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Technical Note

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 length traveled encompasses the unit share of the vehicle lifetime emissions, that of the transport infrastructure, and those of the motor energy, considered both from "well to tank" and from "tank to wheel". In the active modes of transport, i.e., walking and cycling, the counterpart of motor energy is human energy, which is associated 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. In this article, we provide 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 (MET) which gives rise to the energy and carbon flows, and (ii) the ratio of time spent to length travelled. The two influences of speed onto a modal carbon footprint combine in the net MET per unit length, with some compensation. The carbon footprint of food intake varies widely depending on the food diet of individuals. In a numerical study, the Food to Foot carbon emission of walking, cycling, e-scooter riding, and driving a car are estimated and compared to the rest of modal carbon footprint. Under conditions typical of France in the 2010s based on the average food diet and low carbon intensity of electricity, 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; net MET per unit length; respiration; food intake; food diet; electric vehicles

1. Introduction

1.1 Background

Global warming has prompted local and national public authorities to promote the reduction of greenhouse gas emissions (also called "decarbonization") caused by all types of human activities, including manufacturing and building, energy production, food production, etc. [1]. The transport of people and goods is a prominent target since it mostly involves oil-fueled vehicles, especially cars and trucks [2]. The policies for transport decarbonization include not only the adoption of electric vehicles but also the sharing of cars under a variety of forms and modal shift from solo car usage to alternative modes [2]: 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 [3].

The efficiency of a mode of transport regarding carbon emissions (including all kinds of greenhouse gases) is measured as the ratio between the equivalent carbon emissions and the distance traveled by the carried units, typically in gCO_2e per person-km for individuals (gCO_2eppkm) or in gCO_2e per ton-km for goods (gCO_2eptkm) [4]. The energy expenditure of locomotion induces carbon emissions "from tank to wheel" (T2W) related to the vehicle and its energy vector and also those "from well to tank" (W2T) in the production of that energy [5]. Further lifecycle considerations pertain to the constructive phases in the vehicle lifecycle manufacturing, distribution, maintenance, and end-of-life) amortized over its technical course (e.g., 200,000 km for a car) and divided by the average number of occupants of that vehicle [6]. Similar considerations apply to electric batteries and also to the utilized infrastructure, of which the constructive "carbon debt" is amortized over time and the successive trips of multiple vehicles [7].

Recent studies that applied the Life Cycle Analysis (LCA) to transport modes [3, 6, 7] found that the carbon efficiency of modal transport typically ranges from 100 to 300 gCO_2eppkm for oil cars, from 30 to 80 for electric cars, from 5 to 30 for electric trains, metros, and electrically assisted two-wheelers (e-bikes and e-scooters, excluding the carbon footprint of charging logistics), but is only 0–1 gCO_2eppkm for walking and a few gCO_2eppkm for cycling. It would thus appear that human-powered locomotion would be almost carbon free [8, 9]. However, human locomotion entails heightened metabolism of the human body. Early works in ergometrics focused on the maximum distance that infantry soldiers could walk daily without causing unrecoverable fatigue [10], as well as, on the energy spent by individuals during cycling [11]. The additional metabolic activity is associated with two kinds of carbon emissions, including those of respiration [12, 13] and the carbon footprint of the food that fuels the body [14]. Drawing an analogy to T2W and W2T, we denote the former kind as Body to Foot (B2F) and the latter kind as Food to Body (F2B). The F2B carbon footprints of walking and cycling based on different types of food diets and different levels of economic development of a country were estimated to range from 50 to 260 gCO_2eppkm for walking and half those values for cycling [15]. For B2F, the carbon emission of human respiration during cycling at medium speeds (15 km/h) was estimated at 5 gCO_2eppkm [13]. While the B2F carbon impact is lesser than the F2B carbon impact by one order of magnitude, it is comparable to the rest of the carbon emission for cycling or greater than it by one order of magnitude for walking.

Thus, including the specific carbon emissions of human locomotion in carbon footprint and LCA studies for the mode of transport might be relevant. Some studies [13-17] have investigated the F2B part in specific ways that we will discuss later in this study.

1.2 Objective

This article presents an integrated model of energy flows and carbon footprints associated with the physical activities of humans involved in the usage of different modes of transport, with a special emphasis on walking and cycling. We included the F2B and B2F sides of the body-centric flows, thus constituting an F2F chain (from Food to Foot) mirroring the W2W chain (from Well to Wheel) of motor vehicles. The objective is twofold: (i) to state the model as (simple) mathematical formulae, making it easy to understand and discuss, and (ii) to provide some ratios and indicator values for the F2F carbon footprints of walking, cycling and also car driving or just riding.

The rest of the article is divided into three 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, for each mode of transport, the F2F carbon emissions are integrated in the modal carbon footprint, and the resulting overall carbon impact is used to compare different modes of transport. The last part provides a discussion and some conclusions.

2. Human Metabolism, F2F Flows, and Modal Conditions

Here, the objective is to state the carbon footprint of a locomotion task μ per unit length for an individual I_μ, as a mathematical function of the body mass M and modal speed v_μ. The function I_μ is built based on the following steps: first, we recall the quantitative scale of metabolic intensity (§2.1), then we model the metabolic intensity of task μ as a function X_μ that involves speed v_μ (§2.2), next we devise carbon emission factors per unit of metabolic intensity for the B2F side (§2.3) and the F2B side (§2.4), thus leading to the carbon footprint per time unit (§2.5) and in turn to the carbon footprint per unit length (§2.6). Each subsection is divided into two parts; in the first part, the principles are discussed, and in the second part, the parameter values are derived from data found in the literature.

2.1 Measuring Human Energy Expenditure

2.1.1 Principles

The metabolism of an organism encompasses the biochemical reactions that occur in its body, which leads to the production of specific substances and the release of energy [12, 18].

The "basal metabolism rate" (BMR) is the energy released by an organism at rest per unit of time; thus, it represents energy flow rate [18-20]. Generally, any physiological activity of an organism is related to a specific metabolic activity with the task-specific energy expenditure rate denoted $\mathrm{EER}(\mu, i)$ for a task μ accomplished by an individual i.

To allow comparisons between different life stages of the organism, as well as, between different organisms of the same species, the energy expenditure rates are normalized per unit of mass [21-23]. Denoting the body mass of individual i as M_i, the simplest model of BMR can be expressed as:

$$\mathrm{BMR}(i) = M_i . \mathrm{bmr}_1 \tag{1}$$

Here, bmr_1 indicates a reference value for all humans (or a specific group).

In turn, the EER of the task μ accomplished by an individual i is conventionally measured as a ratio of EER compared to BMR, relative to mass [18, 22]:

$$x_\mu \equiv \frac{\mathrm{EER}(\mu, i)}{\mathrm{BMR}(i)} = \frac{\mathrm{EER}(\mu, i)}{M_i . \mathrm{bmr}_1} \tag{2}$$

This ratio is called the Metabolic Equivalent of Task (MET) or the Performance Activity Ratio [24]. Energy expenditure is also called Energy cost [25-27].

Assuming that all individual factors are conveyed by the body mass, the MET is task-specific and does not depend on the individual.

2.1.2 Reference Values

The unit value bmr_1 (of human BMR per body mass unit) is conventionally set up [22]:

$$\mathrm{bmr}_1 \equiv 4.18\ \mathrm{kJ.kg^{-1}.h^{-1}} \tag{3}$$

This convention is equivalent to 1 kcal/h/kg and an oxygen inflow of 3.5 mL/min/kg in an individual [21, 25]. The basic method to measure energy expenditure is an indirect one, based on the measurement of respiration gas flows. Experimental conditions from the 19th century to the 1920s consisted of exercising in "respiration chambers" [21, 28]. In the 1930s, portable "respirometers" were developed, including the "Douglas bag" and the Kofranyi-Michalis respirometer devised at the Max Planck Institute [25, 29]. Specific ISO standards were established to measure body activity (third release as of December 2021 [30]).

Many of the early studies only included young men performing military duties or male workers engaged in specific heavy duties [10, 21]. Even under such age and gender conditions, considerable variations between individuals were observed, for body mass and height, as both factors together determine the body surface area and the related heat flow [21, 31]. Subsequent measurements included women, children, and elderly people, exhibiting even larger variation across a general population [32]. Since specific outcomes are associated with obesity, a distinction is necessary between body mass and "lean body mass" (i.e., the body mass after subtracting the mass of fat) [18].

Large inter-individual variations and intra-individual variations, depending on age, must be considered on establishing formulae for the BMR of an individual. The Harris-Benedict formula, published in 1918, related the BMR to body mass M, height, and age, for men on one hand and for women on the other hand [21, 33]. The parameters were revised in 1984 [34]. The more recent model of Mifflin - St Jeor (1990) has a 5% higher accuracy [31]. The Katch-McArdle-Cunningham formula links the resting daily energy expenditure to the lean body mass only [18].

2.2 Modes of Transport and Their Specific METs

2.2.1 On Physical Activities in the Modes of Transport (Based on [35–39])

A mode of transport is a threefold technique to move people or goods and includes a vehicle, a related infrastructure, and the usage protocol. For ground transport, there are two main kinds of infrastructure, namely railway and roadway (which accommodates the larger part of usages). Railway modes include the train, the metro and the tram. Roadway modes are more diverse, including walking, bicycling, riding a scooter or a motorbike, driving a car or riding it as a passenger, and riding a bus or a coach.

A non-motorized mode of transport is human-powered (or sometimes powered by animals, e.g., riding a horse). Therefore, its usage involves an expenditure of energy stored in the body that is determined by the laws of dynamics. It is influenced by the mass, speed (as the time integral of acceleration), the conditions of slope and curvature, and the ground type (from hard pavement to soft snow or sand). Compared to other types of ground, roadways and railways as ground infrastructures make transport on wheels more energy-efficient than walking, relative to total mass including that of the vehicles and those of its occupants.

Walking and riding a kick scooter involve standing, which requires more effort than sitting. Standing might also apply to bus or train passengers who do not get a seat. Dynamic changes in curvature and slope require more effort than straight and level trajectory, leading to some differences between bus and train rides.

Driving a vehicle requires further effort to monitor the driving environment and control the vehicle trajectory; there is a difference in the effort between driving a car and riding it, between driving a truck and a car. Riding a bike, scooter, or motorbike involves driving them in the vast majority of trips, since these are basically individual modes.

On using a human-powered mode, the carriage of some load e.g. a luggage involves further physical effort [40]. Conversely, cars and larger vehicles not only carry the users and their load but also provide shelter to their occupants, possibly with temperature control that can keep the BMR at moderate levels.

To summarize, the energy expenditure on using a mode of transport depends on the specific mode as a technique, on the usage condition as a driver or passenger, and the dynamic and environmental conditions. Human-powered modes of transport (and partially electrically-assisted modes, such as e-bikes) involve specific energy expenditure that increases with speed. This relationship can be denoted as a mathematical function X_μ linking MET x_μ to speed v_μ of task μ as follows:

$$x_\mu = \mathrm{X}_\mu(v_\mu) \tag{4}$$

2.2.2 The METs of the Modes of Transport: Literature Review

The measurement of energy expenditure by humans has gone from fundamental research in biology in the 19th century (notably to establish the influences of body weight and body surface, see the historical notes in [21]) to an applied issue in the fields of Nutrition [32], Industrial health [27], Physical exercise [18], Sports Medicine [41], and Clinical cardiology [22].

Tables of METs (or of some equivalent measure) have been published in several research monographs [18, 21, 32] and academic articles [10, 22, 25-27, 42]. Many early studies on different kinds of activities, including walking at different paces, were conducted at the Nutrition Laboratory of the Carnegie Institution in Washington [21, 43]. In 1955, Passmore & Durnin [25] compiled outcomes of many previous studies, motivated by the availability of portable respirometers and the technological changes in industrial tasks owing to the rise of automation. They primarily studied walking on level ground, uphill, and downhill (details in Figure 1 and Table 2 of the original article). They proposed a linear regression linking Walking MET to speed as follows: $x_\mu = 0.44 + 0.71v$, where v (km/h) ranged from 3 to 6.5 (after converting kcal/min to METs for a 68 kg subject). Bicycling was also addressed based on previous studies; the use of large tires was found to add about one MET to riding [44]. Driving tasks for cars and trucks were reported at about 2.2 as MET, compared to sitting at 1.0 or standing at 1.7.

Similar tables were provided in a classical textbook on exercise physiology [18], which has been updated several times, and another study [22]. Durnin’s review [32] is primarily oriented to nutritional requirements and their variations across the health conditions of individuals. A study [26] compiled measurements from different developing countries, mainly concerning agricultural and farming tasks. The FAO and the WHO developed reference manuals regarding energy expenditure and energy requirements [45] and emphasized that walking is the basic way to exercise the human body and maintain good health [46].

The issue of cardiovascular health prompted more empirical studies on Walking METs, leading to the construction of quadratic or hyperbolic regression models of the relationship between Walking MET and speed [47-49]. A parallel research stream has dealt with the development of biomechanical models and their application to different walking situations [40, 49, 50]. A similar stream has been prevalent to determine the energy spent during bicycling, starting from the invention of early “cycle ergometers”, i.e., dynamometers by Elysée Bouny in 1894 [51], followed by the application of mechanical models [52].

For compiling the MET data on different kinds of general physical activities, the “Compendium of physical activities” was issued in 1993 [53], with updates and extensions in 2000 [54] and 2011 [55]. The Compendium introduced a five-digit classification of activity types – the first two digits indicate the category ranked by alphabetical order in English. Thus, bicycling makes up category 1, while transportation and walking make up categories 16 and 17, respectively. Most METs in the Compendium were estimated by averaging the respective outcomes of several studies: the underlying references are mentioned in category-specific appendices [56-58].

According to the 2011 Compendium [55], driving a car or truck was rated at 2.5, driving a motor scooter or a motorcycle was rated at 3.5, riding a car was rated at 1.3, and riding a bus or train was rated at 1.3. The METs at walking (resp. at cycling) were reported according to speed, as the primary factor, and also depended on other factors, such as the grade and the ground type. The speed-MET pairs reported in the Compendium for Walking on hard level ground and bicycling under similar conditions showed a monotonic increase with speed (Figure 1).

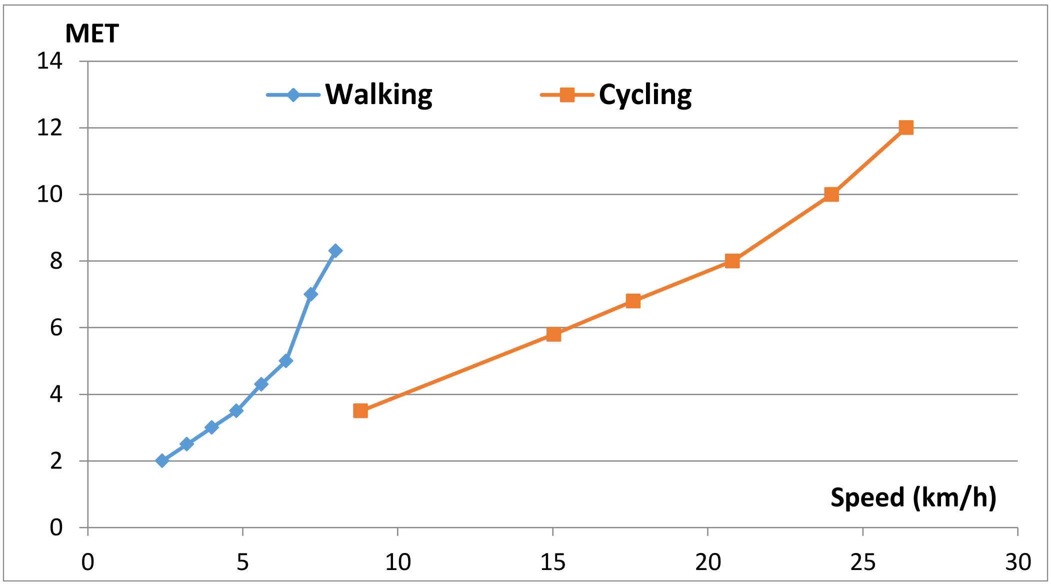

Figure 1. The relationship between modal MET and speed. The representation is based on data from the 2011 Compendium [55].

Rickshaw-pulling has a MET of 6.3 [55], based on several studies [59, 60]. As pulling a rickshaw involves walking or running while pulling at least the rickshaw with one or two passengers for most of the working duration [59], the specific METs are likely higher than those of Walking or Running. This would be consistent with recent studies in which Walk MET was found to increase from 2.5 to 5 when speed increased from 4 to 6.5 km/h [48, 49].

Lastly, for logistical activity that consists primarily of walking and carrying loads [25], the related MET is rated at about 4 [27].

2.3 Human Respiration and B2F Carbon Emissions

2.3.1 Principles

The metabolic activity requires the intake of oxygen, its application in oxidation reactions to release energy, and its chemical combination yielding carbon dioxide [18, 21]. In biochemistry, “respiration” involves the full biochemical process [61]. In physiology, respiration consists of the movement of oxygen from the environment to the cells of the body, and the removal of carbon dioxide from the cells to the environment [62]. Thus, respiration is a cyclic activity involving the intake of oxygen (inspiration) and the release of carbon dioxide (expiration) as the two successive phases in every cycle [63].

For humans, the definition of BMR is closely related to the intake of oxygen: the unit bmr_1 is equivalent to an intake of oxygen of 3.5 mL/kg/min, i.e., 0.21 L/kg/h [22]. The outflow of carbon dioxide is proportional to the oxygen inflow; the ratio of CO_2 outflow and O_2 inflow, both as the number of molecules, is called the Respiratory Exchange Ratio (RER) [49]. Its value depends on the nutrition diet of an individual [18, 21, 32].

We denoted θ_{B2F}, the carbon emission factor of one MET, as the gas mass relative to the body mass per time unit. It depends on the RER and also on the density of carbon dioxide under conventional conditions of pressure and temperature, β. Based on this definition:

$$\theta_{\mathrm{B2F}} = 0.21 \cdot \mathrm{RER} \cdot \beta \quad \mathrm{gCO_2} \cdot \mathrm{h}^{-1} \cdot \mathrm{kg}^{-1} \tag{5}$$

Here, RER is dimensionless and $\beta =$ density of CO_2 in g/L.

The acronym B2F stands for "Body to Foot", which is associated with locomotion tasks; B2F emissions come from one's body on using one's feet.

To measure the individual energy expenditure of using a transport mode μ, we defined its net MET as the difference between the task gross MET and the unit MET associated with a resting state, $x_\mu - 1$. At an individual level, the respiration specific to the locomotion task generates the emission of carbon as follows:

$$C_\mu^{\mathrm{B2F}} = \theta_{\mathrm{B2F}}.M.\left(x_\mu - 1\right) \quad \mathrm{gCO_2.h^{-1}} \tag{6}$$

Here, $M =$ body mass in kg, and $x_\mu =$ MET, $\theta_{\mathrm{B2F}} =$ carbon emission factor in gCO_2e/kg/h.

2.3.2 Value of the B2F Carbon Emission Factor

A conventional value of the RER is at 84% [13]. Thus, the per-MET outflow of carbon dioxide is 0.84 × 3.5 (O_2) mL/kg/min = 2.95 (CO_2) mL/kg/min or 0.16 L/kg/h.

From its chemical composition and the atomic masses of chemical elements, one mole of CO_2 weighs 44 g. By assimilating carbon dioxide to a perfect gas, under standard conditions of pressure and temperature, one mole of CO_2 occupies a volume of 22.4 L (from Avogadro's law, [64]), such that 1 L weighs about 1.96 g. Thus, the specific density β is 1.96 g/L.
In turn, from (5) the B2F carbon emission factor of 1 MET is:

$$\theta_{\mathrm{B2F}} = 0.31 \quad \mathrm{gCO_2e.h^{-1}.kg^{-1}} \tag{7}$$

2.4 Food Intake and F2B Carbon Emissions

2.4.1 Principles

The B2F emissions pertain to the flow of energy out of the body, i.e., downstream it, in a body-centric analysis of energy flow. The F2B emissions are generated upstream the body, and are related to the production of the food that fuels it.

We postulated that (i) the energy expenditure of a human on performing a specific task is compensated by food intake of proportional energy up to some compensatory ratio, say ρ, and (ii) food production entails a carbon footprint per unit of energy content, denoted by σ.

Thus, 1 MET used to perform a task involves food intake of ρ times bmr_1 energy content, and in turn, a carbon footprint of $\mathrm{bmr}_1.\rho.\sigma$.

The F2B carbon emission time rate per task-used MET is denoted by:

$$\theta_{\mathrm{F2B}} = 1.0\,\rho\,\sigma \quad \mathrm{gCO_2e.h^{-1}.kg^{-1}} \tag{8}$$

Here, $\rho =$ compensatory ratio is dimensionless, $\sigma =$ carbon footprint of food intake as $gCO_2e/kcal$, and constant 1.0 = bmr_1 as kcal/kg/h per MET.

Considering the specific human energy expenditure of using a transport mode μ, with net MET of $x_\mu - 1$, the associated food intake induces an F2B carbon emission per unit time at the individual level of

$$C_\mu^{\mathrm{F2B}} = \theta_{\mathrm{F2B}}.M.\left(x_\mu - 1\right) \quad \text{as } \mathrm{gCO_2e.h^{-1}} \tag{9}$$

Here, $M =$ body mass in kg, $x_\mu =$ MET, $\theta_{\mathrm{F2B}} =$ carbon emission factor in $gCO_2e/kg/h$.

We called it "Food to Body", as it comes from food and is stored in the body for later use.

2.4.2 Reference Data and Parameter Values

The compensatory ratio ρ might have a value of one, indicating a balance of energy flow between task expenditure and food intake, at least in developing countries, where food is less abundant than in developed countries. This was commonly assumed throughout the 19th century and up to the 1920s [21]. However, socio-economic development in industrialized countries is also associated with food diet imbalances for large shares of the population [45]. From a cohort study in the UK [65], a long-term ratio ρ was derived, which ranged from 19% to 96%, with an average of 57% [15]. Also, for developed countries, a meta-analysis of laboratory studies [66] showed that such compensation does not occur soon (within a few hours) after physical exercise. Thus, we considered a compensatory ratio ρ ranging from 0.2 to 1.0.

The carbon emissions of food intake, more precisely the carbon equivalent GHG emissions of food intake, are assessed by conducting lifecycle analysis according to the "From Farm to Fork" paradigm [67, 68]. In Europe, the average carbon footprint of food energy is 1.4 $gCO_2e/kcal$ [16]. In France, the average ratio is 1.9, but individual values range from 0.5 (vegetarian diet) to 5 (ruminant meat diet) [68].

Based on the respective ranges of ρ and σ, the related θ_{F2B} in France ranged from 0.1 to 5, with an average value of 0.91 $gCO_2e/kg.h$ in the 2010s.

2.5 From Food to Foot: Integrated Model

2.5.1 Principles

The B2F (respiration and carbon excretion) and F2B (food intake) flows of energy and carbon pertain to the body as a system in interaction with its environment (according to Systems Theory) [69]. The two streams of flows are disjoint since the From Farm to Fork measurement of F2B excludes both the CO_2 intake of crops and the CO_2 expiration of food consumers [4]. Thus, the two streams of carbon emissions add up. As F2B flows occur upstream of the storage of energy in the body, while B2F flows occur downstream of energy storage, together, they might be called From Food to Foot (F2F) to mark the temporal sequence.

If a locomotion task μ is fulfilled by an individual, its specific carbon emissions of F2B and B2F types can be added up in a joint carbon emission time rate as follows:

$$C_\mu^{\mathrm{F2F}} \equiv C_\mu^{\mathrm{F2B}} + C_\mu^{\mathrm{B2F}} \tag{10}$$

As both components are proportional to the body mass M and the net MET $x_\mu - 1$, their sum can be represented as:

$$C_\mu^{\mathrm{F2F}} = (\theta_{\mathrm{F2B}} + \theta_{\mathrm{B2F}}).M.\left(x_\mu - 1\right) \quad \mathrm{gCO_2e.h^{-1}} \tag{11}$$

Thus, the locomotion task has an F2F carbon emission factor per net MET and per body mass unit of

$$\theta_{\mathrm{F2F}} \equiv \theta_{\mathrm{F2B}} + \theta_{\mathrm{B2F}} \quad \mathrm{gCO_2e.h^{-1}.kg^{-1}} \tag{12}$$

2.5.2 Parameter Values

From the last two subsections (under conditions typical of France in the 2010s), the combined factor θ_{F2F} ranges from 0.4 to 5.4 gCO$_2$e/kg/h. The average value amounts to 1.3 gCO$_2$e/kg/h, out of which F2B accounts for three-fourths and B2F for one-fourth. However, θ_{B2F} = 0.31 is constant (up to small variations in RER), while θ_{F2B} shows large variations; its average value is about four times the minimum value of $\rho.\sigma$. Thus, θ_{B2F} is one-half more than the minimum θ_{F2B}.

For net MET ranging from 1 to 5, the associated carbon emissions of a 70 kg person will range from 1 to 5 times $70 \times 1.3 \approx 90$ gCO$_2$/h, i.e., from 90 to 450 gCO$_2$/h.

2.6 Food to Foot Carbon Emissions Per Unit Length

2.6.1 Principles

The fundamental function of human transportation is to make people move through space from one location to another, i.e., from origin places to destination places [38, 70]. Thus, the spatial dimension is prominent and even prevails over the temporal dimension. Hence, the carbon emission factors of the modes of transport are assessed per unit distance traveled [17, 71].

The length traveled ΔL and the travel time ΔT, i.e., the time length of the transportation task are related by the average speed:

$$v = \frac{\Delta L}{\Delta T} \tag{13}$$

For locomotion task μ and any flow of phase $a \in \{\mathrm{B2F}, \mathrm{F2B}, \mathrm{F2F}\}$, the carbon emission per unit length is the carbon emission per unit time multiplied by the travel time over a unit length ΔL = 1 km, i.e., $\Delta T = 1/v$; thus,

$$I_\mu^{(a)} = C_\mu^{(a)} \frac{1}{v_\mu} \tag{14}$$

Here, $I_\mu^{(a)}$ = individual carbon footprint per unit length in gCO$_2$e/km, v = modal speed in km/h, and $C_\mu^{(a)}$ = individual carbon footprint per unit time in gCO$_2$e/h.

It follows that

$$I_\mu^{(a)} = \theta_a.M.\frac{x_\mu - 1}{v_\mu} \tag{15}$$

Thus, the a^{th} type carbon emission per unit length of transport mode μ is proportional to the body mass and a net metabolic intensity per unit length $(x_\mu - 1)/v_\mu$. The latter component is mode specific, whereas, only the coefficient θ_a is phase specific. The body mass M is specific to the user, whose individual features also affect the θ_a factor (at the first order of magnitude through the food diet), the modal speed (at the first or second order, depending on the mode), and the net MET (second-order).

For mode μ, the net MET per unit length (nMpul) depends on the modal speed v through a functional relationship expressed as follows:

$$v \ \longmapsto \ \mathrm{F}_\mu(v) \equiv \frac{\mathrm{X}_\mu(v) - 1}{v} \tag{16}$$

Based on the formula of the function F_μ, modal speed exerts a twofold influence on the net MET per unit length. It has a direct influence, which increases the denominator, and hence, decreases F_μ, and an indirect influence through X_μ that increases the numerator and also F_μ. As the two influences work in opposite directions, some compensation occurs between them.

2.6.2 On the Modal Net MET Per Unit Length

The F_μ functions of driving or riding motorized transport modes (scooter, motorbike, car, bus, coach, and train) are decreasing hyperbolic functions of speed since their gross MET X_μ are constant. For each mode, riding requires lesser energy than driving, thus, F'_μ at riding is lower than F_μ at driving.

Human-powered modes have higher nMpul than motorized modes due to the twofold effect of speed: on the numerator side of F_μ, their net MET is higher, while on the denominator side, their speed is lower.

In general, Cycling speeds are higher than walking speeds. However, the net METs per time unit are of the same order of magnitude and increase with speed (Figure 1). To compare the nMpul between the modes, we calculated them based on the 2011 Compendium data (Figure 2). The nMpul of walking varies with speed from 0.4 to 0.75 MET.h/km in three stages: it increases slowly for moderate speeds up to 4 km/h, then it remains stable around 0.5 from 4 to 6 km/h, beyond which it increases sharply. The nMpul of cycling varies from 0.2 to 0.4 MET.h/km in a smooth and concave manner. Thus, the nMpul of cycling is lower than that of walking.

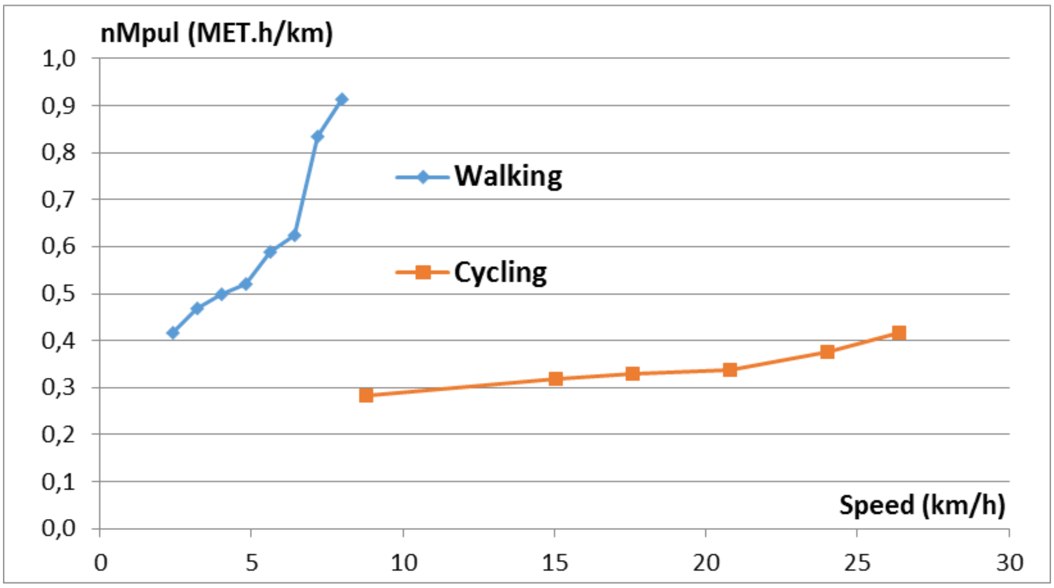

Figure 2. The relationship between Modal (MET-1)/Speed and Speed. Source: the author's calculations are based on the data from the 2011 Compendium [55].

3. F2F in the Carbon Footprint of the Modes of Transport

We integrated the F2F emissions into the overall carbon footprint of the modes of transport. We first considered walking, and then, cycling, which is a mechanized mode. Next, we considered e-scooters and cars. For each mode, besides stating the F2F carbon impact, we estimated the other components of the carbon footprint by analyzing their main parameters.

3.1 Walking

The Walking MET increases from 2 to more than 6 as the travel speed increases from 2.5 to 8 km/h [55], in a superlinear way (Figure 1). The task factor $(x-1)/v$ varies from 0.4 to 0.75 MET.h/km in three stages: it increases slowly for moderate speeds up to 4 km/h, then remains stable around 0.5 from 4 to 6 km/h, beyond which it increases sharply (Figure 2).

The F2F impact of walking is about 45 gCO_2e/km for a 70 kg person under an average French food diet. It ranges from 20 to 90 when the $\rho.\sigma$ product increases from 0.2 to 1 $gCO_2e/kcal$.

These values are considerably greater than the carbon footprint of shoes and road infrastructure. A pair of shoes has a carbon footprint of 3–30 $kgCO_2e$ [72, 73]. Shoes are used not only for walking or running but also for dressing the feet. Thus, their carbon footprint should be divided into two parts, say halves, one for each function. The walking half of the footprint amortizes over the life course of say 1,000 km [73]. Then, the range 1.5–15 $kgCO_2e$ gives rise to a range of 1.5–15 gCO_2e/km, with an average value of 8 gCO_2e/km. It is an order of magnitude lower than the F2F component. Furthermore, walking is performed on roadways. Although a well-known convention is to amortize the roadway carbon debt over cars and heavy vehicles only, a fairer convention is to include all road functions and divide the component for transport among all users, including those on foot, riding, and driving cars. The carbon footprint of infrastructure usage is 1 – 2 gCO_2e/km, which is a negligible value [74].

To summarize, the F2F component is the most important contributor to the carbon footprint of walking. Shoes contribute a minor part and the roadway infrastructure has a still lesser contribution. Assuming an average French diet and an average carbon content of 14 kg CO_2e for a pair of shoes, the integrated carbon footprint of walking is 55 gCO_2e/km.

3.2 Cycling

Here, we considered a fully human-powered bike with no electric assistance. The Cycling MET increases from 4 to 12 as the travel speed increases from 15 to 27 km/h [56], i.e., from moderate to very high for most people. The task factor $(x-1)/v$ varies from 0.2 to 0.4 MET.h/km in a smooth, concave way.

The F2F impact of cycling is about 28 gCO_2e/km for a 70 kg person under an average French food diet. It ranges from 12 to 100 when the $\rho.\sigma$ product increases from 0.2 to 1 gCO_2e/kcal. The infrastructure component is 1 – 2 gCO_2e/km, similar to that for walking, for the same reasons.

For bikes as vehicles on a standalone basis, studies on LCA found a carbon footprint of about 5 gCO_2e/km [3, 13], e.g., a 15 kg bike made mostly of steel at about 6 $kgCO_2$e per kg and amortized over a life course of 20,000 km [75].

To summarize, the F2F component under an average French food diet dominates the vehicle component by an order of magnitude and the infrastructure component by two orders of magnitude. Under these conditions, the integrated carbon footprint of cycling is 35 gCO_2e/km.

3.3 Motorized Modes of Transportation (Driving and Riding)

The car driving task is reported as 2.5 MET in the 2011 Compendium [55]. Even if the driver is seated and does not contribute human power for locomotion, the task requires about twice the human energy of resting. We may compare the task of riding an e-scooter to that of driving a car. Although the rider stands, the distance traveled is generally short, and most of the effort pertains to driving the vehicle. Taking the speed of the vehicles into account, in dense urban traffic, e-scooters at an average speed of 15 km/h (say), i.e., about the same as the speeds of cars. At this speed, the task factor $(x-1)/v$ is about 0.10 MET.h/km, i.e., much lower than that for cycling and walking. In interurban settings, where the average speed of cars reaches 70 – 120 km/h, the factor drops to 0.01 – 0.02 MET.h/km. The F2F of driving a car or riding an e-scooter in urban conditions is about 6 gCO_2e/km for a 70 kg human under an average French diet; it varies from 5 to 37 over the range of the $\rho.\sigma$ product.

Car passengers and seated bus passengers have a MET of 1.3 only, i.e., their riding task is halfway between sitting and standing [55]. For them, the F2F component is almost null.

The road infrastructure component is 1–2 gCO_2e/km for drivers, riders, and other modal users [74].

Additionally, the vehicle and the usage energy need to be considered. The body of an e-scooter is comparable to that of a bike, i.e., about 15 kg of steel, with an expected life course of 20,000 km, yielding a carbon footprint of about 5 gCO_2e/km [74]. An electric battery with an energy capacity of 0.5 kWh, assuming that it is made in China, has a carbon footprint of 120 $kgCO_2$e/kWh. It is sufficiently recyclable to obtain a credit of 55 $kgCO_2$e/kWh [75] and amortized over 20,000 km, it yields an additional 1.5 gCO_2e/km. This makes the vehicle and battery combo roughly equivalent to the F2F emissions under the reference food diet. The motion energy at 14 W.h/km times 300 gCO_2e/kWh out of the European grid induces a specific carbon footprint of 4 gCO_2e/km, or 1

gCO_2e/km only in France, which has a low carbon electricity mix [76]. Thus, the modal carbon footprint of e-scooters is about 15–18 gCO_2eppkm.

For e-cars the considerations are analogous but the vehicle mass is considerably more (by a factor of 100 for a 1.5 t car) and the life course is substantially longer, say 200,000 km [77]. Furthermore, there might be several occupants in the car, say 1.5 as a rough average (1.2 for small cars and 1.7 for large cars in France). The carbon footprint for the construction-related phases in a car lifecycle (manufacturing, maintenance, end-of-life, minus recycling credits) is about 5 $kgCO_2e$ per kg of vehicle mass if it is made in Europe [6]. The resulting carbon footprint per unit length is 25 gCO_2eppkm. To consider a scenario, let us imagine an EV fully made in France. Due to the low carbon electricity mix in that country, the carbon footprint of the vehicle constructive phases would reduce to 2 kg CO_2e per kg of vehicle mass [74]. Thus the vehicle carbon footprint per unit length would reduce to 10 g CO_2e/p.km.

An electric battery of 50 kWh capacity is sufficient throughout the life of the vehicle, yielding an additional 12 gCO_2eppkm. At 0.2 kWh/km and 300 gCO_2e/kWh out of the European grid, the motion energy adds 60 gCO_2e/veh.km and 40 gCO_2eppkm. Out of the French grid, it is reduced to 10 gCO_2e/veh.km and 7 gCO_2eppkm. Thus, an EV both made and used in France (resp. in Europe) would have an overall carbon footprint of 35 gCO_2eppkm (resp. 79), while an EV made in Europe and used in France would have a carbon footprint of 45 gCO_2eppkm.

A diesel car consuming 8 L/100 km of diesel at 3.5 $kgCO_2e$/L emits 280 gCO_2e/veh.km and 187 gCO_2eppkm; thus, yielding an overall vehicle footprint of 215 gCO_2eppkm [74].

Driving an EV in France (resp. Europe) in dense urban traffic generates a carbon footprint of 52 gCO_2eppkm (resp. 99), which is lower than that for a diesel car (223 gCO_2eppkm). Although the F2F contribution of EVs is minor, it is equivalent to the electricity carbon footprint in France. For diesel cars, the F2F component is relatively very low.

3.4 Multimodal Comparison

After comparing the components of carbon impacts for four modes of transport, we compared them regarding their overall carbon impacts. We considered several versions of each mode of transport, depending on their speed regime (active modes) and the carbon intensity of food production and energy production (motorized modes). The arborescence of the notional modes of transport under consideration is presented in Figure 3.

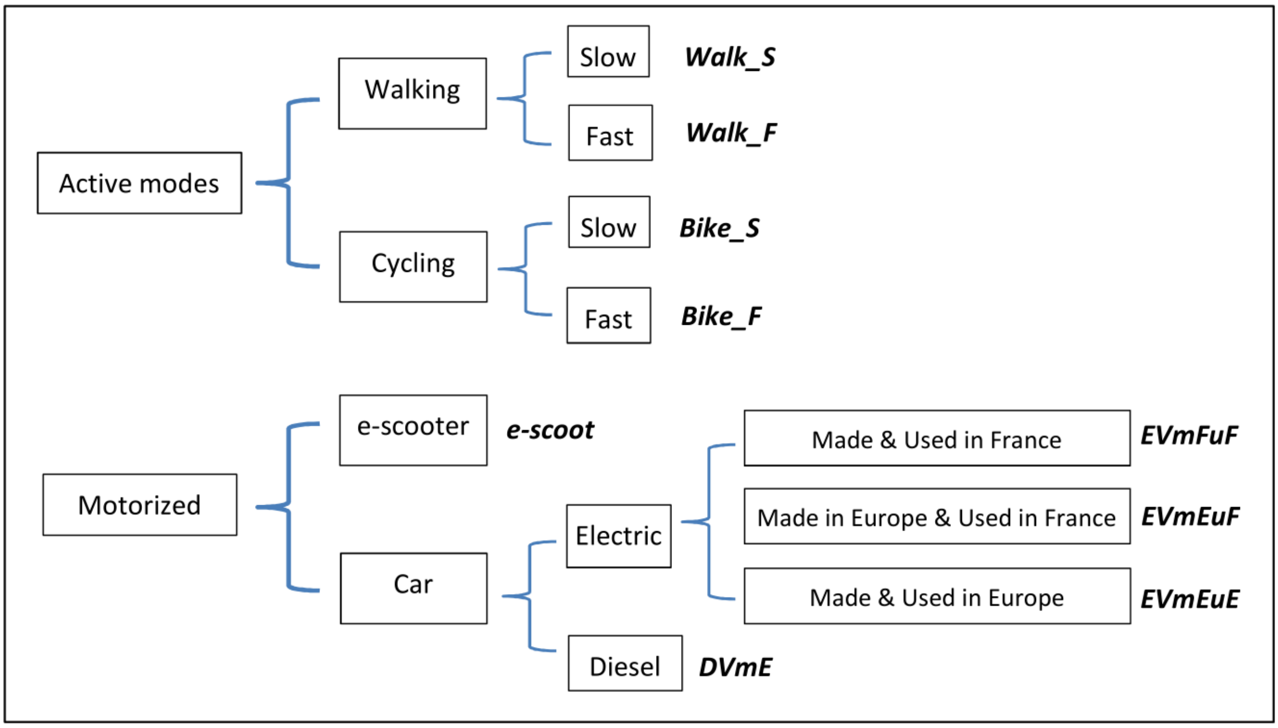

Figure 3. The arborescence of the modes of transport under consideration. Source: author.

The level and composition of the modal carbon footprint per unit length for all modal versions are illustrated in Figure 4; the associated table is provided in the Appendix.

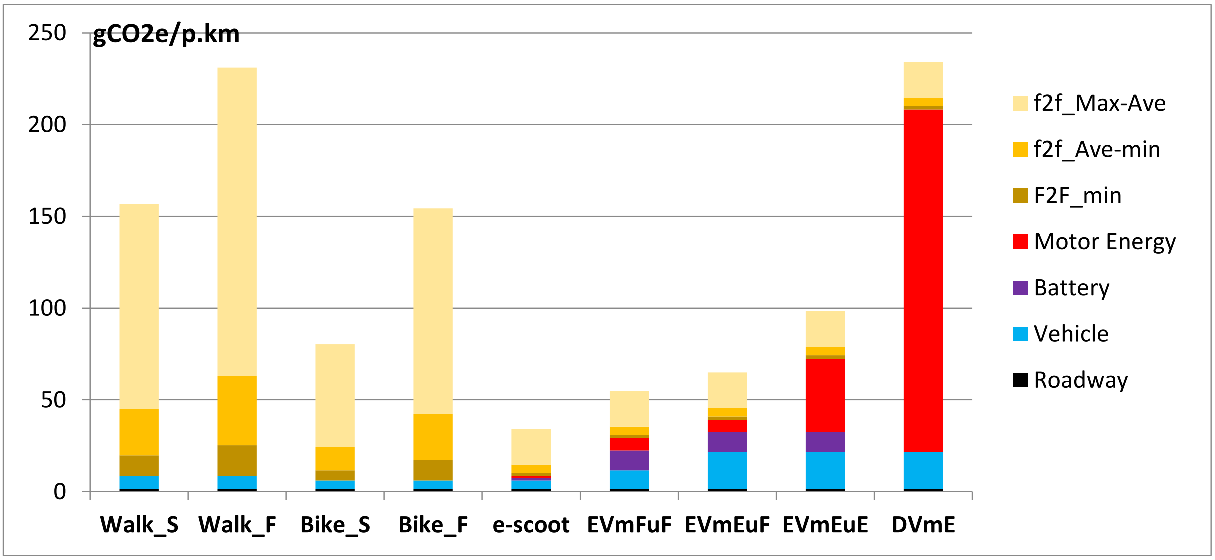

Figure 4. The level and composition of the modal carbon footprint per unit length (Source: author).

To highlight the influence of the F2F component, we ranked the modal versions according to the carbon impact in two ways, i.e., by excluding or including the F2F component. Neglecting the F2F component, the three modes of micromobility had similar low carbon footprints of about 7 or 8 gCO_2eppkm. Walking is associated with the carbon debt of the shoes. For cars, the carbon footprint of EVs changes from simple to double depending on the carbon content of the electricity mix. Diesel cars are the most emissive modes of transport, owing first to the carbon intensity of their fuel and then to the construction of the vehicle. The consideration of biofuels divides the fuel impact by 3 or 4 by reducing it to the W2T component.

Including F2F alters the ranking significantly. For the average French diet, e-scooter riding is the least emissive mode, which is very close to slow and fast cycling, followed by slow walking. EVs used and made in a country with a low carbon electricity mix have the next lowest level of emission, followed by fast walking. The emission of EVs using low carbon electricity but made with medium carb conditions (European mix) is close to that of fast walking.

A low-carb food diet can restore the ranking excluding F2F. Under a high carb food diet, the 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

4.1 Summary

In this article, we introduced a carbon footprint model of transport modes that integrates two kinds of human-centric energy and carbon flows, namely respiration (Body to Foot) and food intake (Food to Body). The associated B2F and F2B components are analogous to the Tank to Wheel and the Well to Tank components of energy flows for motor vehicles. We used simple mathematical formulae to model the influence of modal speed on the metabolic equivalent of a task and the carbon footprint per unit length.

We found that the carbon footprint of food intake is a major determinant of the carbon efficiency of the active modes. Under an average food French diet in the 2010s, the F2F component was about three times greater than the F2B amount. The F2F emissions of walking varied from 50 to 76 gCO_2eppkm depending on speed (slow to fast). The emissions of cycling were about half of those of walking for the B2F component only, as determined by a study [15].

By including the F2F emissions in the modal carbon footprint and accounting for the carbon debt of shoes in the walking footprint, we found that the mechanized modes of micromobility, i.e., cycling and riding an e-scooter, are more carbon-efficient than walking. Furthermore, EVs both made and used in France have carbon emissions similar to that of walking.

We made the study explicit by stating the parameter values and the emissions components of the 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. This makes it easy to apply the model to different sets of assumptions [74].

4.2 Outreach and Relations to Previous Studies

Unlike previous studies, we mentioned the two sides of carbon footprint i.e. F2B and B2F, and the twofold influence of modal speed on the net MET per unit length. Regarding the carbon footprints of walking and cycling for transportation analysis, previous studies considered either respiration [13] or food intake [14-17]. Regarding the influence of speed, previous studies on nutrition, industrial health, physical exercise, and clinical cardiology addressed cycling and walking merely as tasks performed over time and neglected their transportation function, and in turn, the influence of speed on the denominator of nMpul. Additionally, previous studies dealing with the transportation function only considered an average modal speed and neglected the variations in metabolic intensity and its relation to speed [13-17].

The pioneering study of the ECF on the carbon footprint of cycling [16] addressed the metabolic intensity of active modes compared to driving a car in a differential way on a per time basis: this can be valid only if both modes have the same average speed. Our method is more general in this regard, due to the consideration of net METs of transportation tasks relative to the resting state and the comparison based on per unit length.

Our study showed that planning for low carb mobility systems has to rely on a technical infrastructure involving the transport infrastructure, along with the energy infrastructure and the food production infrastructure [74]. Including the F2F component in the carbon footprint per unit length narrows the gap between the active modes and riding e-scooters or EVs under low carb conditions of both manufacturing and usage. Such inclusion also calls for complementary indicators to measure the carbon efficiency of mobility solutions and systems more comprehensively. The system footprint involves not only the footprint per unit length but also the amount of distance traveled. In the latter respect active modes are associated to shorter distances than motorized, painless, comfortable modes, such as cars and larger vehicles.

4.3 Limitations and Directions of Further Research

Our model and previously constructed models in the field of transportation were based on the “Compendium of physical activities” [55] as a reference source of MET data. Despite its broad coverage, the Compendium is incomplete regarding the emerging modes of micromobility; e-bikes, kick-scooters, e-scooters, etc. need specific MET measurements. Furthermore, the modernization of driving cars and trucks, owing to driving aids, suggests that their respective METs need to be updated. Refining the measurements of riding buses and trains by differentiating the user’s state as either sitting or standing, and also the different kinds of trajectories (since bus paths along urban roadway networks have more curves, crossings, and station stops than interurban train trips) would also be appropriate.

The variation in the pace along a user’s path, especially those caused by interruptions at road junctions or along the streets, requires further investigation, both empirically, to consider realistic conditions of urban travel (as opposed to idealized uninterrupted tasks of walking or cycling in laboratory experiments), and theoretically, based on biomechanical models. The prevailing biomechanical models of humans in transportation primarily focus on motion dynamics [40, 50] or crash dynamics [78]. Further development of physiological issues, including the composition and timing of food intake, as well as the progressive expenditure of energy, would be useful for understanding the real-time MET variations of locomotion tasks under realistic conditions of urban mobility.

Finally, there are two “systemic” research directions concerning F2F carbon emissions. The first one concerns human respiration. Following a study [13], we attributed the carbon emissions of the locomotion task to the mode of transport. But the involved carbon element comes from aliments: in IPCC reports the carbon emissions of the respiration of cattle are not taken into account because the carbon element in them comes from plants, which absorbed it directly from the atmosphere, thereby compensating it, from the perspective of a circular economy [4]. For people, the rate of compensation requires a detailed investigation. The second research direction involves the carbon footprint of human excreta, besides that generated through respiration, involving their collection mode and further treatment, possibly with some feedback on food production through field fertilization, which is also an issue of a circular economy.

Notation

M	The body mass of an individual
i	The index of an individual
a	The index of “Emission Phase” in {F2B, B2F, F2F}
μ	A specific activity or task
x_μ	The Metabolic Equivalent of Task μ, as an equivalent number of basal (resting) metabolism
v_μ	The modal speed of locomotion task μ
ρ	The compensatory ratio between food intake and human energy expenditure
σ	The carbon footprint of food intake per unit of energy content
θ_a	The carbon emission factor (time rate per unit body mass and per unit MET)
$C_\mu^{(a)}$	The carbon emission factor per unit time of task μ by individual user on phase a
$I_\mu^{(a)}$	The carbon emission factor per unit length of task μ by individual user on phase a
$\mathrm{F}_\mu(v)$	Net MET per unit length (nMpul) of the locomotion task μ at speed v

Author Contributions

Fabien Leurent: Conceptualization, Methodology, Software, Data curation, Writing - Original draft preparation, Visualization, Investigation

Competing Interests

The authors have declared that no competing interests exist.

Additional Material

The following additional material is uploaded at the page of this paper.

1. Table of Data for Modal Comparison.

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