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Quantifying minimum mobility and transport needs: The who, the where and the why

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ABSTRACT

The concept of “sustainable consumption corridors” bridges two topics critical to assessing energy and transport systems: human wellbeing and planetary boundaries. However, large disagreements remain regarding how to define minimum, essential and decent levels of demand, which form the floor of such corridors. Aggregate approaches based upon distance travelled (e.g. passenger-kilometres) are insufficient, as they omit why people move. To address this gap, we build upon established theories of fundamental human needs and needs-oriented mobility research to define “decent mobility” as the condition when an individual can enact a set of trips that allow satisfaction of their needs, within their resources and capabilities. We explain how this definition unifies (i) individual capabilities and resources (time, money), (ii) available physical infrastructure and services, and (iii) socio-political contexts that shape personal freedom. We then operationalise and quantify decent mobility with a “persona” approach. We model two case studies with very distinct mobility systems – Switzerland and Mauritius – to illustrate the flexibility of the framework. They show which methods and data sources are required to consistently assess decent mobility of individuals, as well as travel time, distance, energy use, and emissions. Overall, the framework offers a method for evaluating present and future transport systems by putting human needs and their heterogeneity at the centre.

1. Introduction

As of today, research has not provided a broadly shared understanding of what is meant by ‘minimum’, ‘essential’, and ‘sufficient’ in the context of personal mobility. Historic analysis has shown a strong correlation between development of passenger-distance travelled (PDT) and gross domestic product (GDP) [1], but this correlation has been questioned as suitable for a sole or chief indicator of human wellbeing. Passenger transport is currently responsible for 13% of the world’s final energy demand [2] and 15% of global greenhouse gas emissions [3]. With an annual emissions growth rate of +1.7%, transport is one of the fastest-growing sectors globally. Beyond from climate change mitigation issues, it encompasses a complex system of institutions, carbon-intensive infrastructures, and socio-political norms, and leads to considerable externalities that have grown historically and are still growing: public expenditures, land-use patterns, safety, and

health impacts [4]. Passenger transport is also the consumption sector with highest inequality between and within countries [5], which raises questions of wellbeing for all.

It is increasingly well understood that transport consumption connects strongly with wellbeing and other aspects of sustainability [6]. For instance, quantitative analyses from integrated assessment models (IAMs) show that demand-side mitigation measures¹ have upstream benefits across multiple sustainability domains and strong upstream leverage effects on energy use and emissions due to inefficiencies in current service provision models [7,8]. Yet still missing are a common conceptualisation of mobility as an aspect of wellbeing, and a shared, quantitative understanding of the *status quo* and possible futures. In their absence, it is difficult to identify where increased consumption would no longer add to wellbeing.

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¹ i.e. climate change mitigation measures that target energy demand sectors, instead of only decarbonising energy supply.

Sufficiency can be understood as staying within sustainable consumption corridors [9]. The upper threshold (ceiling) of this corridor can be defined by environmental boundaries, social considerations, or the (diminishing) contribution of travel to individual wellbeing [10]. The lower threshold (floor) of this corridor describes mobility levels that allow for satisfying fundamental human needs—what we term “decent mobility”. This usage is similar to “essential” mobility [11], whereas the term “sufficient” mobility diverges across research communities. Transport research conceptualises the sufficientarian approach as floor [12,13], while energy research usually treats sufficiency as the range between floor and ceiling. The ceiling must be considered for over-consuming, usually high-income countries, whereas the floor is universally relevant for currently mobility-deprived parts of the world population.² Dillman et al. [15] show in their socio-ecological performance analysis of global mobility provisioning systems that currently no country is able to guarantee a social floor without trespassing the ecological ceiling. This failure of current system designs becomes even more relevant when considering path dependence: if the historic trend of the Global North is followed, passenger travel is expected to grow significantly in the Global South with severe consequences for the climate [16].

To identify minimum infrastructure and material needs as well as their environmental implications, research has used quantifiable thresholds that meet certain criteria [e.g. 17]. Some studies have already tried to quantify levels of “decent” mobility [18–21], but defining such a threshold requires strong and normative assumptions [22]. In this study, we provide a conceptual framework that integrates necessary dimensions of mobility as fundamental needs satisfier (Section 2 reviews corresponding literature). We first derive basic travel needs and acknowledge their heterogeneity through a persona approach (Section 3). The personas capture the fact that real people are differently endowed with resources and capabilities, which interact with the mobility provisioning system embedded in the spatial, socio-economic-technopolitical, and environmental context. We make first assumptions for quantifying decent mobility (Section 4) and evaluate it in two different case studies using different modelling approaches (Section 5). Section 6 discusses our results and the utility of our framework.

2. Existing frameworks on human needs, satisfiers, and their use in mobility research

2.1. Basic needs and capabilities theories

The origins of basic needs related theories trace back to development economics and social theory, when the focus broadened from singular economic metrics such as GDP to a wider set of goals. Max-Neef et al. [23] define *fundamental human needs* as finite, limited in number, classifiable, and the same in all cultures and in all historical periods. They are non-hierarchical and distinguished from *need satisfiers* (viz. means of satisfying more fundamental needs), without a one-on-one correspondence between needs and satisfiers. Mobility can be such a need or need satisfier. Moreover, Max-Neef defines five types of need satisfiers that are useful for societal-level considerations: *singular* (one need satisfied), *synergic* (more than one need satisfied), *pseudo* (false sense of satisfaction), *inhibiting* (satisfying one need but impairing the satisfactions of other needs), and *violator* (impairing the satisfaction of all needs).

Doyal and Gough [24]’s human needs framework is rooted in medical ethics and political economy. They follow a hierarchical approach, moving from universal goals (i.e., avoidance of serious harm), through universal basic needs (i.e., physical health and autonomy) to twelve

categories of intermediate needs. Need satisfiers are culturally and temporally variable and distinguished from human needs, as in Max-Neef’s work.

Sen et al. [25]’s capability approach considers what people are actually able “to be and do”, as key to quality of life. Quality of life or wellbeing are analysed in terms of (a) *functionings* (states of being and doing, e.g., being well-nourished, but not the commodities needed to achieve them) and *capabilities* (sets of functioning one can effectively access). Fittingly to the present topic, Sen uses a bicycle to illustrate this point: A bicycle is generally characterised as a useful transportation vehicle. Yet, whether it can actually provide transportation services depends on the characteristics of the potential user (their skill, health, etc.) and circumstances (e.g., prevailing social norms, environment, or infrastructure) to convert them into valuable functioning (i.e., bicycling). An individual’s capability set may include different mobility functionings, such as walking, bicycling, taking a public bus, and driving a car. The particular functioning they actually select for a particular trip may vary. The capability approach also considers subjective wellbeing as a valuable functioning in its own right.

Unlike Sen, who did not specify capability requirements, Nussbaum [26] derives from the requirements of human dignity a list of universal “central human functional capabilities” to be incorporated into national constitutions and guaranteed to all—up to a certain threshold. The universal approach is similar to Doyal and Gough [24]. The central capabilities, many of which relate to mobility services, are: life, bodily health, bodily integrity, senses, imagination and thought, emotion, practical reason, affiliation, other species, play, and control over one’s environment. This approach connects to Maslow’s hierarchy of human needs, which is also rooted in behavioural psychology and explains the motivation of human behaviour [27].

The Decent Living Standards (DLS) framework of Rao and Min [17] aims to bridge the gap between the theoretical and qualitative theories described above and practical reality. It specifies an inventory of material conditions — at individual, household, and collective levels — that are suggested to be prerequisites for securing wellbeing in modern industrial societies across physical and social dimensions. It provides a basis for sustainability research to link sustainability scenarios to human development goals, as the provisioning systems for goods and services for development can often be related to sectors considered in existing energy and climate models. This allows for estimates of “Decent Living Energy” or “Decent Living Material” requirements, denoted in energy units and in mass of certain materials, respectively, and corresponding gaps. A major difficulty, however — one perhaps most critical in the mobility dimension — is specifying precisely the levels of consumption necessary for securing DLS. Rao and Min [17] recognise this difficulty and constrain themselves to the broad claim that DLS require access to adequate motorised transport, either via public transport in a reasonable distance from one’s home, or, where context demands, private vehicle use.

2.2. Needs-oriented mobility research

In many regions today, large inequalities exist in the distribution of transportation system benefits and burdens across society [28], which raises the question of what a ‘fair’ or ‘just’ transport system should be. Vecchio and Martens [29] suggest a definition based on Sen’s capabilities approach, saying that a just transportation system should provide travellers with access to essential destinations and “a reasonable level of freedom to choose what they want to do and be”. On the same theoretical basis, Pereira et al. [30] argue that distributive justice and equity considerations in mobility highlight the need for transport system accessibility. Martens et al. [31] propose corresponding thresholds of transit access. However, there is no agreement so far on what constitutes sufficient levels of mobility for individuals [32], which would be a crucial figure for equity and environmental purposes.

² To be clear, not only population groups in lower-income countries, but also considerable shares of high-income country’s populations [e.g. 14].

Quantitative assessments of individual minimum mobility levels required to satisfy human needs have so far been scarce, with notably no consensus on corresponding indicators and thresholds. Most existing studies have used the population average of annual travel distance per capita, mainly because of data availability and compatibility with energy systems models such as IAMs. These normative estimates are based on picking the ‘best’ available country cases at present [17,19], with assumed variations between and within countries based on urban population share and population density [20]. Other studies have estimated transportation infrastructure material stocks that are consistent with high levels of road accessibility [18,33]. While all these studies have used a single indicator for mobility needs satisfaction, they have not taken into account population and location heterogeneity, which are key to assess if mobility needs are satisfied or not [32]. However, Czepkiewicz et al. [34] pioneer in those aspects by correlating mobility needs satisfaction with spatial and individual attributes, as well as yearly CO₂ emissions.

Qualitative approaches in literature have conceptualised mobility needs in different ways. Inspired by Maslow’s hierarchy of human needs [27], Musselwhite and Haddad [35] propose a three-level hierarchy of transport needs: (1) practical needs, seen as primary and related to day-to-day and functional travel; (2) social needs, secondary and associated with psychological feelings of independence, sense of control of one’s life, and being in tune with society; and (3) aesthetic needs, which are associated with pleasure and entertainment, such as travel for relaxation, recreation or outdoors activities. Davey [36], Ahern and Hine [37] and Siren et al. [38] employ a binary classification of “serious needs”, such as medical and work-related appointments or emergencies, and “discretionary needs”, such as spontaneous trips, visiting people and other pleasure-related trips. Others define personal mobility needs non-hierarchically [e.g.39], which is consistent with Max-Neef’s framework.

The field of transport-related social exclusion treats the need for mobility as the ability to participate in society. Burchardt [40] defines social exclusion in general across four dimensions, while Church et al. [41] and Lucas [42] define a list of seven exclusion types that relate to mobility. In this sense, unrealised mobility is closely linked to mobility poverty [43]. Noteworthy, unrealised mobility is not necessarily an indication of unmet needs or social exclusion because this mobility could also be motivated by non-essential desires or wants [32,44]. Mattioli [45] proposes a framework to delineate between needs and wants in mobility in order to analyse the transition of transport systems towards environmental and social objectives. He proposes hierarchical “need satisfier chains” with Max-Neef’s and Doyal and Gough’s basic human needs at the top, leading to intermediate needs, then transportation, and finally, a transport mode. Dillman et al. [22] use Mattioli’s framework to derive a lower boundary for urban mobility-related sustainable consumption corridors by considering four dimensions: transport affordability, mobility poverty, accessibility poverty and exposure to transport externalities [43]. Yet, in their indicator review [46], mainly based on Sdoukopoulos et al. [47], the authors do not provide quantification of minimum thresholds on the considered dimensions. However, Ryan and Martens [13] suggest that minimum thresholds could find application in accessibility policy and planning, if their benefits are clear. Such quantification would also help understanding sustainable consumption corridors [9,48] in mobility, which can be a basis to discuss over-consumption [10].

3. Decent mobility

Based on previous needs-oriented transport research, we define the condition that “an individual has decent mobility” as meaning that *the individual can enact a set of trips that allows satisfaction of their fundamental needs within their resources and capabilities*.

This definition is constructed to do several things. First, it ties “decent mobility” to overall needs satisfaction in a simple way: decent

mobility is a *necessary condition* of needs satisfaction.³ Second, it focuses on minima. An individual may choose to take additional trips beyond this minimum necessary set — travel from which they may derive greater subjective enjoyment or “utility” — but these are not included here. Third, the definition centres individual people. This makes clear that aggregate claims (“Decent mobility is achieved in Country X”; “Group A has decent mobility”, etc.) are ultimately claims about the decent mobility of all the individuals making up those groups or populations.

Although qualitative, our definition supports a simple and flexible method for quantification, which we demonstrate in the remainder of this paper: (1) enumerate a set of fundamental needs, (2) identify satisfiers of those needs and their spatial locations, (3) identify trips necessary and achievable to access the satisfiers, and (4) quantify attributes of each trip and the total set. This ensures that resulting measures, such as passenger distance travelled, are consequent of a thorough consideration of travel activity and its purposes.

In the remainder of this section, we first derive needs-satisfier chains for mobility based on Doyal and Gough’s fundamental human needs. We then introduce a method based on *personas* to identify groups of individuals whose needs-satisfaction requires distinct frequency of trips for each purpose; these allow to capture a range of individual heterogeneity. Finally, we discuss in depth the theory and potential quantifications of resource constraints and boundary conditions that may inhibit the realisation of trips: the “can enact” element of our definition.

3.1. Mobility as a need satisfier

Within the human needs conceptualisation of Max-Neef, mobility can be considered as a need satisfier, among others, for the axiological needs of subsistence, protection, affection, understanding, participation, idleness, creation, identity, and freedom [49]. However, this list does not allow for deriving mobility needs in terms of trips for different purposes (or visits to different need-satisfiers; in the following called ‘trips’). Doyal and Gough provide a more operational concept of needs by adding an intermediate needs level [see 22]. Fig. 1 uses this intermediate level to connect trip purposes to basic needs, as proposed by Mattioli [45]. Undertaking those trips in adequate frequencies would effectively eliminate all causes of transport-related social exclusion, as defined by Burchardt [40].

Trips can be differentiated in two types of need satisfaction. *Directed* travel has the primary goal of reaching a destination (i.e., the spatial location where a particular need can be satisfied by some action, service, etc.). It makes mobility a derived demand and indirect need satisfier, and corresponds to the economic perception of travel time and expenditures as disutility, being subject to minimisation [50]. *Undirected* travel, on the other hand, refers to trips for which the destination is not specific or ancillary [51]. In this case, the trip itself is the travel purpose [52] and there is positive utility of travel [53]. [54] highlight four motivations for undirected mobility: improving health and wellbeing, removing negative feelings, enjoying scenery, and out-of-home socialising. This challenges the idea that travel should always be minimised. For instance, the COVID-19 pandemic has shown that individuals complement their directed trips with undirected or longer travel if their daily mobility is restricted [55,56]. While undirected travel represents a low but non negligible share of overall trips (e.g. 8.5% in France in 2008 [57]), it occupies a higher share of daily time use because these trips are made for longer duration than other trip

³ Thus all the usual corollaries of necessary conditions: A person who does not have decent mobility — who is in a state of mobility deprivation or poverty — cannot satisfy all of their fundamental needs. And decent mobility *alone* does not imply fundamental needs satisfaction: for example, other, non-mobility-related satisfiers may not be available or accessible.

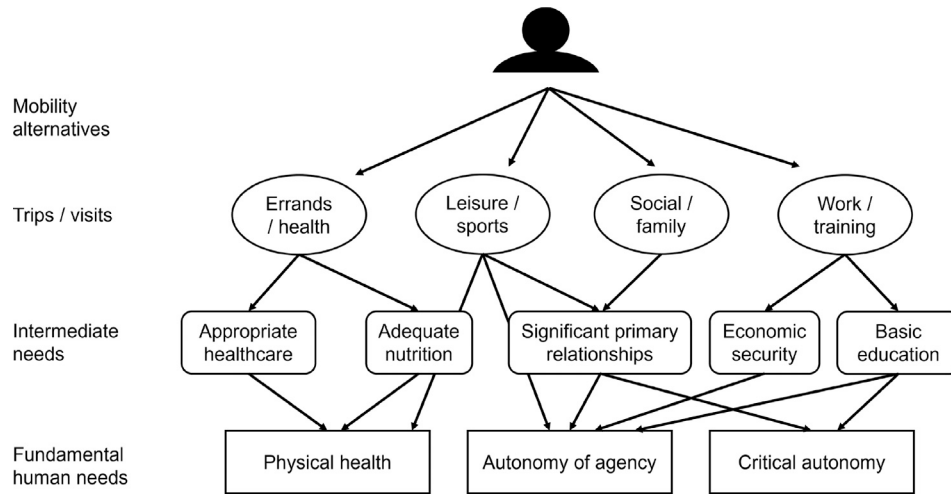


Fig. 1. Mobility-needs-satisfier chains connecting fundamental and intermediate human needs by Doyal and Gough [24] to trip purposes that require physical or digital mobility.

purposes [58]. Undirected trips are most often undertaken to a large extent with active modes and to a low extent with private motorised modes [54].

In addition, directed travel and related physical mobility can be replaced by use of digital services (i.e. remote work, video conferencing, telehealth, e-learning) or freight delivery services through online shopping. Those digital activities saw a significant increase during the COVID-19 pandemic where digital alternatives were available and physical mobility was restricted [59]. For the sake of simplicity, we exclude freight transport rebound effects from this paper, as online shopping potentially reduces environmental impact, depending on the purchase batch size [60,61]. Hence, the availability of digital services and corresponding devices (digital infrastructure) does complement the physical mobility infrastructure.

Where physical mobility is required, there might be more than one alternative trip that allows to satisfy the need, if there are different transport modes, routes, or destinations available. Those alternatives interact with satisfaction of own or other's needs, through limited time/monetary budget or through their externalities. Using Max-Neef's need satisfier characteristics (see Section 2.1), reasonable levels of active mobility contributes to health by increasing physical activity (synergic satisfier) while cars impair satisfaction of other needs (violation satisfier) because of their externalities (for example, air pollution, CO₂ emissions, noise, accidents, and space requirements). Such interdependencies are relevant on a societal level. Individual need satisfaction should not inhibit or violate need satisfaction of others, which is closely linked to mobility provisioning system design. In addition, there are resources and capability constraints which can limit the choice of mobility alternatives.

3.2. Personas and heterogeneity

Practical application of our definition in modelling and assessment must address the simple fact that data for *all* individuals (in any population, but especially the global population) is rarely, if ever, available. While the definition affirms the importance of capturing the range or heterogeneity of travel behaviour across all individuals, this should be achievable without treating the individual as the unit of analysis. To overcome this challenge, we choose a personas approach, which links well to common methods in both fields: Modern transport planning (especially influenced by critical feminist theory [62]) considers personas to investigate mobility needs of all social groups, while activity- and agent-based modelling is the most common method in place-based transport studies. When operationalising this approach, the

Table 1

Fundamental persona characteristics and attributes, which affect the set of necessary trips (needs) and the availability of travel alternatives (capabilities).

Characteristic	Attributes	Affects trip purposes (needs)	Affects mode availability (capabilities)
Age group	Underage; working age; retired	x	x
Care obligation	No; yes	x	
Occupation	Employed; student	x	
Health issues	None; chronic disease; disabled	x	x

set of personas must have universal characteristics that are sufficient to depict the (global) population, while keeping the number of personas as low as possible for its applicability and interpretability.

Personas are characterised by attributes that impact their mobility needs and/or capabilities to travel. As a starting point, we suggest four characteristics given in Table 1 that should allow to differentiate between the most significant mobility groups. Higher levels of detail and specification should correspond to data availability, as sketched out in Fig. 2. There are additional individual characteristics that are observed to be highly correlated with unequal mobility needs or restriction in their fulfilment, like larger care obligations for women [63].⁴ We acknowledge that this observation results from gender roles or any other stereotypes which are based on power inequalities and socio-political system design. In our sufficientarian, normative approach, those attributes should not prescribe decent mobility needs or general (un)availability of transport modes to individuals. Rather, the underlying factors that are directly mobility-relevant and govern need variations are taken into account, such as care obligations or disabilities. Corresponding power inequalities are considered as part of the social and political institutions (Section 3.3.3), which depend on the region of study.

We note that there are other more specific attributes defining distinct needs, which are not reflected in our current persona design. For example, migrants tend to undertake more long-distance air travel as an effect of social network dispersion [65,66]. While visiting family and friends is a fundamental need, whether long-distance travel is considered a necessity is arguably dependent upon the reason for migration. If that migration is a response to economic insecurity or

⁴ Similarly, race restricts individual mobility due to lack of safety in many regions today [e.g. 64].

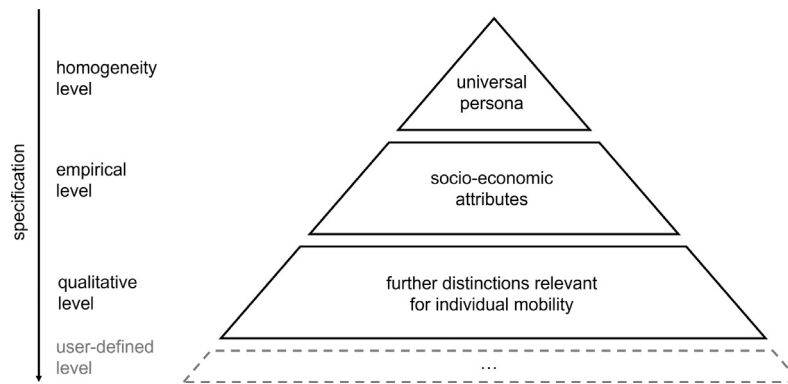


Fig. 2. Heterogeneity of personas based on the level of detail in analysis and data.

political persecution, long distance travel to visit family that did not relocate may be considered a necessity. In contrast, for someone that has relocated to work in a prestigious university or company, the long-distance travel required to visit family may be seen as arising from preferences. Regardless, the environmental implications should not be sidelined. Air travel has a large and growing climate impact and is characterised by various inequalities [see 67]. Further research could address this dilemma of needs satisfaction vs. environmental impact.

3.3. Boundary conditions

Mobility provision is constrained by three interdependent dimensions. The *individual* dimension includes endowments of resources in terms of time use and its trade-offs, monetary budgets, as well as capabilities that restrict travel alternatives. The *environmental and spatial* dimension determines the distances between living spaces and need satisfier locations, as well as the availability and performance of transport modes, which interact with individual resources and capabilities. The *socio-political* dimension may further interfere with individual characteristics through socio-political institutions.

3.3.1. Individual dimension: resources and capabilities

Individuals have certain capabilities that may limit mobility options within a given context. Physical health, for example, is a crucial factor for the ability to access spatial need satisfiers with certain transport options. Hence, providing decent mobility for those who are less capable may mean providing more accessible options. Possession of a driver's licence is another example of an individual capability affecting mode choice.

Alternatives can then be further constrained by resources available to individuals: time and money. While the time resource itself is not directly referred to in the literature on basic needs or the capability approach, it is widely understood as a clear driver of wellbeing [68, 69]. It is a resource input that individuals consider for planning any daily activities, including transport decisions, as they look to secure discretionary time for activities they find valuable. For time-deprived households, excessive time spent on trips for one basic needs dimension impairs the capability to satisfy other needs. Therefore, we argue that decent mobility should consider an upper bound on total committed time spent on directed travel per day.

Earlier empirical work has shown that, at a population aggregate level, total travel time expenditure (TTE) is stable at around 70 min per person per day, regardless of region, culture, income, car ownership shares, or year of observation [1]. But there are also evidences of large heterogeneity across individuals and households in disaggregate time use data [57,70,71]. Tiznado Aitken et al. [72] explore the interplay of time poverty and transport-related social exclusion (see Section 2.2). They adopt 90 min per day per person as a threshold for transport-related time poverty, following literature on extreme commuting [73,

74]. They find, for the Canadian case, that the relationship between time poverty and transport-related time poverty is “not noticeably correlated” but depends subtly on socio-demographic status. As the authors indicate, lack of correlation does not mean lack of interaction: for instance, the wealthier can avoid being time-poor by paying for services. We can also expect the time-poor who cannot afford such paid help avoid being travel time-poor by compromising the quality of services within affordable travel time.

Our own empirical investigation (Fig. B.8) confirms that the average committed TTE across many time use surveys from different regions is observed to be 70–80 min per day per person, but in certain surveys, it reaches 100 min (e.g., Italy 2002/2003 and Spain 2003). It also shows that 25–40% of individuals in most countries are exceeding the 90 min travel time poverty line, or as much as 50% in those two exceptional cases. In ‘committed’ travel we include trips for work/education, personal/family care obligation, shopping, and voluntary/ civic/ religious activities; thus, excluding leisure activities.

Based on this analysis, we adopt the same 90 min per day as our decent time threshold for committed travel, regardless of the heterogeneity in travel time observed across gender or socio-demographic factors [75–78]. We argue that empirically observed differences in transport time expenditure should not be a reason for defining differentiated time thresholds for socio-demographic groups (more discussion in Section 3.3.3).

Similarly, we acknowledge that travel time *quality* differs between transportation modes and due to external factors. For example, public transportation has higher acceptable commuting time compared to other modes [79], and scenery is a particularly important positive experience factor for train passengers [80]. Travelling with public transportation can allow multitasking [81], deliver important social interactions, and promote feelings of connectedness [82]. However, decent mobility does not prescribe certain modes or transport technologies in its definition. Hence, we do not adopt different levels of the decent travel time threshold, based on perceived time qualities.

Additionally, monetary constraints play an important role in transport accessibility, especially the choice between modes and destinations of various distances. However, there is no homogenised definition of “transport affordability”, as there are no standardised metrics associated with the concept [83]. Notably, the majority, if not all, of transport affordability definitions come from high-income countries. Mattioli et al. [14] discuss various definitions of transport affordability and fuel poverty. Defining a universal monetary metric is difficult because income is typically measured for entire households, while mobility needs and capabilities are individual. When defining a household budget threshold for mobility, it is important to exclude rich households which over-spend on mobility without sacrificing other fundamental needs. Hence, they suggest as indicator: households below relative poverty that spend more than twice as much on mobility as the societal median (in the UK, this is around 10% of households). For decent mobility, this connection between individual and household level should be considered, if corresponding data is available.

3.3.2. Spatial dimension: built environment, transport infrastructure, operation, and technology

Built infrastructures determine the opportunities to move about within individuals' capability constraints. The design of transport networks (e.g. roads, public transport including operating times) contributes to accessibility of need satisfiers, as do their distribution and the distribution of housing. Accessibility has become one of the most important areas in mobility research because it contributes to multiple goals of transport policy at once [29]. In a European context, it has been framed around integration or exclusion of members of a society due to aforesaid factors, while in the North American context, accessibility research often includes concepts of environmental justice, civil rights, and anti-racism [84].

Pereira et al. [30] argue that increasing transport system accessibility is a central tool towards distributive justice in mobility and ceasing of transport disadvantages, as it provides social and economic opportunities to individuals. Though, the interconnection between spatial need satisfier distribution and transport system inclusiveness is not finally clarified. For example, Luiu et al. [85] find that built environment and place of living are insignificant for unrealised mobility of older generations, while public transport accessibility is significant. On the other hand, concepts around the "15 min city" put stronger emphasis on need satisfier distribution within reasonable distances around living areas because they assume walking and cycling to be the natural and appropriate mode choices for such distances. Promoting less energy-intensive modes is, thus, supported by proximity-oriented spatial planning [86], which supports needs satisfier accessibility [34].

Transport technology impacts the distances which can be covered in the same amount of time. Historically, new technologies have reduced travel resistance and lead to larger distances travelled across the world [87]. In the present study, we stick with established technologies while keeping in mind technological change can alter a transport system's service provisioning (i.e., e-bikes have increased active transport travel distances; high-speed trains have turned cities to connected neighbourhoods).

The most impactful transport technology of recent decades has been the private car. Mattioli et al. [4] and Sheller [88] argue that transport systems designed towards private car use produce *car dependency*, which does not guarantee needs satisfaction for all. It forces poor households to purchase costly private mobility above their budgets [89], threatens cultural variety of urban areas [90], and limits mobility of elderly [85]—and further influences urban form and population density [91]. Car dependency can thus be viewed as the cementing of 'pseudo', 'inhibiting' and 'violation' satisfiers into provisioning systems; in contrast, 'singular' or 'synergic' satisfiers such as walking, cycling, and public transit infrastructure can better support universal decent mobility.

Other spatially specific factors include climate, weather, and topography, which can limit the applicability of certain modes. For example, walking accessibility of older people can decrease dramatically during winter in colder climates [92], or willingness to cycle decreases on cold or rainy days [93]. Similarly, steep ascents can hinder people from cycling or walking. Those factors can limit mode availability of certain population groups beyond mere preferences or mode choice. As argued above, preferences based on quality of travel, such as comfort, are excluded from this framework. Including climate, weather, and topography and connecting them to population groups requires detailed data about local contexts.

3.3.3. Socio-political dimension: norms and rules

Social and political institutions and frameworks show how the entanglements of power and social exclusion result in unequal access to mobility, leading to unmet needs [94]. Mobility is globally divided along lines of race, gender, class, age, nationality, and a range of other social markers. Taking an intersectional approach to studying travel

needs and behaviour allows for a more nuanced understanding of the complexities and inequalities that exist within transport systems.

There have long been connections between unequal access to mobility and racism [95]; historical exclusion and car ownership as a symbol of security and status [96]. These are just two examples of what Seiler [97] terms the "racialization of mobility", meaning how "the modern practices and institutions of mobility have been and remain highly racialized". Struggles on how to move are thus linked with struggles and contestations over urban space [98], political discourses of resource distribution [99], and the lack of participatory empowerment of citizens in decision making.

Gender dynamics have been explored in transportation research, highlighting how patriarchal structures and norms influence women's mobility patterns and access to transportation resources. Borker [63] shows how travel patterns and experiences of women vary, the barriers they face, and how current transport systems (from public transit to road networks) do not accommodate women's needs [see also 100]. A survey fielded across developed and developing countries reveals that 80 to 90% of women reported having been harassed in public transport [101]. In turn, limited access to safe transportation accounts for an estimated 16.5% reduction in women's probability to join the labour force in developing countries [102]. In general, inadequate public transport (including last mile) coverage perpetuates the gender gap in mobility, as car access in many places is restricted for women.

Additionally, the unequal distribution of care responsibilities, primarily falling on women, can restrict and complicate their mobility and limit their access to transportation options. These gendered differences in unmet travel needs prevail in older generations around the world, mainly due to social roles and caregiving duties [85]. This dimension is closely tied to monetary and time poverty, further reinforcing gender inequalities, and can further limit individuals' ability to engage in activities outside their immediate vicinity. Hence, social roles are closely linked to individual resources and capabilities, as well as infrastructural determinants of decent mobility. However, corresponding literature has not yet dealt with specifying indicators or thresholds related to human needs and wellbeing.

4. Quantification of decent mobility

This section aims to quantify the minimum frequency of trips that is needed for decent mobility. It is noteworthy that we assume such needs vary with persona attributes, but not with the spatial or socio-political context. Mattioli [45] shows that structuration processes within local cultures play a large role for the evolution of need satisfaction. Yet our approach to quantify decent mobility aims at a more fundamental level, which is independent of local context, to enhance applicability. Table 3 summarises our assumptions, which are elaborated in the following paragraphs.

Additionally to those trip purposes listed in Fig. 1, we include home trips, which are relevant for trip chaining or activity scheduling (see Fig. A.7 for elaboration on terminology). Setting those equal to the number of other trips, the persona would take every trip from home and return afterwards. We assume it to be one trip per day as the minimum to satisfy mobility needs. That results in only one tour (chain of trips) per day.

The frequency of mobility throughout the week is another interesting aspect of mobility needs. Madre et al. [103] estimate that, on any given day, 8 to 12% of the population do not make a single trip, mainly based on European travel and time use surveys. For a global dataset of 401 travel diaries, they find a consistent average of around 3.5 trips per day for mobile persons, while 5 to 30% stay home. However, this is aggregated data: the disaggregated analysis supports their estimate of 8 to 12% immobile persons per day. Hence, we assume that one immobile day per week is in line with the need to move (as discussed in Section 3.3.1).

Research on essential travel is a small, but promising field for determining minimum required trips. Krumdieck et al. [11] define essential travel as: “trips which people would struggle to eliminate, and when lost would cause harm to health, deprivation, loss of income, and limit the ability to meet basic needs”. Yang et al. [55] prove empirically that essential travel exists, using GPS data from a Chinese city during and after the COVID-19 pandemic. Similarly, Kar et al. [104] identify essential travel during COVID-19 from highly disaggregated data in the US, finding differences in essential travel destinations across socio-economic groups. However, thus far no study has aimed to quantify the essential number of trips to certain destinations.

Work- and education-related commuting are scheduled trip purposes that depend on the individual's occupation and life status. Trip frequency depends on socio-economic system design, which complicates estimating a lower threshold. However, four trips per week, respectively, is a reasonable assumption that matches essential occupational activity in high-income countries today, as well as empirical evidence from urban India across income classes in the 1990s [105]. Scheduled trips also result from care obligations for children, elderly, or disabled people. Here, we crudely simplify those obligations to one trip purpose and assume one trip per day.

Healthcare trips occur regularly when a persona has a chronic disease or disability. In both cases, we assume one trip per week as the minimum. These attributes also cover special needs of elderly. We do not assume here further differentiations based on the age of personas, based on Rosenbloom [106] who shows that, in the US context, no age group makes more than 6% of trips for medical purposes.

Errands and grocery shopping trips are essential for all households, even though not regularly scheduled. In their travel analysis for China during the COVID-19 pandemic, Chen et al. [56] find 1.67 grocery shopping trips per week were undertaken during the pandemic, compared to 4.12 before the pandemic (other trip frequencies found in this study are not applicable, as this period does not correspond to fulfilment of basic social needs). Astrop [105] finds an even lower number of slightly more than one shopping trip per week for inhabitants of urban India, consistent across income groups. Based on those findings, we assume the minimum number of grocery shopping and errands trips needed to be one per week.

Decent mobility needs for social, cultural, and recreational purposes are more difficult to estimate because such leisure activities depend on individual traits, preferences, and capabilities. For example, the Dunbar number suggests that there is an upper limit to social network size [107,108], based on cognitive ability and time constraints [107,109]. Alessandretti et al. [110] find that the number of locations an individual visits regularly stabilises to about 25, although there is a positive correlation with social network size. Recent mobility surveys for UK and US show that the average number of social and recreational trips per person have been quite stable for the last two decades (except during the COVID-19 pandemic), with a range of 4.9–7.7 trips per week for US [111] and 5.5–6.3 trips per week for UK [112]. We assume then a minimum of two trips per week for social and cultural trips and two as well for recreational and outdoor activities, including undirected trips.

Regarding individual capabilities and corresponding mode availability, the following assumptions apply: Car driving requires a driver's licence and physical ability to do so. Underage personas do not have drivers licences, while a share of older people lose the ability to drive, similar to disabled personas. For sake of simplicity, we assume the share of older people unable to drive is 50%, and 100% for disabled; assumptions that could be varied if adapting this approach to real-world populations for which more precise data is available. There is also evidence that women, low-income groups, and migrants have lower driver's licence shares, but we do not account for this specificity within this normative approach (see the discussion above regarding normativity and care obligations).

While walking should be available to all personas, given sufficient infrastructure, cycling is not considered a valid option for disabled

people. Still, active travel should be part of decent mobility for non-transport related reasons. The World Health Organization recommends that adults engage in at least 150 min of moderate-intensity aerobic physical activity per week, which can include activities such as walking and cycling. We assume this threshold as a minimum for combined walking and cycling travel time.

Table 2 shows a descriptive selection of persona attributes from Table 1 together with their mode use capabilities. Table 3 summarises our assumptions on the minimum number of trips per week for those personas. Within the scope of this paper, we do not estimate the impact of remote work, schooling or online shopping — despite notable developments since the COVID-19 pandemic — because we focus on the operationalisation of needs in transport and energy modelling. The impact of digital domains on (mobility) needs satisfaction should be subject to future research.

5. Application in two case studies

We present here two case studies that showcase how our concept and quantification of decent mobility can be operationalised in radically different contexts. The two case countries, Switzerland (CH) and Mauritius (MU), differ greatly in their topography, land use, built environment, infrastructure, socio-economic development, and wealth. We also employ fundamentally distinct methods and discuss their benefits and shortcomings.

The CH case study considers urban, suburban, and rural areas in Switzerland, a high-income country with generally high wellbeing indicators. We employ aggregated data from official sources to determine average trip characteristics. The MU case is a spatially explicit modelling study of an urban and a peri-urban area in Mauritius, a lower-middle income small island state. In the absence of official data, we employ open data (OpenStreetMap and public transit schedules) and common methods of transport and accessibility modelling.

5.1. The Switzerland (CH) case study

Switzerland is among the wealthiest countries in the world (as measured by per-capita income). While it has one of the cleanest national electricity grids, this comes alongside a high average carbon footprint (14 t CO₂/cap) and high levels of mobility due to its high level of wealth [113]. In 2021, average Swiss mobility was 15,000 km/cap/year, almost double the world average [114].

We estimate distances required for decent mobility needs in Switzerland for personas in Table 3, and for three areas types: urban, intermediate, and rural. The Swiss federal statistical office provides accessibility data describing average distances to the nearest service, for thirty different services [115]. We match these services to our purposes (excluding commuting) and take the mean of all matches to obtain a distance for each purpose (for urban, intermediate, and rural areas). Commuting distances are not easily related to data on accessibility of services, because workplace and residential location choice strongly depend on life decisions and economic circumstances. We make a conservative assumption and simply take current commuting distances for this purpose. In contrast, we are optimistic about meeting friends and family by assuming these meetings occur in social/cultural locations instead of their homes (such preferences should be further explored with insights from social network diffusion research). Assuming that people need only access their most accessible service is clearly a strong assumption, but we balance this out by assuming no trip chaining. For each persona to meet minimum mobility needs, we thus simply multiply our distances for each purpose (for each geographic area) by the trip frequency for each purpose. As such, we neglect mode shares and corresponding travel time implications. Note that we do not evaluate whether the mobility provisioning systems are able to provide decent mobility, as we cannot simulate time use and other expenses with this aggregated data. This case study simply estimates a range of

Table 2

Attributes, labels, and capabilities of the most descriptive personas based on the characteristics from Table 1. The mode restriction columns refer to population shares.

	Age group	Care obligation	Occupation	Health issues	Persona label	Car use restricted	Bicycle use restricted
1	Working age	No	Employed	None	Single worker	–	–
2	Working age	Yes	Employed	None	Caring worker	–	–
3	Working age	No	Student	None	Single student	–	–
4	Retired	No	unempl.	Chronic disease	Unfit elderly	50%	–
5	Working age	Yes	Employed	Chronic disease	Unfit caring worker	–	–
6	Retired	No	unempl.	Disabled	Disabled elderly	100%	100%
7	Working age	No	Employed	Disabled	Disabled worker	100%	100%
8	Working age	No	Student	Disabled	Disabled student	100%	100%

Table 3

Trips/visits per week for each purpose, shown for the most descriptive personas. Trips for recreational and outdoor activities include undirected trips.

	Persona label	Work	Education	Accompaniment	Social, cultural	Shopping, errands	Healthcare	Recreational, outdoors
1	Single worker	4	0	0	2	1	0	2
2	Caring worker	4	0	7	2	1	0	2
3	Single student	0	4	0	2	1	0	2
4	Unfit elderly	0	0	0	2	1	1	2
5	Unfit caring worker	4	0	7	2	1	1	2
6	Disabled elderly	0	0	0	2	1	1	2
7	Disabled worker	4	0	0	2	1	1	2
8	Disabled student	0	4	0	2	1	1	2

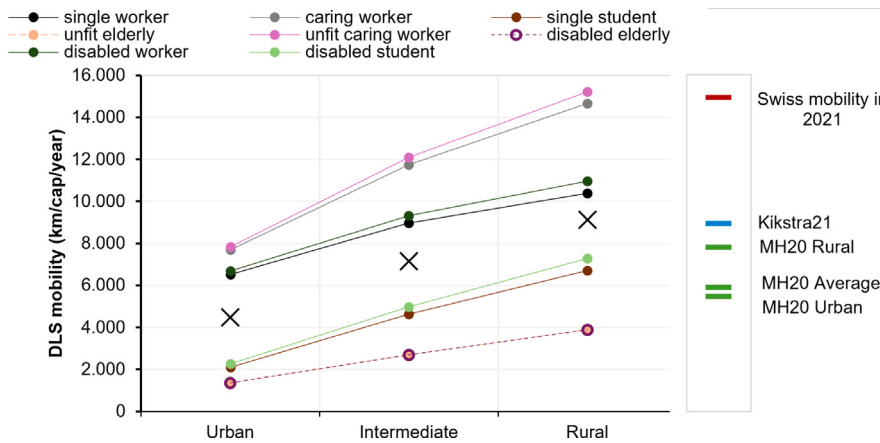


Fig. 3. Annual distance travelled for the 8 descriptive personas (from Table 3) calculated for urban, suburban, and rural Switzerland. The results compare well to previous estimates in Millward-Hopkins et al. [20] (denoted as MH20) and Kikstra et al. [19] (denoted as Kikstra21). Means, denoted as X, do not represent population distributions, but the range of modelled personas.

travel activity, assuming that the Swiss mobility system, one of the most advanced across the world, already provides decent levels of mobility.

Our estimates of passenger distance travelled to provide decent mobility in Switzerland range by an order of magnitude, from 1500–15,000 km/cap/year (Fig. 3). More variation arises from differing trip needs across personas than from aggregate geographic influence on service accessibility. The latter remains significant, however, with decent mobility distances averaged across personas at 4600, 7500, and 9600 km/cap/year in urban, intermediate, and rural areas, respectively. Our lowest estimates (1500–2500 km/cap/year) result from combining personas with low and accessible needs (e.g., students with no health conditions or care obligations; retired people with no care obligations) with the high service accessibility of Swiss urban areas. Our highest estimates result from the opposite (e.g., the high needs of working people with chronic health conditions and care obligations, who live in rural areas).

First, note that our personas are not designed to represent the existing Swiss population, thus the mean mobility requirements of our personas cannot be interpreted as average Swiss requirements. Second, as the Swiss population is largely urban, average Swiss mobility would be strongly biased towards our urban estimate. With this in mind, it is worth noting that the crude estimates for decent mobility in

Switzerland from [20] appear to be within the right range, albeit not sufficiently different in urban and rural areas. The assumption of Kikstra et al. [19], by contrast, appears quite generous. Most importantly, however, current average mobility in Switzerland is higher than all but one of our estimates, indicating substantial excess mobility with respect to the minimum required for human needs.

5.2. The Mauritius (MU) case study

Mauritius is a small-island developing state (lower-middle income) in the Indian Ocean [116] with expanded housing and transport infrastructure stretching from the coastal capital inwards. It has seen a doubling of car ownership in the last decade, leading to increased congestion, pollution, and accidents [117]. We generate transport models for the capital city, Port Louis, and a suburban area, Vacoas, using publicly available data from OpenStreetMap. Both areas have >80% building data coverage in the OSM history eXplorer [118], though data quality is insufficient to model a rural area. Public transit data is manually coded from official schedules, though without the newly built tram line because the only calibration data for modal shares does not yet include this mode [119]. Streets are coded as routable networks for

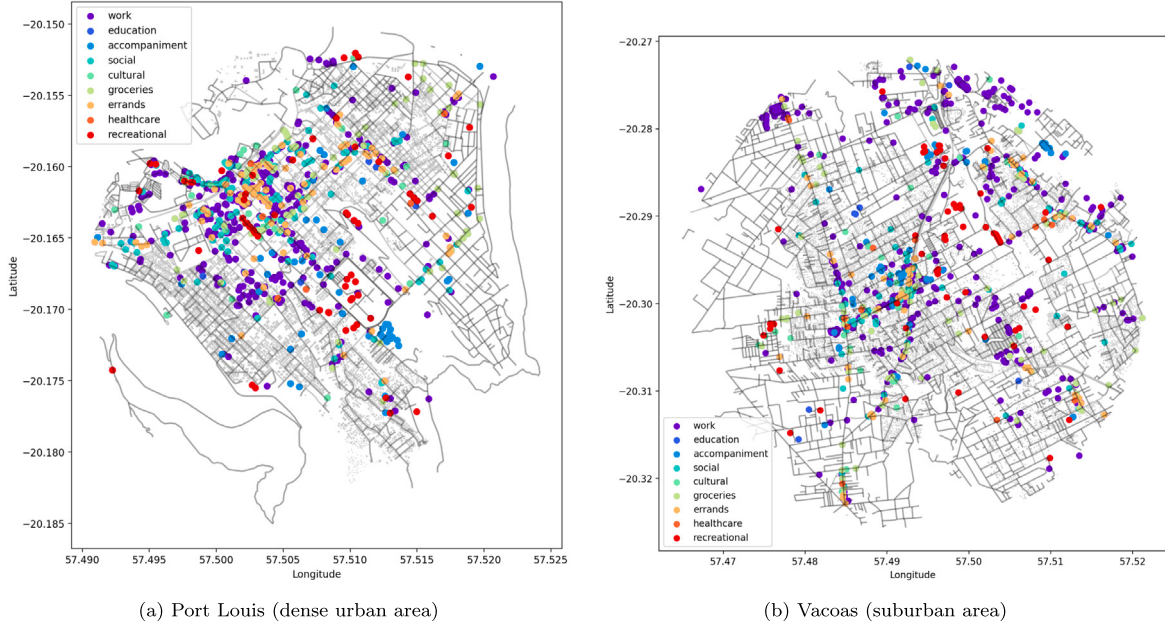


Fig. 4. Mauritius transport network models with street networks (grey), residential building footprints (light grey), and POI markers for different trip purposes generated from OpenStreetMap data.

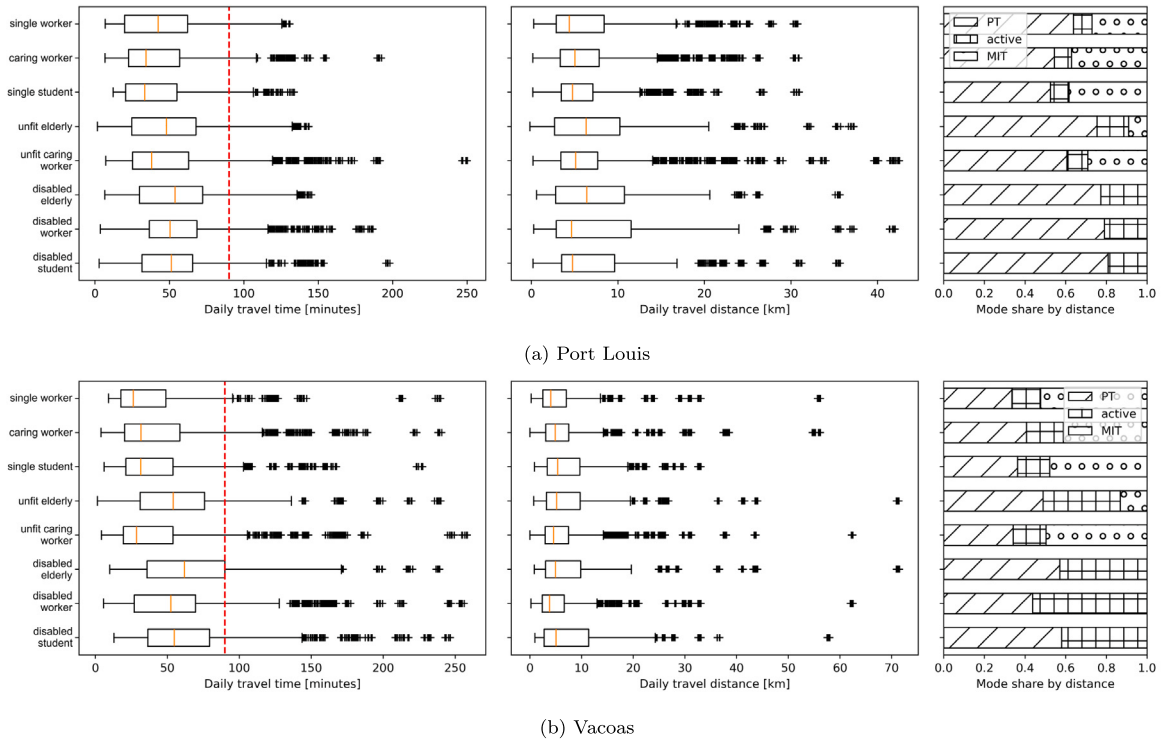


Fig. 5. Distributions of daily travel times, distances, and mode shares (as a measure of distance travelled, not the number of trips) across personas in Mauritius. The red line depicts the 90 min travel time threshold.

motorised individual travel (MIT), bicycles, and walking, respectively (see Fig. 4).

Transport demand simulation consists of four elements: (a) Mobility demand by persona from Table 3; (b) a log-normal gravity model determining the probability of choosing certain points of interest (POIs) based on the distance D between the trip origin o and the respective POI d (Eq. (1) with $\alpha = 1e3; \beta = 1.5$); (c) a simple multinomial logit model simulating mode choice probabilities between walking, cycling, public transport (PT), and MIT based on travel time as measurable

performance attribute (manually calibrated with local expertise and data from [119]); (d) a tour scheduler, combining trips of the same frequency to one daily tour that schedules destinations in a logical order (e.g., first work, then shopping, though neglecting the week-day), minimising the necessity to travel. Executing steps (a) to (d) is equivalent to a standard activity-based transport model, only that trip frequencies are hard coded and there is no equilibration between traffic load and mobility decisions (here, for sake of simplicity).

$$P[d|o] \propto \alpha \cdot \exp\left(-\beta \cdot \log(D_{od})^2\right) \quad (1)$$

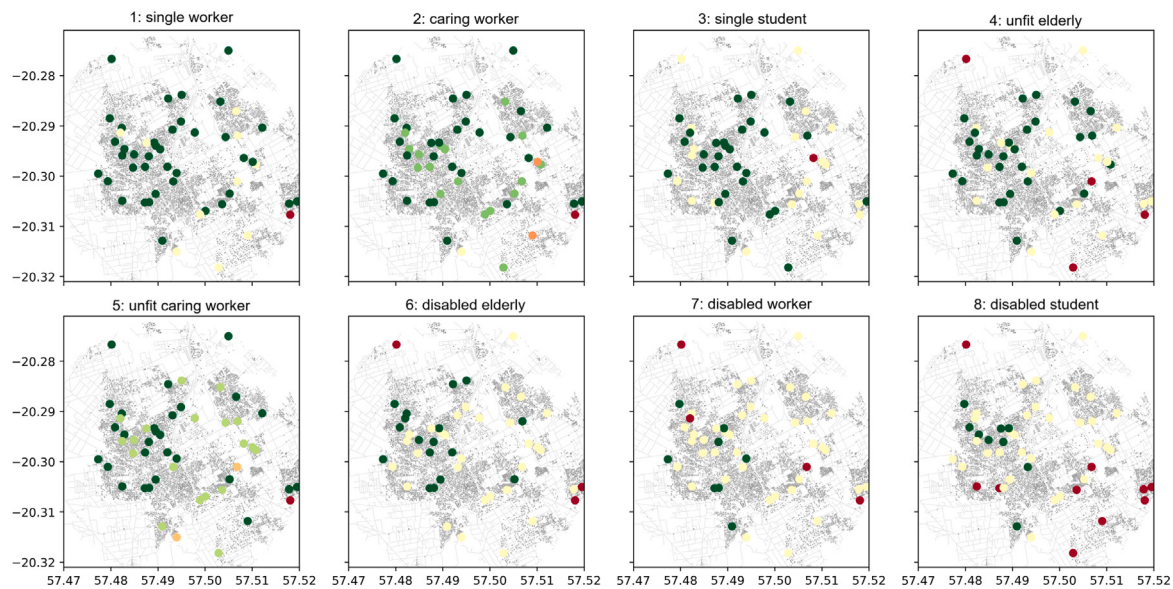


Fig. 6. Persona's home locations (dots), randomly distributed across Vacoas. The colour denotes the share of daily travel schedules that is below 90 min (green for 100%, red for 0%).

All eight personas with their attributes from Table 3 are distributed in 50 randomly drawn home locations, each, to cover the entire mobility provisioning system. Resulting travel schedules are evaluated in terms of travel distance and travel time, with time being the evaluator for the decent mobility criterion in this case study; as long, as the persona is able to reach all need satisfier locations, the daily travel time should not exceed 90 min. A mathematical formulation of these decent mobility conditions can be found in Appendix C.

Results show that the share of personas that exceed the 90 min travel time threshold is greater than zero for all eight persona types (Fig. 5). This is due to different home locations, which might be located in poorly-provisioned neighbourhoods (more so in the suburban area). Still, the 75th-percentile of travel time for each persona is below the threshold, which is consistent with empirical findings on non-leisure travel time from time use surveys (Fig. B.8 in Appendix B). Fig. 6 depicts the share of daily schedules that is below 90 min travel time for each home location and each persona. It showcases more occurrences of decent mobility criterion violation for personas with care obligation (e.g. persona 1 vs. 2) and disabilities (e.g. persona 1 vs. 7). However, average daily travel distances are still lower than in the aggregated CH case study: persona medians are between 1800 and 2500 km/cap/year in both the urban and suburban case. This may indicate a limitation of the data used, as all POIs from OpenStreetMap are considered fully able to satisfy the corresponding need, even though, for example, a corner shop might not suffice for the weekly grocery shopping. Especially in healthcare, individuals are found to travel to POIs that are further away but have higher perceived quality of care, even under severe financial and temporal stress [120]. Moreover, the distance distribution in this case study mainly depends on the parametrisation of the gravity model (Eq. (1)). Hence, such a disaggregated modelling approach should be repeated with better empirical insights in future to generate more realistic estimates of PDT. It would also benefit from demand-supply-equilibration, which would connect individual travel itineraries to societal-level transport system utilisation, and might yield higher travel times.

6. Discussion

In this paper, we provide a new framework for the quantification of decent mobility. Combining literature on human needs and mobility justice, we first conceptualise decent mobility as a list of trips by

purposes that an individual needs to undertake, under conditions that are related to the individuals themselves, their spatial surrounding, and their socio-political context. We then operationalise this framework on different personas by taking into account specific trip frequencies, trip purposes, and transport mode availabilities. This approach targets global applicability and comprehensiveness through few, yet universal, persona characteristics that are subject to individual- and social-level mobility determinants. We finally apply our quantification framework in two case studies: Switzerland at the national level with an aggregated approach, and Mauritius at the city level with a spatially explicit approach.

The aggregate CH case allows us to estimate the travel distance for decent mobility, differentiated between personas and geographic area types. While this simple application does not allow to assess the “decency” of mobility in terms of travel time or monetary expenses, the results nevertheless clearly show the impact of local context and individual heterogeneity on aggregated measures of mobility needs. This case study goes beyond previous approaches that assume the same minimum travel distance for all individuals in all countries. Differentiating mobility needs within populations this way in energy system models and IAMs would allow better representation of actors' heterogeneity, which is key to improving the relevance of scenarios [121,122].

The disaggregate MU case shows how common transport modelling methods can be applied to assess decent mobility for any transport system, given sufficient data. We are able to highlight areas or populations in potential mobility deprivation, where travel times to satisfy basic needs are excessive. The found importance of local service density is supported by the broad field of accessibility research. We also capture and emphasise that individuals with care obligations or disabilities need more support for decent living. Those insights have been highlighted by transport researchers for many years [e.g. 63,88], yet our approach supports quantification of the gap to decent mobility.

6.1. Further framework extension and application

In general, however, we do not claim to have provided a complete or final quantification of minimum mobility needs. Instead, we intend that our methodology and framework can serve as a unifying conceptual basis and integrative approach for multiple streams of future research that improve such quantification. For example, while in Section 3.3.1 we derived boundary conditions on TTE from currently available data,

alternate estimates may be arise from new sources of data from new contexts and/or novel methods. For example, there is no consensus in literature on whether uncommitted travel should be accounted within TTE and time poverty assessments, or not. Within our framework, such hypotheses can be explored, to find how qualitative conclusions and stylised facts about mobility needs satisfaction may change. Researchers could also test alternate ideas about, for instance, which forms of directed/undirected travel are satisfiers of which fundamental needs; or categorisations of those needs *per se*.

Work that elaborates and quantifies other types of boundaries in our three dimensions would also bolster this approach. Examples abound: while it is known that traffic noise exposure, suppressed travel, and travel insecurity are important phenomena, future work that determines quantifiable thresholds for relevant measures could be incorporated here to more precisely constrain the set of enactable trips.

We particularly invite researchers who are familiar with the data available in specific geographical contexts to produce quantifications by combining our definition and high-level method with context-appropriate analysis or modelling, and further to guide data collection (even in “data-rich” countries) to support robust quantification of needs-satisfaction. Such work will support local policymaking through analysis of mobility provisioning systems that measures not just their aggregate energy demand and emissions but also, importantly and vitally, their ability to satisfy needs of all individuals. At the same time, such work can contribute to a growing and mutually-comparable body of knowledge about how local satisfaction of universal needs leads to different transport system requirements across the globe. In turn, this will support understanding of current or possible future inequality in mobility needs satisfaction and related phenomena including affordability, exposure to externalities, social exclusion, and perceptions of safety.

Finally, as an input to global-scope, long-term analyses such as IAMs and scenario exercises, quantifications produced using our framework offer a way to substantially improve on the crude, aggregate, multi-country totals of energy or passenger-distance that are currently used as metrics of wellbeing or needs-satisfaction. Our case studies fit within a growing body of evidence that shows these totals cannot adequately represent the diversity of contexts worldwide. These and other limitations in low-resolution IAMs give rise to critiques that resulting IPCC assessments do not adequately account for inequity of mitigation burdens [123].

Instead, as work expands on “demand-side potentials” for climate mitigation [124–126], mobility and energy modellers can adopt our approach of estimating travel distances (a) for specific personas and (b) as a consequence of trip frequencies, local context, and fundamental needs. As appropriate, this can be either endogenised, or achieved by replacing existing, one-size-fits-all aggregate targets with a range of values derived from needs-based quantification and local data. Such work would make explicit that “demand” for emissions-intensive energy arises from individuals’ activities, including to satisfy their fundamental needs. It would also ensure that IAM-based analyses — in particular, on the physical requirements for materials in transport vehicles and infrastructures — are similarly grounded.

6.2. Conclusion

Researchers charting pathways towards strong sustainability, including in passenger transport, need more nuanced data and methods than are currently widespread. In order to identify safe and just futures, and transitions that bridge to those futures from the current world, it is essential to quantify decent levels of mobility that satisfy the fundamental human needs of every individual, remain within corridors of sustainable consumption, and reflect the diversity of those individuals, their spatial environments, and socio-institutional contexts. When these critical connections are handled via broad, homogenising assumptions, the validity and usefulness of research results is endangered; worse, the

proposed pathways risk illegitimacy if they appear not to centre the wellbeing and fundamental needs of people and groups who are asked to enact the transitions.

To address these risks, this paper builds upon needs-oriented transport research together with theories of fundamental human needs and capabilities, and showed that these provide a sound basis for a simple yet flexible framework for quantifying minimum mobility. This approach allows to move beyond aggregate regularities of “demand” based on gross domestic product and other metrics that were already in the 1970s and ’80s seen as reductive. At the same time, by renewing the focus on individuals’ wellbeing and their spatial and social contexts, it offers a way to directly address questions of mobility justice, equity, inclusion, which grow inexorably in importance.

CRediT authorship contribution statement

Marlin Arnz: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zakia Soomaroo:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Vivien Fisch-Romito:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Jihoon Min:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Joel Millward-Hopkins:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Paul Natsuo Kishimoto:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Benigna Boza-Kiss:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Caroline Zimm:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Bas van Ruijven:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marlin Arnz reports financial support was provided by Energy Demand changes Induced by Technological and Social innovations (EDITS) project. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Notes on terminology

Different research fields utilise different terms to express concepts related to mobility. In this article we try to obtain the most common terms from transport research, acknowledging, that other fields might use them differently. Fig. A.7 outlines the relation of most mobility terms from this article.

$$\begin{aligned}
 p \in P &= \left\{ \begin{array}{l} p_1 = \text{Commuting, business} \\ p_2 = \text{Education} \\ p_3 = \text{Accompaniment} \\ p_4 = \text{Social, cultural} \\ p_5 = \text{Shopping, errands} \\ p_6 = \text{Healthcare} \\ p_7 = \text{Recreational, outdoors} \end{array} \right\} && \text{trip purposes} && (C.1) \\
 i \in I &= \{i_1, i_2, \dots\} && \text{individuals} && (C.2) \\
 t_{p,i} &\in \mathbb{N} && \text{number of trips for purpose } p \text{ in 1 week} && (C.3) \\
 t_{p,i}^* &\in \mathbb{N} && \text{minimum threshold for } t_{p,i} && (C.4) \\
 x_{p,i} &= (t_{p,i} \geq t_{p,i}^*) \in \mathbb{B} = \{0, 1\} && \text{satisfaction of minimum for } p && (C.5) \\
 DM_i^0(x_{p,i}, y_i) &= \left(\bigwedge_{p \in P} x_{p,i} \right) \in \mathbb{B} && \text{decent mobility for } i && (C.6)
 \end{aligned}$$

Box 1.

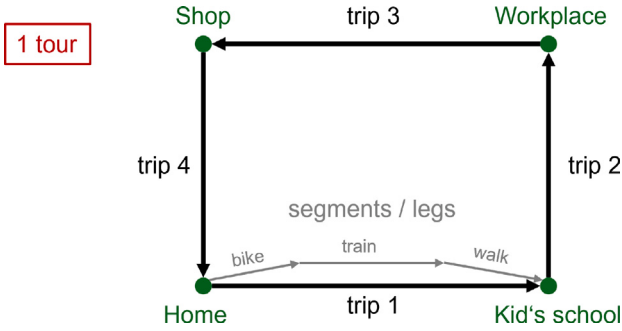


Fig. A.7. Conventional conception of trips, tours, segments used in travel research.

Appendix B. Supplementary material on travel time

Defining universal, globally applicable thresholds for “decent” travel time is a difficult task. As an addition to literature research, we conducted data analysis with a globally comprehensive time use survey repository: the Multinational Time Use Study (MTUS) [127]. It contains 95 time use surveys from 24 countries of different income classes from 1960 until 2018. Our analysis supports the theory that travel time is similarly distributed across world regions, income classes, and periods. Fig. B.8 showcases non-leisure travel time distributions in selected countries and years.

Appendix C. Decent mobility notation, implementation, and data

C.1. Notation

In this section we outline the concept of decent mobility as mathematical formulation, following arguments from Section 3. All assumptions on quantification of trip frequencies and boundary conditions can be applied in the following way—or changed, if better data is available. We begin with some notation (see Eqs. (C.1)–(C.6) in Box 1).

Eq. (C.6) states that a specific individual, i , has decent mobility if a set of trips they can enact meets the *logical conjunction* of several criteria, $x_{i,p}$ —that is, if all of the criteria are 1, or ‘true’. In turn, each criterion is ‘true’ if that individual is able to enact a set of trips such that the count, $t_{i,p}$, of tours which include a visit/stop to a destination associated with a specific trip purpose p is greater than a threshold

value $t_{i,p}^*$. These thresholds are the ones chosen in the paper to express the mobility necessary to achieve satisfaction of fundamental needs.

For example, suppose that individual i belongs to a persona such that the minimum number of tours for the ‘work’ purpose is $t_{work,i}^* = 5$, and the minimum number of tours for the ‘leisure’ purpose is $t_{leisure,i}^* = 1$. Then suppose the individual is able to enact four tours in 1 week: all four including a work stop, and one includes a leisure stop. Then $t_{work,i} = 4 < t_{work,i}^* = 5$, and thus $x_{work,i} = 0$ or false. Likewise $t_{leisure,i} = 1 \geq t_{leisure,i}^* = 1$ and thus $x_{leisure,i} = 1$ or true. Finally $DM_i(x_{p,i}) = x_{work,i} \wedge x_{leisure,i} = 0 \wedge 1 = 0$ or false: this example individual does *not* have decent mobility.

We next include the notion of *boundary conditions* introduced above. For every quantifiable bound on decent mobility, such as the travel time budget, we similarly introduce variables, thresholds, and binary criteria. For example:

$$x_{TT,i} \geq 0 \in \mathbb{R} \quad \text{total travel time [min/day]} \quad (C.7)$$

$$x_{TT,i}^* \in \mathbb{R} \quad \text{maximum threshold for } x_{TT,i} \quad (C.8)$$

These are added to Eq. (C.6), also by logical conjunction:

$$DM_i^1(x_{p,i}) = \left(\bigwedge_{p \in P} x_{p,i} \right) \wedge (x_{TT,i} \leq x_{TT,i}^*) \quad (C.9)$$

In this formulation, an individual does not have decent mobility if they are able to enact their (persona-specific) minimum tours associated with each purpose *but*, in order to do so, spends more than $x_{TT,i}^*$ minutes per day on those trips/tours.

In the paper, we specifically identify $x_{TT,i}^* = 90$, and compute:

$$TT_{p,i} \in \mathbb{R}^+ \quad \text{Travel time [min] for all trips of purpose } p \text{ by } i \text{ in 1 week} \quad (C.10)$$

$$x_{TT,i} = \frac{\sum_{p \in P} TT_{p,i}}{7} \quad (C.11)$$

C.2. Operationalisation

The GitHub repository https://github.com/marlinarnz/decent_mobility contains Python code to operationalise the above calculations for the case of Mauritius.

C.3. Data

Here we describe certain *data flows* and *data structure definitions*, expressed using the Information Model of the Statistical Data and Metadata eXchange (SDMX) standard (ISO 17369).

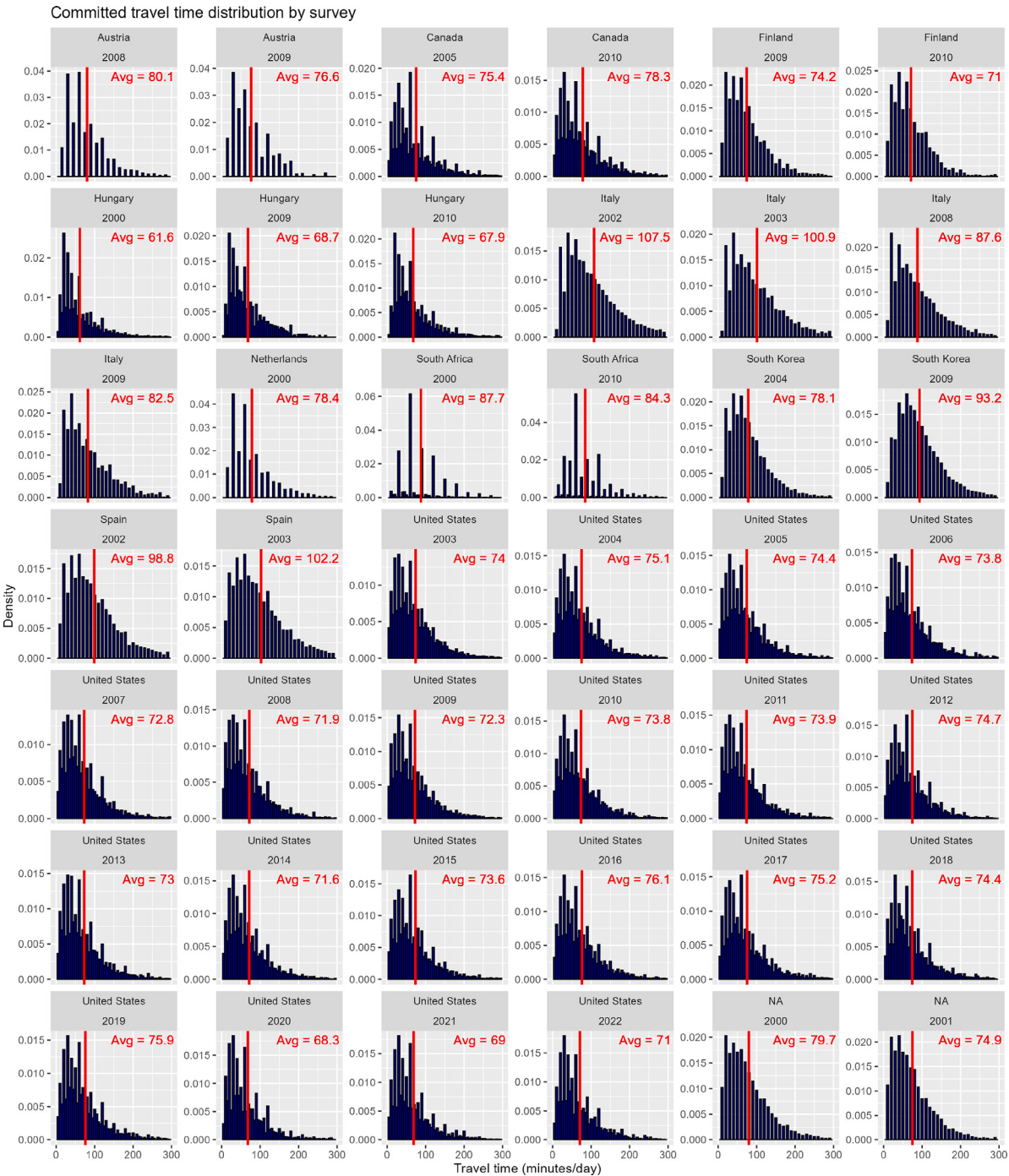


Fig. B.8. Distributions of daily non-leisure travel time per capita, observed from Multinational Time Use Study (MTUS). Surveys before the year 2000 are not considered.

The data from certain tables and figures in the current paper will be published in SDMX-CSV and SDMX-ML formats, with complete meta-data, corresponding to the final accepted version of the paper. Further research adopting the decent mobility definition and operationalisation can use these as guidance or templates to produce comparable data.

Code to operationalise other case studies should take, as **input**, the data from Table 3. Precisely, this data has:

Dimensions

PERSONA The codes ‘1’ to ‘8’.

TRIP_PURPOSE 7 distinct codes ‘A’ through ‘G’.

Measure t^* [unitless] the minimum threshold for weekly trips of the given TRIP_PURPOSE by individuals of the given PERSONA.

For the purpose of comparison, code should **output** data such as:

Dimensions

PERSONA The codes ‘1’ to ‘8’.

TRIP_PURPOSE 7 distinct codes ‘A’ through ‘G’.

Other dimensions as appropriate to the methods chosen. For example, our CH case study uses the dimension AREA_TYPE with 3 distinct codes (urban, intermediate, rural).

Measure The minimum distance [km] for trips of purpose TRIP_PURPOSE by individuals of the given PERSONA.

...as well as output data flows with the *same* structure (dimensionality, labels) and measures including:

TT Travel time [min] for all trips of purpose TRIP_PURPOSE by an individual of the given PERSONA in 1 week.

x_{TT} Travel time [min] for all trips by an individual of the given PERSONA in 1 day. (Without dimension TRIP_PURPOSE.)

D Total travel distance [km] for all trips of all purposes by an individual of the given PERSONA in 1 year.

Data availability

Data and code for generation of our results is openly available, as referenced in the appendix.

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