Conceptualizing Micromobility

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Article

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Conceptualising Micromobility: While micromobility has seen a significant rise of interest across policy, industry and academia, a detailed conceptualisation of it has so far been missing from the scientific literature. This paper develops a multi-dimensional conceptualisation of micromobility, in conjunction with a new socio-technical definition. To do so, it reviews related concepts; it analyses how the term micromobility has been used; and it critically engages with existing definitions most frequently cited in this literature. Building on these insights, we develop a multi-dimensional conceptualization of micromobility. Our definition of micromobility covers a wide range of mobility options that can typically be manoeuvred by one human without motor assistance, at least for short distances, and that are 'micro' in terms of energy demand, environmental impact, and use of road space, relative to automobility. According to our conceptualisation, micromobility modes comprise fully human powered, partially motor assisted and fully powered options. They typically do not exceed 25 kilometres per hour (or 45 for faster ones) and weigh (often significantly) less than 350 kilogram, while often providing some (public) health benefits. Trip lengths are typically less than 15 kilometres and daily distance travelled less than 80 kilometres. This new definition has relevance for future transport and mobility scholarship, as well as policy and evaluation. Advantages of a new and widely accepted definition and conceptualisation of micromobility could include more robust design standards, legislation, as well as evaluation metrics and methods, all leading to greater understanding of, and attention paid to, this form of mobility. This paper highlights the important role that micromobilities could play in moving beyond automobility, to create more sustainable and just mobility futures.

Keywords: micromobility; sustainable transport; electric vehicles; active travel; LEV; socio-technical analysis

1. Introduction

The accelerating climate crisis and transport's stubbornly high carbon emissions highlight the importance of reducing transport emissions (IEA, 2021). Micromobility is often put forward as a potential solution for lowering carbon emissions, alongside positive social and economic benefits, that can clearly help achieve a range of Sustainable Development Goals (United Nations, 2015).

Industry analyst Dediu (Micromobility, 2017) is widely credited for coining the term micromobility in 2017. The term has gained currency very quickly over the last few years, in policy, industry and academic contexts, with multiple definitions and understandings of the term. However, a detailed conceptualization and broadly accepted definition are still missing. This paper complements the emerging body of literature on micromobility

that is largely based on empirical studies, by proposing such a conceptual approach. By doing so it explores new thinking on how to challenge (auto)mobility regimes and radically reduce carbon emissions.

Some of the mobilities understood as micromobility, such as shared electric step scooters are a relatively new addition to our cities and have seen very fast adoption rates in some countries. Other modes, such as bicycles have been around for more than two centuries, and have gone through phases of mass uptake, followed by decades of marginalization and a recent boom and technical development (e.g. e-bikes). While some (e.g. cargo bicycles) used to be marginalized due to not 'fitting' into mainstream categories (see e.g. Cox, 2012), others, such as step scooters, wheelchairs, or mobility scooters were mainly used by young, old, or disabled people, and are largely absent from micromobility debates. It seems that the term 'micromobility' facilitates a shift in the perception of some of these mobilities. While it is important to challenge the "newness discourse" around micromobility, with many modes having long histories both in policy and academic debates (Ploeger and Oldenziel, 2020; Dekker, 2021), a historic perspective is beyond the scope of this paper.

The (re-)emergence of micromobility comes with many contestations, for example around road space and legislation, with associated safety debates. Conflicts between pedestrians and shared step-scooters are one example. Policy makers often scramble to provide frameworks, with responses often allocating small amounts of road/urban space, often in conflict with other micromobility modes such as walking or cycling. However, there are also more radical approaches, that re-allocate automobile infrastructure, with an acceleration during Covid-19 in some places. Overall, the legal frameworks for micromobility vary, and are changing rapidly.

Our conceptual approach to micromobility is broadly informed by a mobility studies perspective and therefore seeks "to address entire mobility systems logistical practices, energy cultures, and the way everyday practices are embedded in these larger socio-technical systems" (Sheller, 2018, p. xv). This paper's main research question is thus: How can we best conceptualise micromobility in a socio-technical and multi-dimensional manner? To answer this question, the paper reviews micromobility-related concepts (section 2), analyses the emergence and use of the term micromobility in the literature (section 3), proposes a conceptualisation of micromobility with key characteristics/dimensions (section 4) and contributes a new micromobility definition (section 5).

2. Micromobility-related concepts

This section reviews concepts that are closely related to micromobility: active travel, non-motorised transport, electric mobility, Light Electric Vehicles (LEVs), microcars and minimobility, multi-modal transport, shared mobility/Mobility as a Service (MaaS), and smart mobility. While they all have certain elements in common, none of these existing concepts covers the same ground. The limited amount of interaction between many of them (e.g. between active mobility and LEVs, or non-motorised transport and electric mobility) leads to research, innovation and policy often happening in rather siloed ways. Similarly, whilst the term micromobility may facilitate debates across these concepts, the lack of broadly accepted conceptualisation and definition can exacerbate any confusion and misalignment across agendas. Our definition of micromobility, with its dimensions and characteristics (see sections 4 and 5), builds on these concepts and intersections between them, thus embedding micromobility within a broad set of literature, disciplines and policy agendas.

2.1. Active Travel

The term 'Active travel' comes from the public health field and covers modes that require some physical activity, such as walking and cycling. More recently, active mobility debates have included assisted modes such as electrically-assisted cycling (Sundfør, Fyhri

and Bjørnarå, 2020). The 'active' element of other modes of micromobility (such as e-step scooters), where users stand up rather than sitting down and push off to get started, is less explored in the literature. It is also important to note that a major mode of active travel – walking – is typically not included in micromobility definitions and debates. Rather, often, tensions are described, e.g. between pedestrians and e-scooters (Fitt and Curl, 2020).

Whilst most active modes tend to be considered under the micomobility umbrella, depending on definitions (see below), micromobility can also include modes that do not include active travel, such as electric mopeds. Nevertheless, the physical activity and associated public health dimension are key for considering the societal and individual relevance of (specific modes of) micromobility, while it is important to keep tensions, alliances and synergies between walking and (other) micromobilities in mind.

2.2. Non-motorised Transport

The concept 'non-motorised' transport/mobility has some overlap with 'active' debates, e.g. in terms of focusing on walking and cycling. It comes from the transport field where it is used to group these modes for modelling purposes. It is a key concept in many transport policy debates such as within the UN (United Nations Environment Programme, 2019). The term is complicated by the emergence of electrically-assisted modes such as e-bikes that are partially human-powered and (optionally) partially by an electric motor.

2.3. Electric Mobility

As many micromobility modes are (sometimes optionally) powered by an electric motor, wider debates on electric mobility are also relevant to this concept. Electric mobility is often conceptualised narrowly in terms of electric cars (Behrendt, 2018). Mapping the interactions between electric modes, whether 'micro' or otherwise (see definition below) is likely to be an important prerequisite for the electric mobility agenda to be broadened and accelerated. A switch to electric cars is also often regarded as the main route to reaching climate targets without re-thinking automobility, when this is unlikely to be sufficient (Henderson, 2020). A broader, micromobility-inclusive understanding of electric mobility would have a better chance of reaching carbon reduction goals.

2.4. Light Electric Vehicles (LEVs)

The term Light Electric Vehicles (LEVs) covers many of the mobilities that are also discussed as micromobility, e.g. "electric bicycles, 3- and 4-wheelers, skateboards and Segways" (Hyvönen, Repo and Lammi, 2016, p. 258) while others define LEVs as being vehicles that fall within the UNECE's M1-category (Ewert *et al.*, 2020) or the EC's L (European Commission, 2022) that define the attributes of various categories of vehicles. These varying LEV definitions do not cover fully human-powered vehicles such as bicycles, but some do include quite heavy vehicles. Adoption is uneven globally, with "considerable market share in Asia, [while] LEV sales in Europe are still very low" and research with a global perspective very much missing (Ewert et al., 2020, p.2) while "outdated" and "inaccurate" regulations are currently a bottleneck (LEVA-EU, 2022). These concerns are largely shared by advocates for both LEVs and micromobility.

2.5. Microcars and Minimobility

Related, and somewhat overlapping with LEVs, there is a small, but a long-standing academic debate on micro-cars, "usually a two-seater two-door lightweight vehicle and less than 3m long" (Mu and Yamamoto, 2019). Some micromobility definitions would include such microcars. Moving away from the car element in the name, there is also a suggestion to introduce the term minimobility "as an attempt to classify small vehicles larger than a bike or scooter and smaller than a car or shuttle that are largely e-powered", mainly meant for short-to-medium distance urban trips (Riggs and Shukla, 2021, pp. 1020, 1023).

2.6. Multi-modal transport

Micromobility is often used in conjunction with other modes such as public transport (Oeschger, Carroll and Caulfield, 2020). Therefore, research on multi-modal transport, especially with regards to integration with active modes, is of key relevance for micromobility. The 'first and last mile' distance traditionally covered by walking and cycling can be extended by other micromobility options, or made possible for those less mobile, widening public transport opportunities. Micromobility definitions, research and policies should therefore include multi-modal elements, especially integration with public transport.

2.7. Shared Mobility and Mobility as a Service

Some forms of micromobility are available as shared schemes, especially bicycles and step scooters (docked and dockless). From a multidimensional approach to micromobility, equity issues (Dill and McNeil, 2021) from the shared mobility literature are especially relevant, for example, to understand actual and potential users, who do or do not have access to these modes and why, and what conflicts over public space and parking emerge (Petzer, Wieczorek and Verbong, 2020). Mobility as a Service (MaaS), where (one or several) shared modes are made available via an app, including services such as wayfinding, booking, unlocking, etc. (Lyons, Hammond and Mackay, 2019; Hensher and Mulley, 2020) may or may not include micromobility. Unintended consequences of MaaS, such as further social exclusion and focus on monetary rather than social goals (Pangbourne *et al.*, 2020) are also potentially relevant to micromobilities.

2.8. Smart Mobility

As many forms of micromobility include some digital/data element, especially shared schemes, the concept of smart mobility is pertinent, focusing on the use of Information and Communication Technology (ICT) in mobility/transport, often in the context of smart cities. Emerging literature considers how to best approach the data elements of shared mobility (Shaheen and Cohen, 2019; Fischer, 2020; Transportation for America, 2020) and MaaS (Cottrill, 2020). This literature critically interrogates smart mobility's knowledge claims and assesses how value is extracted and what issues arise around surveillance and privacy (Spinney and Lin, 2018; Petersen, 2019). Studies of smart mobility frequently draw on micromobility case studies (van Oers *et al.*, 2020) and it follows, therefore, that considerations of the governance of smart mobility need to extend to micromobility to ensure public value and avoid "locking the mobility system into transition paths which exacerbate rather than ameliorate the wider social and environmental problems that have challenged planners throughout the automobility transition" (Docherty, Marsden and Anable, 2018, p. 114).

3. Use and Definitions of the term Micromobility

To complement the micromobility-related concepts discussed above, this section shows specifically how the term 'micromobility' has been used in the academic literature, how the term is defined in this literature and discusses and compares the two non-academic definitions that are frequently used.

3.1. Incidences and trends

We searched Scopus with the following keywords: (1) 'micromobility', (2) 'e-scooters', (3) 'e-bike OR e-bicycle', and 'shared AND bicycle OR bike', on 6 July 2022. Figure 1 shows the prevalence of these words in scientific papers in the (a) title, as well as in the (b) title, abstract and keywords.

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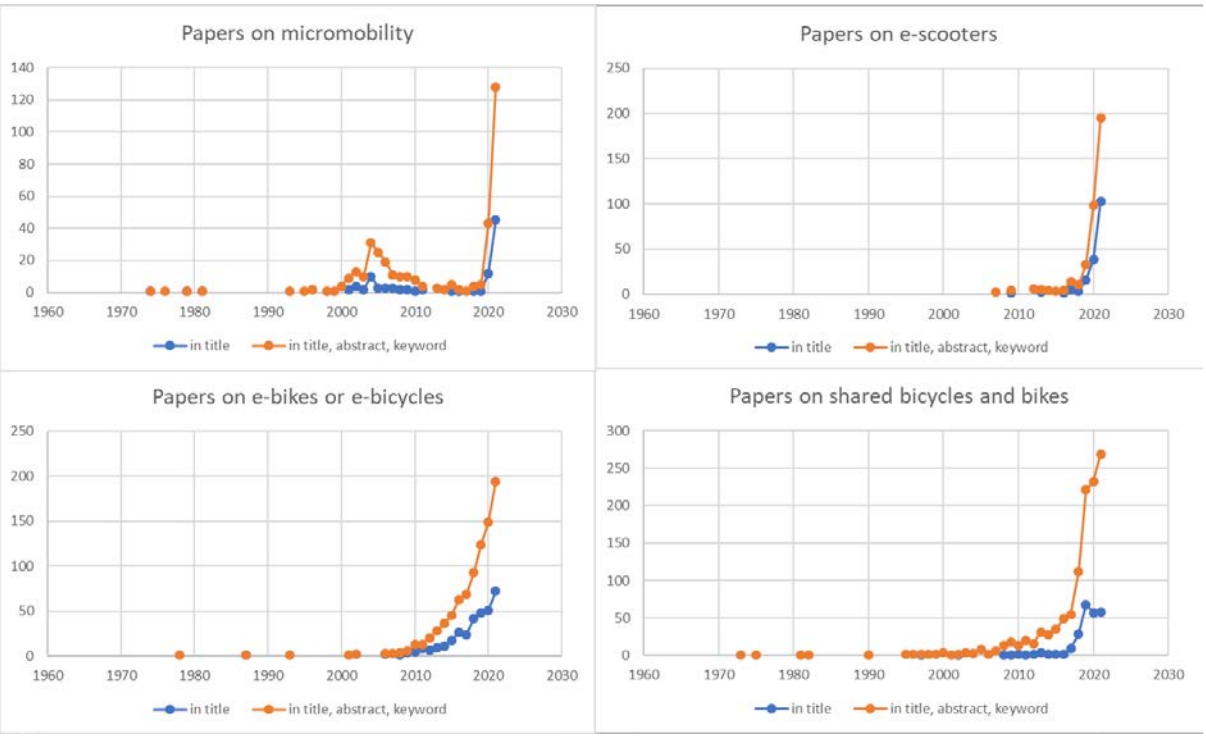

Figure 1. The prevalence of terminology in title, abstract and keywords, and title only

The results show that the term 'micromobility' is mentioned 123 times in the abstract, and 426 times in the title, abstract, and keywords. A sharp rise in academic papers took place in recent years: from 2015 to 2019 there was a maximum of one paper published with micromobility in the title, whilst in 2020 this rose to 12 and in 2021 to 45, and in 2022 the count is already 25. A similarly sharp increase is for papers that used the term in their keywords and abstract. An earlier peak of the term (2004) was not transport related.

A sharp increase in the number of published papers can also be observed for modes that are often associated with micromobility, such as e-scooters and e-bikes. The attention to e-bikes, shared bikes and e-scooters has so far all surmounted the attention to micromobility, and, in the case of e-bikes and shared bicycles has risen over a longer time, approximately since 2010 and 2015 respectively.

3.2. Use and definition of micromobility

Next, the focus is on how the term 'micromobility' is used and defined in the scientific papers identified above. The analysis is confined to those papers having micromobility in the title as compared to only in the keywords or abstract on the premise that they are likely to have a stronger focus on micromobility. Out of the 92 papers identified above, this analysis only considers publications in journals, in English, and for the transport context, and excludes one publication that we could not access, resulting in 36 documents (see Tables 1 & 2).

Table 1 provides an overview of the definitions used in these 36 documents. Interestingly, more than half of the papers did not provide any clear definitions of micromobility. Those that explicitly offered a definition were often based on definitions by the International Transport Forum (ITF) and the Society of Automotive Engineers (SAE), but also sometimes based on Wikipedia, a website, or a provider of audit and assurance (Deloitte). Other papers operationalize the term but do not provide a clear definition. The absence of a broadly agreed definition of micromobility in the scientific literature has therefore resulted in variations of the use of the term and a subsequent lack of clarity and inconsistency in what is or is not included.

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Table 1. Definitions of micromobility in the scientific literature (compiled from different sources).

Author(s)	Reference	Country studied	Definition of micromobility provided	Which is:[1]	Reference to main external definitions
Zhao et al., 2022	(Zhao *et al.*, 2022)	China, India, Japan, and the United States	yes	"micromobility devices include motor scooters, powered two-wheelers, motorcycles, mopeds, bicycles, e-bikes, pedal-assisted bicycles, speed-pedelecs, mobility scooters, standing scooters, and e-scooters."	
López-Dóriga, et al., 2022	(López-Dóriga *et al.*, 2022)	Spain	no		
Romm, Verma, Karpinski, Sanders, McKenzie, 2022	(Romm *et al.*, 2022)	USA	no		
Psarrou Kalakoni, Christoforou, Farhi, 2022	(Psarrou Kalakoni, Christoforou and Farhi, 2022)	France	yes	"The term "micromobility" is used widely to describe modes of individual transportation that are characterized by limited use of space and relatively low mass. However, apart from the vehicle characteristics, a rather mobility-oriented definition of the term includes all transportation modes that allow their users to make a hybrid usage and behave either as a pedestrian or a vehicle at their convenience (e.g. to cross a road or board a bus) when necessary (Christoforou et al., 2021). These can include a wide range of vehicles, from bicycles and electric scooters to segways, kick-scooters, single-wheel boards, and others. They can be either motorized or non-motorized modes, shared or privately owned. In this research, we will mainly focus on bicycles and electric scooters, which are the most widely used modes to date."	
Fang, 2022	(Fang, 2022)	USA	yes	"The Society of Automotive Engineers (SAE) defines micromobility vehicles as "primarily designed for human transport," for use on paved facilities, no greater than 500 lb in curb weight, and have a top speed of no greater than 30 miles per hour (SAE, 2019). While the SAE taxonomy is limited to fully or partially-powered devices, human-powered devices can provide similar mobility. This paper discusses injuries related to the use of eight devices: bicycles, motorized bicycles, kick scooters, motorized scooters, skateboards, motorized skateboards, hoverboards, and devices presumed to be Segways"	SAE
Felipe-Falgas, P.; Madrid-Lopez, C.; Marquet, O. 2022	(Felipe-Falgas, Madrid-Lopez and Marquet, 2022)	Spain		"Micromobility, consisting of private or shared lightweight vehicles, which operate at low speeds and are used for short trips [Roig-Costa, et al., 2021], includes vehicles such as e-bicycles, e-scooters, and e-mopeds. Many authors have theorized that micromobility characteristics, including its flexibility, sustainability, and affordability make them ideal for substituting more private vehicles that contribute to pollution (Bduljabbar et al., 2021)."	
Hamerska, M.; Ziółko, M.; Stawiarski, P. A, 2022	(Hamerska, Ziółko and Stawiarski, 2022)	Poland	no		
Medina-Molina, C., Pérez-Macías, N.,	(Medina-Molina, Pérez-Macías and	Spain, Portugal, Italy, France, Germa	yes	"In accordance with the International Transportation Forum (ITF), micromobility is the use of "micro vehicles with a mass of less than 350 kgs and a design speed of 45 km/hour or less" (2020, p. 10). However, due to their constant evolution, it is recommended that it should not be limited to certain types of vehicles or energy sources (Oeschger et al., 2020), even though	ITF

1 Note: references have been removed from quotes for ease of reading.

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Gismera-Tierno, L. 2022	Gismera-Tierno, 2022)	ny, Turkey and the United Kingdom		this growth is associated with the new generation of shared electric bikes and scooters (O`Hern & Estgfaeller, 2020)."	
Elmashhara, M.G., Silva, J., Sá, E., Carvalho, A., Rezazadeh, A.	(Elmashhara *et al.*, 2022)		no		
Zakhem, M., Smith-Colin, J.	(Zakhem and Smith-Colin, 2021)	USA	no		
Serra, G.F., Fernandes, F.A.O., Noronha, E., de Sousa, R.J.A.	(Serra *et al.*, 2021)	Portugal	yes	"The category of micro-vehicles is quite broad, ranging from human-propelled vehicles to electric and internal-combustion ones, with speeds typically reaching up to 45 km/h." Followed by a discussion of the ITF and SAE definitions.	ITF, SAE
Freire de Almeida, H., Lopes, R.J., Carrilho, J.M., Eloy, S.	(Freire de Almeida *et al.*, 2021)	Portugal	no		
Aman, J.J.C., Zakhem, M., Smith-Colin, J.	(Aman, Zakhem and Smith-Colin, 2021)	USA	not really	"Micromobility solutions include small-scale vehicles, such as bicycles, scooters, skateboards, segways, and hover-boards, can be human-powered or electric, and often cover short-distance trips. Shared micromobility programs, such as docked and dockless bikes and, recently, dockless electric scooters (i.e., e-scooters), have become increasingly ubiquitous in cities worldwide."	
Hosseinzadeh, A., Karimpour, A., Kluger, R.	(Hosseinzadeh, Karimpour and Kluger, 2021)	USA	no		
Sun, B., Garikapati, V., Wilson, A., Duvall, A.	(Sun *et al.*, 2021)	USA	not really	"These small, lightweight mobility options (commonly referred to as micromobility) build on a foundation of shared station-based manual bicycle systems, and have been extended in the past few years to include additional vehicles such as dockless bikes, and electric bikes, and electric scooters."	
Fazio, M., Giuffrida, N., Le Pira, M., Inturri, G., Ignaccolo, M.	(Fazio, Giuffrida, le Pira, et al., 2021)	Italy	yes	"Micromobility is a widely used term for low-speed modes of transport based on the use of electric-powered personal micro vehicles, such as e-scooters. E-bikes can be included in this definition as they have been in the USA, even if in some countries, such as Italy, micromobility usually refers to small electric devices, thus excluding e-bikes." The paper also mentions that micromobility "is used to indicate new types of transport modes that mainly use electric-powered personal mobility vehicles, such as hoverboards, segways, e-scooters, monowheels and e-bikes. They can be rented or shared vehicles or privately owned."	

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Meng, S., Brown, A.	(Meng and Brown, 2021)	USA	not really	"Today, micromobility includes docked (also known as station-based) and dockless bike-share, and dockless e-scooters."	
Şengül, B., Mostofi, H.	(Sengül and Mostofi, 2021)		yes	"Micromobility is defined as small and lightweight (less than 500 kg) modes of transport with speeds less than 25 km/h, most of which are used individually, such as the use of bicycles, and with the standing position, such as the use of scooters. E-micromobility vehicles are different from micromobility vehicles due to their motorized powertrains, which are electric, as in e-bikes, e-scooters, and e-skateboards."	Wikipedia; Deloitte: (https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/micro-mobility-is-the-future-of-urban-transportation.html)
Noland, R.B.	(Noland, 2021)	USA	no		
Pande, D., Taeihagh, A.	(Pande and Taeihagh, 2021)	Singapore	yes	"Theoretically, micromobility constitutes all passenger trips of less than 8 km (5 miles), which account for as much as 50 to 60 percent of today's total passenger miles travelled in China, European Union, and the United States. Micromobility devices can be both human-powered or assisted by electricity. The powered micromobility devices comprising electric scooters or e-scooters, e-bikes, hoverboards, electric unicycles, and e-skateboards have recently become popular." This is followed by a discussion of the ITF and SAE definitions.	ITF; SAE
Sandoval, R., Van Geffen, C., Wilbur, M., (...), Barbour, W., Work, D.B.	(Sandoval *et al.*, 2021)		no		
de Bortoli, A.	(de Bortoli, 2021)	France	no		
Reck, D.J., Haitao, H., Guidon, S., Axhausen, K.W.	(Reck *et al.*, 2021)	Switzerland	no		
Balacco, G., Binetti, M., Caggiani, L., Ottomanelli, M.	(Balacco *et al.*, 2021)	Italy	no	"E-bikes and Micro-Mobility (scooter, one wheel, segway)"	
McQueen, M., Abou-Zeid, G., MacArthur, J., Clifton, K.	(McQueen *et al.*, 2020)	n/a	yes	"We define micromobility modes as small, lightweight human-powered or electric vehicles operated at low speeds, including docked and dockless e-scooters and bike share systems."	SAE, Didiu (https://micromobility.io/blog/2019/2/23/the-micromobility-definition)
Askarzadeh, T., Bridgelall, R.	(Askarzadeh and Bridgelall, 2021)		no		
Esztergár-Kiss,	(Esztergár-Kiss and	Spain, Germa	kind of	"Shared mobility is the usage of bicycles, scooters, or other vehicles that enables users to have short-term access to transportation modes on an occasional basis"	

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D., Lopez Lizarraga, J.C.	Lopez Lizarraga, 2021)	ny, Denmark, Israel, Stockholm			
Luo, Q., Li, S., Hampshire, R.C.	(Luo, Li and Hampshire, 2021)	USA	no		
Oeschger, G., Carroll, P., Caulfield, B.	(Oeschger, Carroll and Caulfield, 2020)		yes	The paper discusses the ITF definition at length.	ITF
O'hern, S., Estgfaeller, N.	(O'hern and Estgfaeller, 2020)		yes	"Microvehicles encompass both traditional and emerging vehicle types, from conventional bicycles and powered-two wheelers, through to power-assisted e-bikes, e-scooters and new vehicles such as electric skateboards and "hoverboards"". The paper also discusses the ITF and SAE definitions.	ITF; SAE
Lo, D., Mintrom, C., Robinson, K., Thomas, R.	(Lo *et al.*, 2020)	New Zealand	no	"A class of low-powered lightweight utility vehicles designed for short trips, collectively termed "micromobility""	
Fitt, H., Curl, A.	(Fitt and Curl, 2020)	New Zealand	no		
Moran, M.E., Laa, B., Emberger, G.	(Moran, Laa and Emberger, 2020)	Austria	no		SAE
Lazarus, J., Pourquier, J.C., Feng, F., Hammel, H., Shaheen, S.	(Lazarus *et al.*, 2020)	USA			
Liao, F., Correia, G.	(Liao and Correia, 2022)	n/a	yes	"The term micromobility first appeared in 2017 and denotes those vehicles which are light (less than 500 kg) and designed for short distances (less than 15 km). It mainly consists of (conventional and electric) bikes and scooters, while it also includes other less common modes such as skateboard, gyro board, hoverboard, and unicycle."	
Feng, C., Jiao, J., Wang, H.	(Feng, Jiao and Wang, 2020)	USA	No		

Several of the papers provide examples of micromobility, most often bicycles, e-bikes and e-scooters. Indeed, Table 2 shows that the majority of papers with micromobility in the title focus on at least one of these modes, including shared schemes. Although most papers consider more than one mode, the majority do not consider a wide range of modes. Shared forms of mobility have received more attention than privately owned transport modes, which could indicate that the term micromobility is commonly linked to shared mobility. Interestingly, the growing literature on cargo-bikes does not appear under the label micromobility.

Table 2. Focus of papers in micromobility in the scientific literature (compiled from different sources).

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Author(s)	Reference	Focus of paper (not its definition of micromobility) on mode(s)											Type of (element of) paper:					Topic
		micromobility	e-scooters	shared e-scooters	e-bikes	shared e-bike	shared bicycles	e-moped	shared e-moped	bicycle	regular kickscooter	Motorcycle	motorized skateboards, hoverboards, Segways	empirical	review	conceptual	desk review laws	case study	
Zhao et al., 2022	(Zhao *et al.*, 2022)									x		x							International comparison road safety
López-Dóriga, et al., 2022	(López-Dóriga *et al.*, 2022)		x		x			x						x					Health impacts
Romm, Verma, Karpinski, Sanders, McKenzie, 2022	(Romm *et al.*, 2022)						x							x					User behaviour
Psarrou Kalakoni, Christoforou, Farhi, 2022	(Psarrou Kalakoni, Christoforou and Farhi, 2022)		x	x	x	x	x		x									x	evaluation of neighborhood suitability for micromobility
Fang, 2022	(Fang, 2022)		x		x					x	x		x	x					safety
Felipe-Falgas, P.; Madrid-Lopez, C.; Marquet, O. 2022	(Felipe-Falgas, Madrid-Lopez and Marquet, 2022)		x	x		x	x							x					LCA
Hamerska, M.; Ziółko, M.; Stawiarski, P. A, 2022	(Hamerska, Ziółko and Stawiarski, 2022)			x										x					quality of services for e-micromobility operators
Medina-Molina, C., Pérez-Macías, N., Gismera-Tierno, L. 2022	(Medina-Molina, Pérez-Macías and Gismera-Tierno, 2022)	X												x					Explaining the use of micromobility services between cities.
Elmashhara, M.G., Silva, J., Sá,	(Elmashhara *et al.*, 2022)	X		x			x		x						x				user behaviour shared

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E., Carvalho, A., Rezazadeh, A.										micromobility
Zakhem, M., Smith-Colin, J.	(Zakhem and Smith-Colin, 2021)		x					x		parking and road use
Serra, G.F., Fernandes, F.A.O., Noronha, E., de Sousa, R.J.A. cFreire de Almeida, H., Lopes, R.J., Carilho, J.M., Eloy, S.	(Serra *et al.*, 2021)	x	x						x	safety
Aman, J.J.C., Zakhem, M., Smith-Colin, J.	(Freire de Almeida *et al.*, 2021)							x		network
Hosseinzadeh, A., Karimpour, A., Kluger, R.	(Aman, Zakhem and Smith-Colin, 2021)		x	x	x			x		equity
Sun, B., Garikapati, V., Wilson, A., Duvall, A.	(Hosseinzadeh, Karimpour and Kluger, 2021)		x		x			x		weather
Fazio, M., Giuffrida, N., Le Pira, M., Inturri, G., Ignaccolo, M.	(Sun *et al.*, 2021)		x	x				x	x	energy
Meng, S., Brown, A.	(Fazio, Giuffrida, le Pira, et al., 2021)									
	(Meng and Brown, 2021)		x		x			x, comparative between modes		geographical inequalities.

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Şengül, B., Mostofi, H.	(Sengül and Mostofi, 2021)		x	x (not specified)	x	?						x		review impacts
Noland, R.B.	(Noland, 2021)			x		x	x				x, comparative between modes			weather
Pande, D., Taeihagh, A.	(Pande and Taeihagh, 2021)	x											x	history in a city.
Sandoval, R., Van Geffen, C., Wilbur, M., (...), Barbour, W., Work, D.B.	(Sandoval *et al.*, 2021)			x							x			parking
de Bortoli, A. Reck, D.J., Haitao, H., Guidon, S., Axhausen, K.W.	(de Bortoli, 2021)		x	x		x		x	x		x			LCA shared/private
	(Reck *et al.*, 2021)			x		x	x				x			mode choice
Balacco, G., Binetti, M., Caggiani, L., Ottomanelli, M.	(Balacco *et al.*, 2021)			(x)		x					(x)			distribution
McQueen, M., Abou-Zeid, G., MacArthur, J., Clifton, K.	(McQueen *et al.*, 2020)	x										x		GHG, equity, sustainability
Askarzadeh, T., Bridgelall, R.	(Askarzadeh and Bridgelall, 2021)						x							bike sharing stations
Esztergár-Kiss, D., Lopez Lizarraga, J.C.	(Esztergár-Kiss and Lopez Lizarraga, 2021)			x	x	x	x		x	x				travel behaviour
Luo, Q., Li, S., Ham	(Luo, Li and						x							network design

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pshire, R.C.	Hampshire, 2021)								
Oeschger, G., Carroll, P., Caulfield, B.	(Oeschger, Carroll and Caulfield, 2020)	x						x	integration with pt
O'hern, S., Estgfaeller, N.	(O'hern and Estgfaeller, 2020)	x						x	publication analysis.
Lo, D., Mintrom, C., Robinson, K., Thomas, R.	(Lo *et al.*, 2020)			x			x		perception regulation
Fitt, H., Curl, A.	(Fitt and Curl, 2020)			x			x		first experiences
Moran, M.E., Laa, B., Emberger, G.	(Moran, Laa and Emberger, 2020)			x			x (mapping)		spatial coverage and regulation
Lazarus, J., Pourquier, J.C., Feng, F., Hammel, H., Shaheen, S.	(Lazarus *et al.*, 2020)				x		x		impact shared e-bike on shared bike
Liao, F., Correia, G.	(Liao and Correia, 2020)	X	x	x				x	
Feng, C., Jiao, J., Wang, H.	(Feng, Jiao and Wang, 2020)			x			x		traffic flow

Most papers are empirical, but there are also six reviews. The topics researched vary widely, ranging from traffic flows, distribution of stations or fleet, parking, safety, and equity, to travel behaviour (see Table 1 and Table 2).

3.3:. Frequently referenced micromobility definitions by international societies and organizations

The academic papers discussed above draw mostly on two (non-national) institutional definitions of micromobility, by the International Transport Forum (ITF) and the Society of Automotive Engineers (SAE). The ITF definition is referenced in 4 papers, the SAE one in 5 papers and both are now discussed in more detail.

According to their own information, the ITF is an "intergovernmental organisation with 60 member countries" and "the only global body that covers all transport modes" while being "politically autonomous and administratively integrated with the OECD" and "act[ing] as a think tank for transport policy" (ITF, 2020, p. 2). Their 'Corporate Partnership Board' (a platform for industry perspectives) published a report titled 'Safe Micromobility' in 2020, in which a micromobility definition is provided.

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For the ITF, speed and weight are two key characteristics. The report thus defines micromobility as "the use of vehicles with a mass of less than 350 kilogram (kg) and a design speed of 45 kilometers per hour (km/h) or less" that can be either "human-powered" or "electrically-assisted" (although it later states that fuels tanks are an option too) (ITF, 2020, p. 14). The ITF indicates that micromobility modes vary considerably in terms of design, stating that these vehicles are "polymorphic" and "cannot be defined by the number of wheels, nor by the riding position, which can be seated or standing" (ITF, 2020, pp. 14–15). Four types of micromobility vehicles are distinguished based on the two key defining characteristics, i.e. speed ("unpowered or powered up to 25 km/h (16 mph)" and "powered with a top speed between 25-45 km/h (16-28 mph)") and mass (below "35 kg (77 lb)" and "35 – 350 kg (77 – 770 lb)") (ITF, 2020, p. 16).

The second definition often used in academic papers is by the SAE. It is interesting to see that a major automotive organization is involved in the micromobility debate, with a classification of micromobility by Society of Automotive Engineers, (2019) as well as Chang *et al.*, (2019) report on it.

The defining factors for the SAE include the kind of power, weight, speed, and purpose. The "wheeled vehicles" should be under 227 kilograms (500lb) and have a speed below 48km/h (30mp/h). It is important to note that the SAE's definition focuses solely on "powered micromobility", either partially or fully powered. This, therefore, excludes exclusively human-powered vehicles. Moreover, their definition states that it is for "vehicles that are primarily designed for human transport and to be used on paved roadways and paths". This implies that transport modes for freight are thus excluded (unlike the definition of ITF).

SAE also has a classification system for describing vehicle types. Key characteristics include curb weight, vehicle width, maximum speed and power source, with 2-4 options each. Furthermore, the types of micromobility are distinguished according to centre column, seat, operable pedals, floorboard/foot pegs, and self-balancing (Society of Automotive Engineers (SAE), 2019). Table 3 (section A) provides a comparison of key parts of the ITF and the SAE definitions.

Table 3. Comparing the micromobility definitions, modes, and purposes in the ITF and the SAE (key differences in italics).

Section A: Comparing the micromobility definitions		
	ITF	**SAE**
How powered?		
Human	*Yes*	*No*
Assisted	Yes	Yes
Fully	yes	Yes
Electric motors	Yes	Yes
Combustion Engines	Yes	Yes
Others		
Top weight	*350kg*	*227 kg*
Top speed	45 km/h	48 km/h
Purpose	*All mobility*	*Only personal transport*
Number of wheels	No	No
Has sub-categories?	Yes, 4	Yes, many
Section B: Modes and purposes considered as micromobility		
Modes and Purpose	**ITF**	**SAE**
Bicycle	yes	No
E-bike	yes	yes
E-scooter (standing)	yes	yes
E-scooter (sitting)	yes	yes
Cargo-bicycle	yes	no
e-cargo-bicycle	yes	if for transporting people: yes; for freight: no
Skateboard	yes	no
Hoverboard	yes	yes
All-terrain vehicle	yes (depending on weight)	yes (depending on weight)

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Human Transport	yes	yes
Freight Transport	yes	yes

The differences between the two definitions may appear small in the first instance. However, they have implications on which modes are considered micromobility (see for example Table 3, Section B), which may partly explain the variety of definitions and inclusions of modes in the scientific literature. For example, many human-powered vehicles, including bicycles, would be included in micromobility following the definition of ITF but not that of SAE. The exclusion of human-powered vehicles is a significant issue that has associated public health implications. The exclusion of long-standing and well-researched modes such as cycling is also rather Western-centric. In addition, the SAE definition focuses solely on personal transport and excludes freight, while the ITF's definition covers both. The ITF definition makes not explicit reference to wheelchairs but includes a mobility scooter in the visual. The SAE definition does not refer to mobility options used around disability.

4. Dimensions and characteristics of micromobility

The analysis in section 3 has shown how the literature primarily uses vehicle examples or technical characteristics to define micromobility. Vehicle weight, range, speed and primary usage are key, of course, but capture only part of what micromobility is. Here we argue that vehicle technology is only one of several dimensions, alongside dimensions that situate the technology within transport systems, infrastructures (transport, energy, ICT), operations (e.g. shared vs private), and the wider socio-technical system that focuses equally on people and technology. Micromobility may also be defined by its core attributes within that system, including social, environmental, economic, and public health benefits and risks/costs. As recent experience in the UK and other countries has shown, the legal and policy frameworks regulating ownership and use of micromobility services are part of the factors that may determine their 'success' or 'failure' in achieving economic, social and environmental goals. This section discusses seven key dimensions, each with several characteristics, building up to the paper's new definition in section 5.

4.1. Vehicle technological dimension

A vehicle – broadly defined as a machine that transports people or cargo (Halsey, 1979) – forms a key dimension of the concept of micromobility. Note that the use of a vehicle is not essential, as walking is also an important part of our understanding of micromobility. Walking may or may not include the pushing or pulling of a vehicle, such as a pushchair, a shopping trolley or a cart.

Main vehicle design characteristics include the vehicle shape, number of wheels, size of wheels, number of seats, and centre of gravity. Here we include fully and partially powered as well as non-powered 'micro' vehicles that allow for a sit-down, recumbent and stand-up positions, with between one and four wheels. The centre of gravity varies, with recumbent bikes having the lowest, and step penny-farthings the highest. Some vehicles can be used for carrying (cargo or people) loads or with physical impairment, often with 3- or 4-wheel design and lower, easy access (Cazzola and Crist, 2020).

The 'micro' in micromobility also refers to vehicle weight. We propose a maximum vehicle weight of 350kg, as per the ITF definition. In contrast, a car will usually weigh over 1000kg or more. Partially and fully powered micromobility vehicles are typically 20-50% heavier than their fully-human powered counterpart (Clark, 2020).

In terms of vehicle speed, two characteristics are important here: design speed (i.e. the top speed a vehicle is designed for) and, for electric vehicles, the max. assistance speed (i.e. the speed at which a motor ceases to assist or accelerate). Both can vary, depending on the vehicle type. Given the evidence in the previous section, it seems practical to see 25

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km/h as a common threshold for many forms of partially- or fully powered micromobility, though with a sub-category that can achieve speeds of up to 45km/h (Cazzola and Crist, 2020).

Human-powered micromobility can exceed these speeds (e.g. race cycling).

Payload capacity refers to the amount of cargo and/or the number of people a vehicle can carry in addition to the main user. For micro scooters, the extra payload is virtually zero. In contrast, e-cargo cycles are capable to transport 50-250 kg of cargo (with a few vehicles able to transport up to 500 kg) (Narayanan and Antoniou, 2021a). For some modes, additional trailers can be used to increase payload capacity.

Motorised forms of micromobility are further characterized by vehicle power, range and specific energy consumption. 'Motorisation' can be specified on a continuum – from non-motorized, to motor assistance, to fully motorised. Both combustion engines and electric powertrains are options, though the focus in vehicle development and deployment worldwide has been on electric (Cazzola and Crist, 2020). Electric powertrains include the motor, transmission and at least one battery as energy storage. There are two systems of motor, namely hub-drive and mid-drive (Narayanan and Antoniou, 2021). While the former is meant for frequent riding on even roads with an occasional inclination, the latter is meant for frequent riding on hilly roads with an inclination of more than 3%. Pedelecs (a term used synonymously with electrically-assisted bicycles and e-bikes in this paper) have an electric motor with max. 250 watts in much of Europe (Switzerland: max. 500 watts).

Battery capacity (a measure of the available power, in watt-hours, Wh) is a key characteristic here, with associated costs and performance largely determining the price and suitability of the vehicle. Typical e-bike batteries range from 250 Wh to 1,000 Wh. Step e-scooter batteries have a capacity of about 500 Wh, weighing 4-5 kg (Kazmaier, Taefi and Hettesheimer, 2020). Today, a small 250 Wh battery on a pedelec will have a range of between 25 and 50 km. E-cargo bikes have a battery range of up to 80 km (Narayanan and Antoniou, 2021a). A typical e-bike charger would have a 5 amp (A) rating, charging a (small) battery to full capacity in an hour.

As speed pedelecs (S-pedelecs) are more powerful and faster versions of pedelecs, the max. motor output is about 4,000 watts (i.e. 16 times higher than pedelecs) – with pedal support working up to the design speed of 45 kph. S-pedelecs are classified as mopeds in the EU (cat. L1e-B) and thus require insurance and a license plate. E-Mopeds – sit-down scooters – typically have a top speed of 45 km/h, an average range of 43 km, and up to 4 kW for the motors (Schelte *et al.*, 2021).

Weather protection on the vehicle itself (instead of weather-proof clothing and storage) is becoming increasingly popular. Some vehicle designs incorporate weather and crash protection. Downsides include increased cost and weight.

Most vehicle steering is via front wheel(s) and some kind of fork. Vehicle braking is standard, i.e. rim brakes or more powerful disk brakes. Energy recovery through regenerative braking mechanisms is technically possible for larger micro-vehicles (Ewert *et al.*, 2021). For smaller ones such as e-scooters, there are too many losses in energy transfer. For e-bikes, most frame designers prefer the mid-drive motor configuration (see above), which implies insufficient scale to develop regenerative braking breakthroughs.

ICT that is, 'smart' or connected vehicles equipped with either a one- or two-way flow of digital data are becoming more popular and are essential for shared services. Data-driven services include GPS tracking, geo-fencing, locking, route guidance, ticketing, and energy consumption monitoring. This is a fast-developing area (Behrendt, 2016; Nikolaeva *et al.*, 2019).

In terms of technological innovation, cycles have been around for centuries, so can be considered mature technology. However, e-bikes and e-scooters, and other forms of newly motorized travel options that are part of micromobility are still evolving and will benefit – in terms of cost, performance and sustainability impacts – from further innovation and development in all technical elements.

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4.2. Transport system and operational dimensions

Transport systems (e.g. passenger road), infrastructures (e.g. transport, energy) and operations (e.g. shared vs private) are important dimensions one level above the vehicles and their users.

The necessary infrastructure is one of the key characteristics of micromobility. Infrastructure should ideally be of high quality and safe for all user types – particularly children and other vulnerable users. This often means purpose-built infrastructure (lanes, tracks, junction designs etc), with space potentially segregated for different sorts of movement. Traditionally, travel space has been divided by vehicle types – e.g. cars, bikes, and pedestrians. Micromobility options may require rethinking whether this is most appropriate or whether it should be based on particular vehicle characteristics such as vehicle speed and/or weight, which may be more directly related to safety. The quality of the road surface is of particular importance for small-wheeled micromobilities. Geofencing may offer the potential to ensure that micromobility modes are speed limited (in specific areas/at specific times) to ensure compatibility between different travel modes. Low-speed/traffic zones (30 km/h) can reduce speed variability between modes or give priority to micromobility modes (separation), both of which make it safer for people to use the slower modes.

As 'micro' suggests, micromobility vehicles typically have a lower spatial footprint than car travel – for both moving and parking. For moving, the ratio is about 1:4 for biking:car, 1:2 for e-cargo bikes:car (Ewert *et al.*, 2021), 1:5.2 for e-step scooters:car, and 1:6.5 for pedestrians:cars (ITF, 2021).

Easy access to secure vehicle parking close to origins and destinations is a major factor influencing people's daily mobility choices. The parking space required by one car can fit about 12 bikes, 15 e-scooters or 3 cargo-bikes. To encourage micromobility use, parking has to be made secure, easy and low cost – both in terms of quality and quantity, and for a variety of micromobility modes. This is relevant both for public and private spaces and for shared and privately-owned modes.

Vehicle access and ownership are key characteristics, particularly for relatively expensive vehicles and in areas where private parking or storage is an issue. The two main business models are individually owned or shared micromobility. For shared, the two main business models to date have been via docking stations or dockless parking/storage. Most shared systems involve ICT 'enabled', smart connectivity and payment methods. They require vans, trucks or e-cargo bikes to collect, charge, and reallocate e-vehicles, with major implications for the carbon footprint (Cazzola and Crist, 2020). A key characteristic is a need for user compliance with the company- and government-mandated policies – from helmet use to parking to a requirement to hold a valid (car) driving license. While individual ownership is free of most of these restrictions and has a lower carbon footprint, the range of micromobility vehicles owned by an individual household is likely to be limited.

As mentioned earlier, micromobility is increasingly integrated with other forms of mobility, particularly public transport. The key characteristics are the ease and legality with which micromobility vehicles can be taken on board a train or bus, ease of access to the nearest bus or train station, integration and availability of parking at public transport hubs, and whether shared vehicles are integrated in terms of ticketing and journey routing.

4.3. Social and cultural dimension

The social dimension covers who use (and who does not use) micromobility, why (or why not), for what purpose, and the relevant social and cultural contexts. It also includes geographical concerns, as cities and countries cultivate different cultures and combinations of micromobility modes, such as high cycling share but no use of step-scooters in the Netherlands, or low cycling share but strong e-scooter usage in large cities in the US.

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To date, certain micromobility modes have appealed more to some user groups or segments of the population than others (Melia and Bartle, 2021; Mitra and Hess, 2021). Age, gender and, socio-economic status all play a role (6-t for Voi, 2021). For example, e-scooters have been popular with the younger generation, while e-bikes have widened the range of users to the older generation and the physically impaired (Spencer *et al.*, 2019). User age can be a criterion for access to shared mobility, e.g. in the UK shared e-scooters can only be used for those aged 18+, whilst e-bike use is limited to 14+. The appropriateness of age restrictions is a matter for debate if trying to foster less car-dependent travel patterns from a young age. Shared micromobility services rely on a limited user base, and in places like Zurich, for instance, this base is comprised mainly of young, well-educated, affluent males (Reck and Axhausen, 2021). While there is a significant white/male/middle-class bias in the West, class connotations also play a part in other countries and cultures (Hasan *et al.*, 2019; 6-t for Voi, 2021).

Households without cars, and individuals who lack access to a car due to factors such as age or income, often have limited access to a full range of services and facilities. Micromobility arguably has the potential to reduce social exclusion (Tyler and Lucas, 2004), since access costs are typically lower, and vehicles are usable by a wider range of people. However, access costs may still be non-trivial, and shared services may often be located in places where revenue can be maximized rather than the need being greatest. Arguably, encouraging more localised patterns of living both facilitates, and is facilitated by, greater use of micromobility vehicles. Opportunities for promoting micromobility may arise in areas which are vulnerable to car-related economic stress and also have a high capability to replace car km with e-bikes. If supported appropriately, encouraging micromobility in such locations could contribute to relatively equitable carbon reduction (Philips, Anable and Chatterton, 2022).

Most types of micromobility can be used for the most common journey purposes and on short- to medium-length trips, including for commuting, shopping, escorting children on the 'school run', and visiting friends or family (Abduljabbar, Liyanage and Dia, 2021). However, some are more suitable for trips that involve transporting cargo (shopping, children) such as e-cargo bikes and trikes. E-scooters are suitable for shorter journeys in towns and cities, while e-bikes extend the range to intra-urban and rural journeys (Philips, Anable and Chatterton, 2022) – and as access to public transport in general (Azimi *et al.*, 2021).

While many forms of micromobility do not require extensive skills (e.g. scooters), many do require some skill development (e.g. cycling). All micromobility options could or should benefit from some form of training. Skills are often provided via informal settings such as in the family. Formal schemes (e.g. cycle or scooting training in schools) also exist – however, most are typically geared towards children, with a lack of provision for adults and those not benefitting from a micromobility-supportive context. The level of training needed is probably the highest for heavier e-cargo bikes and faster e-scooters and S-pedelecs. For those operating on roads in mixed traffic, knowledge of traffic regulations is essential but is not currently legally regulated in most cases. Training for motorists also needs to centrally include micromobility awareness.

This leads to the key issue of perceived safety and crash risks for both riders and others. The current debate about safety issues is often over-simplistic, with particular modes being branded as safe or unsafe. In practice, the details of each mode (speed, safety features) and the nature of the infrastructure, alongside the policy, societal and cultural context are key factors (Branion-Calles *et al.*, 2019; Sanders, Branion-Calles and Nelson, 2020). Above all, however, the dominant system of automobility is central for most safety-related issues around micromobility. The perceived and real safety of micromobility varies widely between countries and cities, but can often be a key barrier to uptake (ITF, 2020; Sanders, Branion-Calles and Nelson, 2020; Sulikova and Brand, 2021).

Fear of vandalism and theft is also a key concern for users, shared micromobility operators and local authorities (Gössling, 2020). Providing secure and safe parking around key destinations (shopping areas, railway stations, etc.) and at home (secure parking and

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storage) can minimize the risks involved. There is also continued innovation concerning vehicle tagging, tracking and locking systems (see section 4.1 on vehicle technological dimension).

4.4. Environmental dimension

The key environmental impacts of micromobility relate to local air quality, greenhouse gas emissions, and noise pollution.

In terms of local air quality, the key regulated air pollutants are nitrogen oxides (NOX), particulate matter (PM) of various sizes and toxicity levels, carbon monoxide (CO) and total hydrocarbons (THC). Some of these are precursors to secondary air pollution, such as ozone (O3). Partially or fully electrically and human-powered micromobility vehicles have zero emissions at the point of use. However, all-electric vehicles will incur upstream emissions from electricity generation – depending on how the electricity is generated, stored and delivered. As a rule of thumb, the higher the share of renewables and the lower the share of coal in the system the lower the carbon content of electricity. There are also non-tailpipe emissions of toxic particulates from brake and tyre wear – but these are very small compared to those from car use.

Greenhouse gas emissions (carbon dioxide equivalent, CO2-eq) from vehicle creation, use and disposal are a key environmental impact metric and are generally lower for micromobility options than for cars (de Bortoli, 2021).

Table 4 shows comparable figures for a range of vehicles, taken from a single source (Cazzola and Crist, 2020). Specifically, this table provides three key measures of the emissions:

- Per vehicle emissions generated by vehicle and battery manufacture, assembly, delivery to point of purchase, and disposal.
- Per vehicle emissions generated by the operational services involved in shared schemes
- Emissions per passenger km directly generated by vehicle use.

Table 4. Comparing average GHG emissions based on (Cazzola and Crist, 2020).

Transport mode and operation	Average GHG emissions (in gCO_2-eq) for (a) Vehicle and battery manufacture, assembly and disposal (including fluids), plus delivery to point of purchase	(b) Operational services (per vehicle)	(c) Energy use, whilst in use, per passenger km (including emissions from fuel production)
Bike	100,398	0	0
Shared bike	128,454	136,111	0
Private e-bike	168,510	0	11.8
Shared e-bike	204,595	136,111	11.8
Private electric step scooter	172,685	0	6.2
Shared electric step scooter (new generation)	374,001	140,886	6.7
Private moped (ICE)	391,272	0	54
Private moped (BEV)	480,145	0	20
Private car (ICE)	6,496,825	0	125.6
Private e-car (BEV)	11,339,015	0	71.5

Data taken from (Cazzola and Crist, 2020), and associated online spreadsheet of calculations:

life-cycle-assessment-calculations-2020.xlsx (live.com)

Specifically, data are taken from the 'Total' worksheet, as follows: (a)= rows 113 and 114; (b) = row 116; (c) = row 101. Infrastructure emission figures are not included given the greater uncertainty associated with calculations, but those given are lower for micromobility vehicles than for cars.

ICE = internal combustion engine (i.e. conventional fossil-fuelled vehicle)

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BEV = Battery electric vehicle (i.e. fully electric vehicle)

The full range of assumptions used to generate the figures is given in the source report.

Component figures from the source are given, rather than traditional lifecycle figures (for 'all emissions' per km or per passenger km travelled), since lifecycle calculations are strongly influenced by lifetime mileages. Since a paradigm shift to micromobility vehicles would arguably involve a shift to more localised living and working patterns, and/or combined use with public transport for longer journeys, in order to understand the scope for emission savings, it is therefore more meaningful to consider emissions separately in terms of 'fixed' emissions (from vehicle creation and disposal) and emissions that result from (different types of) use. For example, lifecycle figures suggest that using an ICE car compared to an e-bike would result in emissions that are only 6x greater2. However, according to the data given in Table 4, the 'fixed' emissions associated with producing a private ICE car compared to an e-bike are 39 times greater, and emissions from use are 11 times greater3, (with other sources suggesting differences may be even more substantial). Consequently, a shift to micromobility has the scope to deliver considerably greater emissions savings than a consideration of lifecycle figures might imply. Put another way, suppose someone only travels 2,000 km per year and plans to keep whatever vehicle they buy for 10 years, then, according to the Table 4 figures, for that travel, buying and using an e-bike would generate 0.4 tonnes of CO2-eq, whilst buying and using an e-car would generate 12.8 tonnes of CO2-eq.

Often overlooked or framed as a safety hazard to pedestrians, the much lower levels of noise pollution of micromobility are potentially a key benefit (Bakker, 2018). Electric bikes and step scooters are generally not much louder than their acoustic versions, while electric cars are often not quieter than ICEs at higher speeds.

4.5. Economic dimension

Personally-owned and shared micromobilities, and both older modes such as bicycles, and newer modes like step scooters have seen significant market growth over the last decade or so, with innovation around vehicle technologies as well as business models. The technological maturity varies across micromobility options; it is relatively high for bikes and low for the more recently emerging modes like e-scooter and e-cargo bikes and trikes.

The shared micromobility sector is rapidly evolving, with technologies, regulations, and business models changing quickly and unexpectedly (Heineke, Kloss and Scurtu, 2020; ITF, 2021). After significant investment (including venture capital), the market saw several mergers, acquisitions and bankruptcies, also in response to post-Covid conditions and regulatory struggles (Ratti and Auken, 2019; Heineke, Kloss and Scurtu, 2020). Still, some forecasts see the market grow from $48.11 billion in 2021 to $300 billion in 2030 (Heineke, Kloss and Scurtu, 2020; CBInsights, 2021; Edward, 2022). It is worth noting that the existing market forces and business models tend to propel profit-maximising outcomes, rather than public interest, risking the exclusion of some social groups (Sareen, Remme and Haarstad, 2021).

The cost of manufacturing, purchase – and maintenance – significantly varies according to the type, range and other technical specifications, production volume, location of

2 Cazzola and Crist suggest lifecycle figures of 24gCO2-eq per pkm for a private ebike and 150gCO2-eq per pkm for an ICE private car.

3 Other papers suggest even lower figures for the use of micromobility modes. Specifically, Cazzola and Crist assume energy use of 21Wh/km for e-bikes. However, for example, Weiss, Cloos and Helmers (2020) suggest a mean value of 7Wh/km for e-bikes (see their Table 1), which is more in line with advertised battery ranges.

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production and distribution, construction materials, brand, accompanying software, and other factors. Batteries and motors are key components in terms of costs. Access costs to shared schemes vary, but often feature a time and/or distance component, while the costs of providing these schemes include re-location, maintenance and credit card fees (Heineke *et al.*, 2019).

Economic spillovers could include increased spending in local food, retail, entertainment, health, and fitness sectors, though eat-in restaurants might be negatively impacted by micromobility home deliveries (Kim and McCarthy, 2021; Rivlin and McCarthy, 2022).

The 'economic lifetime' is often used in economic analyses of the costs and benefits of vehicles and mobility services. Economic lifetime is typically expressed as a lifetime mileage or age before scrappage. Micromobility features a wide range, from 3 months for some shared e-scooters (Schellong *et al.*, 2019) to eight years for pedelecs (Buchert *et al.*, 2015), and several decades for bicycles, though with figures generally rising over time.

4.6. Public health dimension

Most micromobility options require some form of physical activity above resting or car driving. This can have significant public health impacts. The level of physical activity needed depends on the vehicle type – walking and cycling are the most active, electric step-scooters require standing and some pushing off, while electric mopeds are the least active. Micromobility has been shown to improve both physical and mental health (Sanders, Branion-Calles and Nelson, 2020; Sengül and Mostofi, 2021), even if electrically assisted (Castro *et al.*, 2019). The main public health risks are increased mortality/morbidity from crashes and exposure to air and noise pollution – particularly in mixed road traffic (Götschi *et al.*, 2020; Maizlish, Rudolph and Jiang, 2022). The large public health-related variation of different micromobility modes needs to be considered by policymakers.

4.7. Legal dimension

Permitted location of use is a key characteristic and varies by vehicle type and jurisdiction. For instance, restrictions on weight, power, and speed of e-bikes vary by jurisdiction, typically 250 to 500 W maximum motor power and 25 to 40 km/h maximum speed with assistance (Bigazzi and Wong, 2020). As mentioned earlier, the UK allows only shared e-scooters to be used on public roads in trial areas, while private e-scooters are illegal on public roads or pavements. This policy area is dynamic and subject to change rapidly (both at the national and city level) – but is clearly important.

Some micromobility modes are promoted and encouraged vis-a-vis other, less sustainable modes of transport. E-bikes and e-scooters, for instance, are often permitted to be used in clean air zones, city centre pedestrianized zones, and so on. This can be a driver for uptake and encourage substitution of other motorized modes (car, bus, etc.).

In some jurisdictions, riders/users are required to hold a license for public use for some categories of micromobility vehicles. This can be linked to the user's age. Other jurisdictions require riders to carry safety equipment (e.g. helmet, lights) or stipulate third-party insurance as a requirement for use on public roads.

5:. Conclusion and Definition of Micromobility

Drawing on the concepts covered in section 2, the literature analysed in section 3, and the dimensions and characteristics outlined in section 4, here we propose a new, socio-technical and multi-dimensional definition of micromobility:

According to this proposed conceptualisation, micromobility covers a wide range of mobility options that can typically be manoeuvred by one human without motor assistance, at least for short distances. 'Micro' is seen as being a relative term - in terms of energy demand, environmental impact, as well as the use of road space – vis-a-vis automobility. Micromobility comprises both long-standing and novel forms of mobility, including fully human-powered, partially motor-assisted and fully powered options. It can

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move humans, cargo, or a combination. Current examples of micromobility include walking, cycling, (speed) e-bikes, step-scooters, moped scooters, cargo bikes, rikshaws, wheelchairs, mobility scooters, (e)skate and hover boards. They typically do not exceed 25 km/hour (or 45 for faster ones) and weigh (often significantly) less than 350 kgs, while often providing some (public) health benefits. Trip lengths are typically less than 15 km and the daily distance travelled is less than 80 km. Micromobility includes the practices, policies, cultures, and infrastructures that emerge around the use of these mobility options and shape their uptake, including interaction with other systems such as energy and ICT, see Figure 2.

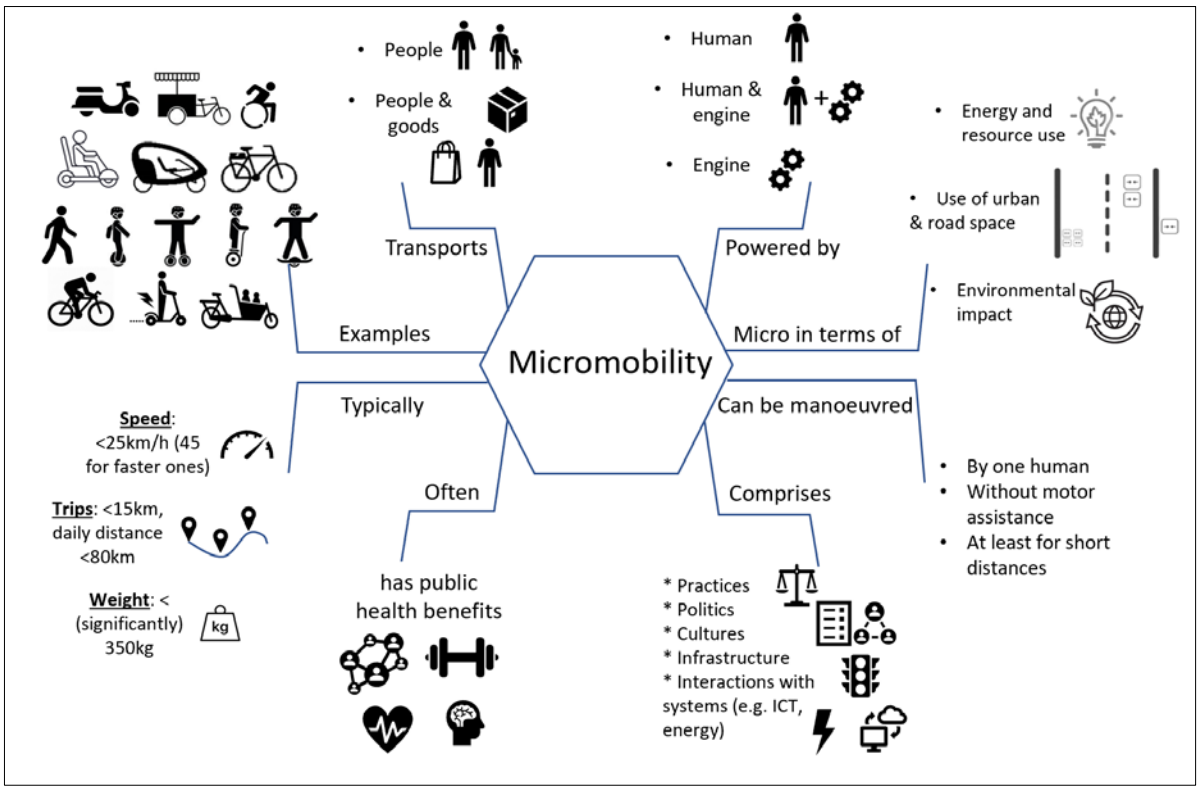

Figure 2. Visualization of our Definition of Micromobility

This new micromobility definition is designed for use in future transport and mobility studies, as well as in policy, to complement existing vehicle-driven definitions and to address the lack of broader conceptual approaches to micromobility. Advantages of a new and widely accepted definition and conceptualisation of micromobility could include more robust design standards, legislation, as well as evaluation metrics and methods, all leading to a greater understanding of and attention paid to this form of mobility.

While the debates and literature on micromobility reported here have focussed on land-based mobility, future research could also explore water- and air-based forms of micromobility. Water-based micromobility is particularly relevant for areas with significant water-based transport, such as some South-East Asian countries, and could include traditional modes such as rowing and sailing, but also recent trends such as small, e-motor-powered boats. Air-based micromobilities are particularly relevant in inaccessible areas or those with little land-based infrastructure and would include traditional modes such as gliding, but also novel forms of drone-based and solar-powered flight. The literature is also relatively Western-centric and it is important to widen the debate to learn from expe-

rience in places like Africa and Asia, where uptake of certain options may be greater. Furthermore, micromobility scholarship and policy should better integrate mobility debates on disability.

In the context of transport emissions still rising globally, despite the urgent need for their reduction (IPCC, 2022), micromobility has significant potential for decarbonizing personal and freight transport. Recent studies estimate that large-scale take-up of LEVs (many of which are considered micromobilities) could lower personal transport-related CO2 emissions by 44% in Germany (Brost *et al.*, 2022), while several studies assess the potential CO2 savings of shifting from car to e-bike at 12-50% (Cairns *et al.*, 2017; McQueen *et al.*, 2020; Philips, Anable and Chatterton, 2020), and 10-30% of last-mile delivery trips could be shifted to e cargo-bikes (Cairns and Sloman, 2019; Narayanan and Antoniou, 2021). It would be interesting to see an inclusion of micromobility in reports such as the IPCC's, which already indicates the high feasibility of non-motorized transport as an important mitigation and adaptation option for climate change (de Coninck *et al.*, 2018, pp. 16–17).

This paper also highlights micromobilities' environmental benefits and potential beyond lowering carbon emissions per kilometre or mile of vehicle use. This includes the combination of micromobility with public transport, where the traditional 'walking' radius around stations and stops is significantly extended in terms of distance, but also in terms of including those less likely, willing, or able to walk. This is directly relevant to urban planning debates such as Transit Oriented Development (Jain, Singh and Ashtt, 2020), rural accessibility of public transport (Hansson *et al.*, 2019), and Liveable Cities (Nieuwenhuijsen, 2020), where a micromobility approach would extend the value of current work on cycling and walking. Micromobility also intersects with debates on more localised living and working, where less distance is travelled, and trends towards less office-based and more ICT-enabled working.

Micromobility-inclusive, or -focussed approaches to transitions to sustainable mobilities would also provide a credible alternative to the current policy focus on electric cars, that is proven to neither reach carbon saving goals quickly enough (Brand *et al.*, 2020), nor to present a just and inclusive solution (Henderson, 2020), in either the Global North or South. This paper thus calls for the central inclusion of micromobility in debates around the Mobility Transition (Moradi and Vagnoni, 2018), to explore how micromobilities could be central to transition pathways in terms of environmental, social and economic elements of sustainability, in relation to the SDGs, and with regards to mobility justice.

Declaration of Interest

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

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