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Leonie Wenz^{1,2,3} , Ulf Weddige^{2,4}, Michael Jakob²  and Jan Christoph Steckel^{1,2} 

¹ Potsdam Institute for Climate Impact Research (PIK), 14473, Potsdam, Germany

² Mercator Research Institute on Global Commons and Climate Change (MCC), 10829, Berlin, Germany

³ Department of Agricultural and Resource Economics, University of California, Berkeley, United States of America

⁴ Leibniz Center for Agricultural Landscape Research (ZALF), 15374, Müncheberg, Germany

E-mail: leonie.wenz@pik-potsdam.de

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Abstract

Transportation infrastructure is considered a key factor for economic development and poverty alleviation. The United Nations have explicitly included the provision of transport infrastructure access, e.g. through all-season road access, in their Sustainable Development Goal agenda (SDGs, target 9.1). Yet, little is known about the number of people lacking access to roads worldwide, the costs of closing existing access gaps and the implications of additional roads for other sustainability concerns such as climate change mitigation (SDG-13). Here we quantify, for 250 countries and territories, the percentage of population without road access in 2 km. We find that infrastructure investments required to provide quasi-universal road access are about USD 3 trillion. We estimate that the associated cumulative CO₂ emissions from construction work and additional traffic until the end of the century amount to roughly 16 Gt. Our geographically explicit global analysis provides a starting point for refined regional studies and for the quantification of further environmental and social implications of SDG-9.1.

1. Introduction

Transportation infrastructure is considered a key factor for poverty reduction and socio-economic development. Access to roads allows access to infrastructure such as schools, hospitals and markets (Jacoby 2000) whereas high transportation costs related to poor transportation infrastructure tend to constrain development (North 1958, Krugman 1991). For example, in subsistence agriculture based economies, high transportation costs are found to impede shifts of labor towards more productive sectors of the economy and hence growth-enhancing structural change (Gollin and Rogerson 2014). In high-income countries about 90% of the population resides within an hour of a city, but in low income countries only about 50% have equivalent access (Weiss *et al* 2018). Studies in many countries support these general findings on reduced poverty and enhanced economic development in the course of improved infrastructure access. As to the first dimension, poverty reduction, it has been shown for

Nepal that the provision of extensive road access to markets would confer substantial benefits for the population on average, much of these going to poor households (Jacoby 2000). In Ethiopia, access to all-weather roads has increased consumption and decreased poverty substantially (Dercon *et al* 2009) whereas high transport costs to ports have been found to reduce agricultural production (Iimi *et al* 2017). Regarding the second dimension, enhanced economic development, the rapid expansion of the road network in Brazil has led to increasing concentration of economic activity and population around the main centers in the south of the country, while spurring the emergence of secondary economic centers in the less developed north (Bird and Straub 2020). India's 'Golden Quadrilateral' highway project has decreased firms' transportation costs and stock of input inventories, and incentivized the switching of suppliers (Datta 2012). It has also led to a higher number of new firms entering the market as well as increased in-plant productivity (Ghani *et al* 2016). In China, regions closer to historical

transportation networks have higher levels of GDP per capita, a larger number of firms and greater average firm profits (Banerjee *et al* 2012). In the US, cities with more highways specialize in sectors producing heavy goods (Duranton *et al* 2014); better road access and hence shorter commuting times have a sizeable impact on female labor market participation (Black *et al* 2014) and employment (Duranton and Turner 2012). Even though demonstrating a *causal* relationship can be difficult (as for instance construction work itself might boost the economy in the short-term), these studies plausibly suggest beneficial effects of improved road access for poverty reduction and economic development.

As a consequence, the United Nations (2015) have explicitly included access to transport infrastructure, e.g. through all-season road access, in their Sustainable Development Goals (SDGs, goal 9), incorporating the target to ‘develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure’ (SDG-9.1). Specifically, indicator 9.1.1 is meant to denote the proportion of the rural population who live within 2 km of an all-season road.

Expanding road networks might, however, conflict with other concerns such as climate change mitigation (Chapman 2007), biodiversity conservation (Chomitz and Gray 1995, Wilkie *et al* 2000, Laurance *et al* 2014, Ibisch 2017), or human health (Currie and Walker 2011) all of which are also part of the UN’s Sustainable Development agenda (i.e. SDGs 13, 15, and 3). Given the inherent trade-offs between different dimensions of sustainable development (von Stechow *et al* 2016, Jakob and Steckel 2016, Laurance and Arrea 2017), additional roads can be ‘roads to glory or highways to hell’. In order to assess how an increase in global road networks might potentially impede or facilitate the achievement of other SDGs, it is important to first gain an understanding of the amount of roads that would have to be constructed and where exactly they would have to be built. For example, additional roads might be a stronger threat to biodiversity in some areas than in others (Ibisch *et al* 2016).

Teravaninthorn and Raballand (2009) estimated that 70% of Africa’s rural population lives more than 2 km from an all-season road. A recently published report (Mikou *et al* 2019) investigates road accessibility in rural areas for 166 countries and explores the cost of improving access in 19 of these countries, mostly through the pavement of unpaved roads. The authors use the Rural Accessibility Index that has been introduced by Roberts *et al* (2006) and methodologically improved by more recent studies through the use of spatial data and techniques (Iimi *et al* 2016).

Our paper extends and complements these works by carrying out a geographically explicit analysis for

250 countries and territories¹ around the world based on two extensive road network datasets. In a first step, we assess how much of the global population currently finds itself more than 2 km (~1.2 miles) away from the road infrastructure. We then estimate the number of road-kilometers that would have to be newly built in each country in order to grant such access for a certain fraction of its population (up to 97.5%²) and compute the associated construction costs. We thereby abstract from potential changes in per-capita income, population density, and other socio-economic variables that might occur in the future (Meijer *et al* 2018), i.e. we conduct a static analysis based on the most recent historical data available. As a first step towards a comprehensive assessment of the trade-offs between improved road access and other SDGs, our study analyzes how SDG-9.1 interacts with climate action (SDG-13) by estimating CO₂ emissions that would (i) be generated by the construction of additional roads and (ii) arise from increased traffic.

2. Methods

All steps of our analysis as well as the underlying data are described and discussed in detail in the *technical appendix* in the supplementary materials. Supplementary tables S1–S6 (<https://stacks.iop.org/ERL/15/075010/mmedia>) provide further information on the data used in and obtained by our analysis. In the following we give an overview.

In a first step, we assess the percentage of population who are currently not located within 2 km of a road for 250 countries and territories. To this end, we conduct a spatial analysis on a global grid of 2.5 arc minute resolution (approximately 5 km × 5 km at the equator). We combine two spatially highly resolved datasets on the global road network—Open Street Map data (OSM³) and the Global Roads Open Access Data Set (gROADS⁴)—with gridded population data

¹We include all countries and territories in our analysis for which road network data are publicly available (provided either by Open Street Map or Global Roads Open Access Data Set; see *Methods* for detail). These are all countries worldwide (except for some tiny states such as San Marino or Vatican City) plus several territories. By territories we mean administrative units such as Aruba or Puerto Rico which we consider as separate entities to avoid distortion of results. A list of all countries and territories covered by our analysis can be found in the *supplementary materials*.

²We provide numbers only up to 97.5% to avoid distortion of results by extremely remote areas.

³Open Street Map data were downloaded in April 2017 from <https://www.openstreetmap.org> and provided to us by CIESIN, University of Columbia, in June 2017.

⁴Center for International Earth Science Information Network—CIESIN—Columbia University, and Information Technology Outreach Services—ITOS—University of Georgia. *Global Roads Open Access Data Set, Version 1 (gROADSv1)*. 2013. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). <https://doi.org/10.7927/H4VD6WCT>. Downloaded: January 2017.

for the year 2015 (GPWv4⁵) and, as a robustness check, WorldPop⁶ data. For each grid cell, we compute the mean (minimum/maximum) distance to the nearest road using a Euclidian distance layer with 1 km pixel resolution. If this distance exceeds 2 km, we count the number of people affected and aggregate results at the country level (and for several sample countries at the subnational level). Since we cannot reliably derive from our datasets whether a road is paved or not (and hence accessible throughout all seasons), we use a second set of data—provided by the World Bank⁷—to gain a general idea of the percentage of paved roads in a country.

Second, we quantify how many meters of roads, Ω , would have to be newly built in each country in order to enable a certain percentage of that country's population, i.e. $x\%$, to live within 2 km of a road. To this end, we employ a simple algorithm that ranks all grid cells according to their attractiveness in terms of road construction requirements. Attractiveness is measured as the ratio of people in that grid cell and the length of roads (in meters) that is required for ensuring road access within 2 km. Specifically, let P^R be the number of people in country R living within 2 km of a road and let P describe the total population of that country. For each grid cell c in country R , we assess the distance d_c to the closest road (in meters). Where this distance exceeds 2000 m, i.e. if

$$\omega_c := d_c - 2000 > 0,$$

we compute the ratio

$$s_c := \frac{P_c}{\omega_c};$$

with P_c denoting the number of people living in that grid cell. This ratio is at the core of our algorithm. The greater it is, the more attractive road building in that grid cell is considered. As long as $P^R \leq x$ holds, the algorithm determines that grid cell c^* for which s_c is maximal. It then adds ω_{c^*} to Ω and P_{c^*} to P^R whereas s_{c^*} is excluded from the set of ratios $\{s_c\}_c$. The algorithm hence effectively points to those grid cells where small extension of the already existing road network would provide access to a large number of people. The smaller this extension and the more people benefitting from it (in the sense that they then live within 2 km of a road), the higher this grid

cell is prioritized in the algorithm. As a consequence, the algorithm minimizes the amount of road kilometers to be constructed for a given access target. It does not take into account who might benefit most from road access (for instance, one could argue that those living the farthest away from the road network are in higher need of getting closer to a road than those who live just outside the 2 km radius). We discuss the algorithm including its limitations and strengths in more detail in subsection 1.6 of the *technical appendix*.

Third, we estimate how much the construction of these missing road-kilometers might cost. Costs of road construction may vary substantially across countries due to, for instance, geographical conditions, labor costs or availability of material. They also depend on the type of road being built (Collier *et al* 2015). In line with SDG-9.1 ('quality, reliable, sustainable and resilient infrastructure', 'all-season roads'), we here derive country-specific estimates of the costs that would arise from the construction of new highways that are paved and have two lanes thereby distinguishing between three cost scenarios. We build on the World Bank's ROCKS (Road Costs Knowledge System) database⁸ that reports, for 17 countries, the average, minimum and maximum costs of constructing 1 km of a two-lane highway with bituminous surface. For all countries not present in this database, we determine and use median, minimum and maximum values that are specific for the world region the respective country is located in (see figure S1 for a mapping of countries to world regions and table S1 for country- and region-specific cost estimates).

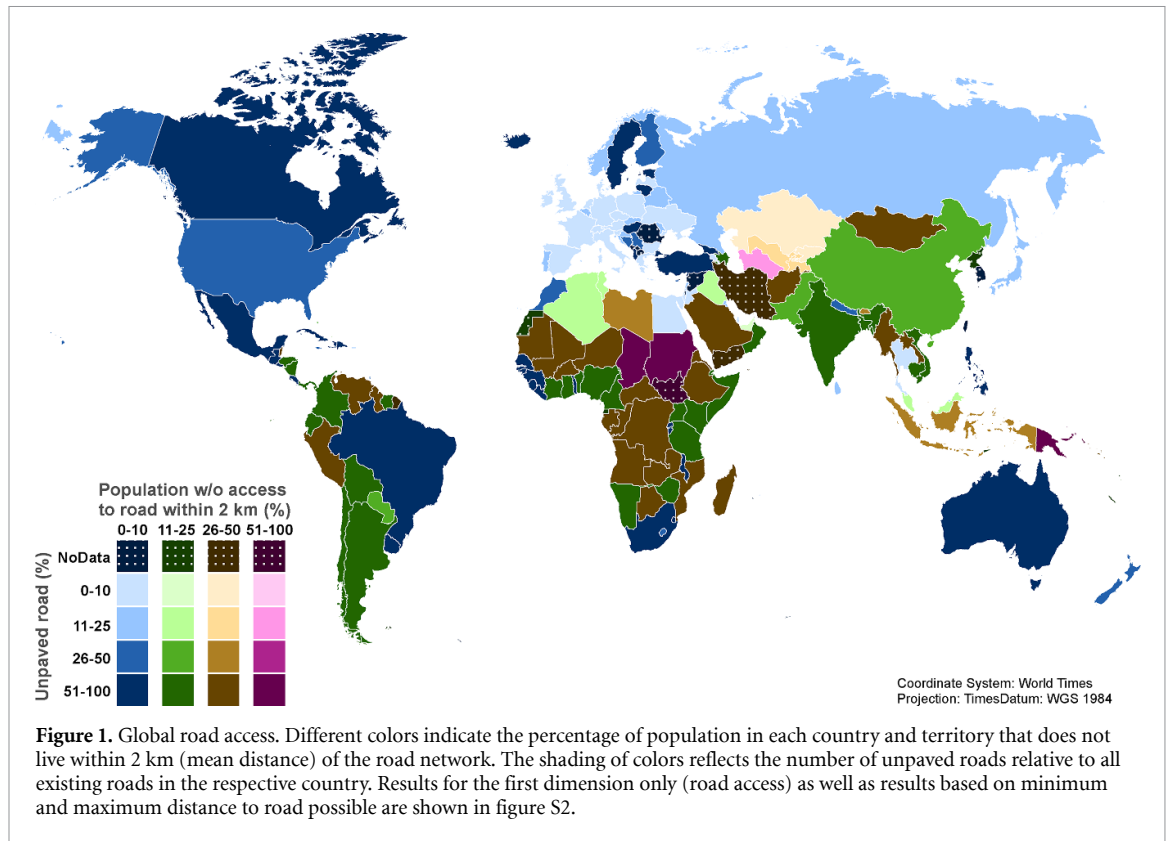
In a final step, we assess CO₂ emissions that would (i) be generated by the construction of these missing roads and (ii) arise from increased traffic. Regarding the first dimension, we estimate region-specific CO₂ emission intensity factors of the materials required to construct a two-lane highway with a bituminous surface. To this end, we combine information on the materials used for road construction from the ROCKS database with information on the direct emissions of the superordinate sectors (see table S2 and subsection 1.8 in the *technical appendix* for detail). The latter is derived from the environmental Input-Output database GTAP-9 (Aguiar *et al* 2016). We multiply the resulting sector- and country-specific emission intensities with the proportional costs of each work process. Here, we consider the same three cost scenarios for road work as before. For each country, we thus obtain the median, minimum and maximum amount

⁵Socioeconomic Data and Applications Center (SEDAC), Columbia University. Gridded Population of the World, Version 4 (GPWv4). Downloaded January 2017.

⁶WorldPop. Open spatial demographic data, University of Southampton. *Population data—whole continent (2015)*. <https://www.worldpop.org/>. Downloaded: April 2019.

⁷World Bank. World Development Indicators and EconStatsTM. *Roads Paved (% of total roads)*. http://www.econstats.com/wdi/wdiv_579.html. and World Bank, Africa Development Indicators. <https://databank.worldbank.org/reports.aspx?source=Africa-Development-Indicator>. Downloaded: April 2018.

⁸The World Bank. Roads & Highways Tools (ROCKS v.2.3) Downloaded from <http://go.worldbank.org/ZF1I4CJNX0> in May 2018 under consideration of a 2018 update available at www.doingbusiness.org/en/reports/thematic-reports/road-costs-knowledge-system (see *technical appendix* for detail); downloaded April 2019.



of CO₂ emissions linked to the construction of 1 km of a two-lane bituminous road (table S3).

In order to assess CO₂ emissions related to increased traffic, we draw on the empirical literature (Handy and Boarnet 2014) and derive a range of elasticities measuring the impact of additional roads on vehicle-miles traveled (table S4; refer to subsection 1.9 in the *technical appendix* for a detailed discussion). Using the median (minimum, maximum) elasticity η we then compute additional emissions $E_{\text{add}}^{\text{traffic}}$ from traffic in each country:

$$E_{\text{add}}^{\text{traffic}} = \left(1 + \frac{\Omega}{\Theta}\right)^{\eta} \cdot E_{\text{current}}^{\text{traffic}} - E_{\text{current}}^{\text{traffic}};$$

where Θ denotes the length of the current road network in that country according to the OSM data. Emissions from road transport in the year 2015 are provided by the International Energy Agency World Energy Balances 2017⁹ (denoted by $E_{\text{current}}^{\text{traffic}}$). An overview of current emissions and road network lengths can be found in table S5.

3. Results

3.1. Road access gaps

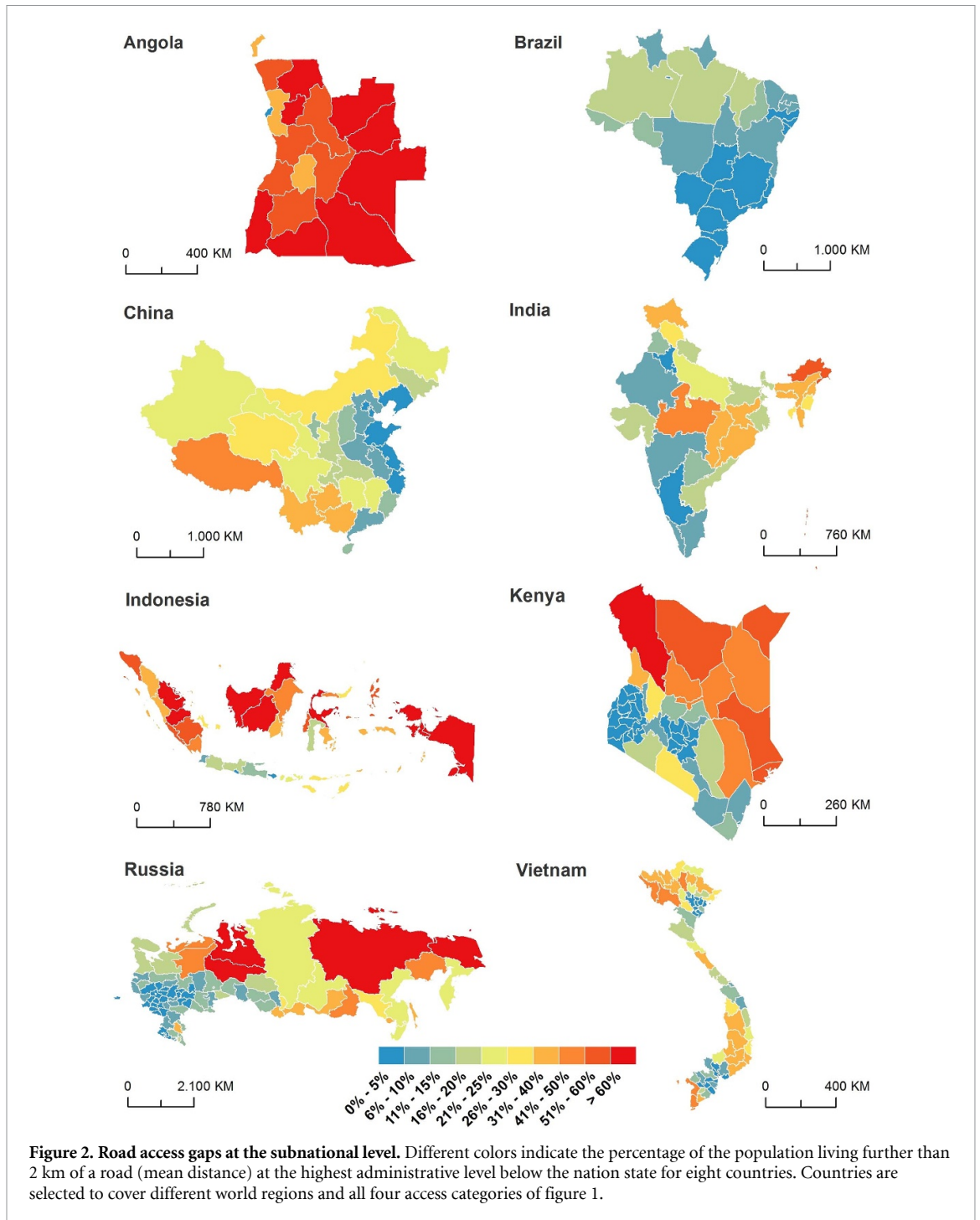
We find that ~14% of the world's population does not have road access. As shown in figure 1 and table S5, there is however a high variation in road accessibility across countries, with access gaps being greatest in

Chad, Sudan, South-Sudan, Turkmenistan and Papua New Guinea. Here, more than 50% of the population is found to live farther than 2 km away from the transport infrastructure.¹⁰ Overall, road accessibility is poorest in countries in sub-Saharan Africa and Southeast Asia, where in many countries more than one quarter of the population lacks access. In addition, a comparatively large proportion of roads in sub-Saharan Africa are unpaved (more than 50% in most countries), further hindering the population's access to major cities and important markets. Further areas with low rates of road access include Central Asia and the Middle East. By contrast, high-income areas such as Europe, North America, Japan and Australia, display almost universal road access with less than 5% of the population living more than 2 km away from a road. However, the proportion of paved roads varies greatly. In most European countries unpaved roads represent less than 10% of the total road network whereas they exceed 50% in Canada and Australia, for example.¹¹ Countries in Latin America, South Asia and East Asia tend to fall between these extremes, with more than 10% but

¹⁰We also find road access gaps of more than 50% for some small island states, i.e. Marshall Island, Paracel Island, Pitcairn Island and Tokelau. In these regions, however, other methods of transport, such as ships and water-airplanes, are likely to render highways redundant.

¹¹It has to be noted that, especially in large territorial states, unpaved roads might primarily be found in sparsely populated areas and that decent quality gravel roads might satisfy the needs of such an area.

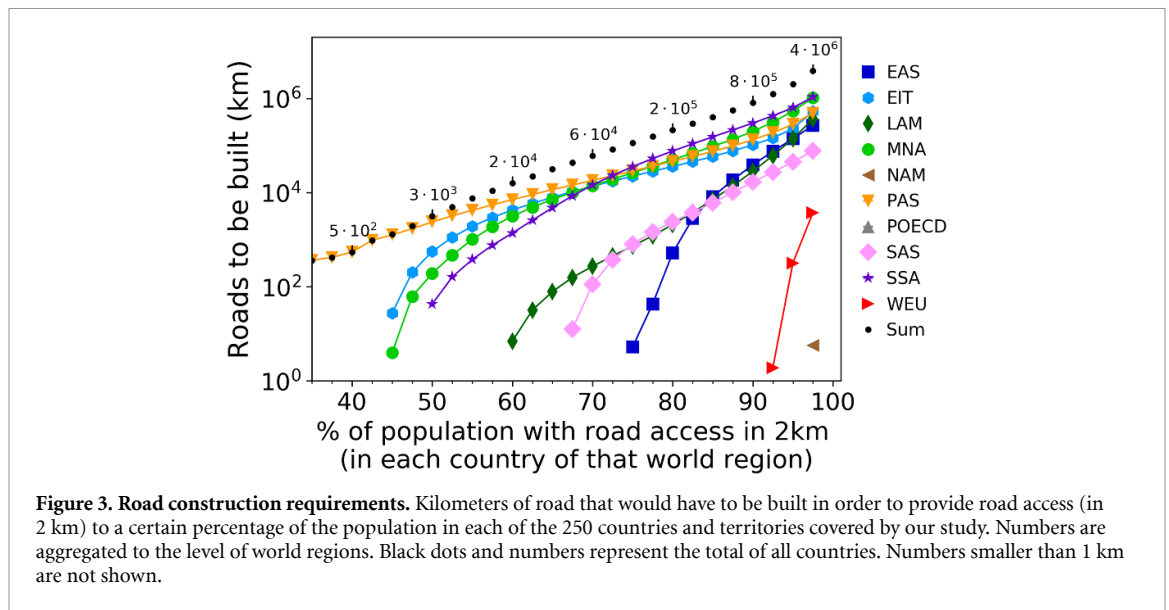
⁹International Energy Agency. World Energy Balances 2017. Online: <https://www.iea.org/statistics/balances/>.



less than 50% of the population lacking access to a road.

With the aim of providing upper and lower boundaries for our estimates, we also compute country-level road access gaps based on the minimum and maximum possible distance to the nearest road, respectively (figure S2). Our findings remain qualitatively robust. In the maximum distance scenario, almost everyone in Australia, Europe, Japan and North America also lives within 2 km of a road and in the minimum distance scenario access gaps are overall also highest in sub-Saharan Africa and Southeast Asia. In many of the countries displaying

significant access gaps, the number of people living close to a road, however, varies substantially between the minimum and maximum distance scenarios. In Zimbabwe, for example, ~4% of the population is lacking access in the best-case scenario (minimum distance) compared to ~45% in the worst-case scenario (maximum distance). Even though this difference is less pronounced in most countries (e.g. 5% vs. 18% in Russia or 4% vs. 16% in Brazil), these two scenarios should be considered as extremes with the medium distance approach yielding plausible middle-ground between them.



As a further sensitivity analysis, we assess road access gaps with population estimates that display a lower concentration of people in rural areas than comparable datasets (WorldPop data). For several countries we find considerably smaller access gaps when using WorldPop data instead of the GPW data set. For most countries, access gaps are however similar (table S5). When comparing our results to previous findings on road accessibility that were also based on WorldPop data (Mikou *et al* 2019), our estimates are—in general—lower. This is likely due to different reasons. First, we combine OSM data with an additional road network dataset, gROADS, to improve information on road network coverage in areas that are less populated and frequented (see *technical appendix* for detail). Second, we include more types of roads in our analysis because our primary goal is to identify areas without any navigable roads and not areas with possibly unpaved roads. Finally, we measure access gaps as a percentage of a country's total population (and not as a percentage of the rural population) to avoid adding more uncertainty through assumptions about rural vs. urban populations.

We enrich the national analysis with more refined investigations at the subnational level for eight example countries that cover different parts of the world and all four access categories of figure 1. This analysis reveals that national results often mask important regional disparities which can be linked to geographic characteristics and the distribution of population, as well as economic and political centers (figure 2 and table S6). For instance, Brazil displays almost universal road access in the south, but in the north—the area of the Amazonas rainforest—up to 20% of the population does not have such access. In China there is a dense road network on the east coast—where a large part of economic activity is concentrated—but in some southern and western

provinces, access is poor for more than 30%–40% of the population. Similarly, Vietnam has a highly developed road network near the major metropolitan areas of Hanoi and Saigon, but substantially lower rates of access in rural areas and in the central regions. The road network in the more developed southern provinces of India is good, however access rates are much lower in the poorer parts of the north-east and east. Indonesia demonstrates typical infrastructure provision in an archipelago situation, with high rates of road access in the (also politically) central island of Java, as well as Bali, but access gaps of more than 60% in numerous other areas, including the populous islands of Sumatra and Sulawesi. In Angola, almost everyone in the province of the capital Luanda (where about one fourth of the population is concentrated) lives close to a road but in many other provinces more than 60% of the population is lacking access. Kenya is practically divided into two parts; whereas the majority of the population in the south-west, including Lake Victoria, the capital and Mombasa, has road access, there are huge gaps in the less densely populated northern parts (exceeding 50% in several regions). The densely populated areas in the European parts of Russia are very well connected, but access for a significant share of the population in the eastern provinces remains poor.

3.2. Infrastructure investments required to meet SDG-9.1

We find that about 60 000 km of roads would have to be built if 70% of the population in every country and territory covered by our study was to be connected to the road network (figure 3). Road access for 90% of each country's population could be achieved by road construction works in the order of 800 000 km. Quasi-universal access of 97.5% would require about 4 million km of additional roads, which amounts

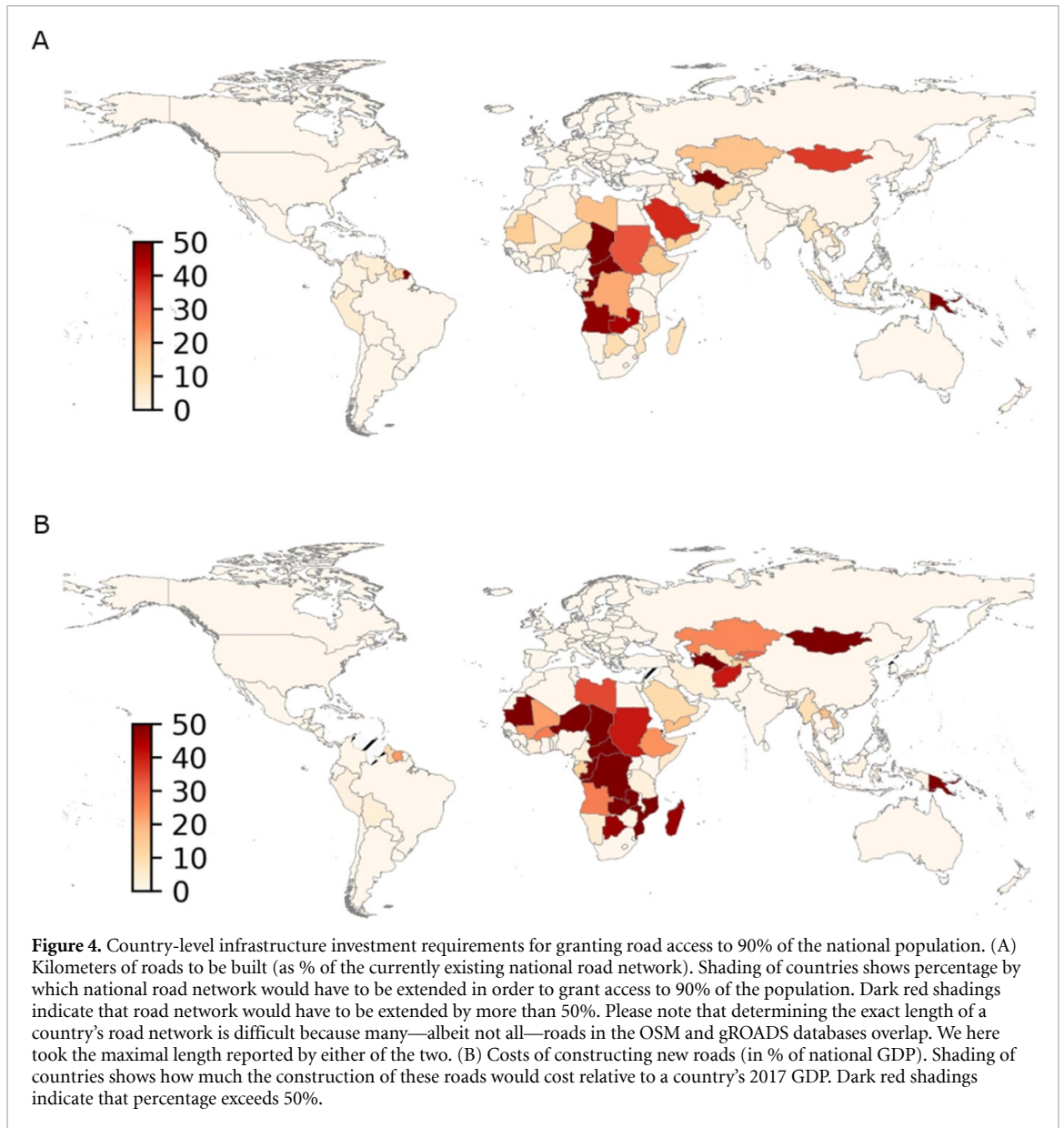


Figure 4. Country-level infrastructure investment requirements for granting road access to 90% of the national population. (A) Kilometers of roads to be built (as % of the currently existing national road network). Shading of countries shows percentage by which national road network would have to be extended in order to grant access to 90% of the population. Dark red shadings indicate that road network would have to be extended by more than 50%. Please note that determining the exact length of a country's road network is difficult because many—albeit not all—roads in the OSM and gROADS databases overlap. We here took the maximal length reported by either of the two. (B) Costs of constructing new roads (in % of national GDP). Shading of countries shows how much the construction of these roads would cost relative to a country's 2017 GDP. Dark red shadings indicate that percentage exceeds 50%.

to roughly 8% of the currently existing global road network. At the national level, relative infrastructure needs may however be substantially higher. In several African countries and small island states as well as in Turkmenistan and Papua New Guinea granting access to 90% of the population would require extending the existing road networks by more than 50% (figure 4(A)). For purpose of exhibition, national results are aggregated to the level of world regions in figure 3 (set in accordance with the RT10 region classification adopted by the Intergovernmental Panel on Climate Change; see figure S1). Results at the country-level are shown in table S5. Overall, most roads would have to be built in sub-Saharan Africa (SSA), Middle East and North Africa (MNA), Southeast Asia and Pacific (PAS) as well as in the 'Economies in Transition' region (EIT) to which Central and Eastern Europe as well as the Commonwealth of Independent States belong. Road construction

needs are highest in the MNA and SSA regions if more than 80% of each country's population is to be connected whereas in the PAS region additional roads are already required for an access goal of 40%. Unsurprisingly, only few additional roads are required in Western Europe (WEU) and North America (NAM) if quasi-universal access is to be ensured. No investment needs at all are found for the Pacific OECD countries (POECD). The remaining three world regions, EAS, SAS and LAM, fall between these two extremes. When using WorldPop data instead of GPW population estimates, we find—in general—smaller road construction needs for the same access goals (figure S3).

The results for the median road cost scenario (figure 5(A)) reveal that the economic costs to provide road access for at least 80% of the population in any country are in the order of USD 200 billion, which corresponds to about 0.25% of the

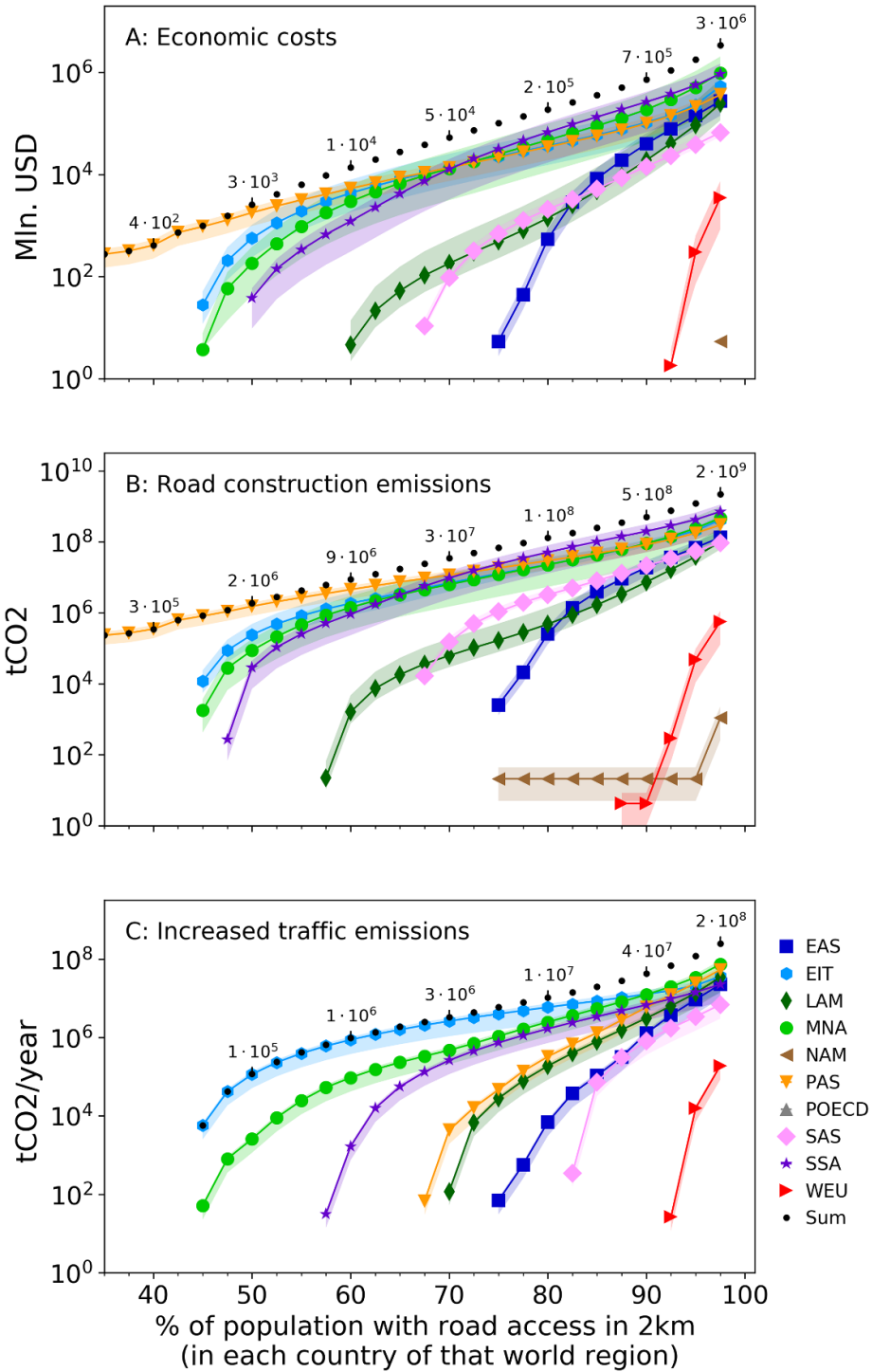


Figure 5. Economic and environmental costs of road construction. Colored markers denote median economic and environmental costs associated with the construction of new two-lane roads with bituminous surface such that a certain fraction of the population in each country/territory had road access. Numbers are aggregated to the level of world regions. Shaded areas show minimum and maximum values to indicate a range of likely costs. Black dots and numbers represent total costs and emissions (sum of median values). Values smaller than 1 Mio USD, 1 tCO₂ and 1tCO₂/year, respectively, are not shown. (A) Economic costs of constructing new roads. Economic costs were assessed based on average (minimum, maximum) construction costs reported for all countries in a region. (B) Emissions generated by road construction. Road construction emissions were derived by estimating country-specific emission intensity factors of the materials required for road construction. Range of values corresponds to different cost scenarios used in panel (A). (C) Additional annual emissions resulting from increased traffic. The impact of additional roads on vehicle-miles traveled was assessed by determining the median (minimum, maximum) elasticity from the empirical literature. Additional emissions were calculated assuming that emissions per vehicle-mile traveled remain at their current level.

world's GDP in 2018.¹² These investment needs rise to up to USD 3 trillion, i.e. about 3.5% of the world GDP; if access is to be provided for 97.5%. For comparison: Schmidt-Traub and Shah (2015), after harmonizing and consolidating published assessments on the investment needs of individual SDGs, estimate that incremental spending needs in low- and lower-middle-income countries may amount to about USD 1.3–1.5 trillion per year. In their (preliminary) assessment, they consider different investment areas; transport infrastructure accounts for only USD 89 billion whereas estimated costs for access to modern energy and telecommunication infrastructure are in the order of USD 350 billion, respectively.

The achievement of ambitious access goals would come at the highest costs in SSA and MNA, both at the regionally aggregated level and when considering the burden that could be posed upon individual countries (figure 4(B)). In the absence of international transfers and support schemes, several countries in Africa and the Middle-East would have to cover costs amounting to more than 50% of their current GDP in order to connect 90% of the population to the road network.

3.3. Road construction and climate change mitigation

We find that the construction work necessary to provide road access to 70% of the population in any country could cause cumulative emissions of about 30 Mt CO₂ (figure 5(B)). A 90% access goal corresponds to about 500 Mt CO₂ which is in the same order of magnitude as Canada's CO₂ emissions in 2018.¹³ Beyond 90%, emissions related to road construction would significantly increase. For example, connecting 95% of the population in each country would lead to emissions of more than 1 Gt CO₂; quasi-universal access would be around 2 Gt CO₂ which corresponds to ~5%–6% of global CO₂ emissions in 2018.¹⁴ The majority of emissions would arise in SSA, for which we not only find the lowest rate of road access but also comparably high emission intensity factors (table S3).

As depicted in figure 5(C), additional 3 Mt CO₂ per year could be generated from traffic if at least 70% of the population in any country had road access. This number goes up to 40 Mt CO₂ per year if 90% were to be connected and to about 200 Mt CO₂ per year for a 97.5% access goal. The majority of additional CO₂ emissions would stem from those world regions that currently have the highest access gaps, i.e. EIT, MNA, PAS, and SSA. Unlike emissions related to road construction, these are however not one-time-only

emissions, but emissions that would occur each year.

If we assume that all roads required for the 97.5% access goal are built by 2030, the resulting emissions from construction work and traffic until the end of the century will hence be in the order of 16 Gt CO₂. This is less than half of the amount of energy-related CO₂ that is currently emitted worldwide within a year (~ 36 Gt CO₂).¹⁵ It would consume about 1.5% of the carbon budget still available to achieve the 2 °C target (which is slightly more than 1070 Gt CO₂¹⁶).

4. Discussion

In order to assess trade-offs between the economic benefits of roads and their adverse impacts on environmental quality, biodiversity or human health, it is important to obtain a geographically explicit understanding of where exactly access to roads is currently lacking and where it could be beneficial to the population.

Based on our newly constructed dataset, we show that in many countries of sub-Saharan Africa and Southeast Asia significant parts of the population do not have access to roads. Closing these access gaps would come at considerable costs, in particular if (almost) everyone was to be connected and if low-income countries were to bear the costs themselves (compare figure 4(B)). Even though the SDG agenda entails the outlook of increased provision of financial assistance, costs might still be substantial for individual countries. Besides road construction costs, further costs would arise from road maintenance and road safety. For example, our analysis implicitly assumes that all roads shown in our two datasets are in good condition. Given that at least some of them would have to be paved in order to enable 'all-season' access, additional pavement costs would arise (Mikou *et al* 2019). On the contrary, technological innovation might decrease costs of construction and maintenance in the future.

The associated cumulative CO₂ emissions from construction work and additional traffic until the end of the century seem moderate compared to current global CO₂ emissions per year—even for the more ambitious access goals. This finding fits into a broader body of literature that has found that basic needs, such as access to clean cook-stoves (Cameron *et al* 2016), electricity (Pachauri 2014) as well as nutrition and sanitation (O'Neill *et al* 2018), could be obtained at comparatively low costs for the climate, even when today's carbon-intensive modes of provision are employed.

¹²Source: World Bank (GDP, current US\$). Online: <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD>.

¹³Source: Global Carbon Atlas (CO₂ Emiss. 2018). www.globalcarbonatlas.org/en/CO2-emissions.

¹⁴Source: Global Carbon Atlas (CO₂ Emiss. 2018). www.globalcarbonatlas.org/en/CO2-emissions.

¹⁵Source: Global Carbon Atlas (CO₂ Emiss. 2018). www.globalcarbonatlas.org/en/CO2-emissions.

¹⁶Source: MCC Berlin in line with the recent IPCC Special Report on Global Warming of 1.5 °C (IPCC 2018). <https://www.mcc-berlin.net/en/research/co2-budget.html>.

However, our results should not be understood as to imply that road construction is unproblematic from an environmental perspective, as extending the existing road networks might challenge the achievement of other SDGs. In particular, there is valid concern about the long lasting threat of roads to biodiversity and natural ecosystems (Chomitz and Gray 1995, Wilkie *et al* 2000, Laurance *et al* 2014, Ibisch 2017). For instance, uninterrupted roadless areas are a key refuge for many species and provide globally relevant ecosystem services (Ibisch *et al* 2016, Ibisch 2017). In contrast, building roads is identified as an important driver of biodiversity loss (Benitez-López *et al* 2010) and land-use changes (Laurance 2001, Verburg *et al* 2011). It has also been found to contribute to deforestation in the Amazon rainforest (Geist and Lambin 2001). Placing roads within protected areas can seriously reduce their capacity to sustain wildlife populations and potentially threaten livelihoods of indigenous groups who depend on these resources for their survival, as argued for the Yasuni national park in Ecuador (Espinosa *et al* 2014). Roads, and more specifically interstate highways in the US, have been shown to significantly reduce agricultural land (Mothorpe *et al* 2013), and contribute to relocation from city centers to suburbs, thus aggravating urban sprawl (Baum-Snow 2007, Garcia-López *et al* 2015).

Land-use changes induced by road construction could also have a feedback effect on the climate. Deforestation, which removes important carbon sinks, has been shown to be closely linked to road construction or upgrading,¹⁷ as the latter facilitate access for logging and expansion of agricultural activities (Barber *et al* 2014). Moreover, additional greenhouse gas emissions could be generated if road construction necessitates the transport of materials to remote places as well as through subsequent road maintenance or upgrading works. Even though our analysis covers two important sources of CO₂ emissions (associated to road construction and induced additional traffic), it cannot claim to comprehensively incorporate all associated effects on the climate.

Albeit SDG 9.1 makes an explicit point on road infrastructure, it might hence be more useful to focus on travel times or transportation costs. Several regional studies provide helpful insights into local conditions, e.g. by modelling accessibility of land transport infrastructure in Mexico (Duran-Fernandez and Santos 2014), or by mapping (Pozzi *et al* 2009) and computing (Porteous 2019) the travel time to markets in African countries. At the global scale, travel times to major cities have been estimated by Nelson (2008) with a recent update based on newly available data (Weiss *et al* 2018). In this respect,

alternatives to road transportation, e.g. railroads or water transport, might be available. Moreover, where it becomes (environmentally and/or economically) very costly to connect rural communities, supporting people to migrate to better connected and hence developed regions (e.g. cities) might also be a solution if communities are willing to resettle. Population dynamics and the rate of urbanization could in general alter the pattern of road network accessibility in many countries (Jones and O'Neill 2016, Meijer *et al* 2018). At the same time, improvements in road infrastructure have also been shown to facilitate migration through the reduction of relocation costs (Morten and Oliveira 2016).

More generally, the proposition of 'more roads equal more development' has been questioned. Analyzing spatial inefficiency in Africa's transport system, Graff (2019) argues that current infrastructure is often in the wrong place to promote beneficial trade. By simulating how a social planner would design the perfect transport network, he finds that a reshuffling of roads within African countries could improve overall welfare on the entire continent by about 1.15%. In a similar vein, Asher and Novosad (2020), after evaluating the effects of India's \$40 billion national rural road construction program, reason that lower transport costs alone may not be sufficient to transform economic activity and outcomes in rural areas.

Strategic planning of road infrastructure projects is hence essential for reducing adverse environmental impacts of new roads and for ensuring that they translate into tangible development outcomes. We believe that our geographically explicit analysis of current road access gaps provides a useful starting point for such studies. It can serve as a basis for more refined regional investigations addressing specific geographic and other characteristics of an area that our global analysis cannot incorporate (such as additional investments needs due to the necessity of bridges or tunnels). Depending on the region in question, regionally explicit high-quality data might be available. With its global scope, our analysis faces data constraints; in particular data underlying the cost and emission estimates are available for some countries only. Here we have to rely on approximations and extrapolations (compare the *technical appendix*, subsections 1.7–1.9). Furthermore, we conduct a static analysis that abstracts from potential future changes in population size, the built environment, energy use per vehicle km and other socio-economic and socio-geographic variables. Dynamic approaches that consider different scenarios of development in specific regions could hence extend our work. Finally, apart from the climate change mitigation dimension, our data set could be used to quantify further environmental and societal impacts of the goal of universal road access.

¹⁷Investigating the construction of new roads and the upgrade of existing national highways in India, Asher *et al* (2020) find that new rural roads had no effects on local deforestation whereas the upgrading of existing highways caused substantial forest loss.

5. Conclusions

In this study, we combine data on road networks, population density, road construction costs, emission intensity factors of construction sectors and transport-related emissions in a global analysis to assess the economic costs and climate implications of providing universal road access to achieve Sustainable Development Goal 9.1.

We find that about 14% of the global population lives more than 2 km away from the nearest road. Access gaps are highest in sub-Saharan Africa and Southeast Asia. Ensuring that at least 90% of the population in every country had road access would require an investment of approximately USD 700 billion over the course of a decade. In particular going the ‘last mile[s]’ or rather the ‘last person’, i.e. increasing this ratio well beyond 90%, would become costly with investment needs rising to up to USD 3 trillion when giving access to 97.5%.

In terms of climate change implications, we find that the ambitious goal of providing road access to at least 97.5% of the population in any country would imply one-time emissions of about 2 Gt CO₂ and additional transport emissions of about 200 Mt CO₂ per year, resulting in cumulative emissions of approximately 16 Gt CO₂ until 2100 if we assume that all roads are built by 2030. These numbers seem relatively modest considering that they represent only ~1.5% of the carbon budget still available to achieve the 2 °C target.

However, our study covers only two potential sources of CO₂ emissions from additional roads and does not address other environmental and societal concerns associated with the construction of roads. Many of these other concerns (e.g. loss of biodiversity or health impacts) are directly linked to the Sustainable Development Agenda as well. We hope that our geographically explicit data set provides a useful starting point for complementary analyses that further improve our understanding of SDG-9.1, its climate and societal implications and potential alternatives to road infrastructure.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Leonie Wenz  <https://orcid.org/0000-0002-8500-1568>

Michael Jakob  <https://orcid.org/0000-0001-5005-3563>

Jan Christoph Steckel  <https://orcid.org/0000-0002-5325-9214>

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