



From Food to Foot: the Energy and Carbon Flows of the Human Body at Walking and Cycling

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Abstract

The carbon footprint of motorized transport modes per unit of travel length encompasses the unit share of the vehicle lifetime emissions, that of the transport infrastructure and those of the motor energy, considered from both “well to tank” and “tank to wheel”. In the active modes of transport, i.e. Walking and Cycling, the counterpart of motor energy is human energy. It comes with two kinds of carbon flows: the carbon footprint of food intake – which we call the Food to Body component – and the carbon dioxide emissions of respiration – say the Body to Foot component. The article provides a model in simple mathematical form to assess those carbon flows per unit length. It involves the modal speed in (i) the Metabolic Equivalent of the Task which gives rise to the energy and carbon flows, and (ii) the ratio of time spent to length travelled. The carbon footprint of food intake varies widely depending on the person food diet. In a numerical study, the Food to Foot carbon emissions of Walking, Cycling, e-scooter riding and car driving are estimated and compared to the rest of modal carbon footprint. Under average food diet as of France in the 2010s, the inclusion of F2F in modal footprints changes the ranking of the modes according to the carbon footprint per unit length.

Keywords

Carbon footprint; Human metabolism; Locomotion task; Transport mode; Modal speed; Respiration; Food intake; Food diet; Electric vehicles

1/ Introduction

Background. The substantiated evidence of global warming has prompted public authorities, local as well as national, to foster the reduction of greenhouse gas emissions (the so-called “decarbonization”) in all sectors of human activity, including manufacturing and building, energy production and food production etc. (IPCC, 2018). The transport of people and goods is a prominent target since it mostly involves oil-fuelled vehicles, especially cars and trucks. Policies for transport decarbonization include not only the adoption of electric vehicles, but also the development of car sharing under a variety of forms and modal shift from solo car usage to alternative modes: the bus or the train to achieve scale economies in energy expenditure, or the “active” modes of walking and cycling which apparently involve no energy consumption – or little so in the case of e-bikes.

The efficiency of a transport mode regarding carbon emissions (enlarged to all kinds of greenhouse gases) is measured as the ratio between the equivalent carbon emissions and the lengths travelled by the carried units: typically in gCO₂e per p.km for persons (p) or in gCO₂eptkm for goods (t for tons) (IPCC, 2006). The energy expenditure of locomotion induces carbon emissions “from tank to wheel” (T2W) specific to the vehicle and its energy vector and also those “from well to tank” (W2T) in the production of that energy (e.g. Prussi et al. 2020). Further lifecycle considerations pertain to the constructive phases in the vehicle life (manufacturing, distribution, maintenance, end-of-life) amortized over its technical course (e.g. 200,000 km for a car) and divided by the vehicle average

number of occupants. Similar considerations apply to electric batteries and also to the utilized infrastructure, of which the constructive “carbon debt” is amortized over time and the passage of all kinds of vehicles.

From recent studies applying Life Cycle Analysis to transport modes (Chester & Horvath, 2009, De Bortoli, 2021), the carbon efficiency of modal transport typically ranges from 100 to 300 gCO₂eppkm for oil cars, from 30 to 80 for electric cars, from 5 to 30 for electric trains and metros and also for electrically assisted two-wheelers (e-bikes and e-scooters, excluding the carbon footprint of charging logistics), but amount only to 1 or almost zero for walking and a couple of gCO₂eppkm for cycling. It would thus appear that human-powered locomotion would be almost carbon free. But there is no such miracle. Human locomotion entails heightened metabolism of the human body. The additional metabolic activity comes along with carbon emissions of two kinds: those of respiration and the carbon footprint of the food that fuels the body. In analogy to T2W and W2T, let us call the former kind as Body to Foot (B2F) and the latter kind as Food to Body (F2B). Mizdrak et al. (2020) estimated the F2B carbon footprint of walking and cycling under a variety of food diets and according to different levels of country economic development: their outcomes range from 50 to 260 gCO₂eppkm for walking and half those values for cycling. As for B2F, the carbon emissions of human respiration generated by cycling at moderate speeds (15km/h) were estimated at about xx gCO₂eppkm by Walsh (2008). While the B2F carbon impact appears smaller than the F2B carbon impact by one order of magnitude, it is still comparable with the rest of carbon emissions for cycling or greater than it by one order of magnitude for walking.

Objective. This article presents an integrated model of the energy flows and carbon footprints associated to the human body on performing physical activities, with special emphasis on walking and cycling. It brings together the F2B and B2F sides of the body-centric flows, thereby constituting an F2F chain (from Food to Foot) mirroring the W2W chain (from Well to Wheel) of motorized vehicles. The objective is twofold: we shall state the model in (simple) mathematical formulas to make it easy to understand and discuss, and we shall provide some ratios and indicator values for the F2F carbon footprints of walking, cycling and also car driving or just riding.

The remainder of the article is in two parts. The first part brings about the flow model: the metabolic activity is quantified depending on the task, generating B2F and F2B flows, and in turn carbon efficiency per unit length according to the modal speed. In the second part, per transport mode the F2F carbon emissions are integrated in the modal carbon footprint, and the resulting overall carbon impact is used to compare different transport modes.

2/ Human metabolism, F2F flows and modal conditions

2.1/ MET as a unit energy flow

In biology, the metabolism of a living being encompasses the biochemical reactions taking place in its body, thereby producing specific substances and releasing energy. The “basal metabolism” is the amount of energy released by the being at rest per time unit: thus it is an energy flow. Any physiological activity of the being gives rise to a specific metabolic activity that can be measured in the equivalent number of basal metabolisms. To make things comparable between different life stages of the being as well as between different beings in a given species, the basal metabolism is normalized per unit of mass. For human beings, one “Metabolic Equivalent of Task” (MET)

corresponds to sitting at rest: it is measured by the following energy flow per mass unit (Walsh, 2008):

$$1 \text{ MET} = 4.18 \frac{\text{kJ}}{\text{kg} \cdot \text{h}} \quad (1)$$

2.2/ Metabolic intensity per task

In medicine and specifically sport medicine, the energy released by humans involved in specific physical tasks is measured as an equivalent amount of MET. For instance, car driving is estimated at 2 MET. A locomotion task μ such as walking or cycling gives rise to a specific number of MET, say x_μ , that increases with the intensity of the effort, which also determines the resulting speed. Other factors are involved, such as ground conditions (slope, pavement quality) and also bike conditions for cycling (e.g. the type and inflation of tires, presence or absence of electric assistance, additional load such as some freight in a cargo bike).

We shall rely upon the “Compendium of Physical Activities” (Ainsworth et al., 1993, 2000, 2011), in short The Compendium, as a well-established source of numerical values for the METs of diverse kinds of human activities. Based on the Compendium, Figure 1 illustrates the intensities x_μ associated to walking and cycling according to speed, assuming flat and even ground and no carriage by the person.

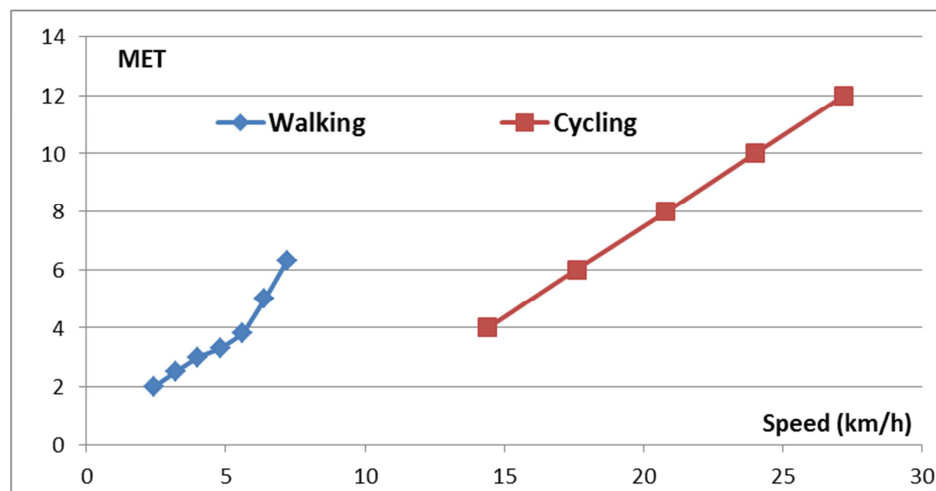


Fig. 1. Modal MET according to Speed. Data from Ainsworth et al (2000).

2.3/ Human respiration and B2F carbon emissions

The metabolic activity of any being involves the intake of oxygen O₂, its usage in oxidation reactions that release energy and its chemical combination yielding carbon dioxide CO₂. In biology, “respiration” is defined as the full biochemical process. In common language, respiration is the cyclic activity involving the intake of oxygen (inspiration) and the release of carbon dioxide (expiration) as the two successive phases in every cycle.

For human beings, per MET the corresponding gas flows are (Walsh, 2008):

Inflow of oxygen: $3.5 \frac{\text{ml}}{\text{kg.min}}$ hence $.21 \frac{\text{l}}{\text{kg.h}}$,

Outflow of carbon dioxide: $2.95 \frac{\text{ml}}{\text{kg.min}}$ hence $.16 \frac{\text{l}}{\text{kg.h}}$.

By assimilating carbon dioxide to a perfect gas, under standard conditions of pressure and temperature one mole of that gas (weighing 44 g) occupies a volume of 22.4 liters, so that 1 liter weighs about 1.96 g. Then the CO₂ mass outflow of one MET amounts to:

$$\theta_{\text{B2F}} = .31 \frac{\text{gCO}_2}{\text{kg.h}} \quad (2)$$

We call “Body to Foot” that kind of emissions because it comes from one’s body on using one’s feet.

Let us consider a locomotion task involving the individual’s feet, for instance walking or cycling. After subtracting one MET for the resting basal body metabolism the specific metabolic activity amounts to $x_\mu - 1$ MET.

Denoting as M the body mass in kg, the respiration specific to the locomotion task generates the specific carbon emission as follows:

$$C_{\text{B2F}}^{(\mu)} = M \cdot \theta_{\text{B2F}} \cdot (x_\mu - 1) \quad \text{in} \quad \frac{\text{gCO}_2\text{e}}{\text{h}} \quad (3)$$

2.4/ Food intake and F2B carbon emissions

We shall postulate here that the energy expenditure of a human being on performing a specific task is compensated by a food intake of proportional energy, up to some compensatory ratio say ρ . We may expect the ratio to be about 1 meaning energy flow balance between task expenditure and food intake, at least in developing countries where food is less abundant than in developed ones. From a cohort study in the UK (Martin et al., 2013), Mizrak et al. (2020) derived a long term ratio ρ ranging from 19% to 96% around an average value of 57%. Also for developed countries, a meta-analysis of laboratory studies carried out by Schubert et al. (2015) showed that such compensation does not occur in the immediate hours after physical exercise. We shall thus consider a compensatory ratio ρ ranging from .2 to 1.0.

The energy content of food diets is measured in kilo calories (kcal): 1 kcal amounts to 4.18 kJ i.e. to 1.17 W.h, or equivalently 1 W.h amounts to .83 kcal. Thus 1 MET amounts to 1.0 kcal/kg.h. As for the carbon emissions of food intake, the GHG emissions of food production are assessed using lifecycle analysis. On average in Europe the carbon footprint of food energy amounts to 1.4 gCO₂e/kcal. In France, the average ratio amounts to 1.9 but individual values range from .5 (vegetarian diet) to 5 (ruminant meat diet). We shall denote σ the carbon footprint of food production, in gCO₂e/kcal.

Let us then define the Food to Body carbon emission rate of one MET as follows:

$$\theta_{\text{F2B}} = 1.0 \rho \sigma \quad \text{in} \quad \frac{\text{gCO}_2\text{e}}{\text{kg.h}} \quad (4)$$

We call it “Food to Body” in a natural and obvious way, as it comes from food and is stored in the body which will output it. From the respective ranges of ρ and σ , the $\rho \cdot \sigma$ product will range from .1 to 5, with average value at .91 gCO₂e/kg.h as of France in the 2010s.

Then, for a person of mass M the food intake associated to a task μ of x_μ MET induces an F2B carbon footprint of

$$C_{F2B}^{(\mu)} = M \cdot \theta_{F2B} \cdot (x_\mu - 1) \quad \text{in} \quad \frac{\text{gCO}_2\text{e}}{\text{h}} \quad (5)$$

2.5/ From Food to Foot: integrated model

We are now able to combine the specific F2B and B2F carbon emissions of any locomotion task μ . The respective coefficients add up and yield an overall coefficient of

$$\theta_{F2F} = \theta_{F2B} + \theta_{B2F} \quad (6)$$

The .31 value of θ_{B2F} constitutes about 35% of the average value of θ_{F2B} , .91. However the .31 value is given, whereas θ_{B2F} has a large range of variations: θ_{B2F} is about 4 times greater than the minimum value of $\rho \cdot \sigma$. The combined rate θ_{F2F} ranges from .4 to 5.4 gCO₂e/kg.h with average at 1.3 gCO₂e/kg.h in France.

For a person of mass M , a locomotion task μ of x_μ MET induces an F2F carbon footprint of

$$C_{F2F}^{(\mu)} = M \cdot \theta_{F2F} \cdot (x_\mu - 1) \quad \text{in} \quad \frac{\text{gCO}_2\text{e}}{\text{h}} \quad (7)$$

2.6/ Food to Foot carbon emissions per unit length

Using transport mode μ , the persons avail themselves of travel speed say v_μ . One unit of travelled length requires a travel time of $1/v_\mu$, which is the time length of the locomotion task. Thus, per unit length the carbon footprint of the locomotion task amounts to

$$I_{F2F}^{(\mu)} = \frac{C_{F2F}^{(\mu)}}{v_\mu} \quad (8)$$

Under v_μ in km/h, the detailed formula is

$$I_{F2F}^{(\mu)} = M \cdot \theta_{F2F} \frac{x_\mu - 1}{v_\mu} \quad \text{in} \quad \frac{\text{gCO}_2\text{e}}{\text{km}} \quad (9)$$

Figure 2 depicts the mass-proportional coefficients of the walking and cycling modes depending on the travel speed. Median values of .5 MET.h/km for Walking and .3 MET.h/km for Cycling are fairly representative. For a 70 kg person, the modal footprints amount to 35 gCO₂e/km for Walking (average in range from 12 to 100) and 18 gCO₂e/km for Cycling (average in range from 6 to 50).

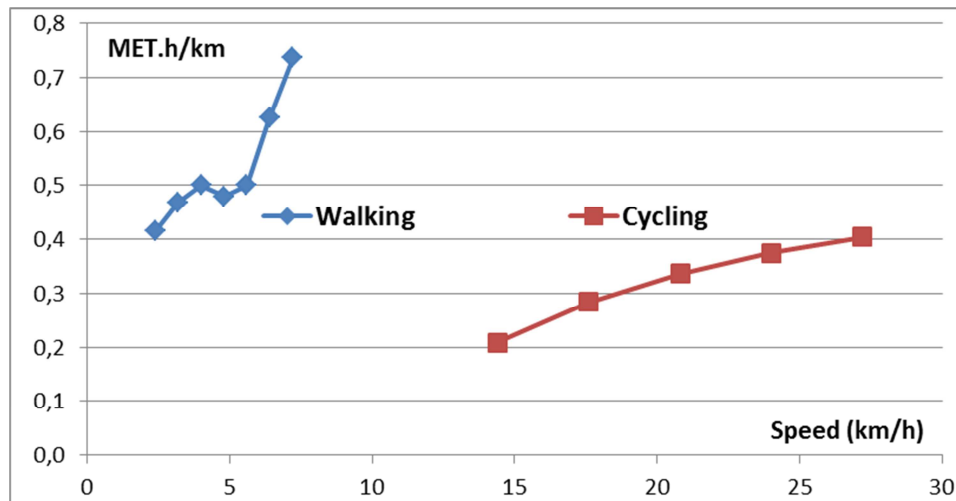


Fig. 2. Modal (MET-1)/Speed according to Speed. Source: author's calculation based on data from Ainsworth et al (2000).

3/ F2F in the carbon footprint of transport modes

Let us now integrate the F2F emissions in the overall carbon footprint of transport modes. We shall consider first Walking, then Cycling which is a mechanized mode, next a pair of motorized modes, namely e-scooters and cars. Per mode, aside from stating the F2F carbon impact we shall estimate the other components of the carbon footprint by recalling their main parameters.

3.1/ Walking

The Walking MET increases from 2 to more than 6 as the travel speed goes from 2.5 to 8 km/h, in a superlinear way (see figure 1). The task factor $(x - 1)/v$ varies from .4 to .75 MET.h/km in three stages: it increases slowly for moderate speeds up to 4 km/h, then it is fairly stable around .5 from 4 to 6 km/h, beyond which it increases again and in a steeper way (see figure 2).

For a 70 kg person, the F2F impact of Walking amounts to about 45 gCO₂e/km under average French food diet. It ranges from 20 to 90 when the $\rho \cdot \sigma$ product goes from .2 to 1.

All of these values are far greater than the carbon footprint of (1) shoes and (2) road infrastructure. A pair of shoes has a carbon footprint in the 3-30 kgCO₂e range (Olivetti et al. 2012; TheCarbonFact, 2021). To be fair, shoes have two functions: they are used not only for walking or running but also to dress the feet. Thus their carbon footprint should be divided in two parts, say halves, one for each function. The walking half of footprint amortizes over the life course of say 1000 km: then the range 1.5 – 15 kgCO₂e gives rise to a range of 1.5 – 15 gCO₂e/km, with average value of 8 gCO₂e/km. It is one order of magnitude lower than the F2F component. Furthermore, walking uses the roadway infrastructure. While a well-known convention is to amortize the roadway carbon debt over cars and heavy vehicles only, a fairer convention is to extend the basis to all road functions and to divide the component for people transport among all users be they on foot, riding or driving their cars. Consequently, the carbon footprint of infrastructure usage amounts to 1 or 2 gCO₂e/km – indeed a very minor part (Leurent & Prié, 2021).

To sum up, the F2F component is by far the essential contributor to the carbon footprint of the Walking mode. The shoes component contributes a minor part and the infrastructure component a very minor part. Assuming an average French food diet and an average carbon content of 14 kg CO₂e for the pair of shoes, the integrated carbon footprint of Walking amounts to 55 gCO₂e/km.

3.2/ Cycling

Here we consider a fully human powered bike with no electric assistance. The Cycling MET increases from 4 to 12 as the travel speed goes from 15 to 27 km/h, i.e. from moderate to very high for plain people. The task factor $(x - 1)/v$ varies from .2 to .4 MET.h/km in a smooth, concave way.

For a 70 kg person, the F2F impact of Cycling amounts to about 28 gCO₂e/km under average French food diet. It ranges from 12 to 100 when the $\rho \cdot \sigma$ product goes from .2 to 1. The infrastructure component amounts to 1 or 2 gCO₂e/km – same as for Walking, for the same reasons.

As for the bike per se, LCA studies evidence a carbon footprint of about 5 gCO₂e/km – e.g. a 15 kg bike made mostly of steel at about 6 kgCO₂e per kg and amortized over a life course of 20,000km (Ademe, 2016).

To sum up, the F2F component under average French food diet dominates the vehicle component by one order of magnitude and the infrastructure component by two orders of magnitude. Under these reference conditions the integrated carbon footprint of Cycling amounts to 35 gCO₂e/km.

3.3/ Motorized modes at driving or riding

The car driving task is reported at 2 MET in the Compendium: even if the driver is seated and does not contribute human power to the locomotion, the task requires twice the human energy of just resting. We may assimilate the task of riding an e-scooter to that of driving a car: even if the rider is standing, the length of travel is generally short so that most of the effort pertains to driving the vehicle. It remains to take speed into account. In dense urban environments e-scooters at say 15 km/h will be competitive with the cars. Keeping to this speed value the task factor $(x - 1)/v$ is about .07 – i.e. far lower than for Cycling and Walking. In interurban settings with average car travel speed reaching 70 or 100 km/h, the factor falls down to .02 or .01. For a 70 kg person, the F2F of car driving or e-scooter riding in urban conditions is about 6 gCO₂e/km under average French diet; it ranges from 3 to 25 with respect to the $\rho \cdot \sigma$ product. CHECK

Car passengers as well as seated bus passengers can be considered to travel at one MET only, i.e. their riding task is equivalent to resting. This is confirmed in the Compendium. Then for them the F2F component is null.

The road infrastructure component is the same for drivers, riders and other modal users, at 1-2 gCO₂e/km.

We still have to take the vehicle and the usage energy into consideration. As for an e-scooter, its body is quite comparable to that of a bike: about 15 kg mostly steel, with expected life course of 20,000 km, yielding carbon footprint of about 5 gCO₂e/km. An electric battery with nominal energy capacity of .5 kWh, assumedly made in China at 120 kgCO₂e/kWh and sufficiently recyclable to obtain a credit of 55 kgCO₂e/kWh (French convention), amortized over 20,000 km, yields an additional 1.5 gCO₂e/km. This makes the vehicle and battery combo roughly equivalent to the F2F

emissions under reference food diet. The motion energy at 14 W.h/km times 300 gCO₂e/kWh out of the European grid induces a specific carbon footprint of 4 gCO₂e/km – or 1 gCO₂e/km only in France which is endowed with a low carbon electricity mix. All in all, the e-scooter modal carbon footprint is about 15-18 gCO₂eppkm.

For e-cars the considerations are analogous but the vehicle mass is much larger (by a factor 100 for a 1.5 t car) and the life course is much longer, say 200,000 km. Furthermore there may be several occupants in the car, say 1.5 as a rough average (1.2 for small cars vs. 1.7 for large cars in France). As for the carbon footprint of the constructive phases in the car lifetime (manufacturing, maintenance, end-of-life), it is about 5 kgCO₂e per kg of vehicle mass if it is made in Europe. The resulting carbon footprint per unit length amounts to 25 gCO₂eppkm. As a forward looking scenario, let us imagine an EV fully made in France: then, owing to the low carb electricity mix in that country, the carbon footprint of the vehicle constructive phases would reduce to 2 kg CO₂e per kg of vehicle mass (Leurent and Prié, 2021, based on results from Ellingsen et al. 2016). Thus the vehicle carbon footprint per unit length would reduce to 10 g CO₂e/p.km.

An electric battery of 50 kWh capacity would suffice over the life course, yielding an additional 12 gCO₂eppkm. At .2 kWh/km and 300 gCO₂e/kWh out of the European grid, the motion energy adds 60 gCO₂e/veh.km hence 40 gCO₂eppkm. Out of the French grid it is reduced to 10 gCO₂e/veh.km and to 7 gCO₂eppkm. Then, an EV both made and used in France (resp. in Europe) would have an overall carbon footprint of 29 gCO₂eppkm (resp. 91), whereas an EV made in Europe and used in France entails 44 gCO₂eppkm.

A diesel car consuming 8 l/100km of diesel at 3.5 kgCO₂e/l emits 280 gCO₂e/veh.km hence 186 gCO₂eppkm, yielding an overall vehicle footprint of 215 gCO₂eppkm.

Driving an EV in France (resp. Europe) in dense urban conditions thus generates a carbon footprint of 52 gCO₂eppkm (resp. 99), versus 223 gCO₂eppkm for a diesel car. In the EV case the F2F contribution is minor, yet it is equivalent to the electricity carbon footprint in France. For diesel cars the F2F component is very minor.

3.4/ Multimodal comparison

After comparing the components of carbon impacts for four transport modes, let us now compare them regarding their overall carbon impacts. We shall consider several versions of each transport mode, depending on their speed regime (active modes), on the carbon intensity of food production and that of energy production (motorized modes). Figure 3 depicts the arborescence of the notional transport modes under consideration.

Figure 4 depicts the level and composition of modal carbon footprints per unit length for all modal versions.

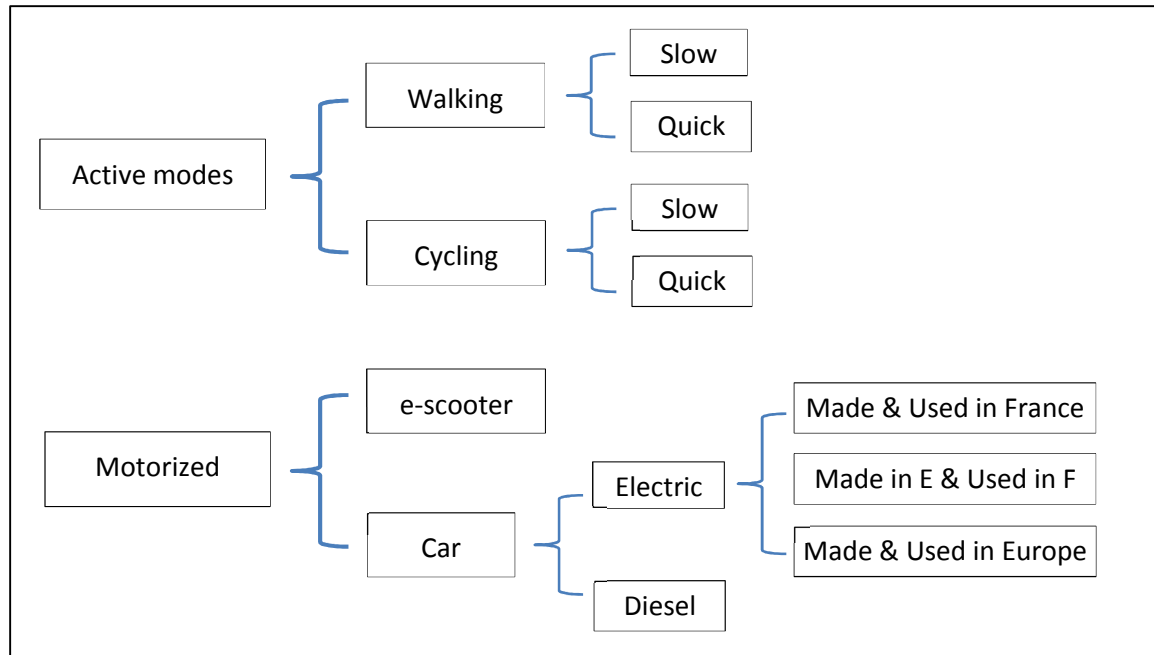


Fig. 3. Arborescence of transport modes under consideration. Source: author.

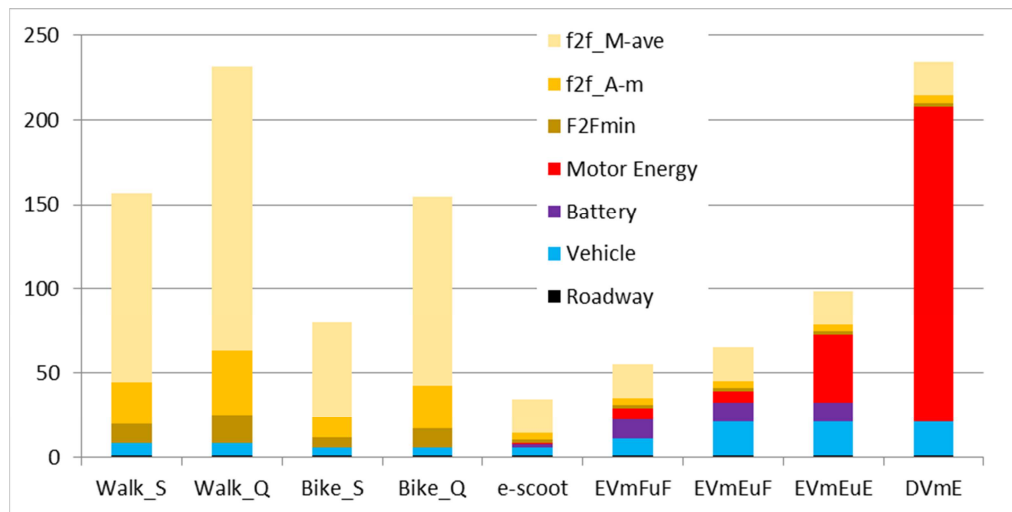


Fig. 4. Level and composition of modal carbon footprints per unit length. Source: author.

To highlight the influence of the F2F component, let us rank the modal versions according to the carbon impact in two ways, respectively excluding or including the F2F component. Neglecting the F2F component, the three modes of micromobility have similar low carbon footprint at about 7 or 8 gCO₂eppkm. Walking does not stand alone since it is burdened by the carbon debt of the shoes. Within the car options, the carbon footprint of EVs changes from simple to double depending on the carbon content of the electricity mix. Diesel cars are by far the most emissive modes, owing to first the carbon intensity of their fuel and then to the vehicle construction. (The consideration of biofuels would divide the fuel impact by 3 or 4 by reducing it to the W2T component.)

Including F2F alters the ranking significantly. Under French average diet, Cycling at moderate speed becomes the least emissive mode, followed by e-scooters, then by Walking and Fast Cycling. EVs both used and made in a country with low carbon electricity mix would come next, before fast

Walking. EVs using low carbon electricity but made with medium carb conditions (European mix) are close to Fast walking.

Of course a low carb food diet would restore the ranking excluding F2F. Under high carb food diet, active modes would become high emitting modes, at much higher levels than e-scooters and EVs fed with low carb electricity.

4/ Conclusion and discussion

The article introduced a carbon footprint model of transport modes that integrates human-centred energy and carbon flows on two sides: respiration (taken as Body to Foot) and food intake (i.e. Food to Body). The associated B2F and F2B components mirror the Tank to Wheel and the Well to Tank components of energy flows for motor vehicles. We devised simple mathematical formulas to model the influence of modal speed on the metabolic equivalent of task and the carbon footprint per unit length.

It comes out that the carbon footprint of food intake is a major determinant of the carbon efficiency of active modes. Under average food diet as of France in the 2010s, the F2F component is about three times greater than the F2B amount. The F2F emissions of walking were found to vary from 50 to 76 gCO₂eppkm depending on speed low to quick. The emissions of cycling are about half those of walking, as pointed out by Mizrak et al. (2020) for the B2F component only.

By including the F2F emissions in the modal carbon footprint, and also taking into account the carbon debt of shoes in the Walking footprint, it comes out that the mechanized modes of micromobility: cycling and e-scooter riding are more carbon efficient than Walking. Furthermore, EVs both made and used in France would be competitive with Walking.

We made the numerical study explicit by stating both the parameter values and the emissions components of modal carbon footprints, including the vehicle mass, lifetime course and energy consumption rate, possibly the battery capacity, as well as the carbon intensities depending on the conditions of vehicle manufacturing and usage. It will then be easy to apply the model to different sets of assumptions.

Our study confirms that planning for low carb mobility systems has to rely upon a technical infrastructure involving the transport infrastructure together with the energy infrastructure and also with the food production infrastructure. Including the F2F component in the carbon footprint per unit length narrows down the gap between, on the one hand, active modes and, on the other hand, e-scooter riding or EV under low carb conditions of both manufacturing and usage. It also calls for complementary indicators in order to measure the carbon efficiency of mobility solutions and systems in a more comprehensive way: the system footprint involves not only the footprint per unit length but also the amount of travelled lengths. In the latter respect active modes may be expected to serve shorter lengths than motorized, painless, comfortable modes such as cars and larger vehicles.

Let us finally point to two directions of further research on F2F carbon emissions. The first one pertains to human respiration: after Walsh (2008) we attributed the specific carbon emissions of the locomotion task to the transport mode. But the involved carbon element comes from aliments: in

IPCC reports the carbon emissions of the respiration of cattle animals are not taken into account because the carbon element in it comes from plants that took it directly from the atmosphere, thereby compensating it in a circular economy perspective (IPCC, 2006). As for people, the rate of compensation deserves specific investigation. The second research direction is about the carbon footprint of human excreta other than respiration, depending of their collection mode and further treatment, possibly with some feedback on food production through field fertilization – again an issue of circular economy.

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