–57%
Tram	In reserved lane	120	21	5.833	4.9	7–25	15	22–40	31%–63%
Metro	Turin’s metro	120	35	9.722	2.3	3–12	11	15–26	27%–58%
Regional train	Average regional train	120	80	22.222	1.3	2–7	9	11–16	17%–42%
High-speed train	Long	120	250	69.444	0.4	1–2	9	10–11	6%–19%

^a The fleet rebalancing requires that the e-kick scooter is moved with a vehicle [12].

The $ER\%$, which can be expressed as a percentage, is used to assess with one parameter the reduction in CO_{2eq} emissions.

2.2.9. Scenarios

The authors conducted analyses across 36 scenarios to encompass a wide range of parameter variations. A condensed summary is presented in Table 5, with a detailed explanation following.

2.2.9.1. Influence of price and cruising speed. Two primary scenarios were identified for modal shift accounting. The first scenario, labelled “All subs” in Table 5, considered all substitutions reported in the MoStoVIt survey. The second scenario, labelled “Partial subs” in Table 5, only accounted for the substitutions of respondents who declared, among the velomobile characteristics, both the two following features which are realistically attainable in the short term:

1. A price to the public of 2500 € or more;
2. A cruising speed of no more than 40 km/h.

The survey results were not intended to predict exact behavioural changes, but to provide a context-specific baseline and a data-driven indication of the potential for modal shift toward human-powered vehicles. These insights were used to define realistic adoption scenarios for the comparative LCA. While we acknowledge that stated preferences may not always translate into actual behaviour, the inclusion of two sub-scenarios (“All subs” and “Partial subs”) allows for variability in user requirements such as price and speed, thereby mitigating over-optimistic assumptions and increasing the robustness of the analysis.

2.2.9.2. Variation in caloric expenditure. Scenarios were further differentiated based on whether the modal shift changes the caloric expenditure of individuals. As discussed in Section 2.2.7, the challenge with calculating human caloric expenditure lies in its integration with the broader context of our lifestyle, where feeding is an integral component. Mobility is just one aspect of this larger picture. Therefore, when evaluating the variation in caloric expenditure due to modal shift, it is crucial to consider the individual’s feeding habits. The key considerations are not only the change in metabolic rate over the short span of the trip but, more importantly:

1. The impact on caloric intake (whether it increases, decreases, or remains unchanged);
2. The type of diet the individual follows.

This concept is fundamental for the calculation, as the GHG emissions of food are embedded, and no emissions are directly associated with its consumption. In this context, four different scenarios have been identified:

- Sc_1 , Same caloric intake after the modal shift. This scenario accounts for individuals who increase physical activity without adjusting caloric intake. These individuals may experience body fat loss without increasing their food-related carbon footprint. A similar scenario involves those who maintain their dietary habits but adjust physical activity intensity during the rest of the day to a lower level of intensity, resulting in no weight loss;
- Sc_2 , Increased caloric intake after the modal shift. This scenario accounts for individuals who fully replenish the excess calories expended due to the modal shift by eating more;
- Sc_3 , Decreased caloric intake after the modal shift. Some people may eat less after shifting to an active mode of transportation, reducing snacking habits. However, this scenario Sc_3 is not accounted for in the model due to challenges in making widely accepted assumptions;
- Sc_0 , Caloric intake not accounted for. To circumvent the issue of non accepted assumptions, calculations were also performed for the subscenario Sc_0 that does not consider any human caloric expenditure ($C_{H_j} = 0$ for every trip).

2.2.9.3. Dietary habits and subscenarios composition. A previous review [43], showed a wide variability in the emissions embedded in our dietary habits. To address this issue, values of the dietary emission factor EF_{diet} spanning from the maximum and minimum values reported in [44] (1.4 g of $CO_{2eq}/kcal$ and 5.1 g of $CO_{2eq}/kcal$) were considered. These two values were introduced in the EF_{diet} factor of our model when evaluating “low impacting diets” and “highly impacting diets” respectively. It should be noted that the lower value is related to a vegetarian diet, whereas a vegan one could possibly impact even less [43]. Using the vegetarian lower value will lead to conservative results (i.e., to higher CO_{2eq} than the actual lower threshold).

Table 5

The analyses were performed in 36 different scenarios. S_{c_0} : caloric expenditure not accounted; S_{c_1} : no caloric deficit for modal shift; S_{c_2} : complete replenishment of the excess of calories expended due to the modal shift.

Diet scenario	All subs	Partial subs		
No diet	S_{c_0}	S_{c_0}		
LID (0.0014 kg of CO _{2,eq} /kcal) for everyone	S_{c_1}, S_{c_2}	S_{c_1}, S_{c_2}	$EF_{El_{ISPRa}}$ (0.3089 kg of CO _{2,eq} /kWh)	$EF_{El_{AIB}}$ (0.45715 kg of CO _{2,eq} /kWh)
HID (0.0051 kg of CO _{2,eq} /kcal) for everyone	S_{c_1}, S_{c_2}	S_{c_1}, S_{c_2}		
MixD: LID for non-HPVs, HID for HPVs and walking	S_{c_1}, S_{c_2}	S_{c_1}, S_{c_2}		
MixDv2: HID for non-HPVs, LID for HPVs and walking	S_{c_1}, S_{c_2}	S_{c_1}, S_{c_2}		

These two types of diet were then used to generate four subscenarios for S_{c_1} and S_{c_2} :

1. LID: *low impacting diet* associated to everyone;
2. HID: *highly impacting diet* associated to everyone;
3. MixD (Mixed Diet): *low impacting diet* associated to people moving with non-HPVs, and *highly impacting diet* associated to people moving with HPVs or walking;
4. MixDv2 (Mixed Diet version 2): *highly impacting diet* associated to people moving with non-HPVs, and *low impacting diet* associated to people moving with HPVs or walking.

Note that the MixD and MixDv2 scenarios are considered only to account for extreme variability in the results. However, especially the MixD returns very conservative and unlikely results. Lastly, all these scenarios were calculated with two different emission factors for the electric consumption (right side of Table 5), for a total of 36 scenarios.

2.2.9.4. Electricity energy mix variability. For electricity consumption, a first set of analyses was conducted using the emission factor calculated by ISPRa ($EF_{El_{ISPRa}} = 0.3089$ kg of CO_{2,eq}/kWh) for the production of electric energy in Italy in year 2022 [45]. A second set of analyses was performed with the emission factor from AIB ($EF_{El_{AIB}} = 0.45715$ kg of CO_{2,eq}/kWh), which considered the Italian residual mix [46].

2.2.9.5. Considerations on public transportation: the rebound effect. Finally, it is important to point out that, for all the scenarios described above, the authors calculated the emissions under the assumption that the public transit fleet remains unchanged after the modal shift to velomobiles. This means that, under the assumption that the specific consumption of heavy vehicles (such as buses, trams, trains and metros) is not related to the number of people using them, the GHG emission reduction induced on the whole fleet by a person that ceases to use public transportation is negligible.

Therefore, although the personal emissions of those who start using velomobiles as a substitute for public transport may decrease, one should take into account other passengers' emissions going up to compensate for a less crowded vehicle whose emissions, as said, need to stay unchanged (hence, the rebound effect). For this reason, in the model, the total revised emissions for these people were calculated with Eq. (10), where $E_{revised,PT}$ are the revised emissions after the modal shift from public transportation, $E_{baseline,PT}$ are the emissions in the baseline scenario due to the use of public transportation to the velomobile, and $E_{velomobile}$ are the emissions produced by the usage of the velomobile after the modal shift.

$$E_{revised,PT} = E_{baseline,PT} + E_{velomobile} \quad (10)$$

This assumption produces conservative results that tend to penalize the modal shift to velomobiles of people who usually use public transit. Nonetheless, this approach is representative of what would occur at first. A more long-term approach could consider a rebalance of the fleet to avoid very low occupation levels of the vehicles. However, since too many assumptions should be accounted for this calculation (i.e., the uncertainty of results would be difficult to assess), the authors decided to avoid it.

3. Results and discussion

3.1. ER% and APER analysis

The ER% was defined in Section 2.2.8 as the saved emissions in the projected future scenarios after the modal shift, with respect to the emissions in the baseline scenario. It is the core of the impact assessment, as through this parameter one can really appreciate the effects of the modal shift, later analysed in Section 3.3. Table 6 shows all the results of the ER% analysis. It is clear that the variability of the emission factors for the electric energy is negligible. For this reason, in Fig. 4.a only the results with $EF_{El_{ISPRa}}$ are shown. ER% does not reach 10% only in two sub-scenarios, when accounting for a total replenishment of the excess calories expended. All the other cases of the "Partial subs" analysis report an ER% above 20%. In the "All subs" analysis, only the two worst case scenarios do not reach the 20% threshold, while most of the others stand around 40%. Finally, in the S_{c_0} scenarios the ER% gets as high as 52.5% and 30.0% for the "All subs" and "Partial subs" analyses, respectively. A compact representation is depicted in Fig. 4.b.

The corresponding APER results (Table 7) show an average yearly saving of 125 kg of CO₂ after the modal shift, for the "Partial subs" scenario when taking into account the human consumption. When considering the vehicle emissions only, the saving raises to 179 kg of CO_{2,eq}. A compact graphical representation of the APER results is reported in Fig. 5.

An average Italian person produces about 6 tons of CO_{2,eq} each year [7]; therefore, the modal shift could account on average for 2.1% to 3% reduction of the total GHG emitted by a person of the MoSToVIt population. In the "All subs" scenario these savings increase to a range of 3.8% to 5.2%, depending on whether the analysis accounts for:

1. Both vehicle and human consumption (average value);
2. The vehicle consumption only.

3.2. Analysis of the population

The authors began the analyses by studying the population to gauge the significance of the LCA results. This analysis involved examining the geographical distribution, comparing age distribution, and assessing the modes of transport used for commuting to work and school. Data from ISTAT (Italian National Institute of Statistics) were employed for these comparisons.

3.2.1. Geographical distribution

Among the 1247 valid answers, 87% of the respondents (1085 people) reside in Piedmont, but as much as 91% (1136 people) travel on its territory. Of the 1136 people travelling in Piedmont, 64.17% are from the Turin province and 24.56% are from the Cuneo province. During their trips of routine, 76.95% of the MoSToVIt population travels in the Turin province, and 24.91% travels in the Cuneo province. As for the actual Piedmontese population, Turin and Cuneo make for the two most populated provinces, with 51.9% and 13.6% respectively [47]. Together they account for 65.5% of the Piedmontese population, in contrast with 88.7% of the MoSToVIt population. Therefore, these data show that the respondents are more polarized around these two areas than the average Piedmontese person.

Table 6
ER% analysis summary.

	S_{c_0}	S_{c_1} LID	S_{c_1} HID	S_{c_1} MixD	S_{c_1} MixDv2	S_{c_2} LID	S_{c_2} HID	S_{c_2} MixD	S_{c_2} MixDv2
All subs $EF_{El_{ISPRa}}$	52.54%	46.73%	36.15%	41.00%	40.54%	40.28%	17.99%	13.76%	41.52%
All subs $EF_{El_{AlB}}$	52.28%	46.52%	36.03%	40.83%	40.38%	40.10%	17.93%	13.70%	41.35%
Partial subs $EF_{El_{ISPRa}}$	30.07%	26.74%	20.69%	23.46%	23.20%	22.41%	8.48%	5.26%	23.74%
Partial subs $EF_{El_{AlB}}$	29.94%	26.64%	20.63%	23.38%	23.12%	22.32%	8.46%	5.26%	23.66%

Table 7
APER analysis summary. All values expressed in kg of $CO_{2,eq}$.

	S_{c_0}	S_{c_1} LID	S_{c_1} HID	S_{c_1} MixD	S_{c_1} MixDv2	S_{c_2} LID	S_{c_2} HID	S_{c_2} MixD	S_{c_2} MixDv2
All subs $EF_{El_{ISPRa}}$	313	313	313	313	313	270	156	105	320
All subs $EF_{El_{AlB}}$	313	313	313	313	313	270	156	105	320
Partial subs $EF_{El_{ISPRa}}$	179	179	179	179	179	150	73	40	183
Partial subs $EF_{El_{AlB}}$	179	179	179	179	179	150	73	40	183

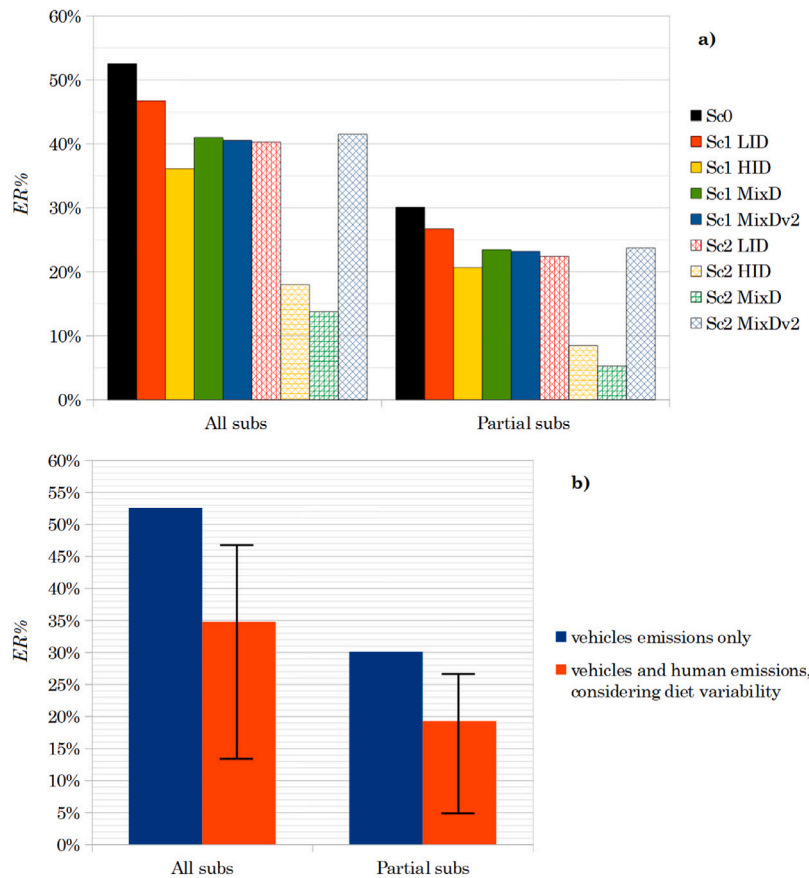


Fig. 4. Emission reduction percentage (ER%) analysis. (a) Presents the complete results for the 18 scenarios calculated with the $EF_{El_{ISPRa}}$ emission factor for the electric energy production. As shown in Table 6, these results are almost identical to those calculated with the $EF_{El_{AlB}}$ emission factor. The legend abbreviations were explained in Section 2.2.9. (b) Shows the aggregated results: when accounting for the dietary habits, the height of the red column represents the average value, while the black “I” represents the maximum variability of the results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Age distribution

Fig. 6 compares the age distribution of the MoSToVIt population with that of the Piedmontese population [47]. It should also be noted that the Piedmontese distribution of the population is aligned with that of all the other 19 Italian regions [48], as shown in Fig. 7.

In the MoSToVIt sample, 69.3% are workers, 28.45% students, and 2.25% homemakers, retired, or unemployed. This distribution closely approximates the age range of 40 to 60 years in the Piedmontese population. Notably, this age group emits the highest GHGs related to the transportation sector, mainly due to their predominant use of cars. There is a noticeable peak in the younger demographic, surpassing

the statistical average from ISTAT. This is not as bad as it could seem, though, as younger individuals have significant future emission potential, and the study focuses on an emerging technology that could greatly impact future generations. Students constitute 53.77% of the MoSToVIt population below 35 years and 64.78% below 30 years. Despite this youth peak, the mean age of workers is 42.5 years, aligning closely with the reported mean age for the Italian working population (42.7 years) [49]. People over 65, constituting about 20% of the Italian population, are typically retired, resulting in a low impact on work-related trips. Therefore, a lower percentage of respondents in that age range is not critical.

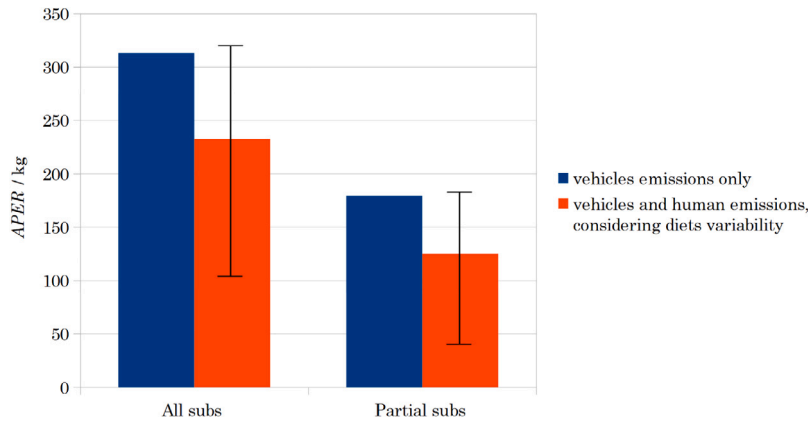


Fig. 5. Average annual personal GHG emissions reduction.

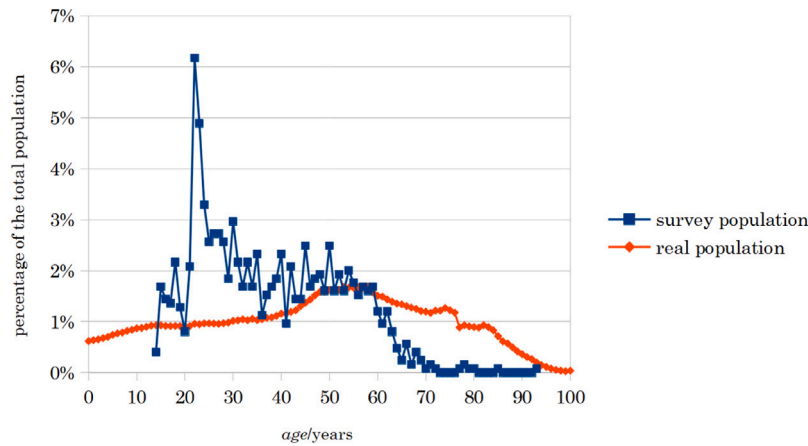


Fig. 6. Age distribution of the MoSToVIt population compared to ISTAT data of the Italian population.

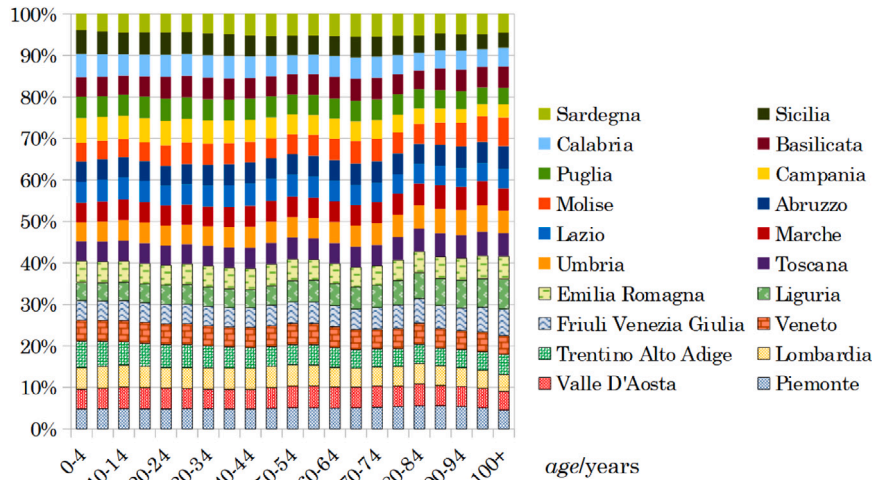


Fig. 7. Relative distribution of the Italian population across its 20 regions.

3.2.3. Modes of transportation for workers and students

The trips of the MoSToVIt population were compared to a reference population calculated as an average from 2018 to 2022 using ISTAT data for routine trips by Italian students and workers, excluding 2020 due to lockdown-related distribution differences. It is important to note that ISTAT data does not account for alternative HPVs and electric kick-scooters. However, this is not critical, as they are marginal modes of transportation for the MoSToVIt population (see Section 3.3).

Regarding the working population, the survey data closely align with ISTAT quotas for people travelling on foot or using at least one vehicle for their work commute (see Fig. 8.a). However, when considering individual modes of transportation, the data show variations. Compared to ISTAT, the MoSToVIt population uses public transportation more (+12.1% for the train, +11.8% for bus and tram, +4.9% for the metro) and bicycles more (+12.2%), while car use is significantly lower (-24.6%). These differences are more pronounced in urban areas,

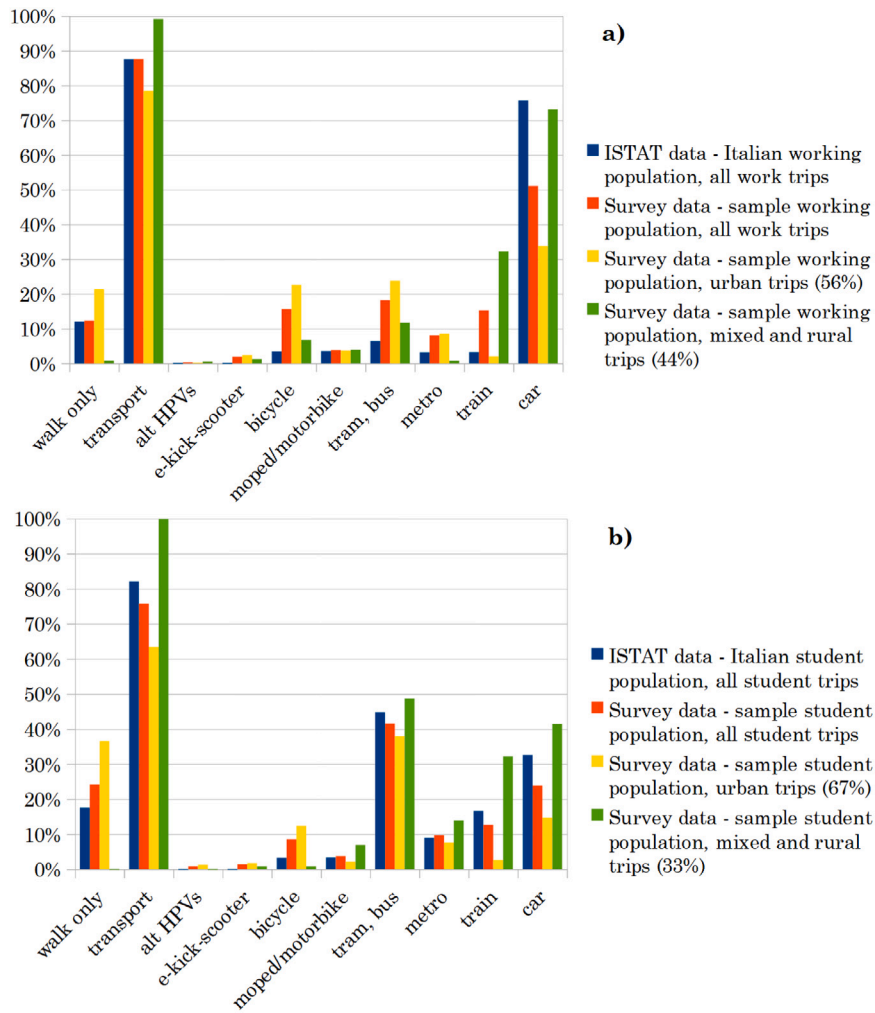


Fig. 8. (a) Italian working population trips (ISTAT data) compared to the trips of the MoSToVIt working population; (b) MoSToVIt student population trips compared to those of the Italian student population (ISTAT data). Bars labelled “transport” represent the complement of “walk only”, indicating the percentage of people using at least one vehicle of any kind for their trip.

especially in Turin, potentially influenced by the city’s cycling infrastructure and public transportation. This, however, is not problematic, as explained in Section 2.2.9.5, where increased public transportation use in the baseline scenario results in more conservative *ER%* and *APER* outcomes.

On the other hand, the distribution of transportation modes used by the MoSToVIt student population closely matches the actual Italian distribution (see Fig. 8.b). The maximum difference is reported for cars and bicycles, with a smaller gap (−8.7% and +5.2%, respectively), while other modes fall within an even smaller range of ±4%.

Homemakers, retirees, or unemployed individuals (representing only 2.25% of the MoSToVIt population) were not included in this analysis due to the lack of suitable comparative data. Overall, the student population serves as a representative sample, and the working population provides conservative results for the *ER%* and *APER* analyses.

3.3. Modal shift index potential (*MSIP*) for each mode of transportation

Fig. 9.a reveals unexpectedly high values for the *MSIP*, which was calculated for each mode of transportation as the ratio of the people inclined to use the velomobile in the future, over the total population using that mode of transportation in the baseline scenario. In the “All subs” scenario, the velomobile demonstrates the potential to substitute for over 50% of all modes of transportation, except for trains. Moving

to the more realistic “Partial subs” scenario discussed in Section 2.2.9, the *MSIP* values become more moderate but still notably high. Even trains, typically regarded as a resilient mode due to their comfort and the possibility of engaging in other activities during travel, exhibit a *MSIP* of nearly 15% in this scenario. These data showcase a promising outlook for the velomobile, suggesting that we are now closer than ever to the non-linear sociotechnical framework discussed in Section 1.3. In Fig. 9.b, the analysis is extended to age groups, revealing nuanced preferences within different demographics. Older individuals appear less inclined to replace public transportation, possibly due to its convenience and lack of driving necessity. In contrast, younger respondents, valuing independence, might find the velomobile appealing. The substitution of walking with a less strenuous option is more favoured by older participants. The prospect of replacing a car could be seen positively by older individuals as an alternative means of transport without the need for periodic license renewal. Modal shifts from trains remain consistently lower across all age groups, reflecting the efficiency of train travel for longer distances without physical exertion and with the added possibility of engaging in other activities (e.g. reading, studying). Young individuals already accustomed to bicycles or alternative HPVs may appreciate the versatility of the velomobile. Older individuals, on the other hand, might display a slightly lower enthusiasm, potentially due to preferring bicycles for specific routes and seeking greater comfort for other trips. Additionally, age-related reluctance to change may contribute to the varied responses. These trends observed in the

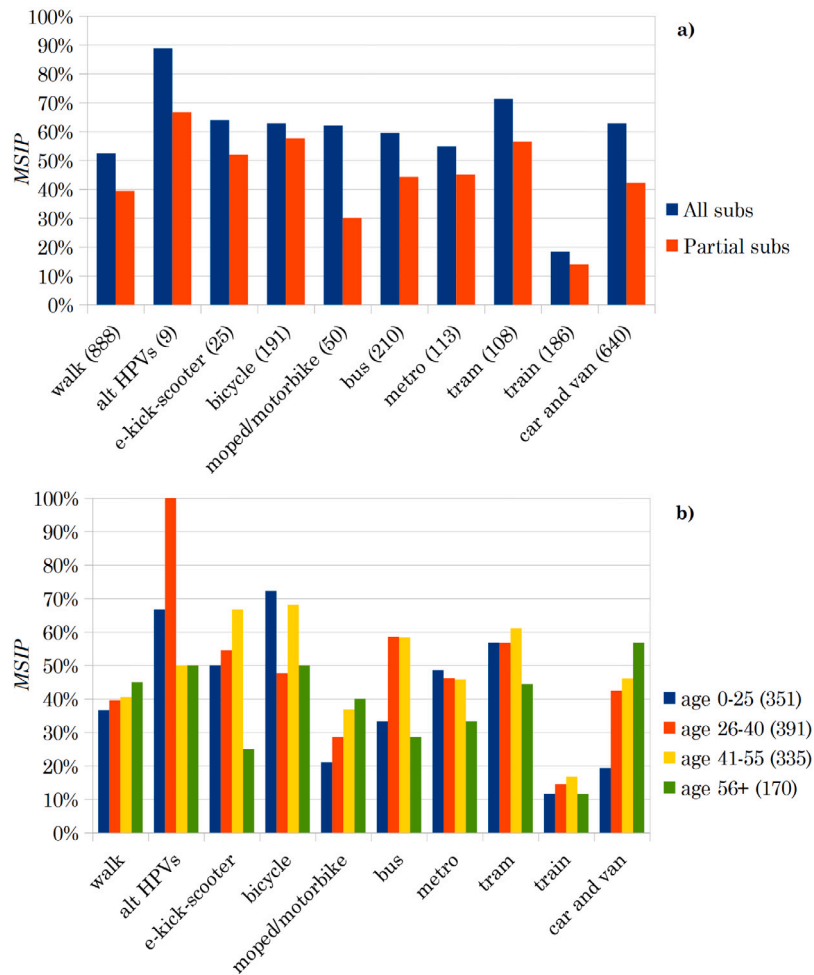


Fig. 9. *MSIP* of the velomobile for each mode of transportation. Between brackets: for each mode, total trips reported in the baseline scenario (note that, due to intermodality, the sum of these values exceeds the number of trips reported in the survey). In blue: all the substitutions declared in the survey are considered. In red: only the substitutions of people who declared a maximum price of at least 2500 € and a cruising speed of no more than 40 km/h are considered. (b) Focus on the “partial subs” scenario: analysis for age groups. Between brackets: sample size of the population. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

data align with reasonable expectations, enhancing the credibility and robustness of the study results.

3.4. Assessing modal shift with broader system boundaries: The case of car replacement

Considering that the *MSIP* values reported are quite high, and that in our calculation the possible reduction in the emissions of public transportation due to fleet rebalance was not accounted for (Section 2.2.9.5), the prospects for a long-term reduction in the emissions are even higher.

Finally, it is also important to remind that these results come from a Well-To-Wheel analysis. Different results could arise from the adoption of broader system boundaries.

What clearly emerges, however, is the relevance of scenario multiplicity when evaluating the environmental impact of velomobile adoption. To better contextualize the analysis, the authors chose to focus on the modal shift from cars to velomobiles. This decision is supported by the fact that cars represent one of the most widespread means of transportation among respondents (see Fig. 8), and also one of the modes for which the interest in switching to velomobiles appears to be higher (see Fig. 9). To better assess the problem, one can look at Fig. 10, where the cumulative emissions of production and use-phase (measured in tons of $\text{CO}_{2,\text{eq}}$) are plotted against time (measured in years). This

picture shows five different scenarios of possible modal shift from cars to the velomobile. Results here are shown performing calculation with the S_{c_2} method defined in Section 2.2.9.2 for diet-related emissions, and a vegetarian diet is assumed. In this figure, the system boundaries are expanded to include the production of vehicles: 5 tons and 9 tons of $\text{CO}_{2,\text{eq}}$ are assigned to the production of ICE cars and BEV cars, respectively [50]; and 750 kg of $\text{CO}_{2,\text{eq}}$ are assigned to the velomobile. The latter emissions are an estimation of a commercial velomobile production (i.e., the Frikar, by Norwegian producer Podbike) found in a recent study [51]; calculations in that study were based on a thesis [52] written by a student directly involved in the end-point LCA of said velomobile. Such emissions, do not necessarily overlap with the emissions related to the future production of the velomobile discussed in the present paper (which will need to be calculated), but are still an indicator for this example.

Fig. 10 specifically shows a person that travels by car for 8500 km/year on average and who changes the car after it has run for 200 000 km. In the example, the individual becomes aware of velomobiles after travelling 30 000 km in a diesel car and then faces the choice of either purchasing a velomobile to use for part of their trips (green, yellow, orange, and red lines) or continuing to rely solely on cars (blue line, baseline scenario). It is immediately evident that the emissions associated with the hypothetical velomobile production are practically negligible compared to those of cars. For this reason, if

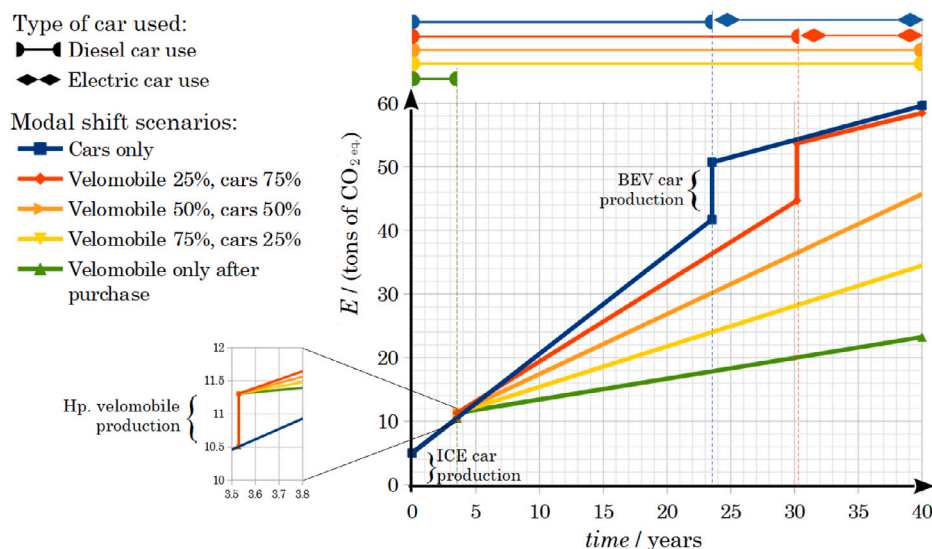


Fig. 10. Example of an analysis of modal shift from cars to velomobile comprehensive of production and use phases (cumulative emissions E on the vertical axis). Modelled considering: average car use of 8500 km/year, vegetarian diet and caloric emission calculated with increased metabolism and full caloric replenishment (S_{c_2} in Section 2.2.9.2), 22 km/h of average speed for the velomobile, 35 km/h of average speed for cars, retirement of the ICE car after running it for 200 thousand km, velomobile introduced after 30 thousand km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the velomobile is used sufficiently, there is a “bonus” in terms of emissions saved due to the avoided purchase of a second car in the long term (see the postponed offset of BEV production). However, the primary driver of emission reduction lies in the use phase, determined by the extent to which the velomobile can substitute the car, as this directly influences the slope in Fig. 10. Notably, using the velomobile for only 25% of the travelled distance already results in a specific $CO_{2,eq}$ emission per kilometre lower than that of a full hybrid segment C car, without incurring the production burden typically associated with motorized alternatives. The specific values of produced $CO_{2,eq}$ may vary significantly depending on how many kilometres the ICE car is driven before being retired, as well as on the individual’s diet and the attributional method used for diet-related emissions (i.e., the various S_c scenarios defined in Section 2.2.9.2). Nonetheless, such analyses may reveal that, for some individuals, using a velomobile while retaining their existing ICE car could lead to greater reductions in transport-related GHG emissions than switching to a BEV and entirely overlooking the potential of HPVs.

Extending this analysis to encompass all modes of transportation requires careful consideration and dedicated research to capture the nuanced differences across various potential scenarios. This task lies well beyond the scope of the present already extensive study, and is therefore left for future work.

4. Conclusions

This paper introduces a comprehensive model that considers all significant sources of emissions during the use phase of various transportation modes, including velomobiles.

A survey, named MoSToVIt, was conducted to map commuting patterns among 1247 individuals and gauge their inclination toward adopting velomobiles for future routine trips. Based on these results, a comparative Life Cycle Assessment (LCA) was performed to quantify the effects of modal shift on Global Warming Potential (GWP) using a well-to-wheel approach. This analysis determined the total annual Emission Reduction Percentage ($ER\%$) of passenger road transport emissions and the Average annual Personal GHG Emission Reduction ($APER$).

Calculations were executed across 36 scenarios to accommodate diverse parameters. The results demonstrate a reduction in CO_2 emissions

ranging from 5% to 52% in two unlikely scenarios. More plausible scenarios indicate a 20% reduction in greenhouse gas (GHG) emissions when considering human emissions and a 30% reduction when focusing solely on emissions from internal combustion engine (ICE) and electric vehicles. These reduction account for up to a 5% reduction in the total GHG emitted by an average Italian person (i.e., including all emissions sources, including those not related to the transportation sector).

All calculations were conducted conservatively, assuming low mechanical efficiency and no energy recovery from the velomobile electric motor. Additionally, the study excluded vehicle production and end-of-life (EOL) considerations. This tends to penalize the estimated impact of the modal shift to the velomobile because, compared to cars and other motorized vehicles, the velomobile is expected to have a very low impact in terms of both production and EOL.

As the research progresses and the velomobile design is finalized, the production phase and the EOL will be incorporated into the model. Furthermore, if secondary emissions related to non-human-powered vehicles (non-HPVs) are considered, such as increased road repairs due to heavier vehicles, the modal shift to velomobiles could lead to even greater emission reductions. These are all impacts that in a future work could be implemented in the model to refine the present results.

Population analysis yielded representative data, particularly for students. Although workers data did not perfectly align with statistical trends, the survey responses appear truthful, providing confidence in the representativeness of the data for predicting future choices within the sampled population. The misalignment in working population trends tends towards a more conservative estimation of $ER\%$ and $APER$ in the MoSToVIt population.

It is important to note that these findings are not claimed to be universally applicable to the entire Piedmontese or Italian population. However, while acknowledging the lack of data from previous surveys regarding interest in transitioning to velomobiles, the results have surpassed the authors’ expectations. The Modal Shift Index Potential ($MSIP$) in the MoSToVIt population averaged over 40%, indicating promising prospects for this technology in other regions of Italy as well, where a lower $MSIP$ could still possibly be significant, or at least non negligible.

CRedit authorship contribution statement

Alessandro Di Gesù: Writing – original draft, Validation, Software, Conceptualization. **Chiara Gastaldi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Cristiana Delprete:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.treng.2025.100401>.

Data availability

Data will be made available on request.

References

- [1] E. Commission, Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions, 2019, URL <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640>. (Accessed 04 August 2023) at 21:45 (CET).
- [2] E.E. Agency, EEA greenhouse gases - data viewer, 2023, URL <https://www.eea.europa.eu/publications/data-and-maps/data/data-viewers/greenhouse-gases-viewer>. (Accessed 04 August 2023) at 21:51 (CET).
- [3] M. Meinshausen, N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, M.R. Allen, Greenhouse-gas emission targets for limiting global warming to 2°C, *Nature* 458 (7242) (2009) 1158–1162, <http://dx.doi.org/10.1038/nature08017>.
- [4] D.B. Müller, G. Liu, A.N. Løvik, R. Modaresi, S. Pauliuk, F.S. Steinhoff, H. Bratetebo, Carbon emissions of infrastructure development, *Environ. Sci. & Technol.* 47 (20) (2013) 11739–11746, <http://dx.doi.org/10.1021/es402618m>.
- [5] C. Buysse, J. Miller, Transport could burn up the EU's entire carbon budget, 2021, URL <https://theicct.org/transport-could-burn-up-the-eus-entire-carbon-budget/>. (Accessed 04 August 2023) at 22:13 (CET).
- [6] Eurostat, Climate change - driving forces, 2022, URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Climate_change_-_driving_forces. (Accessed 04 August 2023) at 22:47 (CET).
- [7] E.C.J.R. Centre, CO2 Emissions of All World Countries: JRC/IEA/PBL 2022 Report., Publications Office, 2022, <http://dx.doi.org/10.2760/07904>.
- [8] P. Jaramillo, S. Kahn Ribeiro, P. Newman, S. Dhar, O.E. Diemuodeke, T. Kajino, D.S. Lee, S.B. Nugroho, X. Ou, A.H. Strömman, J. Whitehead, Transport, in: P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III To the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, <http://dx.doi.org/10.1017/9781009157926.012>, Published by the Intergovernmental Panel on Climate Change (IPCC).
- [9] M. Weiss, L. Irrgang, A.T. Kiefer, J.R. Roth, E. Helmers, Mass- and power-related efficiency trade-offs and CO₂ emissions of compact passenger cars, *J. Clean. Prod.* 243 (2020) 118326, <http://dx.doi.org/10.1016/j.jclepro.2019.118326>.
- [10] V. Foster, J.U. Dim, S. Vollmer, F. Zhang, Understanding drivers of decoupling of global transport CO₂ emissions from economic growth : Evidence from 145 countries, 2021, URL <https://documents1.worldbank.org/curated/en/766991634561185532/pdf/Understanding-Drivers-of-Decoupling-of-Global-Transport-CO2-Emissions-from-Economic-Growth-Evidence-from-145-Countries.pdf>.
- [11] K.J. Dillman, Á. Árnadóttir, J. Heinonen, M. Czepkiewicz, B. Davíðsdóttir, Review and meta-analysis of EVs: Embodied emissions and environmental breakeven, *Sustainability* 12 (22) (2020) 9390, <http://dx.doi.org/10.3390/su12229390>.
- [12] P. Felipe-Falgas, C. Madrid-Lopez, O. Marquet, Assessing environmental performance of micromobility using LCA and self-reported modal change: The case of shared E-bikes, E-scooters, and E-mopeds in Barcelona, *Sustainability* 14 (7) (2022) 4139, <http://dx.doi.org/10.3390/su14074139>.
- [13] IPSOS, Cycling across the world: A 28-country global advisor survey, 2022, URL <https://www.ipsos.com/en/global-advisor-cycling-across-the-world-2022>.
- [14] S. Nurila, Nordic recumbent championships 2016, 2016, URL <http://www.saukki.com/2016/08/nordic-recumbent-championships-2016/>.
- [15] S. Nurila, I met tero haapanen on his 1100 km velomobile trip, 2020, URL <https://www.youtube.com/watch?v=xZGmOPYjvIw>.
- [16] A. Di Gesù, C. Gastaldi, C. Delprete, Human-powered vehicles as a way to abate transport-related greenhouse gas emissions: Part 2 - a virtual prototype for emissions and performance analyses, *Transp. Eng.* 18 (2024) 100278, <http://dx.doi.org/10.1016/j.treng.2024.100278>.
- [17] F. Van De Walle, The velomobile as a vehicle for more sustainable transportation, 2004, URL http://www.jobike.it/public/data/tino/200851815837_vm4sd-fvdwsm.pdf.
- [18] Statista, Number of bicycles sold in Italy from 2000 to 2021, 2023, URL <https://www.statista.com/statistics/398304/bicycle-sales-in-italy/>.
- [19] Statista, E-bike sales volume in Germany from 2011 to 2022, 2023, URL <https://www.statista.com/statistics/1265760/e-bikes-sold-number-germany/>.
- [20] M. Sutton, European electric bike sales on course to overtake bicycle sales in the coming years, 2023, URL <https://www.cyclingelectric.com/in-depth/european-electric-bike-sales-overtake-bicycle-sales>.
- [21] R.T. Alliance, Large-tired and tested: How europe's cargo bike roll-out is delivering, 2021, URL <https://rapidtransition.org/stories/large-tired-and-tested-how-europes-cargo-bike-roll-out-is-delivering/>.
- [22] U.N.C. Change, Greenhouse Gas Inventory Data - Detailed data by Party. URL https://di.unfccc.int/detailed_data_by_party.
- [23] ISFORT, AGENS, asstra, 19° report sulla mobilità degli italiani, principali risultati, 2022, URL https://www.isfort.it/wp-content/uploads/2022/12/19-Rapporto_mobilita_italiani_Sintesi.pdf. (Accessed 06 August) at 17:57 (CET).
- [24] Eurostat, Urban-rural europe - introduction, 2022, URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Urban-rural_Europe_-_introduction. (Accessed 07 August 2023) at 11:45 (CET).
- [25] ISTAT, Principali dimensioni geostatistiche e grado di urbanizzazione del paese, 2014, URL <https://www.istat.it/it/archivio/137001>. (Accessed 07 August 2023) at 11:47 (CET).
- [26] G.T. Trasporti, Parco veicoli schede tecniche, 2021, URL https://www.gtt.it/cms/risorse/gruppo/veicoli/parco_veicoli_tpl.pdf.
- [27] alVolante.it, Vi spieghiamo le nostre prove, 2019, URL https://www.alvolante.it/da_sapere/le-prove-di-alvolante-come-si-svolgono-365596.
- [28] L. Ntziachristos, Z. Samaras, K. Kouridis, C. Samaras, D. Hassel, G. Mellios, I. McCrae, J. Hickman, K.-H. Zierock, M. Keller, M. Rexeis, M. Andre, M. Winther, N. Pastramas, N. Gorissen, P. Boulter, P. Katsis, R. Jourard, R. Rijkeboer, S. Geivanidis, S. Hausberger, EMEP/EEA air pollutant emission inventory guidebook 2019 - update oct. 2020, 2021, URL <https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view>.
- [29] URL <https://www.newsauto.it/notizie/auto-ibride-piu-vendute-dati-classifica-2021-295786/#foto-4>.
- [30] URL <https://www.newsauto.it/notizie/auto-ibride-piu-vendute-2021-classifica-2022-346759>.
- [31] URL <https://www.newsauto.it/notizie/mercato/auto-ibride-piu-vendute-2022-397068>.
- [32] Electric Vehicle Database. URL <https://ev-database.org/>.
- [33] URL <https://www.moto.it/prove>.
- [34] A. Dutto, Analisi dei dati di consumo ai fini della diagnosi energetica del "sito virtuale" di GTT, 2019, URL <https://webthesis.biblio.polito.it/12976/1/tesi.pdf>.
- [35] M. Weiss, K.C. Cloos, E. Helmers, Energy efficiency trade-offs in small to large electric vehicles, *Environ. Sci. Eur.* 32 (1) (2020) <http://dx.doi.org/10.1186/s12302-020-00307-8>.
- [36] L. Davis, Body Physics: Motion to Metabolism, Open Oregon Educational Resources, 2020, URL <https://openoregon.pressbooks.pub/bodyphysics/>.
- [37] S. Gribble, Cycling power and speed, 2023, URL https://www.gribble.org/cycling/power_v_speed.html. (Accessed 05 August 2023) at 17:13 (CET).
- [38] B. Szyk, Ł. Zaborowska, Cycling wattage calculator, 2023, URL <https://www.omnicalculator.com/sports/cycling-wattage>. (Accessed 05 August 2023) at 17:03 (CET).
- [39] W.M. Bertucci, S. Rogier, R.F. Reiser, Evaluation of aerodynamic and rolling resistances in mountain-bike field conditions, *J. Sports Sci.* 31 (14) (2013-10) 1606–1613, <http://dx.doi.org/10.1080/02640414.2013.792945>.

- [40] D. Meyer, G. Kloss, V. Senner, What is slowing me down? Estimation of rolling resistances during cycling, *Procedia Eng.* 147 (2016) 526–531, <http://dx.doi.org/10.1016/j.proeng.2016.06.232>.
- [41] G. Ettema, H.W. Loràs, Efficiency in cycling: A review, *Eur. J. Appl. Physiol.* 106 (1) (2009) 1–14, <http://dx.doi.org/10.1007/s00421-009-1008-7>.
- [42] R. Edwards, J.-F. Larivé, D. Rikeard, W. Weindorf, Well-To-Tank Report Version 4.1: JEC Well-To-Wheels Analysis, Publications Office of the European Union, 2014, <http://dx.doi.org/10.2790/95629>, URL <https://publications.jrc.ec.europa.eu/repository/handle/JRC85326>.
- [43] L. Aleksandrowicz, R. Green, E.J.M. Joy, P. Smith, A. Haines, The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review, in: A.S. Wiley (Ed.), *PLoS One* 11 (11) (2016) e0165797, <http://dx.doi.org/10.1371/journal.pone.0165797>.
- [44] D. Tilman, M. Clark, Global diets link environmental sustainability and human health, *Nature* 515 (7528) (2014) 518–522, <http://dx.doi.org/10.1038/nature13959>.
- [45] A. Caputo, Efficiency and Decarbonization Indicators in Italy and in the Biggest European Countries. Edition 2023, Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), 2023, URL <https://www.isprambiente.gov.it/files2023/pubblicazioni/rapporti/r386-2023.pdf>.
- [46] AIB, European residual mixes, 2023, URL https://www.aib-net.org/sites/default/files/assets/facts/residual-mix/2022/AIB_2022_Residual_Mix_Results_.pdf.
- [47] ISTAT, Popolazione residente al 1° gennaio, 2023, URL http://dati.istat.it/Index.aspx?DataSetCode=DCIS_POPRES1.
- [48] Osservatorio demografico territoriale del Piemonte, Regioni - popolazione per età, 2024, URL <https://www.demos.piemonte.it/regioni-a-confronto/regioni-popolazione-per-eta>.
- [49] Il Messaggero, Sale l'età media dei lavoratori, ma i giovani guadagnano sempre meno, 2023, URL https://www.ilmessaggero.it/economia/news/sale_eta_media_lavoratori_giovani_guadagnano_sempre_meno-7387516.html.
- [50] F. Del Pero, M. Delogu, M. Pierini, Life cycle assessment in the automotive sector: A comparative case study of internal combustion engine (ICE) and electric car, *Procedia Struct. Integr.* 12 (2018) 521–537, <http://dx.doi.org/10.1016/j.prostr.2018.11.066>.
- [51] A. Di Gesù, C. Gastaldi, E. Brusa, C. Delprete, Progettazione circolare di un velomobile - LCA della fase di produzione di un veicolo esistente quale riferimento progettuale, in: *Atti Del 53° Conv. Naz. AIAS, AIAS*, 2024, URL <https://hdl.handle.net/11583/2996219>.
- [52] M. Mashayekh, Using lifecycle analysis (LCA) towards environmental and human health footprints of electrically assisted velomobile, *PODBIKE*, 2020, URL <https://hdl.handle.net/11250/2678611>.