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Measuring just accessibility within planetary boundaries

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ABSTRACT

Our societies struggle to provide a good life for all without overconsuming environmental resources. Consequently, scholarly search for approaches to meet environmental and social goals of sustainability have become popular. In transport research, accessibility is a key tool to characterise linkages between people, transport, and land use. In the current paper, we propose a conceptual framework for measuring just accessibility within planetary boundaries. We reviewed transport studies and discovered a substantial literature body on accessibility and social disadvantage, much vaster compared to the literature around environmental and ecological impacts of accessibility. We also show a gap in approaches that have integrated these two perspectives. Building on the review, we suggest a conceptual framework for incorporating environmental and social sustainability goals in accessibility research. We conclude the paper by pointing to key challenges and research avenues related to the framework, including (i) dealing with uncertainty and complexity in socio-ecological thresholds, (ii) integrating environmental limits into the conceptualisations of transport equity, (iii) measuring accessibility through other costs than travel time, and (iv) integrating both quantitative and qualitative data.

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Accessibility; social disadvantage; planetary boundaries; equity; transport; safe and just space

1. Introduction

Limited natural resources bind all human activity. However, contemporary societies consume these natural assets vastly beyond sustainable levels, and we have exceeded or are about to exceed several "planetary boundaries" (Rockström et al., 2009; Steffen et al., 2015), with potentially devastating consequences for natural and human life. Simultaneously, no country has been able to meet the basic social needs of its residents at a sustainable level of natural resource use, and growing environmental stresses are only adding to social

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challenges (Fanning et al., 2022; O'Neill et al., 2018). As a response, the interdisciplinary discourse combing the social and environmental perspectives of sustainability has been expanded. One key idea in this discussion is the "safe and just space" framework proposed by Kate Raworth (2012, 2017). Building on the "planetary boundaries" concept, this framework aims to help to avoid both the critical planetary degradation and social deprivation while highlighting the need to approach social and environmental goals as being interdependent. While the model was originally developed for economy, it may be useful in other contexts.

Spatial mobility of people and goods is a prominent factor in pursuing environmental and social sustainability. The increased mobility over the last century has brought remarkable benefits for individuals and societies, and our current lifestyles depend on travel (Banister, 2011). Nonetheless, mobility is outstripping planetary limits. The transport sector is among the chief contributors of greenhouse gas emissions, air pollution, and is a driver of land use change and biodiversity loss (Anenberg et al., 2019; Dillman et al., 2021; IPCC, 2022). Deep emission cuts are required to make transport compatible with limiting global warming to 1.5°C, but the progress remains highly insufficient (IPCC, 2022). After a short dip due to the COVID-19 pandemic, the emissions from road transport have quickly bounced back (Rivera et al., 2022), and projections estimate motorised mobility to almost double globally in cities by 2050 from the 2015 levels (ITF, 2018).

In transport research and planning, spatial accessibility has become a key tool for characterising the spatiotemporal linkages between people, transport, and land use. By being conceptually rich and diverse, accessibility has a range of definitions. We employ the one that defines accessibility as the potential of opportunities for interaction (Hansen, 1959). Hence, we refer to access as the ease and freedom with which everyday destinations, such as services, jobs, and leisure activities can be reached. Accessibility is an essential component of many urban processes. It is a major factor in explaining location decisions of people and services, incomes, property prices and investment decisions (Cervero, 2005; Levinson & Wu, 2020). Thus, measuring accessibility helps in assessing how equitably urban and rural environments serve different groups of people (Järv et al., 2018; Lucas, van Wee, et al., 2016; Martens, 2017; van Wee & Geurs, 2011). A wide variety of simple to highly sophisticated accessibility measures has been developed in various disciplines (see several reviews and overviews by Geurs & van Wee, 2004; Handy & Niemeier, 1997; Miller, 2018; Paez et al., 2012; Wu & Levinson, 2020).

Accessibility is also decisive for many of the social and environmental impacts of transport. For decades, transport, geography and planning scholars have argued that accessibility is an important measure of the overall life quality (Wachs & Kumagai, 1973). More recently, an extensive literature has studied how (the lack of) accessibility plays a role in social exclusion (e.g. Farrington & Farrington, 2005; Lucas, 2012; Luz & Portugal, 2022). Others have critiqued the environmental impacts of transport, and highlighted the link between higher access and lower emissions in urban contexts (Banister, 2008; Bertolini et al., 2005; Owens, 1995). To improve the ability of transport planning and policy to address persisting social and environmental struggles, a wide range of scholars has called for the transport sector to reorient its purpose from expanding mobility to improving accessibility (Banister, 2011; Cervero, 1997; Handy & Niemeier, 1997; Levine et al., 2019; Martens, 2017; Miller, 2018; Pereira et al., 2017; van Wee & Geurs, 2011).

Compared to the mobility-focused approach, the accessibility-oriented planning is better positioned to advance both the environmental and social sustainability of transport. By relating directly to what people can or cannot do, accessibility describes the potential rather than the actual travel behaviour. This is important, because the focus on observed travel behaviour easily ignores the unfulfilled needs of disadvantaged population groups (Luz & Portugal, 2022). Accessibility also enables a wider range of solutions for improving social outcomes without exceeding planetary limits. Changes in land use, time policies and virtual means may provide solutions, which improve accessibility, but also lead to fewer travel kilometres and less energy use through increased walking and cycling (Banister, 2008; Bertolini et al., 2005).

However, it is still common for accessibility studies and for transport research more broadly to treat social and environmental issues separately (Grossmann et al., 2022; Karjalainen & Juhola, 2021). There is a growing scholarly consensus that improving accessibility is paramount in promoting social inclusion, and just cities (Martens, 2017; Pereira et al., 2017). Decent transport accessibility is fundamental to reach essential activities (such as employment, health services and grocery shops) and thus satisfy basic needs (Farrington & Farrington, 2005; Lucas, Mattioli, et al., 2016; Pereira & Karner, 2021). However, realising the accessibility potential usually requires some level of resource use. The accessibility levels conferred by different transport modes and configurations of transport networks and land use systems entail different environmental costs, such as in CO2 emissions and air pollution (Cui & Levinson, 2018). From these observations arises a latent tension between promoting accessibility and environmental sustainability, a trade-off that is often disregarded in studies about transport justice and equity (Mattioli, 2016; Mullen & Marsden, 2016). On the one hand, some policies that improve accessibility can entail more energy consumption, depletion of natural resources and environmental impacts, particularly when such policies are guided by the promotion of motorised transport and infrastructure expansion. The concern is not the environmental cost of accessibility per se, but the environmental cost required to provide certain levels of accessibility considering alternative transportation modes and spatial configurations of the built environment. On the other hand, some policy measures to reduce transport emission (e.g. road pricing and fuel tax) may disproportionally harm disadvantaged communities, increasing accessibility barriers and transport-related social exclusion.

In this paper, we propose a conceptual framework for accessibility research that simultaneously incorporates concerns with both social equity and planetary boundaries. Our framework builds on the theoretical and empirical developments in the environmental sciences, sustainability, and transport literature. We first present the "safe and just space" framework and then turn to review accessibility studies to distinguish how they have approached social and environmental issues. We do not aim to cover every study related to these topics, but to identify distinct approaches to and strands of thought on the overlap between social disadvantage and environmental impacts. We proceed to present the conceptual framework, which outlines how social and environmental goals, boundaries and interrelationships could further be integrated into accessibility research. Finally, we discuss challenges related to the framework and propose avenues for future research.

2. The safe and just space framework and transport

2.1. Overview

The "safe and just space" framework (also known as the "doughnut model" (Raworth, 2012, 2017)), builds on the "planetary boundaries" framework (Rockström et al., 2009) and is a socially and ecologically integrative approach to assess the sustainability of societies. The framework's core is formed by two critical thresholds for human societies: the **environmental ceiling**, above which the consumption of natural resources leads to critical planetary degradation, and the **social foundation**, below which the consumption of natural resources leads to critical human deprivation. The doughnut-shaped space between these thresholds represents "a safe and just space for humanity", which should be the goal of all economic activity. By repositioning economy as a tool rather than a goal, the framework aligns with a range of classical discourses on sustainability including "limits to growth", "ecological economics", and "degrowth"/"post-growth" which criticise economy's normative role in the society and in the sustainability framework (Purvis et al., 2019). The perspective resembles the work by Holden et al. (2017) who emphasise that satisfying basic needs, ensuring social justice, and respecting environmental limits pose three moral imperatives for sustainable development. The "safe and just space" framework similarly stands out in its emphasis on equity reflecting the origins of the sustainability concept, which was based on the principles of social justice (Brundtland, 1987; Purvis et al., 2019). Raworth (2012) argues that "the double objective of providing everyone the social foundation within planetary boundaries should be achieved through far greater global equity in the use of natural resources, with the greatest reductions coming from the world's richest consumers".

2.2. Ecological ceiling

The ecological ceiling in the "safe and just space" framework is formed by the advances in defining biophysical processes, pressures and boundaries at the planetary scale. These advances were brought together by a large group of leading earth-system scientists in the "planetary boundaries" framework (Rockström et al., 2009), which has been highly influential in generating and shaping research actions and policy recommendations towards sustainable development.

The planetary boundaries comprise nine ecological dimensions that define the safe operating space for humanity and demarcate the current stable state of Earth. For each dimension, the boundary represents an estimation of a safe limit of environmental degradation, the crossing of which could push the planet towards unsustainable paths. The planetary boundaries as defined by Steffen et al. (2015) are: climate change, biosphere integrity (genetic diversity and functional diversity measured as biodiversity loss), land-system change, freshwater use, biochemical flows (nitrogen and phosphorus loading), ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, and novel entities (e.g. new substances or modified life forms causing unwanted geophysical or biological consequences). The boundaries are separated into two tiers, recognising that climate change and biodiversity loss constitute the first tier of core boundaries due to their fundamental importance to all other earth systems (Steffen et al., 2015). The fundamental risk in exceeding the boundaries lies in the destabilisation of Earth's systems, which may abruptly shift into a new state with devastating impacts for humanity, which depends on natural resources and ecosystem services. Worryingly, Steffen et al. concluded (2015) that in five of the nine dimensions (biodiversity loss, climate change, land system change, and nitrogen and phosphorus loading) the safe boundary for the planet has already been exceeded.

2.3. Social foundation

Equally important in the "safe and just space" framework is the social foundation, which refers to the societal goal of providing everyone the minimum level of life's basic needs. The social foundation consists of 12 dimensions derived from internationally agreed minimum social standards identified in the Sustainable Development Goals (SDGs). The dimensions include food security, income and work, water and sanitation, health care, education, peace and justice, energy, gender equality, social equity, political voice, housing and (social) networks. The selection of categories reflects the main social goals of countries based on an extensive text analysis of government submissions to Rio 20+ conference where current SDGs were defined (Raworth, 2017).

The social foundation aligns with the original goal of sustainable development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The goal is based on a premise that there are a finite number of basic human needs that are universal, satiable, and non-substitutable and that should be guaranteed for everyone. Several influential theories and approaches on human development and justice reflect such perspective including the Human needs' theory (Doyal & Gough, 1984), Rawls' egalitarian theory of justice (Rawls, 1999) and the Capability Approach (Sen, 2009). These have been some of the most influential theories in establishing ethical principles for distributive justice. Lately, several empirical studies have drawn from these theories to define and measure the social foundation of the "safe and just space" framework (e.g. Dillman et al., 2021; Fanning et al., 2022; O'Neill et al., 2018). While previous research has looked at broader social and environmental limits, there has been a lack of studies that use the "safe and just space" framework as a lens to reflect on the tensions between pursuing social and environmental goals in the transport sector.

2.4. Linkages to transport

Transport and accessibility are connected to a range of environmental and social concerns. Transport induces significant pressure to the earth systems. With about a 30% share of the total carbon emissions in the developed countries (IPCC, 2022), transport is a major contributor to climate change through direct emissions and indirect effects. The sector also remains difficult to decarbonise. To limit the warming to 1.5°C, the transport sector will need to undertake wide range of actions in eliminating emissions. These actions range from behavioural change to the uptake of improved vehicle and engine performance technologies, low-carbon fuels, investments in related infrastructure, and changes in the built environment (Banister, 2008; IPCC, 2022).

Another core planetary boundary, biodiversity loss, is also pressured by travel demand and transport infrastructure. Adverse impacts include habitat loss and fragmentation, habitat pollution, wildlife injuries and deaths resulting from vehicle collisions, and invasive species spread (Bennett et al., 2011; Fahrig & Rytwinski, 2009). Relatedly, scholars have long recognised transport's influence on land use patterns, both directly and indirectly (Hansen, 1959). While physical transport infrastructure requires large land areas, roads and other transport networks also enable access, which is a strong predictor of human pressure at the regional level (e.g. Nagendra et al., 2003). Transport is also the single most important source of ambient air pollution, especially of particulate matter (PM) with almost a third of all PM emissions being linked to transport (Anenberg et al., 2019). According to estimations, ambient air pollution resulting from transport accounts for almost 400 000 premature deaths per year (Anenberg et al., 2019). When lifecycle emissions from vehicle production, use and disposal to supportive infrastructure like roads and fuel stations are considered, the direct and indirect outputs of transport affect all the remaining boundaries (Dillman et al., 2021).

In contrast, transport plays a crucial social role in enabling people to access opportunities, providing a fundamental means to support satisfaction of human needs and flourishing (Luz & Portugal, 2022; Pereira & Karner, 2021). Accessibility, enabled by the transport system, is widely regarded as a necessary construct of social inclusion (Farrington & Farrington, 2005; Lucas, 2012) and the social good that is distributed by transport policy (Martens, 2017; Pereira et al., 2017; van Wee & Geurs, 2011). Empirical transport research has looked at the role of accessibility in social goals. Scholars have explored the links between accessibility and the distinct dimensions of the social foundation including employment (e.g. Deboosere & El-Geneidy, 2018; Grengs, 2010), education (e.g. Moreno-Monroy et al., 2018; Talen, 2001), social networks (e.g. Farber et al., 2013), food (e.g. Widener et al., 2015), health (e.g. Tenkanen et al., 2016), gender equality (e.g. Kwan, 1999), social equity (e.g. Grengs, 2015; Lucas, van Wee, et al., 2016), and political participation (e.g. Gimpel & Schuknecht, 2003). These works among many others have highlighted the fundamental role of accessibility for the wellbeing of people. However, this literature has almost exclusively focused on the social, economic and health benefits of accessibility enabled by transport and land use systems without recognising the transport externalities and environmental justice implications that different accessibility levels might entail (Mattioli, 2016; Mullen & Marsden, 2016).

3. Socio-ecological approaches to accessibility

In the following subsections, we review the transport accessibility literature that focuses on social disadvantage, on environmental impact, as well as more recent studies that pursue to integrate social and environmental concerns. These studies can be organised according to distinct approaches (See Table 1 and supplementary material).

3.1. Approaches to assess social disadvantage and needs satisfaction

A growing interest in transport equity has characterised accessibility research in recent decades. Drawing from political philosophy including Rawls' egalitarianism (Rawls, 1999) and the Capability Approach (Sen, 2009), several authors have developed the field by conceptualising transport equity as a way to frame distributive justice concerns in relation to the distribution of transport benefits and burdens in society (Lucas, van

Table 1. Approaches to assess social disadvantage, environmental impacts, and combinations of these two.

Study focus	Approach	Description	Example questions	Empirical references
Social disadvanage and needs satisfaction	Disparity analyses	Comparing access levels between population groups or areas with distinct characteristics	Is there inequality in access between population groups? Do socially disadvantaged groups experience poorer accessibility than other groups?	**Disparities in employment access:** Bocarejo and Oviedo (2012); Boisjoly, Serra, Oliveira, and El-Geneidy (2020); Deboosere and El-Geneidy (2018); Delbosc and Currie (2011); Dixit and Sivakumar (2020); El-Geneidy et al. (2016); Ellwood (1986); Foth, Manaugh, and El-Geneidy (2013); Giannotti, Tomasiello, and Bittencourt et al. (2022); Golub and Martens (2014); Grise et al. (2019); Guzman, Oviedo, and Rivera (2017); Hess (2005); Hu, Fan, and Sun (2017); Jang and Lee (2020); Kawabata (2003); Kawabata and Shen (2007); Liu and Kwan (2020); Manaugh and Geneidy (2012); Paez et al. (2013); Pereira, Banister, Schwanen, and Wessel (2019); Slovic, Tomasiello, Giannotti, Andrade, and Nardocci (2019); Yeganeh, Hall, Pearce, and Hankey (2018). **Disparities in access to other activities:** Casas (2007); Casas, Horner, and Weber (2009); Chen and Yeh (2021); Cheng et al. (2019); Grengs (2015); Järv et al. (2018); Kelobonye, Zhou, McCarney, and Xia (2020); Kwan (1999); Lee and Miller (2018); Moreno-Monroy et al. (2018); Oviedo and Sabogal (2020); Paez et al. (2010); Scott and Horner (2008); Talen (2001)
	Sufficiency analyses	Assessing accessibility of individuals or groups against normative judgements of minimum thresholds	Does a person or a group have enough accessibility to meet their basic needs?	Allen and Farber (2019, 2020); Lucas, van Wee, and Maat (2016); Martens et al. (2022); Smart and Klein (2020); van der Veen, Annema, Martens, van Arem, and Correia (2020).
		Identifying spatial gaps in accessibility to a certain activity or a service in socially disadvantaged areas	Are there areas with high levels of social disadvantage and low (public transport) accessibility to services (e.g. to food outlets)?	**"Public transport deserts":** Carroll et al. (2021); Currie (2004, 2010); Fransen et al. (2015); Jaramillo, Lizárraga, and Grindlay (2012); Jomehpour Chahar Aman and Smith-Colin (2020) **"Food deserts":** Apparicio, Cloutier, and Shearmur (2007); Bao, Tong, Plane, and Buechler (2020); LeClair and Aksan (2014); Su et al. (2017); Widener et al. (2015) **"Health care deserts":** Archibald and Putnam Rankin (2013); Field (2000); Gong et al. (2021); Pednekar, Peterson, and Meliker (2018).
	Linking accessibility and activity participation	Investigati the relationship between accessibility levels of socially disadvantaged and their activity behaviour	Does accessibility potential realise into actual activity participation among socially disadvantaged?	Adeel et al. (2016); Allen and Farber (2020); Farber et al. (2018); Luz et al. (2022); Kamruzzaman and Hine (2011); McCray and Brais (2007); Wang, Kim, and Xu et al. (2022).

(Continued)

Table 1. Continued.

Study focus	Approach	Description	Example questions	Empirical references
Environmental impacts	Environmental impact analyses	Measuring environmental impacts of access by different modes	What are the impacts of a certain policy measure to accessibility and emissions?	Cui and Levinson (2019); Lahtinen et al. (2013); Escobar, Sarache, and Jiménez-Riaño (2022); Avogadro et al. (2021); Määttä-Juntunen et al. (2011); Vasconcelos and Farias (2012); Song et al. (2017).
	Environmental boundary analyses	Constraining accessibility with a travel mode specific environmental boundary (e.g. a carbon budget)	What is the extent of accessible area by a certain travel mode under an emission budget that does not exceed sustainable level of resource use?	Mahmoudi et al. (2019); Kinigadner et al. (2020); Kinigadner et al. (2021)
Socially and environmentally integrative approaches	Accessibility at short travel distances	Examining social disparities in access to/by sustainable travel modes	Which population groups can access opportunities by sustainable means of transport? Where do these population groups live?	**Disparities in access by walking/cycling:** Calafiore et al. (2022); Elldér, Larsson, Solá, and Vilhelmson (2017); Lucas et al. (2018); Rosas-Satizábal et al. (2020); Willberg et al. (2023); Yang et al. (2018). **Disparities in car dependency:** Carroll et al. (2021); Cheng et al. (2007); Wiersma, Bertolin, and Straatemeier (2013); Wiersma et al. (2021).
	Linking accessibility, equity and environmental exposure	Examining the relationship between accessibility, social disadvantage and environmental exposure (e.g. air pollution)	How different social groups can balance environmental quality and accessibility in their housing decisions?	da Schio et al. (2019); Higgins et al. (2019); Jiang et al. (2021); Zhao et al. (2018).

Wee, et al., 2016; Martens, 2017; Pereira et al., 2017; Pereira & Karner, 2021; van Wee & Geurs, 2011). An abundance of empirical studies has measured, analysed, and explained the linkages between social impacts, accessibility levels and equity from various perspectives and in a variety of geographical contexts (see e.g. Golub & Martens, 2014; Lucas, 2012; Luz & Portugal, 2022). In this review, we limited ourselves to accessibility studies focused on social disadvantage and needs satisfaction, which are central themes from the social foundation perspective. From this body of literature, we have identified three distinct approaches (Table 1).

The most common analytical approach to social disadvantage in accessibility studies have been the disparity analyses. Studies based on this approach focus on relative inequalities of transport accessibility and compare access levels between population groups distinguished by demographic and socioeconomic characteristics, or physical abilities. Another way to examine disparities is to compare areas with a distinct geographical context (e.g. urban/rural). The general purpose of disparity analyses is to investigate accessibility inequality between groups, and to examine whether socially disadvantaged groups experience poorer accessibility than other groups.

Of the various activity types, disparities in employment access have received most attention from scholars (e.g. Bocarejo & Oviedo, 2012; Deboosere & El-Geneidy, 2018; El-Geneidy et al., 2016; Golub & Martens, 2014; Liu & Kwan, 2020; Paez et al., 2013). The interest in employment accessibility has stemmed from various reasons, including the influence of the spatial mismatch hypothesis (Kain, 1968). Job accessibility has also been a proxy for capturing the extent of activity opportunities more broadly (Boisjoly & El-Geneidy, 2017). In addition to employment, many disparity studies have focused on access to other activities, which are important for the satisfaction of basic needs including education (e.g. Moreno-Monroy et al., 2018; Talen, 2001) and essential services like health (e.g. Lee & Miller, 2018; Paez et al., 2010) and food (e.g. Grengs, 2015; Järv et al., 2018), and leisure activities like being in green spaces (e.g. L. Cheng et al., 2019; Kwan, 1999). Distinct population groups in disparity studies have included low-income (Paez et al., 2010), single-parents (Paez et al., 2013), the disabled (Grise et al., 2019) and residents of informal settlements (Oviedo & Sabogal, 2020). While the disparity studies have brought awareness to equity issues in transport studies, they have been criticised for being descriptive without linking to normative principles on how to distribute access fairly (Martens et al., 2022).

Complementing disparity analyses, sufficiency analyses have emerged as another approach to social disadvantage in accessibility studies. The guiding question of this approach has been whether a person or a group has *enough* accessibility to meet their basic needs. While it has been notoriously difficult to answer this given the variability in spatial and social contexts and in individual capabilities, needs and preferences, the question of accessibility poverty is nevertheless central for distributive justice in transport. Several authors have advocated efforts to investigate guaranteed minimum levels of accessibility to key activities laying the ground for sufficiency analyses (Lucas, van Wee, et al., 2016; Martens, 2017; Pereira et al., 2017; van Wee & Geurs, 2011).

Empirical sufficiency analyses have measured the proportion of people in a certain group who are above or below selected sufficiency thresholds using one or multiple activity types and travel modes. Lucas, van Wee, et al. (2016) proposed a method to evaluate equitable accessibility in which an egalitarian disparity analysis was complemented with a sufficiency analysis. Martens et al. (2022) found large inequalities in accessibility within ethnic groups in the U.S. that were captured by the sufficiency approach, but not the disparity approach. Criticising the tendency of transport studies to restrict sufficiency to a quantitative threshold concept, Cooper and Vanoutrive (2022) showed how sufficiency often has a qualitative rather than a quantitative meaning that is tied to local factors and individual preferences. Another perspective on sufficiency has been to identify gap areas, or "accessibility deserts", where hotspots of social disadvantage simultaneously suffer from the lack of certain services. Such studies have assessed shortages in public transport connections, healthy food outlets and healthcare services or while more recently including quality of service (LeClair & Aksan, 2014), people's time constrains (Widener et al., 2015) or travel mode (Su et al., 2017). While empirical studies in the sufficiency approach provide planners with practical guidance for prioritising local actions, like studies on disparity analyses, many of them pay little attention to social and ethical theories when defining accessibility thresholds and gaps, even if exceptions to this tendency exist (e.g. Allen & Farber, 2019; Martens et al., 2022).

The third distinct approach to social disadvantage in accessibility studies has linked accessibility and activity participation levels from the perspective of social exclusion. These studies have concerned whether accessibility translates into realised participation in activities, and how activity participation is affected by accessibility barriers. These studies have explored potentially disadvantaged population segments including refugees (Farber et al., 2018), rural dwellers (Kamruzzaman & Hine, 2011), and slum dwellers (Adeel et al., 2016). Some studies have developed models to explain how accessibility impacts activity participation across socio-economic groups and identified social characteristics of areas having particularly low levels of observed activity participation (Allen & Farber, 2020; Luz et al., 2022). A major advantage of this approach is the ability to provide insights into the type of opportunities people value or can reach (Vecchio & Martens, 2021). However, the need for individual-level datasets makes the implementation challenging.

A common characteristic across all three categories is their reliance on measuring travel time as the only socially relevant transport cost. Environmental costs are rarely considered (see section 3.3). Studies that consider other types of cost usually include monetary expenses, such as public transport fares or vehicle operating costs, which have been considered in cumulative measures (El-Geneidy et al., 2016; Herszenhut et al., 2022), gravity-measures (Bocarejo & Oviedo, 2012; Liu & Kwan, 2020) and in utility-measures (Cui & Levinson, 2018; Dixit & Sivakumar, 2020). This integration is important since multiple studies have shown how the accessibility levels of low-income populations are easily overestimated without considering the monetary costs (Bocarejo & Oviedo, 2012; El-Geneidy et al., 2016; Liu & Kwan, 2020). More broadly, few studies have gone further to integrate costs related, for example, to travel safety or comfort into the accessibility calculation.

3.2. Approaches to accessibility and environmental impacts

The literature assessing the environmental impacts of accessibility is much scarcer than that on social disadvantage, even if the broader field of transport research has concentrated on the impacts of infrastructure developments. While accessibility scholars often link their work with the environmental sustainability discourse, environmental impacts are rarely incorporated into accessibility measures. Some studies consider environmental concerns indirectly, by developing accessibility tools for non-motorised travel modes or comparing their competitiveness against the private car (Gehrke et al., 2020; Iacono et al., 2010; Salonen & Toivonen, 2013). While these approaches are important in pursuing a sustainable modal shift, they do not help us understand the extent of environmental and ecological impacts associated with a given level of accessibility nor resource boundaries related to the provision of accessibility by different modes. To these ends, we have identified two emerging approaches from the accessibility literature (Table 1).

The first category are the environmental impact analyses. At their core, studies in this group are concerned with assessing the environmental burden of access. The work of Cui and Levinson (2018, 2019) presents and empirically tests a comprehensive conceptual model to account for both internal and external travel costs in accessibility analysis. Their full cost accessibility model proposed the integration of travel mode-specific crash costs, vehicle operation and infrastructure costs, noise costs and emission costs into a (utility-based) accessibility analysis in addition to the travel time cost. Other empirical research in this category has operationalised environmental impacts by estimating carbon emissions and potential reductions of various green policies and their accessibility impacts (Avogadro et al., 2021; Lahtinen et al., 2013; Song et al., 2017) or by creating accessibility-sensitive carbon indexes (Määttä-Juntunen et al., 2011; Vasconcelos & Farias, 2012).

Another nascent approach is seen in the environmental boundary analyses, which constrain accessibility levels for different transport modes based on mode-specific emission budgets. Mahmoudi et al. (2019) proposed an approach to integrate resource constrains other than time to person-based accessibility measures as *resource hyper-prisms* and illustrated the approach by applying a carbon budget to electric car accessibility in the U.S. Kinigadner et al. (2020, 2021) applied a carbon constrain to place-based accessibility (cumulative opportunities) using Germany's carbon reduction targets as thresholds and estimated the impacts on accessibility in multiple current and future scenarios. While losing their predictive power on an individual's travel behaviour, emission-sensitive measures of accessibility provide understanding on the gap between the current and environmentally sustainable levels of accessibility, which is currently much needed in transport planning and policy.

3.3. Efforts for socially and environmentally integrative approaches

There is a research gap concerning interlinkages and conflicts between environmental and social goals. No studies explicitly connected social and planetary limits in accessibility research, but two groups of studies focused on social concerns while indirectly addressing environmental concerns (Table 1).

The guiding focus within the first group has concerned who short travel distances are available to. Perspectives to this question have included explorations of socio-economic and spatial disparities in walking and cycling access (Calafiore et al., 2022; Rosas-Satizábal et al., 2020; Willberg et al., 2023) and their effects on gentrification and housing prices (Yang et al., 2018), and travel frequencies (Lucas et al., 2018). From another angle, accessibility studies have examined patterns and areas of car dependency (Carroll et al., 2021; J. Cheng et al., 2007; Wiersma et al., 2021). Both perspectives show latent tensions between the environmental and social goals in ensuring social fairness of the sustainability transformation. Mattioli (2016) discussed such tensions, arguing that increasing social equity and rapidly reducing carbon emissions from transport to targeted levels can be mutually exclusive goals, especially in car-dependent areas. Stokes and Seto (2018) provided empirical evidence for this argument. They studied longitudinal job accessibility from 2002 to 2014 using a series of counterfactual scenarios across U.S. urban areas and found that accessibility increases almost never accompanied by simultaneous social and environmental "win-win".

Another group of accessibility studies at the nexus of environmental and social realms has focused on the local linkages between accessibility, social inequality, and environmental exposure. These studies examined at the spatial correlation between job accessibility and air pollution (da Schio et al., 2019; Zhao et al., 2018), their interlinked effects on housing prices (Higgins et al., 2019), and the extent to which different social groups can balance environmental quality and accessibility in their housing decisions (Jiang et al., 2021).

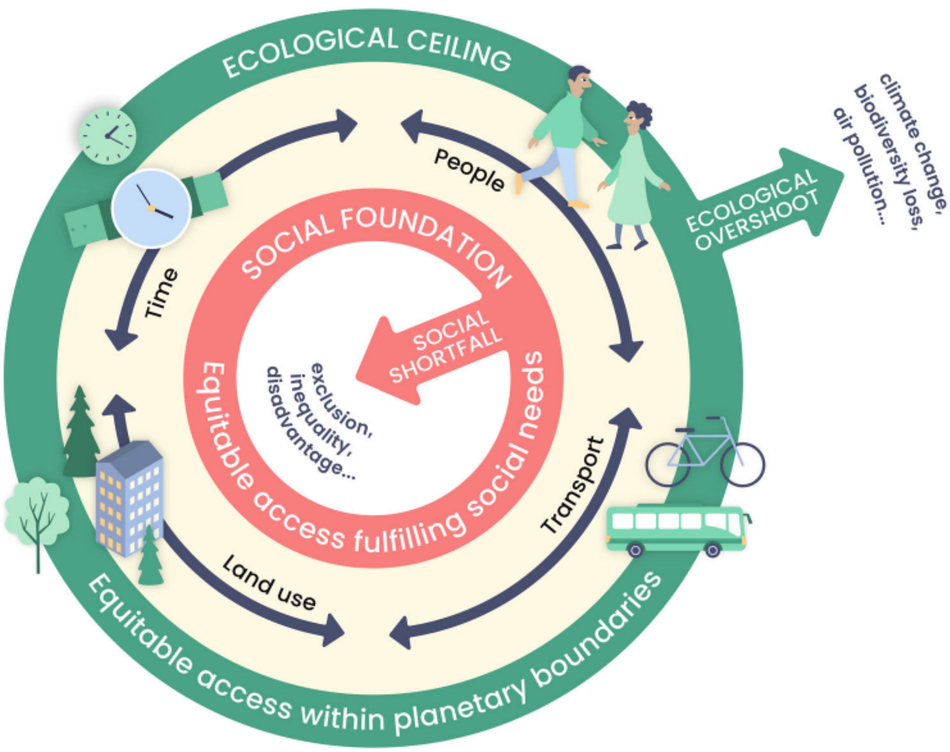

Figure 1. Conceptual model for accessibility within the safe and just space. Adapted from Raworth (2012).

4. Conceptual framework for measuring just accessibility within planetary boundaries

4.1. Accessibility within the safe and just space

We now propose a conceptual framework for measuring just accessibility within planetary boundaries. The framework is based on a conceptual model, which understands accessibility as a necessary construct of social wellbeing, but also as a construct, whose realisation depends on limited environmental resources (Figure 1). The model recognises four accessibility components, people, transport, land use and time, which were identified as theoretically important for measuring accessibility by Geurs and van Wee (2004). The inner ring relates to the basis of social foundation and represents the minimum amount of accessibility necessary to guarantee the satisfaction of basic needs. Accessibility levels below these minimum levels mean accessibility poverty that contributes to social exclusion. The outer ring relates to the ecological ceiling limiting the amount of energy and resources that can be used to promote accessibility without exceeding planetary boundaries. The ring in the middle represents the "safe and just space" where the use of energy and resources to promote accessibility is enough to achieve both environmental and social goals simultaneously.

Our review shows a substantive research body that has established the ground for untangling accessibility's role in social goals, but it also indicates that environmental impacts and the integration of environmental and social goals remain understudied topics in accessibility research. In our view, fostering research on the environmental impacts of accessibility and their social implications is critical. Accessibility can be distributed in many ways and travel modes, but only those ways, which respect environmental limits can be considered to be truly sustainable. Land use policies that promote proximity between people and opportunities (through increased land use mix and density for example) can be an important approach to improve accessibility at relatively lower environmental costs because it reduces the need for longer motorised trips. Therefore, the capacity to compare environmental and social implications of different levels and configurations of accessibility analytically is necessary.

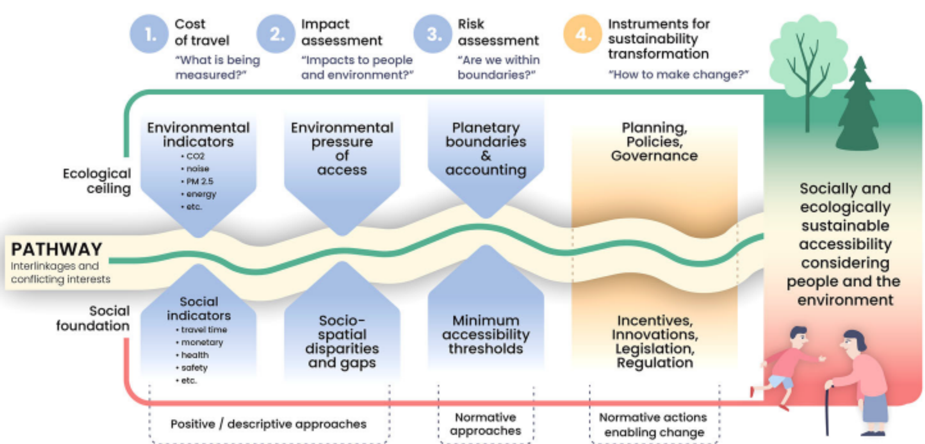

Figure 2. Framework for measuring just accessibility within planetary boundaries.

4.2. Framework for practical implementation

The framework outlines four components in integrating the environmental and social goals and their interrelationships in accessibility research (Figure 2). While much of this research focuses on urban areas, we see the framework's ideas applicable to both urban and rural contexts and on scales from local to global accessibility. However, the framework's interpretation may be context dependent. We also see all components as necessary for the full integration, but do not intend to suggest that all steps should be integrated at once.

The **first component** is about diversifying the ways in which travel costs should be measured in accessibility metrics. While travel time and distance are the most common costs in the accessibility literature, this component extends the notion of accessibility costs to incorporating individual and societal (i.e. internal and external) impacts of travel more fully (Cui & Levinson, 2018). Given the improved data availability, accessibility costs can increasingly be expressed through monetary, safety, health, and environmental impacts. Travel costs can be conventionally calculated metrics or describe perceived or experienced costs (Levinson & Wu, 2020). Even if conventionally referred to as costs, they can also describe positive impacts such as health benefits linked to active travel (Saunders et al., 2013). Environmental costs should describe relevant environmental outputs of travel including carbon, air pollution or noise emissions. When integrating travel costs other than time, the use of estimates for the impacts remains necessary, which emphasises the need for transparency in the parameter and data selection. While the literature is still limited, several emerging approaches presented in section 3 have demonstrated the conceptual and technical feasibility of extending the notion of travel costs both socially and environmentally in accessibility research.

The **second component** is about assessing the impacts of accessibility including socio-spatial disparities, gaps, and environmental pressures. Approaches to this component are positive (i.e. descriptive) in nature, meaning that they aim to describe the state of affairs without moral positioning, such as describing accessibility levels rather than how they ought to be (Paez et al., 2012). Such approaches can be implemented in various ways, but typical are comparisons between population groups (e.g. income classes), travel modes (e.g. car, bicycle) or activity types (e.g. employment types). Having applicable data, the focus can concern certain population groups, such as comparing the environmental impacts of the accessibility levels experienced by low-income or high-consumption individuals. However, studies should avoid common analytical pitfalls in under- or overcounting spatial opportunities (Pereira et al., 2021). As the review demonstrates, a multitude of place-based, person-based, and utility-based accessibility approaches provide empirical guidance for measuring social impacts. While fewer attempts exist to measure environmental impacts, our review demonstrates significant potential for advancing that front.

The **third component** includes linking the disparity, sufficiency, and impact analyses with normative (i.e. prescriptive) judgements relating to fairness and limits. Approaches to social disadvantage and boundaries should be guided by normative perspectives to transport equity (e.g. egalitarianism, sufficiency, capabilities) (see e.g. Martens, 2017; Pereira et al., 2017; van Wee & Geurs, 2011). Even if definitive judgements cannot be set, the approaches in this component should provide evidence to support discussions on socially acceptable minimum accessibility thresholds. However, such thresholds should not understood only as single quantitative indicators (e.g. 30 min employment access), but also as relative constructs with different and contextual meanings measured with multiple indicators and adapt to local contexts (Cooper & Vanoutrive, 2022). Socially-focused analyses of this component may also benefit from linking accessibility potential and achieved access to understand how especially socially disadvantaged can convert the potential into actual activity participation given their capabilities (Luz & Portugal, 2022; Pereira et al., 2017; Vecchio & Martens, 2021).

The theoretical ground to address environmental boundaries in accessibility research is currently insufficient. Operationalisation of planetary boundaries for meaningful accessibility analyses requires disaggregation of global quotas to locally applicable and normatively grounded thresholds that are relevant to the transport sector. Such disaggregation protocols to urban areas already exists for several planetary boundaries (e.g. Hoornweg et al., 2016). Ideally, such quotas are theoretically grounded in frameworks like planetary accounting (Meyer & Newman, 2020) that employ principles of fair burden sharing between countries and regions in reducing environmental harm. However, more recognition of the historical and environmental pathways of high- and low-income countries is needed. The environmental boundaries may also be operationalised through downscaling national targets or laws (e.g. on climate or air pollution) and setting them as upper limit parameters in accessibility analysis. In downscaling environmental boundaries, issues of scale should be considered. As access often requires crossing administrative boundaries, it is not always readily clear, how should the quotas be allocated between the departure and origin areas. Another consideration concerns manifestations of different planetary boundaries. Where greenhouse gas emissions are absorbed by and circulate in the global atmosphere, the carrying capacity of the biosphere is more locally dependent in its sensitivity to human activity, which should be considered when defining quotas.

Once operable environmental and social thresholds are established for a particular analysis, the studies of this component can employ comparisons similar to those in the previous component between population groups, areas, and travel modes, or between current conditions and future scenarios.

The **fourth component** concerns instruments that enable advancements towards sustainability transformation, including planning, policy, and governance. The value of any new accessibility measure or approach is ultimately determined by whether they provide benefit and become established in practice. Establishing social and environmental boundaries for accessibility is a highly political issue and gaining acceptability for such changes is essential for successful implementations. The first three components of the framework play a significant role in supporting these public and political debates with comprehensive and systematic evidence. They provide valuable input for creating better-informed and effective policies, incentives, regulation, legislation, and innovations for reaching socially and ecologically sustainable society.

Finally, **the pathway to sustainable accessibility is surrounded by interlinkages and conflicting interests** and involves choices within and between the environmental and social dimensions. There is a tension between promoting the accessibility necessary for satisfying basic needs and social inclusion, and the environmental cost that such accessibility levels might entail in a world of planetary limits. Without acknowledging this tension, one would conclude that the best approach to improve accessibility is usually to promote cars because cars provide better accessibility almost everywhere (except in congested urban areas).

Approaches crosscutting the first two components should contrast social and environmental implications of current accessibility levels or conditions. Moving further, approaches crosscutting components three and four deal with and provide evidence for normative debates on environmental and social boundaries, especially when they conflict. In this respect, our framework reflects the notion of "strong sustainability", which emphasises limits to natural resources, ecosystem resilience and substitutability between natural and man-made resources (Irwin et al., 2016). This notion also requires the extension of social equity considerations to include intergenerational perspectives, given how sustainability is essentially about guaranteeing similar opportunities for both present *and* future generations. Methodologically, integrating social theories and methods like the conflict analysis may provide useful avenues for accessibility research to uncover trade-offs between environmental and social goals (Grossmann et al. 2022).

5. Ways forward

5.1. Dealing with complexity and uncertainty in social-ecological thresholds

By proposing a pathway to socially and environmentally sustainable accessibility, we do not intend to claim that following this approach would be straightforward, on the contrary. The approach requires normative judgements on how accessibility should be distributed fairly, which can be criticised on many grounds including paternalism (Vanoutrive & Cooper, 2019), and the unsuitability of general normative views and thresholds that might not be applicable to particular contexts. The approach also requires dealing with methodological uncertainty and relying on rough estimations and imperfect measures when establishing environmental cost thresholds for accessibility. Also, the planetary boundaries represent only first estimations and significant knowledge gaps remain (Steffen et al., 2015). Their disaggregation to the local limits is a nascent topic field filled with ethical disputes on how global quotas should be fairly allocated (Meyer & Newman, 2020). Similarly, the debate on the ethical principles of accessibility distribution continues.

That said, it is evident that the transport sector does not exist in a vacuum from broader societal needs and environmental constraints. Transport directly or indirectly impacts all planetary boundaries when total lifecycle emissions are accounted for (Dillman et al., 2021). Currently, the relationship between environmental impacts and accessibility remains understudied. Given the extent of the required sustainability transformation, it is likely that the tightening legal regulation on environment at international and national levels will also translate into increased local and sectoral regulation in transport. Without the capacity to measure and understand how such regulations may constrain accessibility, planners and policymakers risk making uninformed decisions. Simultaneously, the theoretical and empirical background behind the planetary boundaries, and ways to disaggregate them, are mature *enough* for the development of approaches to apply them in accessibility research. This also holds for the conceptualisations and applications of social equity in transport. Advancing the integration of social and environmental concerns in accessibility research is thus critically important, but also increasingly possible.

5.2. Advancing the integration of environmental limits into the conceptualisations of transport equity

The joint consideration of environmental limits and social equity raises difficult ethical questions, which currently remain insufficiently conceptualised in otherwise mature transport equity literature. While ensuring sufficient accessibility has become a core concern of transport equity (Martens et al., 2022; Pereira & Karner, 2021), current studies concerned with transportation equity seldom engage with intergenerational justice issues as they commonly overlook the extent to which providing certain levels of accessibility for present generations could undermine the environmental capacity of future generations in meeting their minimum accessibility requirements. In this respect, much more discussion is needed to improve our understanding of how intergenerational justice concerns can be accommodated and reconciled with guiding principles of egalitarianism and sufficientarianism in the context of transport justice and accessibility. To what extent, would transportation policies guided solely by egalitarianism and sufficientarianism concerns slow down the implementation of policies required to rapidly reduce environmental emissions? Meeting the basic needs in rural areas, would require maintaining or increasing car access, which may place even greater pressure on curbing car use elsewhere, which can be deemed unfair (Mattioli, 2016). From another angle, some environmentally-driven accessibility policies may lead to adverse consequences (e.g. gentrification) for disadvantaged communities undermining social goals (Yang et al., 2018).

Developing conceptualisations of transport equity to address such dilemmas across spatial and temporal scales is necessary and would also support more multi-perspective accessibility measuring. Empirical studies can advance the endeavour by exploring, which configurations of accessibility distribution in various contexts are compatible with the idea of "safe and just space", i.e. simultaneously achieving both environmental and social goals, and which policies should be disregarded. In this effort, empirical studies should pay special attention in distinguishing between positive and normative approaches (Paez et al., 2012) and linking with ethical theories.

5.3. Going beyond travel time

One practical barrier for measuring wider impacts and constrains of accessibility is the continuing reliance on travel-time based measures (as shown in section 3). Travel time is behaviourally a key factor for an individual's travel decisions, but the lack of alternative measures poses several challenges for planners. One is that the focus is directed to things that can be measured, which reinforces the false impression of travel time as the only relevant cost for accessibility. Another relates to seeing travel only as a cost, which easily neglects its positive impacts on health and well-being (Banister, 2008). Above all, it is evident that the focus on travel time savings has not improved the environmental sustainability of transport and is unlikely to do so in the future.

Accessibility scholars have long championed the move from mobility-based indicators (e.g. travel time savings) to accessibility indicators (e.g. cumulative opportunities) as performance measures of transport (Banister, 2011; Cervero, 1997; Levine et al., 2019; Miller, 2018). Even if this ongoing change represents a fundamental and welcome shift for transport planning and policy, we contend that in its current form, it does not support advancing sustainability well enough. When accessibility continues to be measured solely on travel time costs, the focus on travel time savings is retained and other social and environmental costs remain invisible. The decarbonisation of travel is thus assumed to happen primarily through efficiency increases, which contradicts the assessments of what is needed to achieve carbon-neutral transport (IPCC, 2022). When generalised costs including environmental costs are included in the calculation, investing into slower modes suddenly may make more sense. For example, under this perspective, congestion and parking charge policies can be understood valuable instruments to increase generalised travel costs of car users and thus to cap motorised accessibility.

A key challenge for accessibility research is develop new ways to measure accessibility within social and environmental limits that span both dimensions theoretically rigorously. There is a need for approaches, which include both internal and external travel costs and are constrained by resource limits. Such approaches should represent accessible areas as regions inside a mappable space (geographic or network space), which satisfy planetary boundaries, social minimums, and people's time budgets. That said, the well-known trade-offs between accessibility measures remain (Geurs & van Wee, 2004; Miller, 2018). While person-based and utility-based measures are likely to provide more potential for theoretically-sound approaches to applying broader costs and relevant constrains, finding ways to integrate these principles to place-based and infrastructure-based measures is also essential for communicating and transferring them into planning practice (see e.g. Kinigadner et al., 2021; Sarlas et al., 2020). Consequently, developing capacities to integrate estimates of social costs of carbon emissions across different types of accessibility measures would already be a step towards more sustainable planning.

5.4. Integrating qualitative and quantitative data and taking advantage of novel computational tools

Lastly, important practical challenges remain in terms of computational tools and data to advance the accessibility literature towards broader accounting of social and environmental costs. The massive increase in the collection and availability of spatial data on people, transport, and land use (e.g. from OpenStreetMap, GTFS, or mobile phone data) has supported multimodal accessibility comparisons globally. Similarly, the recent development of open spatial network analysis tools for mass calculations of accessibility (e.g. R5 and the related r5r and r5py packages, or OpenTripPlanner) has enabled new and more refined quantitative approaches. Yet, these tools are still predominantly based on travel time and monetary costs, so future work is necessary to integrate environmental impacts into accessibility modelling. There is great potential for advancements given the recent growth in the availability of environmental data. Simultaneously, qualitative approaches remain crucial to understanding social realities and causes of accessibility poverty, and further integration of qualitative and quantitative data is required in transport studies (Vecchio & Martens, 2021). While quantitative data are needed to measure conventional accessibility levels and environmental impacts, qualitative approaches are vital for understanding the real experiences of socially disadvantaged groups, their perceptions, and challenges of accessibility. Future studies should also explore synergies and application of various data sources to advance the addressing of both environmental and social goals in accessibility research.

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