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Transport within earth system boundaries

Joyeeta Gupta, Yang Chen & Crelis Rammelt

Achieving a socially and environmentally sustainable mobility and transport system necessitates a multifaceted approach that considers just Earth System Boundaries. Just Earth System Boundaries are domain-specific (e.g. climate change, water) thresholds beyond which significant harm is done to people and other species. We have crossed these thresholds in 7/8 domains and not yet met the minimum needs of people worldwide. The challenge is to return to the safe and just corridor while prioritising the access of the poorest people to minimum resources as called for by the principle of leaving no one behind. Within this context, the transport sector, a major contributor to climate change and environmental pollution, requires significant and swift transformations. This comment proposes six key principles for building a sustainable transport system: prioritising equitable access, enhancing public transport and limiting private transport, decarbonising fuel and fleets, decoupling freight transport from fossil fuel trade, repurposing infrastructure, and ensuring just financing. These principles may enable just living within just Earth System Boundaries.

The resources and carrying capacity of the Earth are limited and unequally used, requiring sharing between humans and between humans and nature[1]. The Earth Commission has proposed safe and just Earth System Boundaries beyond which significant harm is done to humans and other species. Since most of these boundaries have been crossed, without even meeting the basic needs of people worldwide as required by the leaving no one behind principle, we call for a return to the safe and just space while meeting basic needs. This will have implications for the mobility and transport sector as it has social and environmental impacts, is unequally used, and requires a new conceptualisation of future transport systems that enables better sharing. This Comment proposes six principles for inclusive transport design.

Limited ecospace: just boundaries and floors

Resource and carrying capacity limits are determined by assessing: biophysical limits (e.g., to land); the Holocene variability range which enabled life on Earth; and knowledge of tipping points beyond which the Earth's ability to support life may diminish. The Planetary Boundaries literature[2] proposes 'safe' global limits for nine domains. The Earth Commission, set up by Future Earth and the Global Commons Alliance, goes further to: (a) develop an Earth System Justice framework[3]; (b) propose 'just' limits that avoid significant harm to all species; (c) propose policy-relevant local to global level limits; (d) include quality standards where missing; (e) assess whether safe and just boundaries have been crossed[4]; (f) analyse what meeting basic needs means in terms of additional pressure on the boundaries[5]; (g) calculate the space between the boundaries and the floor (based on calculating the pressure on the boundary using the same units of meeting the basic needs of *all* people) thereby delimiting quantitatively a corridor; (h) present methods for downscaling safe and just Earth System Boundaries (ESBs) to actors[6], and (i) analyse the global transformations needed (see Fig. 1).

While 'safe boundaries' enable human survival, 'just boundaries' avoid significant harm to humans and other species. For example, while 1.5 °C is seen as the safe limit, 1 °C is proposed as the safe and just limit because already at 1 °C tens of millions of people suffer from wet bulb temperatures to say nothing of those who suffered from other climate change impacts[7]. Similarly, to protect biodiversity, 50–60% of land areas need to be reserved for intact nature and 20–25% of every square kilometre of managed lands needs to be biodiverse to enable nature to flourish and provide services to humans. On aerosol pollution, the global safe boundary based on when monsoon patterns are affected has been tightened to account for local air pollution that causes millions of deaths annually.

Seven of the eight Earth System Boundaries have been crossed. The eighth boundary on aerosols has been crossed locally across the world. This implies that we must collectively reduce our use of resources and pollution of the sinks in order to live within these boundaries. Moreover, the aggregate pressures on the Earth systems must be reduced even more to allow for meeting the needs human currently lacking minimum access to resources and services. This has implications for the mobility and transport sector which needs to reduce its environmental footprint while ensuring that minimum needs are met, both within the boundaries.

Transport and mobility

The transport sector contributes 14[8]–15.6%[9] global GHG emissions, amounting to 8.3 (2018) and 8.4 (2022) $GtCO_2eq$, making it the third largest direct emitting sector after power and industry. Between 1990–2022, emissions from the transport sector grew annually by 1.7%; while getting to net zero emissions by 2050 requires emissions to fall by 3% annually by 2030 (https://www.iea.org/energy-system/transport). Transport, both directly[10] and indirectly[11], uses significant amounts of water. Transport also contributes to aerosol emissions that affect human health, associated with 385,000 premature deaths in 2015 globally[12], including 37,795 in Europe[13]. Transport infrastructure requires land, water, energy, raw materials, capital, labour and causes various environmental impacts. If we do not change course, the transport sector is expected to triple in both passenger (from 62 to 183 trillion pkm) and freight (from 132 to 395 trillion tkm) travel demand

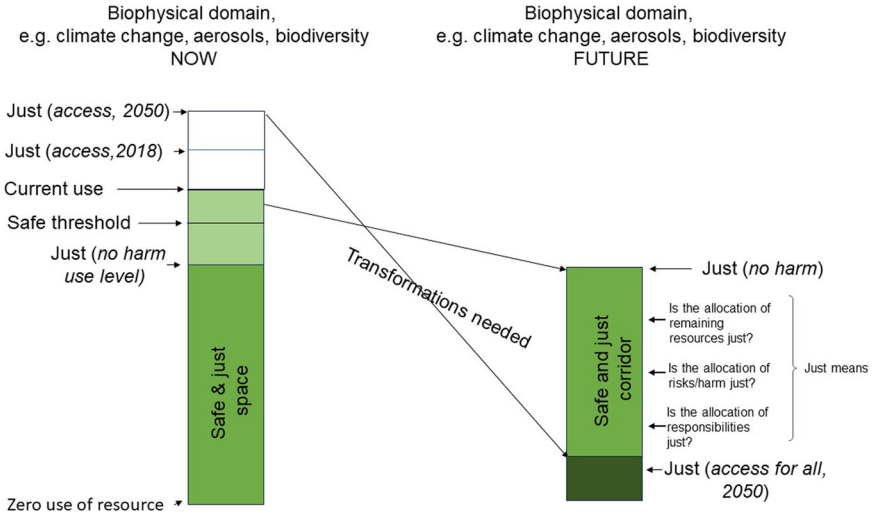

Fig. 1 | Transformation needed to enter the safe and just corridor, while ensuring that all humans have access to basic needs. The left figure shows the safe and just space in a specific domain in green, the outer limit is defined by the just no significant harm boundary. The safe boundary is less stringent than the just no significant harm boundary. The current use is beyond the safe boundary. These boundaries have been crossed and the minimum needs of people have not even been met in 2018—a gap that will increase in 2050 under business as usual. The right figure shows a world where the social SDGs have been achieved and the dark green area represents the use of resources by all humans to meet their minimum needs. The more stringent of the safe and just boundary marks the upper limit. The green space denotes the safe and just corridor. The diagonal arrows show the transformations needed from now to the future to ensure that we move into the safe and just corridor. Moving into the safe and just corridor is a necessary condition for justice, not a sufficient one.

by 2050[14]. This greatly challenges the sector to deliver fundamental mobility and transport services within safe and just Earth System Boundaries.

Transport floor and boundary

A minimum per capita mobility level sufficient to meet basic transport needs is estimated to range between 9.6 and 12.3 passenger kilometres (pkm) per day[15]. This range is based on a review of the literature to represent a global average and to represents adequate minimum access levels, ranging from enabling a dignified life beyond survival (level 1—dignity) to escaping from poverty and vulnerability (level 2—capability)[5]. These distances cover attending school, collecting drinking water, travelling to work, etc.[5]. Accordingly, if everyone (in 2020) had transportation services at access level 1 or level 2, this would amount to 27 trillion pkm or 35 trillion pkm, respectively. These 'sufficiency' levels are about half the actual travel demand in 2020, estimated at 62 trillion pkm[14] (see floor of the corridor, right column, Fig. 1).

Transport floors also generate pressures on the environment. Passenger transport emissions per pkm are 101.6 gCO_2/pkm (https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-passenger-3#tab-chart_1). Hypothetically ensuring universal level 1 and level 2 access to passenger transportation would result in emissions of 0.36 and 0.56 tCO_2 yr^{-1}, respectively. For 9.7 billion people by 2050 (https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100), the floor of the corridor for passenger transportation alone would be between 3.5 and 4.5 $GtCO_2$ yr^{-1}— based on current technology and energy mix. This would amount to ~14% of the total estimated potential climate impacts for the floor of the corridor in 2050, when also accounting for minimum access to food, water, energy and housing[5] (but not accounting for freight transportation). This implies that those who travel a lot need to reduce drastically in order to make space for others to access the minimum within the boundary.

Beyond minimum access, current passenger transport is responsible for ~56% of global transport emissions, with the rest emitted by freight transport (https://ourworldindata.org/co2-emissions-from-transport). The transportation of goods via road, rail, air, water, and pipelines together contributed to an estimated 132 trillion tonnage kilometre (tkm). Living within boundaries requires freight transport to both change its dependence on fossil fuel and reduce the volume of goods transported.

Freight transport also moves oil, gas, coal for combustion in powerplants and internal combustion engines. Meeting the 1.5 °C climate target requires reducing greenhouse gas emissions by 43% by 2030 and 60% by 2035 with respect to 2019 levels[16]. This implies a rapid phase-out of fossil fuels, including their trade, which must decrease by 80% (88% for coal, 59% for oil, and 74% for gas) in 2050 as compared to the traded volumes in 2020[17].

If the world decarbonises to meet the 1.5 °C target, transport infrastructures will become stranded assets if they cannot be repurposed for other uses. Investing in fossil fuel-based transport and the transport of fossil fuel will become risky business.

Implications for the transport sector

Hence, a mobility and transport system that respects safe and just Earth System Boundaries in the context of the 2030 Agenda will require adopting six principles. First, minimum needs must be met for all through fossil free transport, minimising water use and aerosol pollution, and land-use change. Both the infrastructure and mobility services must be built and provided to those whose minimum needs are not yet satisfied. This would require policy, technology, support, and finance so that they are not built and delivered in ways that further burden the climate, biodiversity and other Earth systems.

Second, public transport should be prioritised and become cost-competitive, efficient, affordable and accessible in comparison to private transport with its huge pressures. (New) cities and transport systems must be (re)designed to encourage public and shared transport and incentivise a

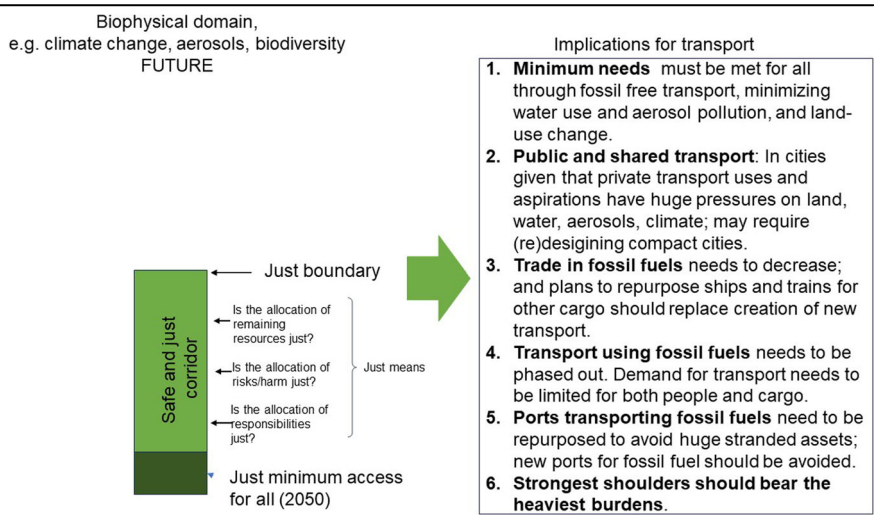

Fig. 2 | The safe and just corridor has implications for the transport sector. These implications start with meeting minimum needs and conclude with sharing the burdens.

sustained modal shift from private to public or shared transport. Compact cities that spare land bring destinations closer and will reduce mobility needs. The 15-Minute City[18], where most needs of people are met within 15 minutes of walking or cycling, is one possible idea.

Third, transport (road, rail, air, water) using fossil fuels needs to be phased out as soon as possible to avoid too much of a transgression of the 1.5 °C target. Alternatives such as biofuels and hydrogen should be critically assessed since they demand water and drive land use change, may affect food security, and increase water vapour - another greenhouse gas. These fuels have substantial shares in transport energy demand scenarios by 2030 and 2050 aligned to climate goals[19]. Electric vehicles can also not replace the existing fleet to say nothing of meeting growing demand, because of the unsustainable demand for crucial metals and minerals, exemplified by lithium. Fully converting the global internal combustion engine vehicles (in 2019) into electric vehicles (EVs) would require 282.6 Mt of lithium[20], surpassing known and potential lithium reserves[21]. Even a 75% conversion (to align with the IEA's climate neutral scenario on EVs composition of on-road energy demand by 2050[20]) would require more lithium than available. Moreover, the 8 to 10-year lifespan of lithium-ion batteries poses a recurrent challenge. Current recycling rates are less than 1%[22], and intensified recycling efforts will come with higher energy consumption. Substituting lithium would require new exploration to extraction times spanning 10–30 years[21]. Country policies need to promote public and shared transport, and more ambitious commitments will need to account for these hard limits in navigating the transition to sustainable renewable transport systems.

Fourth, trade in fossil fuels needs to decrease and plans to repurpose fleets for other cargo should replace creation of new transport. The global economy is highly coupled with trade and transport of fossil fuels[23]. To meet 1.5 °C most of fossil fuel trade, including gas (considered as a transitional fuel by COP28), has to stop quickly[17]. As 80–90% of the traded volume is enabled through maritime means, the decoupling implies that most of the bulk, liquefied natural gas (LNG), and oil tankers employed for transporting fossil fuels should be repurposed or become stranded assets. However, these tankers and carriers are currently the faster-growing segments of maritime fleets.

Fifth, infrastructures that enable transporting fossil fuels, such as port terminals for coal, gas and oil, need to be repurposed to avoid severe costs associated with stranded assets. New fossil fuel infrastructures must be avoided. With coal prioritised for phase out, we find (based on https://globalenergymonitor.org/) that 357 coal terminals are still operating, with 42 (11.8%) opened after the Paris Agreement of 2015, and another 41 proposed. Today 369 LNG terminals operate with 172 (46.6%) opened after the Paris Agreement, and another 328 proposed. While information on oil terminals is scarce in publicly available datasets, these facilities likely represent a significantly higher portion of global fossil fuel transportation infrastructure. World ports, hosting these infrastructures, should proactively facilitate transitions for these infrastructures to avoid stranded assets.

Finally, the phase out of fossil fuels and the redesign of cities and transport requires that the strongest shoulders should bear the heaviest burdens. Those who have overused resources in the past and over-polluted must bear the responsibility for financing the global transformation (see Fig. 2). Financing transformation projects in developing countries is often seen as riskier by financiers, leading them to charge higher interest rates. This approach is problematic and unjust because it discourages these countries from undertaking essential sustainability initiatives. If they use the available fossil fuel in the global South (estimated as 78% of the global total), as rich countries have done in the past, everyone loses as we cross 2.7 °C or go even higher. Existing instruments such as state credit guarantees can be used to support low-cost interest rates. Future support should not be constrained to financing alone, but also include aid to mitigate these perceived risks and create a more equitable playing field.

Recommendations for future studies

A sustainable mobility and transport system requires assessment of its impacts on climate, land, water, aerosols, amongst others, to ensure that it operates within safe and just boundaries. As a significant contributor to climate and environmental impacts, the transport sector requires substantial and timely transformations. Future studies should focus on i) ensuring access to emission-free and low resource-burdening transport for those currently underserved; ii) encouraging public transport through efficient, affordable, and resilient systems, along with reduced trip demands and trip distances via improved urban planning and design; iii) decarbonising transport fuels and vehicles, but critically assess alternatives for their water and land-use impacts and resource demands; iv) decoupling the freight transport sector from the fossil fuel-based energy system and economic growth, and preventing from building new transport infrastructure for fossil

fuels; v) avoiding stranded assets by repurposing existing infrastructures and fleets for new uses; vi) ensuring support and just financing from resourceful to resourceless countries for their transformations. In many ways, this implies changing the consumption patterns of the rich people and countries and possibly even setting limitarian standards on consumption to support redistribution of transport services and infrastructures within a finite ecospace.

Joyeeta Gupta[1,2] ✉, **Yang Chen**[1] **& Crelis Rammelt**[1]
[1] Amsterdam Institute for Social Science Research, University of Amsterdam, Amsterdam, The Netherlands. [2]IHE-Delft Institute for Water Education, Delft, The Netherlands. ✉e-mail: J.Gupta@uva.nl

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J.G. wrote the conceptual framework. Y.C., C.R. and J.G. wrote the main text. J.G. prepared Figures 1, 2. J.G., C.R. and Y.C. revised the main text based on comments and suggestions from two anonymous reviewers.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Joyeeta Gupta.