Optimal Investments in Africa's Road Network

Abstract

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This paper characterizes economically optimal investments in Africa's road network in partial and general equilibrium-based on a detailed topography of the network, road construction costs, frictions in cross-border trading, and economic geography. Drawing from data on 144 million trans-continental routes, it first assesses local and global network efficiency and market access. It then derives a large network connecting 447 cities and 52 ports along the fastest routes, devises an algorithm to propose new links, analyzes the quality of existing links, and estimates link-level construction/upgrading costs. Subsequently, it computes marketaccess-maximizing investments in partial equilibrium and conducts cost-benefit analysis for individual links and several investment packages. Using a spatial economic model and global optimization over the space of networks, it finally elicits welfare-maximizing investments in spatial equilibrium. Findings imply that cross-border frictions and trade elasticities significantly shape optimal road investments. Reducing frictions yields the greatest benefits, followed by road upgrades and new construction. Sequencing matters, as reduced frictions generally increase investment returns. Returns to upgrading key links are large, even under frictions.

Keywords: African roads, spatially optimal investments, big data, PE and GE analysis
JELs: O18; R42; R10; O10

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*Latest version at sebastiankrantz.com/research, data and code at github.com/SebKrantz/OptimalAfricanRoads

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1 Introduction

For several decades, development economists and policymakers have highlighted insufficient or inefficient transport infrastructure, coupled with border frictions and high trading costs, as a major obstacle to African economic development and regional integration. A World Bank report from 2010 states that Sub-Saharan Africa (SSA) has 31 paved roads km per $100km^2$ of land, compared to $134km$ in other low-income countries, estimates the annual infrastructure gap at US\$93 billion and urges SSA countries to spend 1 percent of GDP on roads (Foster & Briceño-Garmendia, 2010). This is echoed by the African Development Report 2010, attesting a financing gap at 5 percent of GDP to overhaul the infrastructure sector (ADB, 2010). More extensive and detailed work by Teravaninthorn & Raballand (2009) and Lamarque & Nugent (2022) unveils the nature of transportation and trucking in Africa, the determinants of transport costs and frictions, and discusses potentials and policy options for development along specific transport corridors. Yet, still little is known about the economic optimality of such (large-scale) transport investments.

This paper thus presents a comprehensive, data-driven, and quantitatively rigorous assessment of Africa's road network and optimal investments into it at the trans-African scale. It (1) conducts a detailed empirical stocktake of Africa's present road network; (2) characterizes global economic optimality in network investments from a market access and welfare perspective; (3) investigates the effects of cross-border frictions on optimal spatial allocations; and (4) presents cost-benefit analyses and evidence on the macroeconomic feasibility of large scale (optimal) investments. This agenda mirrors questions of international policymakers who, in theory, can invest in roads anywhere on the continent and may ask: (1) is it still important to invest in African roads?; (2) where exactly should we invest in African roads?; (3) are investments sensible with/without trade facilitation?; and (4) are they macroeconomically feasible? The paper engages this ambitious agenda by building realistic economic topographies informed by routing engines, geospatial big data, and surveys, and analyzing investments on them using tools from graph theory and spatial economic modeling.

Several significant contributions have already been made in economic literature. Atkin & Donaldson (2015) show that the effect of log distance on trade costs within Ethiopia or Nigeria is 4-5 times larger than in the US, and ≤30% of this effect is explained by the availability and quality of roads. Using 10 years of disaggregated monthly price data, Porteous (2019) estimates a dynamic model of agricultural storage and trade comprising 6 grains traded across 230 regional markets in 42 SSA countries, connected in a network with 413 links to 30 international ports. He finds median trade costs 5x higher than elsewhere in the world. Reducing trade costs to the world average would yield a 46% reduction in grain prices and a welfare gain equivalent to 2.17% of GDP. He further shows that 88% of the welfare gain can be achieved by lowering trade costs through ports and links representing just 18% of the trade network, supporting corridor-based approaches.

Graff (2024) studies spatial inefficiency in African national road networks using a regular 0.5° grid-network parameterized with Open Street Map (OSM) routes between adjacent cells. Employing data on population, nightlights (productivity) and ruggedness (Nunn & Puga, 2012), and the quantitative framework of Fajgelbaum & Schaal (2020), he generates ideal national networks, and estimates that Africa would gain 1.3% of total welfare from better organizing its

national road systems (with national welfare gains ranging between 6.6% for Somalia and 0.5% for South Africa), and 0.8% from a 10% optimal expansion. He also documents that colonial infrastructure projects skewed trade networks towards a sub-optimal equilibrium and that regional favoritism and inefficient aid provision hinder optimal network investments (Graff, 2024). The latter is consistent with findings by Jedwab & Moradi (2016); Jedwab et al. (2017), Burgess et al. (2015), and Bonfatti et al. (2019). Similarly, Gorton & Ianchovichina (2021) analyze trade network inefficiencies and optimal expansions for Latin America closely following Fajgelbaum & Schaal (2020). They find average welfare gains of 1.6% from optimal reallocation and 1.6%/1% from a 50%/10% optimal expansion of national road networks. They also consider transnational networks in the MERCOSUR and Andean Community trade blocs. Disregarding borders, they find that optimal expansions better connect major cities across countries at welfare gains of 1.5%-1.9%. Throughout, they find that optimal network investments reduce spatial wealth disparities.

An emerging policy literature evaluates the effects of planned road interventions in Africa. Notably, Fontagné et al. (2023) model the effects of planned trade (AfCFTA) and transport (PIDA) integration and find that AfCFTA alone would raise exports by 3.4% and GDP by 0.6%, whereas concurrent completion of PIDA priority road projects up to 2040 would raise exports by 11.5% and GDP by 2%. The novel analysis incorporates data on border frictions and trade through ports. Further similar works investigate West-Africa (Lebrand, 2023) and the Horn of Africa (Herrera Dappe & Lebrand, 2023) regions. Lebrand (2023) finds that upgrading the Dakar-Lagos road corridor yields benefits 3x the estimated costs, and 6x with reduced border delays. Herrera Dappe & Lebrand (2023) find a 1% welfare gain from road investments along 4 corridors, which is raised to 4.3% if border delays are reduced by 50%, and to 7.8% with added electrification.

Many further works such as Jedwab & Storeygard (2022), Peng & Chen (2021), Abbasi et al. (2022), Fiorini et al. (2021), and Moneke (2020) study the economic effects of past road interventions in Africa. The latter two find that road network expansion in Ethiopia enhanced the impact of trade liberalization/electrification on local firm productivity/industrialization, respectively. A vast further literature studies the effects of road interventions in other world regions, particularly in China (Faber, 2014; Baum-Snow et al., 2020) and India (Asher & Novosad, 2020; Alder, 2016).

This paper does not examine planned or past interventions but instead characterizes optimal investments.[1] Apart from the partial equilibrium simulations by Porteous (2019) on a heuristic agricultural trade network, and the general equilibrium work by Graff (2024) examining hypothetical optimal reshuffling and 10% expansion of national road networks on a regular 0.5° grid parameterized in a way that has limited resemblance to optimal routing (see Section 4), the literature has not yet (to my knowledge) seen a detailed quantitative attempt to compute what should optimally be done to improve or extend Africa's present road network. This paper attempts to fill this void.

Starting from a precise continental grid of 12,016 cells with centroids exactly 50.28km apart, I obtain 144 million OSM routes connecting all points and compute distance-weighted local measures of network quality and continental market access (MA). Using data on trading across borders, which I translate into road distance/travel time, I characterize how cross-border trade frictions impede cell-MA. A trade across the median African border is equivalent to ∼1000km of national roads or 3.2 road days. My results imply that particularly cells across the border from major markets such as Nigeria suffer ≤80% MA losses due to frictions.

In the second part of the paper, I identify 447 large cities with populations above 100,000 and 52 international ports with a quarterly outflow above 100,000 TEU and obtain routes between them. I process these routes into a realistic representation of the African transport network comprising 1379 nodes and 2344 edges representing 315,000km of road segments. The network connects 444 million people or 86% of the African urban population. I parameterize the network with fresh routing information along all links and develop an algorithm to find 481 new links (104,000km), yielding route efficiency gains of ≥ 50%. Using this network graph, I simulate partial equilibrium MA returns from extending and/or upgrading the entire network or individual links. I find that continental MA, denominated in travel time, can be improved by ≤78% through eliminating cross-

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[1]Eyeballing the results of this paper against PIDA investments (Fontagné et al., 2023) suggests that they resemble optimal general equilibrium trans-African road network investments under (unrealistically) low trade elasticities.

border frictions. Upgrading the entire network to allow travel speeds of 100km/h yields a 42% frictionless MA gain and a 27% MA gain under current frictions. MA gains from new roads are lower and also decrease under frictions. Spatially, including frictions favors investments in national links, significantly reducing the value of transnational and remote links. I also find sizeable differences in the marginal values and cost-benefit ratios of links and propose three investment packages containing high-return links with and without border frictions. These packages cost between 17 and 61 billion 2015 USD and generate MA gains between 20% and 38%. They are macroeconomically feasible if they can raise the aggregate economic growth rate by $\leq 0.54\%$.

The final part of the paper moves this to a general equilibrium setting following Fajgelbaum & Schaal (2020) and Graff (2024). I let cities trade with each other and with port cities, computing optimal investments into the full continental scale transport network. To simulate optimal investments in trans-African roads, I then reduce the network to links connecting the 47 largest (port-)cities. On both networks, I let welfare maximizing social planners spend budgets covering $\sim 1/3$ of all work—15 and 35 billion USD'15, respectively. I simulate cases with/without frictions, increasing returns to infrastructure, and inequality aversion in the planner's objective.

The \$35B planner on the full network optimally connects large cities with ports and surrounding cities. Investments are redistributional as in Gorton & Ianchovichina (2021). Under increasing returns to infrastructure, this planner upgrades many more roads and expands into remote regions, yielding higher and more equitable welfare gains. Similarly, the trans-African \$15B planner primarily upgrades road segments within different populated regions, enhancing connectivity between major cities and with ports. An inequality-averse planner also upgrades an entire corridor crossing southern central Africa from Luanda/Kinshasa to Mombasa/Dar es Salaam. Lowering the elasticity of substitution between different goods to a value of 1.5 creates incentives to also build corridors spanning northern central Africa, better connecting Rwanda/Bukavu and Khartoum to Western Africa. Under current border frictions, investments in connections through Congo and into Nigeria are reduced. Prioritizing the central African infrastructure gap thus requires inequality-averse planners, unrealistic trans-African trade elasticities, and/or efforts to reduce border frictions.

Methodologically, in this paper, I develop a rigorously quantitative approach to characterize economically optimal investments into large road networks. I demonstrate the use of geospatial big data and routing engines to algorithmically create large and accurate network graphs, including potential new roads, and simulate investments on them via established quantitative frameworks. I am also the first to account for cross-border frictions and trade through ports to study their implications for optimal spatial allocations. Detailed estimation of road construction/upgrading costs facilitates interpretation and enables link-level cost-benefit analysis. A corollary of the work is an easily accessible Julia implementation[2] of Fajgelbaum & Schaal (2020)'s MATLAB toolbox.[3]

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2 Africa's Present Road Network

Africa's road network, like any road network, is multi-layered, consisting of major transport routes between cities across countries, smaller roads connecting villages and towns, inner-city roads, and residential roads. Open Street Map (OSM) has an established hierarchy of tags to classify roads comprising motorway > trunk > primary > secondary > tertiary > residential roads. Table 1 shows a summary of all non-residential roads (excluding short links connecting these roads), and Figure 1 a corresponding map. Combined there are 673,045 roads with a total length of 1,611,912km.

Table 1: African Roads (OSM April 2024)

Highway Tag	N	Length in km	Paved Length in km
motorway	14,986	22,400	17,744 (79.2%)
trunk	75,265	181,459	128,978 (71.1%)
primary	124,547	252,047	136,452 (54.1%)
secondary	158,674	365,939	97,904 (26.8%)
tertiary	299,573	790,067	94,373 (12.0%)
Total	673,045	1,611,912	475,450 (29.6%)

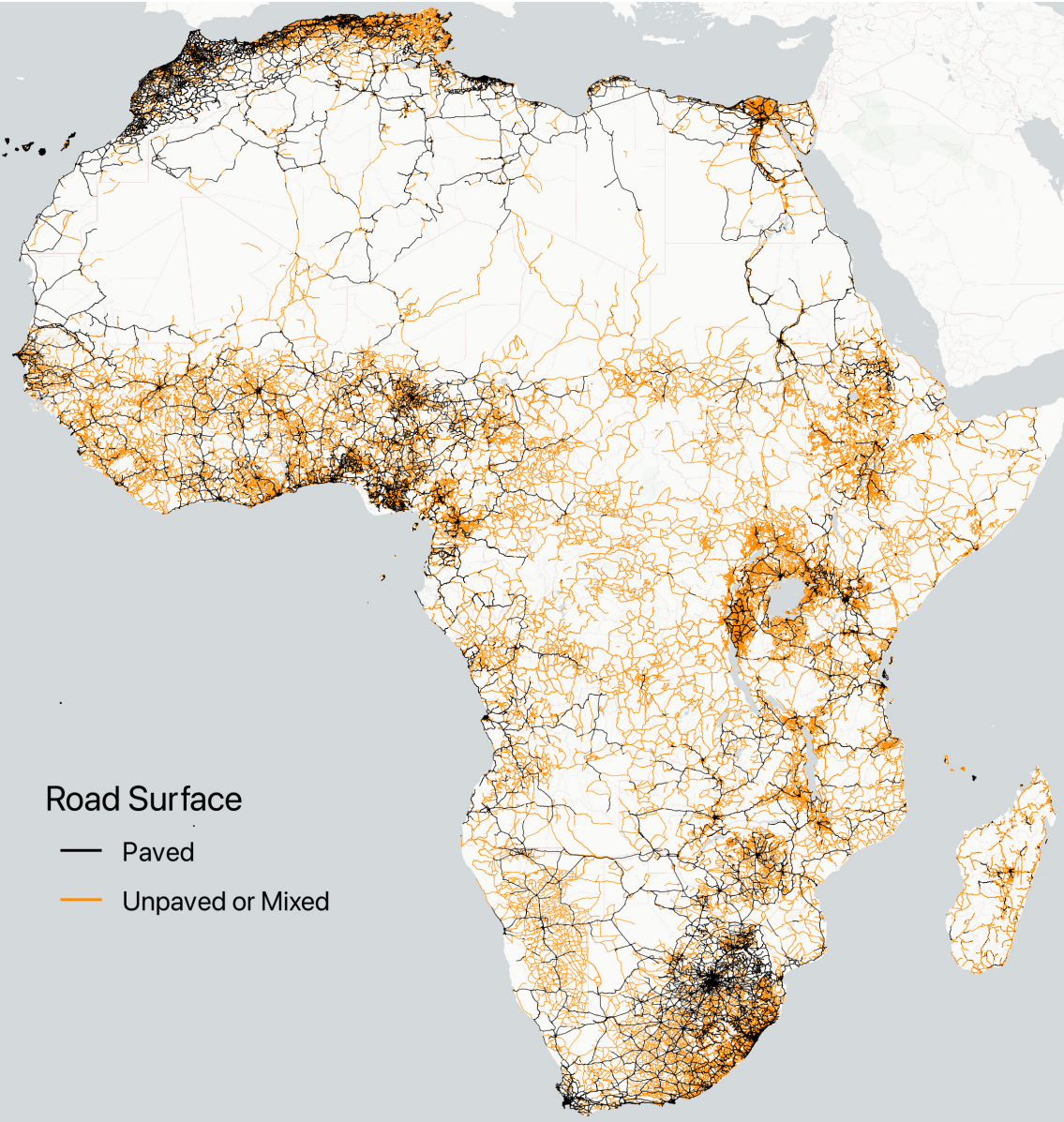Figure 1: African Roads (OSM April 2024)
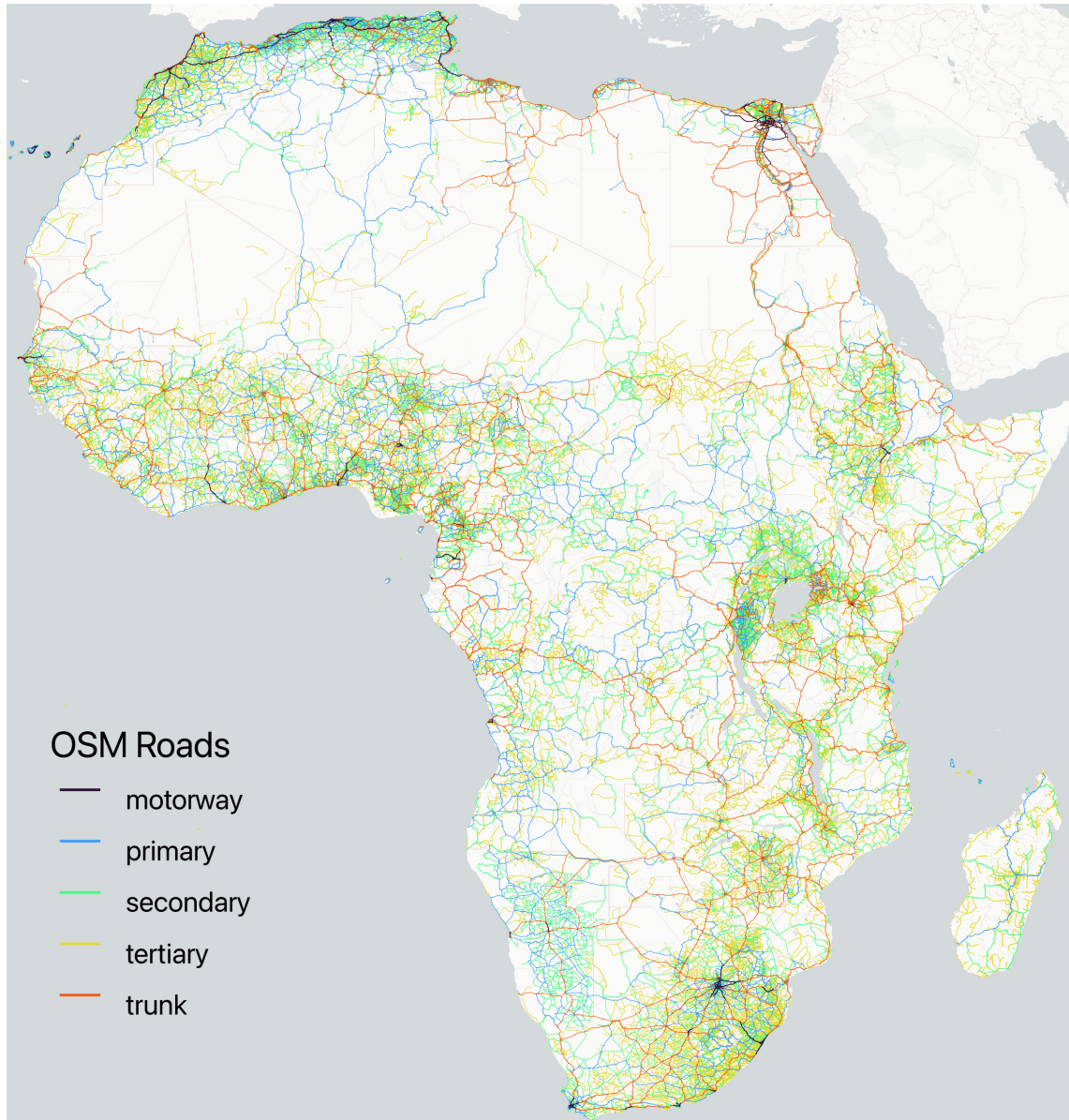
Notes: Figure shows all non-residential roads in the Africa OSM (April 2024) colored by type (OSM 'highway' tag).

Is this a comprehensive account of the network? There is reason to believe so: in 2022, Microsoft Research released a global dataset of segmented roads indicating that globally, 2.3% of roads are missing from OSM, and in Africa around 2.6%. Presumably, most of these are tertiary roads.

Apart from the sheer extent of the network, the surface material and quality of roads determine their efficacy. OSM has a detailed tagging system for roads, including tags such as 'surface,' 'smoothness,' 'tracktype,' 'lanes,' 'lit,' 'maxspeed,' etc. To keep things simple, I develop a binary classification based on whether the 'surface' tag unambiguously indicates that a road is paved, which I summarize on the right hand side (RHS) of Table 1, and plot in Figure 2.

In early 2024, 29.6% of African transport roads are paved, amounting to 475,450km. The actual fraction is presumably a few percentage points higher due to missing 'surface' tags for 38% of roads, all of which are classified as unpaved. But it may also be that a few roads labeled as 'paved' are actually mixed. It is probably relatively safe to assume that at least 1/3 of the network is paved. Among motorways ≥79%, trunk roads ≥71%, and primary roads ≥54% are paved. Significantly lower shares of secondary and tertiary roads are paved; ≤88% of tertiary roads are dirt roads. Paved roads are also concentrated in Northern, Southern, and Western Africa, and are largely missing in central Africa, the Horn of Africa, and Madagascar.

Figure 2: Surface of African Roads (OSM April 2024) | Paved: 475,450km (29.6%)

Notes: Figure shows all non-residential roads in the Africa OSM (April 2024) colored by the 'surface' tag.

2.1 Routing Data

Plotting the road network, while informative about its extent, does not permit a rigorous assessment of its efficiency. Routing engines[4] provide more precise information on how cars can use the network to get from A to B. In my case, A and B could be anywhere on the continent. Two approaches invite themselves to choose points: (1) using a uniform spatial grid and taking the cell centroids, or (2) selecting the centers of important cities/places. In this paper, I employ both approaches, but for spatial analysis, the grid approach is more suitable. Hence, I begin with it.

Accurate spatial analysis at the continental scale warrants using an equally spaced grid. Discrete Global Grid Systems (DGGS) provide these via hierarchical tessellation of cells partitioning the globe. Sahr et al. (2003) propose the Icosahedral Snyder Equal Area Aperture 3 Hexagon (ISEA3H) as a good general-purpose Geodesic DGGS. The grid is implemented as part of the DGGRID C++ library (Sahr, 2022), accessed via the 'dggridR' R package (Barnes, 2020). To limit complexity, I choose a resolution 9 ISEA3H grid, with a cell area of 2591.4km^2 and a centroid spacing of 50.28km. Partitioning the African mainland and Madagascar with this grid yields 12,016 cells.

Figure 3: Grid Cell Centroids and OSRM Route Starting and End Points

Grid Centroids (Inaccessible Cells in Grey)   Actual Route Starting/Destination Points
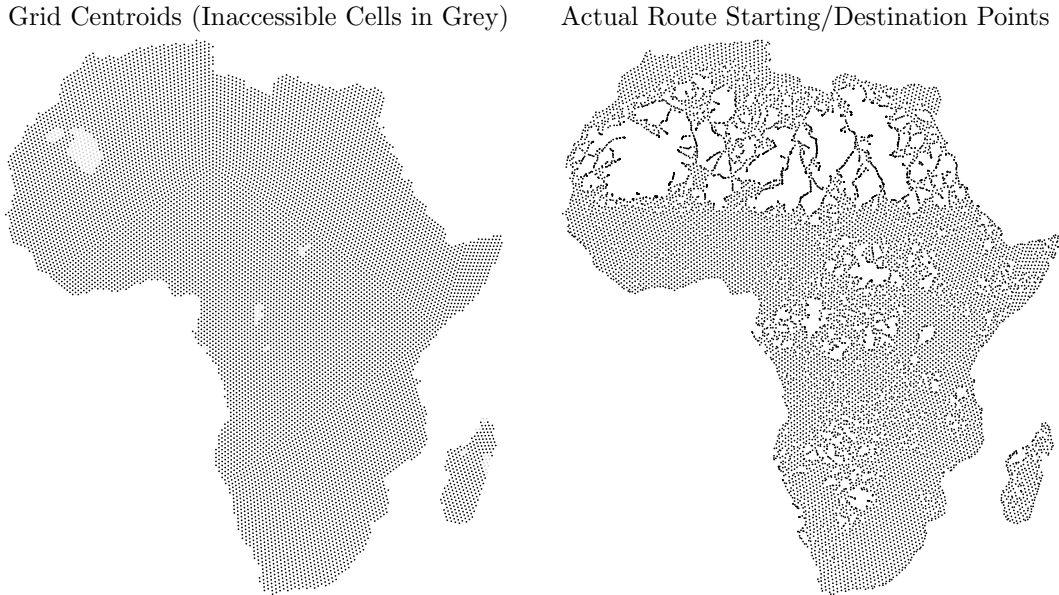
Notes: Figure shows centroids of 50.28km ISEA3H grid (LHS) and the nearest road segment to each centroid (RHS).

To compute a large number of routes, I configure a server with the Open Source Routing Machine (OSRM)[5] and a copy of the Africa OSM from the 5th of June 2023, and compute fastest car routes between all cell centroids. This amounts to $12,016^2 - 12,016 = 144,372,240$ routes, for which I obtain both the road distance in m and the estimated travel time in minutes. OSRM 'snaps' cell centroids to the nearest road, yielding divergent route start/endpoints. Figure 3 shows the outcome of this process. For some cells in the Sahara, the Congo Basin, and Madagascar, colored in light grey on the left-hand side (LHS), OSRM cannot find the nearest road and returns 'NA'. For many further cells, the nearest road snapped to is outside of the cell, as shown on the RHS.

I clean the data by first mapping inaccessible cells to the nearest route start/endpoints. I then follow Graff (2024) in adding the spherical centroid-start/end distance to all routes. This increases the length of routes by 0.53% on average. I also adjust travel time estimates by assuming a travel speed of 10km/h on these straight passages, increasing travel time by 3.4% on average.[6]

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[4]Large computer programs used for navigating (routing) through digitized transport networks.

[5]A high-performance open routing engine in C++ optimized for OSM. Website: https://project-osrm.org/.

[6]In this regard I differ from Graff (2024), which assumes walking speed of 4km/h. My main reason is that the centroid of such cells is unlikely of economic significance, and assuming a travel speed of 4km/h increases travel time by 8.5% on average, whereas assuming 10km/h only increases travel time by 3.4% on average. Furthermore, since most cells where the distance between the cell centroid and the route stating/endpoints is large are in the Sahara, I believe that motorized transport with specialized vehicles (4x4) is possible.

2.2 Efficiency of Africa's Road Network

With realistic road distance and travel time estimates for 144 million trans-African routes, I measure the African network's local and global efficiency. Following Wolfram (2021), I first compute two metrics to assess the efficiency of individual routes: (1) route efficiency (RE), which divides the geodesic distance s_{ij} between two locations i and j by the road distance r_{ij}, resulting in an index between 0 and 1 with 1 implying a direct straight road; and (2) time efficiency (TE), which divides s_{ij} by the travel time along the fastest route t_{ij}, and thus measures the average travel speed in the direction of the destination. Formally, for any route between two cells i and j,

$$\delta_{ij}^r = s_{ij}/r_{ij} \qquad \text{(Route Efficiency)} \tag{1}$$

$$\delta_{ij}^t = s_{ij}/t_{ij} \qquad \text{(Time Efficiency)}. \tag{2}$$

To visualize these metrics, I compute a weighted average across all routes starting in cell i, using the inverse area of an expanding circle around the cell as weight.[7] For each cell i, I obtain

$$\kappa_i^m = \sum_{j \neq i} \frac{\delta_{ij}^m}{s_{ij}^2} \Big/ \sum_{j \neq i} \frac{1}{s_{ij}^2} \quad m \in r, t. \tag{3}$$

Figure 4 reports the cell-level route and time efficiency estimates. Appendix Figure A1 additionally shows the average network speed (NS), computed as r_{ij}/t_{ij}.

Figure 4: Local Route and Time Efficiency of Africa's Road Network
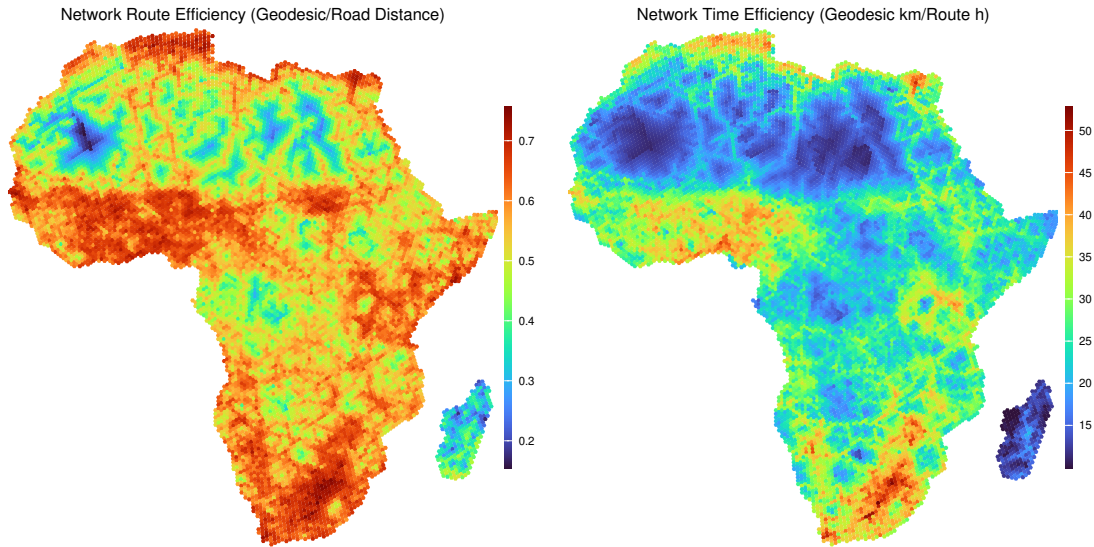
Notes: Figure shows local route efficiency (Eq. 1) and time efficiency (Eq. 2) for each cell i, computed as an inverse-squared spherical distance weighted average across all routes starting in i (Eq. 3).

All three metrics are higher in cities or close to major transport routes. RE is less concentrated than TE and NS, indicating significant heterogeneity in road quality. Particularly outside of major cities, the difference between route and time efficiency is significant. For example, the Southern part of Sudan has, according to Figure 2, a quite dense network of mostly dirt roads, permitting, as Figure 4 suggests, route-efficient navigation at slow driving speeds. Since OSRM does not take into account traffic volumes, TE estimates inside cities and populated areas are too high.

A simple average of these cell-level estimates (κ_i) yields a NS of 40.3km/h (maximum 69.7km/h), RE of 0.534 (maximum 0.756), and TE of 24.9km/h (maximum 52.8km/h). As κ_i is low in uninhabited areas, I also compute a population-weighted average using 2020 total population counts from WorldPop, shown in Appendix Figure A1. This yields a NS of 53.2km/h, RE of 0.625, and TE of 34.4km/h. Wolfram (2021) computes global efficiency directly by probabilistically sampling

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[7]The reason for considering the area (πs_{ij}^2, π cancels out) as a weight on individual routes is that with increasing distance from i there are more cells j, and each of these cells is a less important destination for cell i dwellers.

route start/end points using population weights.[8] To approximate this, I compute a global weighted average across routes with weights equal to the product of start/end cell populations divided by their spherical distance.[9] This yields NS of 64.2, RE of 0.68, and TE of 43.9, reflecting greater efficiency on longer routes (Wolfram, 2021). But even the most favorable RE estimate of 0.68 is far below Wolfram (2021)'s estimates of 0.843/0.767 for US/European road networks.

2.3 Market Access

Whereas route and time efficiency are important from a transportation standpoint, the spatial economics literature such as Donaldson & Hornbeck (2016), Jedwab & Storeygard (2022) or Peng & Chen (2021) has used market access (MA), typically defined as an inverse-distance weighted sum of population, or a proxy therefore such as built-up in the case of Peng & Chen (2021), to evaluate economic gains from transport investments. The MA measure for cell i is

$$\text{MA}_i = \sum_{j \neq i} L_j \tau_{ij}^{-\theta},\tag{4}$$

where L_j is a measure of population and τ a measure of distance, travel time, or transport cost, weighted by an elasticity θ measuring how trade volumes fall as distance/time/costs increase. The value of θ is contentious, for example Jedwab & Storeygard (2022) use $\theta = 3.8$ whereas Peng & Chen (2021) use $\theta = 1$. In both cases, τ_{ij} measures travel time.

To appropriately measure continental MA implied by the road network, I incorporate spatial differences in purchasing power into L_j. Kummu et al. (2018) provide a spatial estimate of GDP in 2015 USD PPP terms by distributing national GDP estimates from the World Development Indicators at 5 arc-min (0.0833 degrees or 9.3km at the equator) resolution using subnational value-added estimates from Gennaioli et al. (2013) and population from the HYDE 3.2 database.

Using Eq. 4, I compute MA maps using both measures of economic mass (L_j), and trade elasticities of $\theta = 1$ (Peng & Chen, 2021) or $\theta = 3.8$ (Jedwab & Storeygard, 2022). As Eq. 4 excludes cell i itself, the centers of several large cities have a lower MA measure than adjacent cells. To remedy this, I add i's GDP/wealth to the MA measure using a distance $\delta_{ij} = 25\text{km}/\kappa_i$, where κ_i is cell i's RE/TE measure from Figure 4. Figure 5 shows the resulting maps with $\sigma = 1$ and Appendix Figure A4 with $\sigma = 3.8$.

Evidently, $\theta = 3.8$ yields a much stronger concentration of MA around major cities and a high correlation of the MA measure with cell GDP. Both θ values elicit northern Egypt, Nigeria, and, to a lesser extent, greater Johannesburg as high MA areas. Cairo has the greatest MA.

3 Barriers to Cross-Border Trade

Africa has 'thick borders,' and any evaluation of continental roads should at least be mindful of them. Trade barriers can broadly be distinguished into traditional trade tariffs and regulatory obstacles and frictions at the border. This paper will concentrate on the latter as tariffs and other non-tariff barriers tend to be product- and quantity-specific. But, for the sake of completeness, I begin with a brief overview of tariffs applied by African countries in international comparison.

3.1 Trade Tariffs

The World Development Indicators provide aggregate estimates of the extensive and intensive margins of trade tariffs applied by each country. Table 2 summarizes these indicators for different country groups. While SSA countries only apply specific (non-ad-valorem) rates on 0.1% of tariff lines, 33.9% of African tariffs exceed 15%. When weighted by the product import shares

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[8]Concretely, Wolfram (2021) computes the route efficiency of the US road network using OSRM-generated routes between 2000 population-weighted random points in the US and finds a median route efficiency of 0.843 with a standard deviation of 0.045 across 4 million routes.

[9]Following Newton's Law of Gravity as as operationalized in the empirical trade literature (Head & Mayer, 2014), which finds a distance elasticity around $\theta = -1$. Inter-city migration gravity models such as Zipf (1946) or Poot et al. (2016) also suggest that migration varies according to the distance rather than the squared distance.

Figure 5: Market Access Maps using GDP in 2015 USD PPP

$\theta = 1$ (Peng & Chen, 2021), cor(MA, GDP) = 0.480-0.484
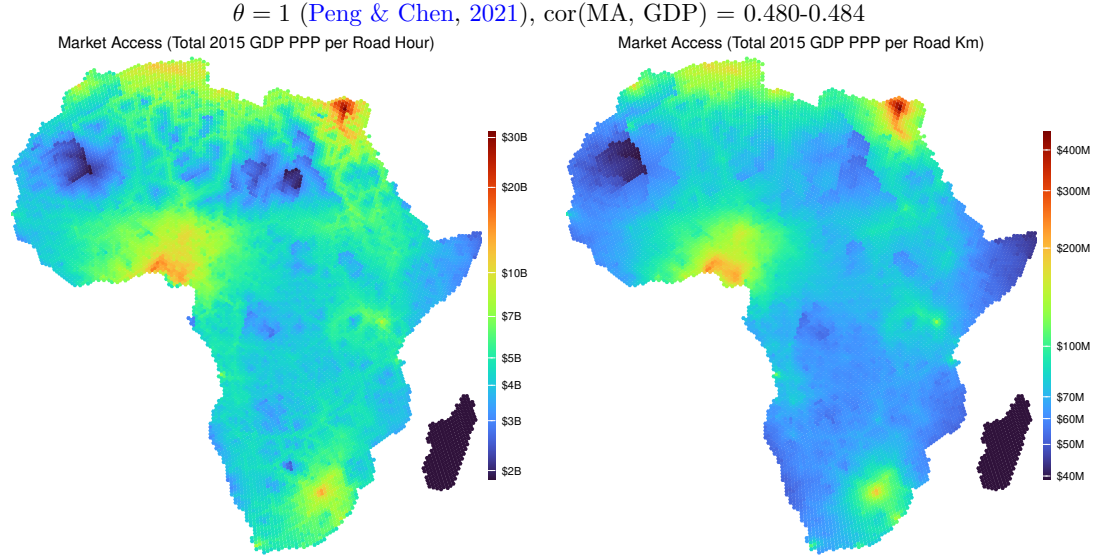
Notes: Figure shows local market access using Eq. 4 where L_j is cell-GDP in 2015 USD PPP from Kummu et al. (2018).

corresponding to each partner country, the average SSA country applies an 8.2% import tariff and a 7.5% tariff on manufactured products. This is comparatively high and only exceeded by South Asia and the low-income country (LIC) average. Averaging across all African countries using 2020 GDP in PPP terms as weights yields very similar outcomes, at an average tariff rate of 8.7%.

The African Continental Free Trade Agreement (AfCFTA), concluded in 2019 and ratified by 47 African states by the end of 2023, aims to facilitate trade by eliminating 97% of tariff lines between members alongside most NTBs. Yet, trading under the agreement has started sluggishly; at present, only 8 countries trade 96 products under the Guided Trade Initiative.[10] With LDCs given 10+ years to remove tariff lines and the sluggish start of trade under the agreement, it is expected that the full benefits of the agreement will only accrue by the middle of the century.

Table 2: World Development Indicators: Tariffs Applied in 2020

Region/Income Status	All Products				Manufactured Products			
	SSR	SIP	TR	WTR	SSR	SIP	TR	WTR
OECD	5.7	2.7	2.0	1.6	0.3	0.6	1.5	1.5
Non-OECD	0.5	19.1	8.0	6.3	0.2	17.8	7.5	6.0
High income	4.3	4.7	3.0	2.6	0.2	3.0	2.6	2.4
Low income	0.0	34.3	11.1	9.3	0.0	32.4	10.6	8.4
Europe & Central Asia	5.0	2.4	2.5	1.9	0.3	0.6	2.2	1.9
Latin America & Caribbean	0.0	19.2	8.0	6.7	0.0	17.7	7.5	6.6
South Asia	0.6	28.6	10.6	8.8	0.6	27.8	10.2	9.9
Middle East & North Africa	0.8	9.3	6.4	5.1	0.1	8.8	5.6	4.8
Sub-Saharan Africa	0.1	33.9	10.8	8.2	0.1	32.5	10.5	7.6
All Africa wtd. GDP PPP	0.0	26.9	11.2	8.7	0.0	26.1	9.0	7.6

SSR = Share of Tariff Lines with Specific Rates (%)
SIP = Share of Tariff Lines with International Peaks (%)
TR = Tariff Rate, Applied, Simple Mean (%)
WTR = Tariff Rate, Applied, Weighted Mean (%)

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[10]https://au-afcfta.org/, https://www.macmap.org/en/learn/afcfta

3.2 Regulatory Obstacles and Border Frictions

The World Bank's Doing Business (DB) ranking recorded the time and costs (excluding tariffs) required for trading across borders[11] in all African countries, with the latest surveys done in 2019. The surveys record separately the time and cost in USD of documentary compliance (DC) and border compliance (BC) for both exporting and importing. Table 3 summarizes these results. Overall, SSA is at the bottom of the ranking, and the MENA region is not much advanced either. Weighting the estimates by countries' 2019 GDP in PPP terms also yields no improvements. The weighted estimates imply an average cost of 808 USD for exporting a container in Africa, most of which is payable at the border, and an average time investment of 170 hours, 81 of which are spent at the border. The costs of importing are even worse, at an average of 1177 USD per container and an average time commitment of 292 hours, 124 of which are spent at the border.

Table 3: World Bank Doing Business: Trading Across Borders in 2019

| | Exporting | | | | Importing | | | |
| | USD | | Hours | | USD | | Hours | |
Region/Income Status	BC	DC	BC	DC	BC	DC	BC	DC
OECD	149.7	34.8	12.8	2.5	106.5	26.5	9.4	3.8
Non-OECD	453.8	145.0	64.0	55.8	531.5	191.4	82.5	66.5
High income	228.4	68.0	24.8	12.6	252.1	74.3	22.1	16.0
Low income	528.8	197.1	84.1	78.9	670.7	348.0	125.9	124.3
Europe & Central Asia	117.8	47.1	11.9	12.2	91.8	42.1	10.4	11.2
South Asia	310.6	157.9	53.4	73.7	472.9	261.7	85.7	93.7
Latin America & Caribbean	513.2	99.5	55.7	36.4	625.3	106.5	55.8	44.3
Middle East & North Africa	447.0	239.7	54.1	63.1	526.0	261.8	97.3	72.4
Sub-Saharan Africa	603.1	172.5	97.1	71.9	690.6	287.2	126.2	96.1
All Africa wtd. GDP PPP	628.9	178.8	89.3	80.5	717.6	459.6	167.9	123.9

DC = Documentary Compliance, BC = Border Compliance

Figure 6 shows symmetrized exporting + importing border compliance times and costs for each border. In central African countries such as Congo, the costs are exorbitant, whereas particularly in Southern Africa, they are quite efficient, coming as low as 509 USD for trades across the Rwanda-Burundi border and 40 hours for trades between Mozambique and Eswatini.

Figure 6: World Bank Doing Business: Border Compliance Frictions in 2019

Border Compliance Cost, Median: 1222$　　　Border Compliance Time, Median: 224h
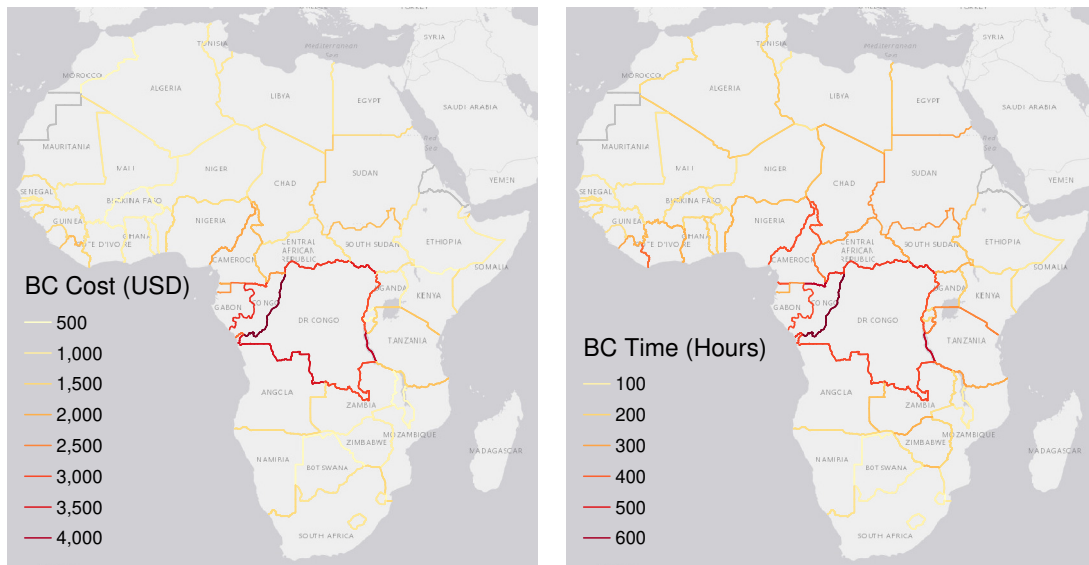
Notes: Figure shows average (bi-directional) 2019 border compliance cost/time of trading a standardized product.

[11]https://archive.doingbusiness.org/en/data/exploretopics/trading-across-borders

3.3   Border Frictions Adjusted Routes

It is difficult to take tariffs and NTMs into account when evaluating transport networks and market access because their effects depend on the value, type, and quantity of products being traded. In addition, AfCFTA has set clear aims to eliminate most inner-African tariffs in the foreseeable future. Regulatory and border frictions on the other hand are more uniformly applicable.

A critical question then is how the estimates from Table 3 can be sensibly added to road distance and travel time estimates. Surely time spent preparing documents or waiting at the border is different from driving time. To better understand the relative cost of these times, I collect data on domestic transport costs from the 2019 DB survey for a sample of 23 (mostly landlocked) African economies where exporting/importing involved domestic transportation of 100km or more. This information is not standardized across countries and thus not published in the DB indicators. For each country surveyed, the distance in km to the border, the time in hours to the border, and the cost in USD of exporting/importing a representative product are recorded.

To estimate the average cost of an hour spent on the road, I regress the cost of the trip on the travel time in hours while controlling for the log of the velocity and a dummy indicating whether the transport was import related.[12] I do the same for the distance traveled. Since I am more interested in converting times into each other rather than converting cost to time, I also regress the cost of border and documentary compliance from Table 3 on the respective time required using data for all 53 available African economies. Table 4 reports the results.

Table 4:   Relative Cost of Exporting/Importing Times

Cost in USD:	Transport		Border	Documentary
Model:	(1)	(2)	(3)	(4)
Constant	-711.6**	276.7	217.8***	51.83*
	(285.9)	(317.4)	(65.28)	(29.63)
Travel Time (Hours)	15.79***			
	(2.074)			
Travel Distance (Km)		1.560***		
		(0.2987)		
Border Time (Hours)			3.988***	
			(0.6781)	
Documentary Time (Hours)				1.655***
				(0.3954)
Log Velocity (Km/Hour)	346.3***	-43.95		
	(85.84)	(102.9)		
Import Dummy	106.6	107.7	-44.92	78.76***
	(133.3)	(135.9)	(66.38)	(25.79)
Observations	46	46	106	106
R^2	0.448	0.415	0.471	0.388
Adjusted R^2	0.408	0.373	0.461	0.376

Heteroskedasticity-robust standard-errors in parentheses.
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Evidently, time spent on the road, valued at 15.8 USD per hour in the average African country, is more costly than time spent at the border (4\$/h) or filing documents (1.7\$/h). The estimates imply that in the average African country, road time is $15.79/3.988 = 3.959 \approx 4$ times more costly than border time, and $15.79/1.655 = 9.540785 \approx 10$ times more costly than documentary time. To create the NTB-adjusted travel time matrix, I divide border compliance time by 4 and documentary compliance time by 10 before and add them to the OSRM estimates. Using the coefficient on distance indicating an average cost of 1.6\$/km, I also obtain an adjusted road distance matrix by dividing documentary and border compliance costs by 1.6. These estimates are

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[12]I also test the interaction of travel time and the import dummy, but the term is insignificant; thus export and import time do not differ in terms of cost.

roughly consistent with Djankov et al. (2010)'s result that a day of border delay is equivalent to a country distancing itself from its trade partners by ~70km since 24h × 4\$/h ÷ 1.6\$/km = 60km.

This accounting likely underestimates the true extent of frictions as I only convert time/cost to travel time/distance rather than converting both measures. Table 4 would allow converting both, but I suspect cost estimates to include labor time. Having two different adjusted MA measures can thus capture different aspects of frictions. Another consideration is that OSM travel speeds are too fast since they ignore congestion; thus, very large time-denominated frictions would overstate their effects. African borders also likely have improved significantly since 2019.

It remains to specify how to adjust routes between cells that are not in neighboring countries. The DB surveys do not give information about the time and cost of transiting through a country. Efficient calculation of multiple routes with OSRM also does not return the geometries of routes but only the total distance and travel time. I thus opt for a simple approach and stipulate a lump-sum transit time of 2 days on all routes transiting through 3rd countries. Using the estimates from Table 4, this yields a 48h / 4\$/h = 12h increase in travel time and or a 48h × 4\$/h ÷ 1.6\$/km = 120km increase in road distance. The reader scrutinizing this generic adjustment should remember that long routes do not impact market access calculations much.

Figure 7 shows the frictions denominated in travel distance and time implied by each border crossing—again after imposing symmetry regarding the direction of travel. The median African border imposes an additional cost equivalent to 1043km of road travel or 76h = 3.2 road days.

Figure 7:   Road Distance and Time Equivalent 2019 Border Frictions

Distance-Equivalent Frictions, Median: 1043km   Time-Equivalent Frictions, Median: 76h
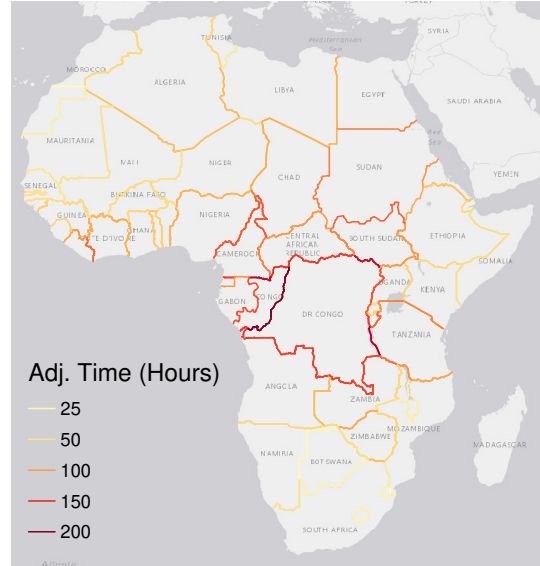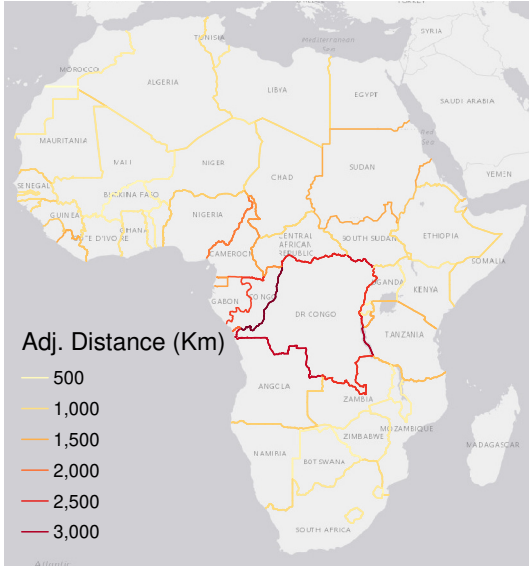
Notes: Figure shows average (bi-directional) 2019 border and documentary compliance cost/time converted to road distance/travel time following Table 4, i.e., dividing costs by 1.6 and documentary/border times by 10/4, respectively.

## 3.4   Border Frictions Adjusted Market Access Maps

Appendix Figure A5 shows the frictions adjusted market access maps. They indicate that, especially when θ is low, border frictions significantly obstruct access to markets in neighboring countries. The adverse effects are especially strong for cells surrounding major African markets such as Nigeria.

Summing together the MA of all locations, I estimate the total cost of these frictions. Under $\theta = 1$, the estimated travel times imply a total MA of 980 billion USD/min in 2015 PPP terms, which is reduced by 52.3% to 467 billion USD/min under the 2019 trade frictions. When considering only distance, with $\theta = 1$ MA is 922 billion USD/km, and reduced by 25.5% to 687 billion USD/km under 2019 frictions. Thus, under a low trade elasticity, the African continental market could be up to twice its effective size, even with the current transport network. Under $\theta = 3.8$, the reduction

in MA shrinks to 1.13%-1.19% in all cases, implying that with a high trade elasticity, cross-border frictions become largely irrelevant. Evidence from inter-city migration (Zipf, 1946; Poot et al., 2016), international trade (Head & Mayer, 2014), and by Peng & Chen (2021), suggests that a lower elasticity is more plausible.

Cell-level MA losses due to border frictions range between -6.6% and -81.1% in GDP/min terms with $\theta = 1$. Figure 8 shows their spatial distribution. Large parts of central Africa incur 50-80% time- and 20-50% distance-denominated losses. Cells across the border from major markets also incur very large losses. Under $\theta = 3.8$, losses are large in some cells close to borders but negligible in most populated cells. Appendix Figure A6 shows the changes under $\sigma = 3.8$.

Figure 8: Market Access Loss (%) from Border Frictions under $\theta = 1$
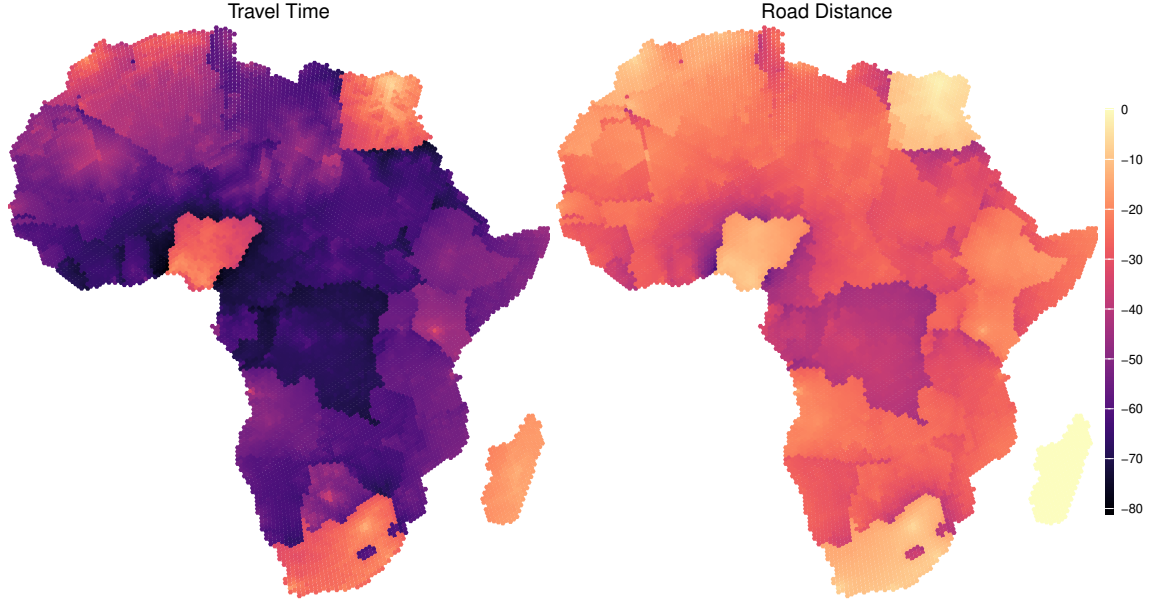
Notes: Figure shows local MA %-loss from frictions (using Eq. 4 where L_j is cell-GDP from Kummu et al. (2018)).

In summary, assuming $\theta \ll 3.8$, many regions could gain significant MA from lower border frictions. In the following sections, I show that these frictions also reduce the benefits of (trans-African) road investments. Thus, their reduction should be a top policy priority. To simulate such investments, however, I first need to create suitable graph representations of Africa's road network.

4 Optimal Network Representations and Extensions

The central aim of this paper is to provide quantitative evidence on which roads should be enhanced or built. This requires accurate representations of the road network via graphs to simulate the effects of network investments. Most research creates these graphs in an ad-hoc fashion by either connecting adjacent cells in a gridded representation and parameterizing them by the connectivity along these links, or by choosing the largest roads and their intersections as nodes/edges of the graph. This section instead uses a routing engine (OSRM) to create graphs that optimally represent the road network as interpreted by the engine, implying that the optimal network graph produces road distance/travel time estimates that closely approximate those of the routing engine. I then extend this graph with high-value new links connecting previously unconnected nodes.

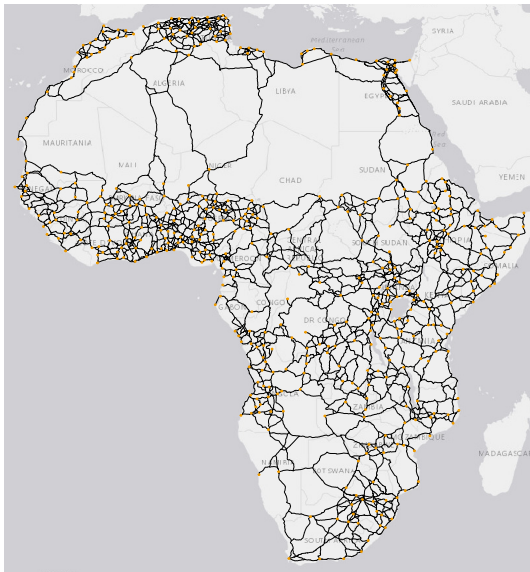## 4.1 An Optimal Graph of Africa's Transport Network

Previous research such as Graff (2024) has created a graph representation of Africa's road network by dividing the continent into cells and computing routes connecting adjacent cells. However, cell centroids may not be of economic interest or well-connected at all. I thus generate a more realistic network representation by sampling important cities and ports and letting OSRM compute routes between them, which I then process into an accurate graph. To sample cities, I use the updated

(March 2024) world cities database from simplemaps.com sourced from the US National Geospatial Intelligence Agency.[13] I derive, in multiple steps,[14] the largest cities with a population of more than 100,000 within a radius of 70km in continental Africa.[15] This yields 447 cities. I add populations of smaller cities within 30km of these cities to create agglomeration data. In addition, I use data on international ports compiled by the World Bank[16] to select ports with a deployed capacity of more than 100,000 TEU in Q1 of 2020, which are 57 in Africa. From these, I take the largest within 100km, yielding 52 large ports at least 100km apart. I then match these ports to my 447 large cities within a 30km radius and am able to match 46. To the remaining 6 (among which Walvis Bay in Namibia), I add the population of cities/towns within a 40km radius (including Swakobsmund for Walvis Bay) to create more loosely defined 'port cities'. In total, I obtain $447 + 6 = 453$ important (port-)cities in continental Africa. Figures 9 and 11 plot them.

I then let OSRM compute precise routes between all 453 (port-)cities that are spherically less than 2000km apart. This yields 25,742 routes, shown on the LHS of Figure 9. To generate an undirected graph representation, I apply several algorithms[17] to intersect and segmentize the routes, smooth them, and finally contract intersection points within 30km of each city/node.[18] This yields a discretized network representation comprising 1,379 nodes and 2,344 edges - shown on the RHS of Figure 9. Appendix Figure A7 provides an overlay version of Figure 9, illustrating the accuracy of the network representation thus created.

Figure 9:   Computing an Optimal Graph of Africa's Transport Network

25,742 Routes Connecting 453 (Port-)Cities   Undirected Graph Representation
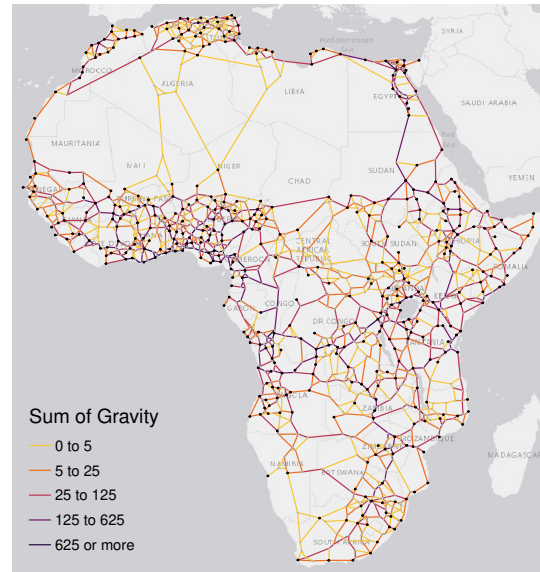
Notes: The LHS shows 25,742 fastest car routes connecting all 453 (port-)cities less than 2000km spherical distance apart. The RHS shows an undirected graph comprising 1,379 nodes and 2,344 edges generated from these intersecting routes.

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[13]The Africapolis project (https://africapolis.org/) is more prevalent among researchers but does not provide precise city centroids, and the 2015 edition available at the time of writing is a bit dated.

[14]Concretely, I first find the largest cities within a 30km radius through an iterative algorithm that finds the largest city within 30km of each city, drops all non-selected cities, and repeats. I weight the population of cities with a higher administrative function by 5, such that national and administrative capitals are selected unless they are more than 5 times smaller than close cities. I repeat this process with an increased radius of 50km. Then, I add the populations of all cities within 30km of the selected (largest in 50km) cities to create urban agglomerations. I then remove agglomerations with a population below 100,000 and apply the algorithm one last time to find the largest agglomerations within 70km. In this last run, no additional weight is given to cities with higher administrative functions, i.e., only total population is used to select the largest urban agglomerations within 70km.

[15]I.e., excluding small island states, Madagascar, and also excluding cities not connected to the mainland via roads, such as Zanzibar City.

[16]https://datacatalog.worldbank.org/search/dataset/0038118/Global—International-Ports

[17]Available in R packages *rmapshaper*, *stplanr*, *sfnetworks*, *tidygraph/igraph*, and *dbscan*.

[18]I first contract all nodes/intersections within 30km of the 453 cities and ports to the respective city/port centroid. I then cluster the remaining nodes with a 30km radius using density-based spatial clustering and contract these clusters to the most important node, i.e., the node used by the routes with the greatest 'gravity implied flows'.

The overall length of the transport network is 315,000km. The edges/links on the RHS of Figure 9 are colored by the appropriately scaled 'sum of gravity' across all 25,742 routes. Each route connects two cities i and j with populations P_i and P_j and road distance D_{ij} (in km) between them. Following Poot et al. (2016), migration flow can be modeled as

$$M_{ij} = G \frac{P_i^\alpha P_j^\beta}{D_{ij}^\gamma}. \tag{5}$$

In their New Zealand case study, the parameters α, β, and γ are all around 0.8-0.9. A famous early study by Zipf (1946) on US inter-city migration showed that $\alpha = \beta = \gamma = 1$ gives a good fit to the data. For simplicity, I adopt this specification and set $G = 1e-9$ to reduce the size of the estimates. The RHS of Figure 9 shows the sum of M_{ij} across all routes using the link. Darker edges are thus expected to receive higher traffic volumes. The highest volumes are expected in the Nile Delta and along the West African coastline. Due to the border closure between Algeria and Morocco since 1994, OSRM routes all car traffic between both countries through Western Sahara, yielding an unrealistic medium-sized gravity-implied flow along this link.

To parameterize the network, I add city populations within 30km of the $1379 - 453 = 926$ navigational nodes, yielding 530 or 57% of navigational nodes with populations. Figure 12 shows these as small dark nodes. In total, $453 + 530 = 983$ nodes, comprising 71.3% of the 1,379 nodes, are associated with cities. Compared to the initial network of 453 (port-)cities (large dark nodes), the population represented by this network increases by 14.7% to 444.2 million, which, according to the simplemaps world cities dataset, represents 86.3% of the African city population of 515 million.[19] I also use OSRM to obtain road distance and travel time along each link, yielding edge weights representing the real road network. Figure 12 visualizes the corresponding segments.

4.2 Optimal Network Extensions

Africa's transport network is underdeveloped, and, with an average route efficiency of 0.68 vs. 0.84 for the US, far from ideal. To characterize optimal network investments on a sparse graph, including the possibility of new roads, I first need to find sensible new links and add them to the graph as potential (presently impassable) edges. I devise a network finding algorithm tailored to this task and establish its properties by letting it draw an ideal hypothetical transport network. I then apply it to the transport network graph to select high-value new links.

The algorithm begins with a complete graph where all nodes are connected and eliminates edges intercepted by other nodes which should be connected first. I illustrate it by letting it generate an ideal network between the 453 (port-)cities with a geodesic US route efficiency of ≥ 0.843 and a maximum 20° deviation from the direction of travel. Figure 10 helps explain the algorithm.

Figure 10: Network Finding Algorithm Illustration
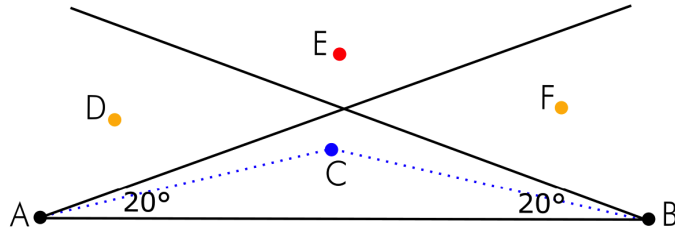
It first computes the geodesic distance between some point A and another point B. Then, it computes the distance from A to all other points (cities), such as C, D, E, and F, and, using the triangle equation, the angle α between AB and AC, AD, AE, and AF. It then drops points where the distance is greater than AB or $\alpha > 20°$. For the remaining points (C and F), it computes the distance ACB and AFB, and compares ratios AB/ACB and AB/AFB to the US route efficiency measure of 0.843. If either C or F are found route-efficient, the algorithm concludes that there

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[19]The Africapolis 2015 estimate sums to 574 million across 9186 urban agglomerations, versus 4339 cities in the simplemaps dataset summing to 515 million. I use simplemaps because it is more up-to-date and precise.

should be no direct AB link because these points should be connected via C or F. The same process is repeated taking point B as a vantage point, such that if the algorithm finds either AB or BA intercepted by other route-efficient points, this link is dropped from the undirected graph. Figure 11 shows the thus generated US-grade hypothetical network connecting the 453 (port-)cities. It has 1459 edges, some of which intersect and should be broken up further.

Figure 11:   Demonstration of Network Finding Algorithm

543 (Port-)City Sizes (Population)   US-Grade Hypothetical Network
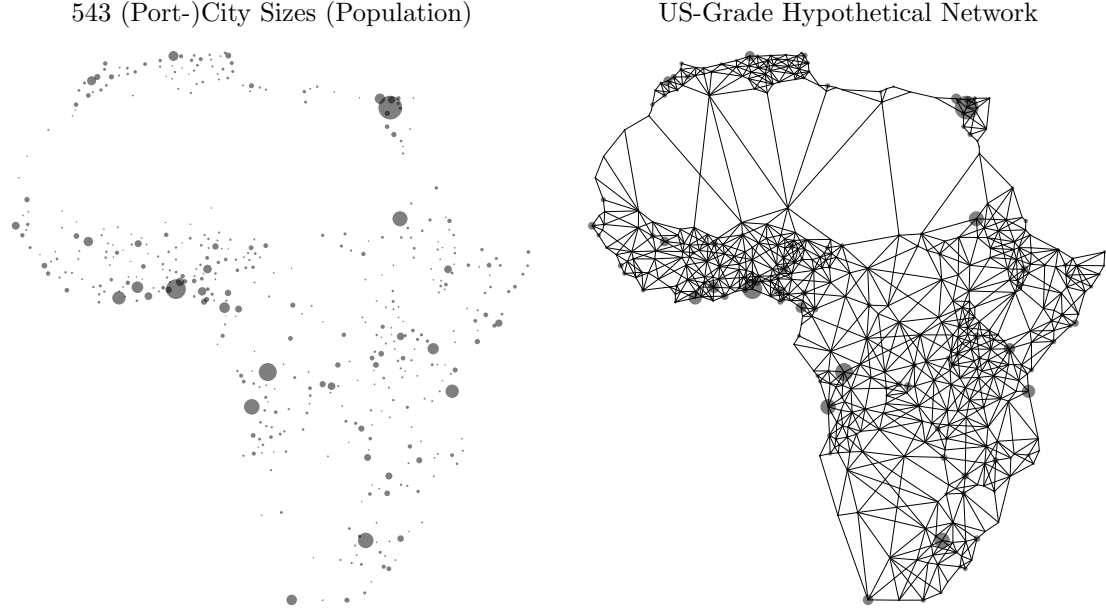
Notes: The LHS shows the 453 (port-)cities; circles reflect population. The RHS shows the result of applying the network finding algorithm described above, requiring US route efficiency of 0.834 (Wolfram, 2021) and a maximum 20° deviation.

To propose optimal network extensions, I apply the algorithm to a complete transport network graph where all 1379 nodes are fully connected. Using the US network efficiency and 20° angle criterion as illustrated above yields a staggering 2,031 new edges, shown in Appendix Figure A8. Since this is close to the number of existing edges, and many of the new links overlap, I adjust the parameters of the algorithm to generate fewer potential links. Concretely, I increase the maximum angle for intercepting nodes to $\alpha = 45°$, and use the European route efficiency estimate of 0.767 by Wolfram (2021), which is lower than the US value of 0.843 partly due to Europe's more fragmented (water-bound) geography. In addition, I let OSRM compute a full road distance matrix between all 1,379 nodes and remove connections that already have a route efficiency of 2/3 or higher. The 516 links retained by this modified algorithm, if straight, thus reduce travel distance by $\geq 50\%$.

I then verify whether these links can be constructed and remove 46 links significantly intercepted by waterbodies or protected areas. Some proposed links across the closed Morocco-Algeria border already exist. I keep them and reduce their construction costs in the network optimization process. Finally, I manually add 11 links that I consider important for improved transport flow. In total, I retain 481 new links. Figure 12 draws them as thin green lines. Exempting one crossing in northern Mali, where adding a node would add no value for routing purposes, and a similar case in central Kenya, these links don't intersect and thus imply no additional nodes to the graph.

In reality, roads constructed along these links will not be perfectly straight. I assume that new links have the same average route efficiency as existing links, which is 0.83.[20] Thus, I divide the spherical distance spanned by new links by 0.83 to estimate their road distance (edge weight), yielding 104,000km in total. In the remainder of this paper, I show simplified graphs with straight edges in all smaller plots to make them more legible. All computations, however, use edge weights corresponding to actual road distances and travel times, with existing network as in Figure 12.

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[20]The route efficiency across individual links of 0.83 is larger than the overall network route efficiency of 0.68 because the latter considers full trans-African routes comprising multiple links.

Figure 12: Discretized and Calibrated African Transport Network incl. High-Value New Links
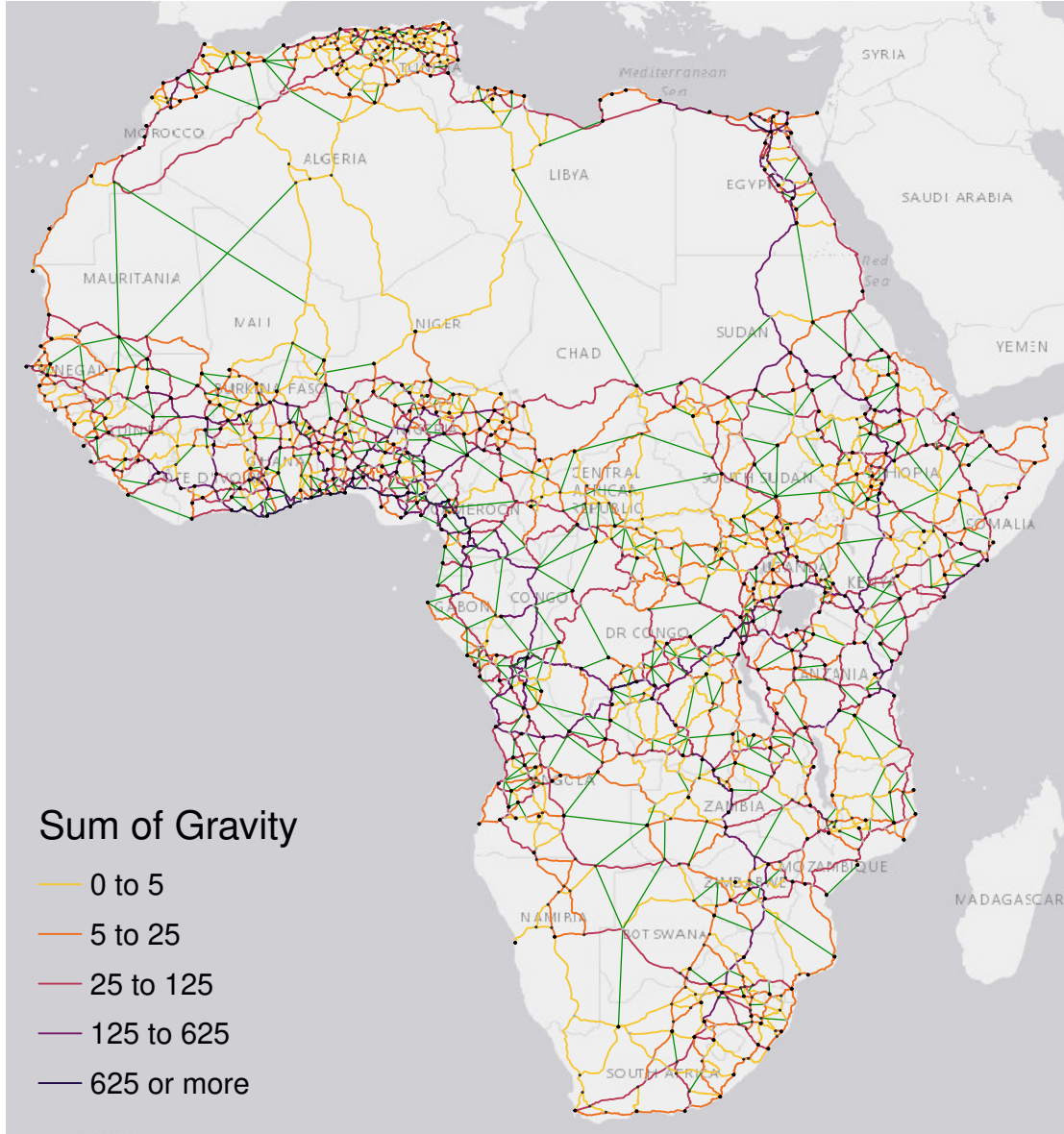
Notes: Figure shows optimal graph with 1,379 nodes and 2,344 edges (= links/road segments), including 481 feasible new links proposed by the network finding algorithm. The sum of gravity (Eq. 5) is calculated across all routes using a link.

Having thus created detailed graph representations of Africa's road network, I now examine economically optimal investments in the network—first in partial and then in general equilibrium.

5 Optimal Network Investments in Partial Equilibrium

This section characterizes optimal road network investments in partial equilibrium (PE). This term, in the context of this study, is used to decribe the selection of links based on their individual marginal benefits, without considering path-dependencies that apply when selecting multiple links. PE estimates capture the effects of changes to the network on overall network efficiency and continental MA, keeping fixed the distribution of economic activity. Since for computational reasons I only consider fixed-labour scenarios, the distribution of economic activity is also fixed in the general equilibrium (GE) simulations of Section 6, which, however, solve the path dependency issue through optimization over the space of networks. PE tools can be used to compare investments in individual links or predefined investment packages, but they cannot determine how a given infrastructure budget should be optimally spent on improving the network—as in GE simulations. This section, however, reaches important conclusions using much fewer assumptions

than required for GE simulation and offers some insightful cost-benefit analyses. The PE objective of MA maximization is also fundamentally distinct from welfare maximization considered in GE.

5.1 Investments in New Links

Considering the full transport network, I begin with a set of transport-oriented simulations to gauge the value of adding the 481 proposed links. Computing the route efficiency across all routes with and without the new links yields a 7.1% increase in average direct RE, from 0.68 to 0.72. When weighting routes by gravity (Eq. 5 but with the spherical distance), RE increases by 5% from 0.73 to 0.76, suggesting that travel between populated areas is more efficient (ignoring congestion).

By virtue of the smaller network size, I can also run these computations on a link-by-link basis by adding a link to the network, recomputing all shortest paths, and then computing the percentage change to the existing RE. Figure 13 shows the outcome of this process both with and without gravity weights. The results are similar regardless of weighting. The most valuable links with an impact of more than 0.1% on overall RE (up to a maximum of 0.8%) reconnect Morocco to Algeria, followed by improved trans-Saharan connections through Mauritania, Mali, and Chad. Also vital are additional links connecting Southern Africa (Johannesburg) to Western Africa and new links in (South-)Sudan facilitating north-south and east-west connections.

Figure 13: Percentage Gain in Network RE from Constructing Each Proposed Link
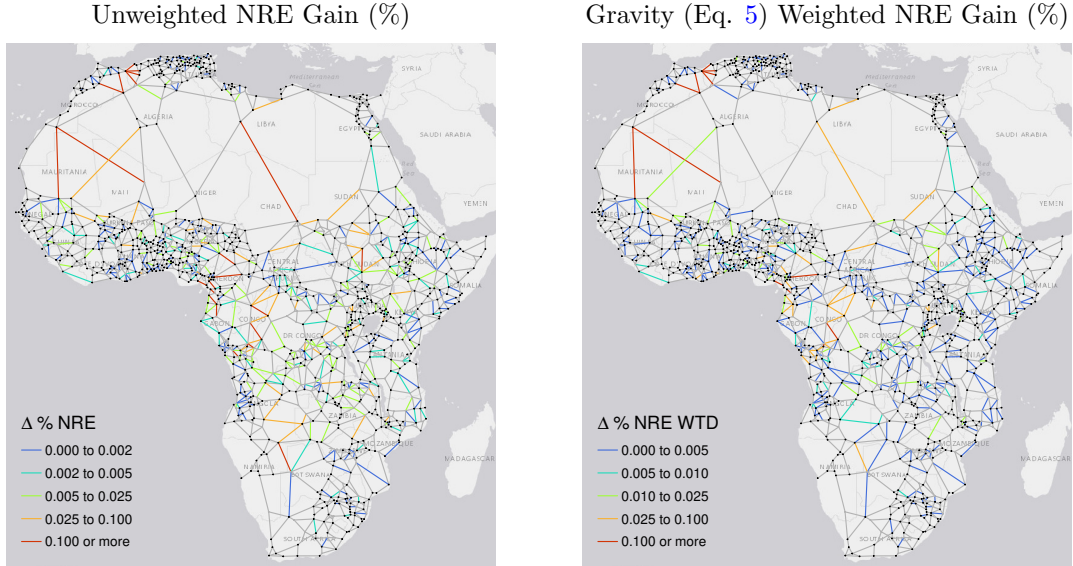
Notes: Figure shows (weighted) average route efficiency (RE) gains across all trips from building a specific link/edge.

I also examine MA gains from the proposed links by computing the GDP per capita of each city as the inverse-distance weighted average of observations within 30km using data from Kummu et al. (2018) and multiplying it by city (agglomeration) population. I then calculate MA for all cities using the network and Eq. 4, and sum them to measure total MA. Setting $\theta = 1$, the total MA implied by this transport network is 1.42 billion USD/m in 2015 PPP terms, short \$1.42B/m, or around \$1M/m in the average node. With high trade elasticity ($\theta = 3.8$), total MA is below \$1/$m^{3.8}$. The MA gain from adding all proposed links is 5.5% if $\theta = 1$ and 1.9% if $\theta = 3.8$.

The MA gains from adding individual links, reported in Figure 14, are similar to the route efficiency gains if $\theta = 1$. With high trade elasticity ($\theta = 3.8$), only links near agglomerations yield high returns. For the remainder of this section, I set $\theta = 1$ to limit the complexity of exposition and facilitate interpretation of results. There are also substantive reasons for adopting this value.[21]

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[21]Using the Bayesian Information Criterion (BIC), Peng & Chen (2021) show that $\theta < 3$ yields decent models predicting various outcomes (incl. built-up and nightlights) by the log of MA, choosing $\theta = 1$ as their preferred value. This value is also more consistent with the evidence on inter-city migration (Poot et al., 2016; Zipf, 1946). Once considering road upgrades in Section 5.5, I find that MA gains under $\theta = 3.8$ are significantly higher than under $\theta = 1$ because upgrades also increase travel speeds at short distances in populated areas. In contrast, new

Figure 14: Percentage Gain in Market Access (GDP) from Constructing Each Proposed Link

$\theta = 1$ (Peng & Chen, 2021) $\theta = 3.8$ (Jedwab & Storeygard, 2022)
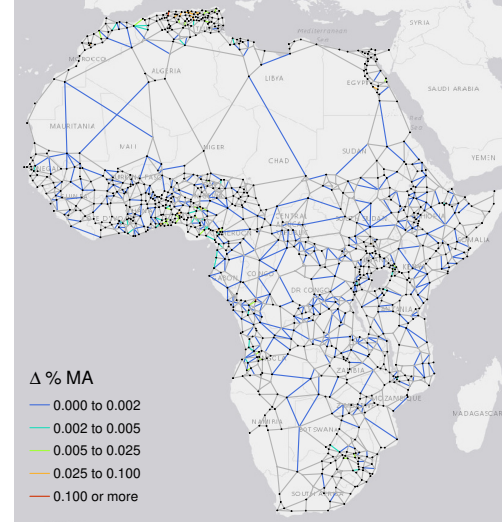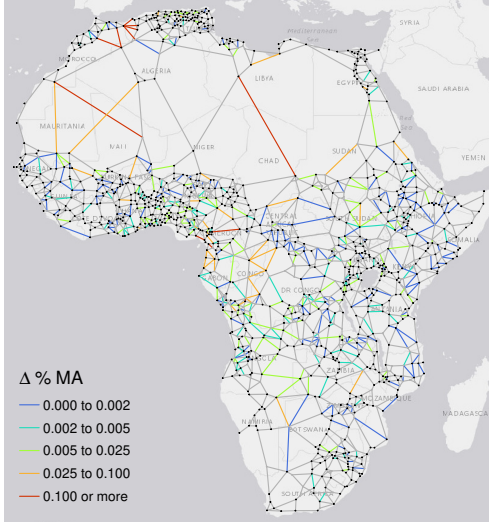
Notes: Figure shows total road-distance denominated MA gains measured (summed) across all trips from building a link.

To investigate how the presently high trade costs between borders may impact returns to link building, I add the respective export/import documentary and border compliance costs of the start and end country to each route—divided by 1.6 to turn them into kilometers following Table 4—and also add a transit cost of $(48h \times 4\$)/1.6 = 120$km for routes spanning any third country. Consequently, the total MA implied by the network decreases from \$1.42B/m to \$1.08B/m, and the total gain from building all proposed links reduces to 3.9%, versus 5.5% without frictions. Thus, border frictions reduce the aggregate returns to building new roads. They also imply relatively greater gains from building domestic links. The LHS of Figure 15 shows MA gains under frictions, and the RHS the ratio of the gains with frictions to the frictionless gains (LHS of Figure 14).

Figure 15: Percentage Gains in Market Access (GDP) under Border Frictions

%-Gain in MA from Each Link   Ratio of Gains to Frictionless Network
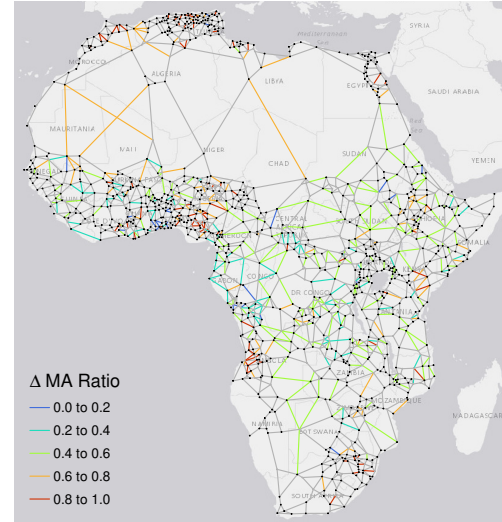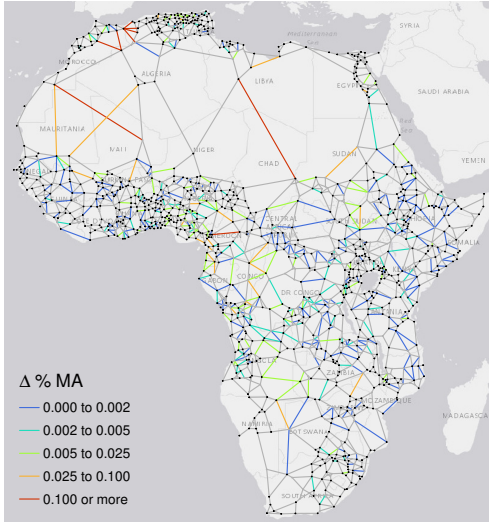
Notes: Figure shows absolute and relative distance-denominated MA gains from building a link under trip-level frictions.

Ostensibly, frictions always reduce the gains from building links but mainly affect transnational links and links in remote areas (which are also more likely to cater to transnational traffic). New national links in populated areas (in red) yield almost the same MA gains compared to a

links primarily improve connectivity through remote regions. Since total MA gains from road upgrades are much larger vis-a-vis new roads, setting $\theta = 1$ yields a lower bound on total MA gains from road network improvements.

frictionless environment. The median ratio is 0.52, implying a 48% lower return on the median link. Nevertheless, the LHS of Figure 15 suggests that certain trans-national links, especially additional trans-Saharan connections, bring the greatest MA gains even under high frictions. Thus border frictions considerably reduce the value of trans-national links and links in remote areas but do not appear capable of dramatically altering the overall distribution of returns.

However, this conclusion is tentative as it only measures border frictions at the origin and destination country border (+ lump-sum 24h transit frictions), giving traders no incentive to deviate from the frictionless route. In reality, traveling through many countries may be significantly more costly, and traders are reasonably assumed to optimize their route. To approximate this case, I ignore transit costs and add each border's average export and import cost (in km) to the respective border-crossing link. This parameterization thus conflates exporting, importing, and transit but introduces cumulative frictions prompting traders to avoid expensive borders.

Computing all shortest paths along this network has a substantial impact on trade costs. Whereas under the previous assumption routes are on average 32% more expensive than in a frictionless scenario, building these costs into the network makes them 117% more expensive, despite optimizing behavior. Total MA is reduced to $0.91B/m$, versus $1.08B/m$ under the simple transit scenario. Yet, building all proposed links in this network still increases total MA by 4%.

Figure 16 visualizes the corresponding MA gains from building each link and the ratio of MA gains to frictionless gains. Similar to Figure 15, under frictions, most gains are lower, especially from border-crossing links. The median ratio is 0.43, implying a 57% reduction in value. The RHS of Figure 16 shows that, with optimizing agents, the ratio of MA gains to the frictionless network is not bounded above by 1. Some links, colored in dark orange/red, yield greater MA gains with border frictions than without. Thus, if traders are optimizing, border frictions not only reduce average gains but also complicate the evaluation of road network investments.

Figure 16: Gains in Market Access (GDP) with Optimizing Agents
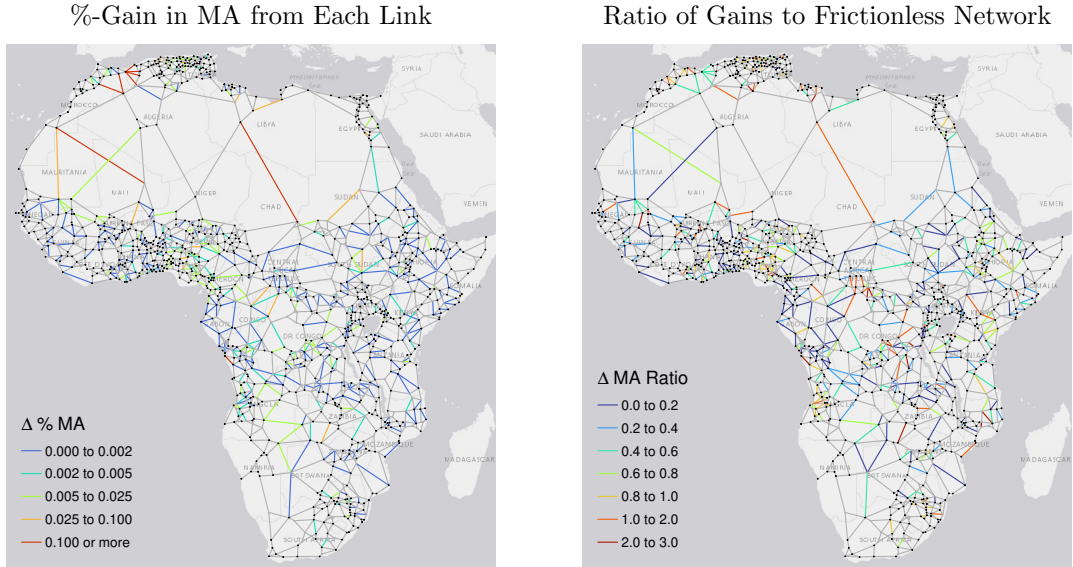
%-Gain in MA from Each Link   Ratio of Gains to Frictionless Network

Notes: Figure shows absolute and relative distance-denominated MA gains from building a link under link-level frictions.

5.2 Road Building Costs

A central consideration for any infrastructure project is its cost-benefit ratio. In this subsection, I thus factor in heterogeneous link-building costs. The most well-known empirical work on road construction costs in developing countries is Collier et al. (2016), who analyze unit costs from 3,322 activities across 99 countries obtained from the World Bank's Road Costs Knowledge System (ROCKS) database. They find that the cost of an asphalt overlay of 40-59mm can vary by a factor of 3-4 between countries. Regressing this cost on various geographic and non-geographic factors,

they find that terrain ruggedness and population density increase unit costs, whereas long roads (>50km) decrease it. Furthermore, conflict, corruption, the business environment, and the origin of construction firms affects unit costs. ROCKS version 2.3 used by Collier et al. (2016) runs up to 2008. In 2018, the World Bank's transport unit released an update including only projects with complete information (Bosio et al., 2018). Unfortunately, most projects in this database are road upgrades, but a few new road projects are included as well and summarized in Table 5.

Table 5:   Road Building Costs: Road Costs Knowledge System (ROCKS) - 2018 Update

Work Type	N	Length (km)	Cost (M\$'15)	Cost/km
Continental Africa				
New 1L Road	1	99.0	21.15	0.214
New 2L Highway	4	122.0	59.53	0.611
All Low and Lower-Middle Income Countries				
New 1L Road	6	59.5	7.65	0.135
New 2L Highway	6	84.5	44.09	0.611
New 4L Expressway	1	84.8	328.08	3.869
All Countries				
New 2L Highway	7	50.0	43.03	0.682
New 4L Expressway	24	74.9	213.01	5.152

Notes: Statistics are aggregated across projects using the median. Costs are in millions of 2015 USD. The raw costs in current USD were deflated at their project end date using the US GDP deflator with base year 2015.

According to the final column of Table 5, which provides median costs per km in millions of constant 2015 USD, the median new African road in the 2-lane highway category (implying one lane in each direction) costs \$611K/km. This estimate, though derived from only four projects, is consistent with other estimates: a 2014 report by the African Development Bank (African Development Bank, 2014) analyzes 172 Projects contracted between 2000 and 2008 and reports a median cost of 227,800 2006 USD per lane-km. This figure includes road upgrades. Multiplying by 2 for a 2-lane highway and inflating by 16% to 2015 USD yields 528,800 USD per lane-km.

Following Collier et al. (2016), I allow for heterogeneity in road construction costs. Since it is difficult to measure (ever-changing) political conditions across the continent, I follow Fajgelbaum & Schaal (2020) and Graff (2024) and only consider average returns to ruggedness and distance, as well as population. My preferred specification is

$$\ln\left(\frac{\text{cost}}{km}\right) = \ln(120{,}000) - 0.11 \times (\text{dist} > 50km) + 0.12 \times \ln(\text{rugg}) + 0.085 \times \ln\left(\frac{\text{pop}}{km^2} + 1\right). \quad (6)$$

The first part is taken from Eq. (21) of Fajgelbaum & Schaal (2020). The 120,000 USD/km constant makes the mean cost/km across all existing links approximately equal to \$611K/km. The population coefficient is averaged across Tables 4 and 5 of Collier et al. (2016), following Fajgelbaum & Schaal (2020), which obtain the other coefficient in this way. The tables suggest that Collier et al. (2016) regressed the log of cost on the population density (in 100 people/km^2), but applying the coefficient to the levels density yields peak construction costs above \$10M/km near large cities, which I regard as unrealistic. Thus, I use the natural log of the population density and add 1 to avoid negative values in remote regions. This effectively reduces the relevance of this term and remains close to Fajgelbaum & Schaal (2020). I extract ruggedness from the original 30 arc-second layer by Nunn & Puga (2012) within a 3km buffer around existing and proposed links, and do the same for population from the WorldPop 2020 population layer at 1km resolution.[22] Figure 17 shows ruggedness and population density thus estimated for each link.

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[22]It is possible to track the terrain around existing roads more closely, but being more realistic with existing links complicates comparison with potential new links. Thus, I opt for a simpler approach of considering terrain within a broad 3km buffer in the direction of travel for both existing and potential new links.

Figure 17:   Ruggedness and Population Density within 3km Buffer around Links

Ruggedness (Nunn & Puga, 2012)   Population Density (WorldPop 2020)
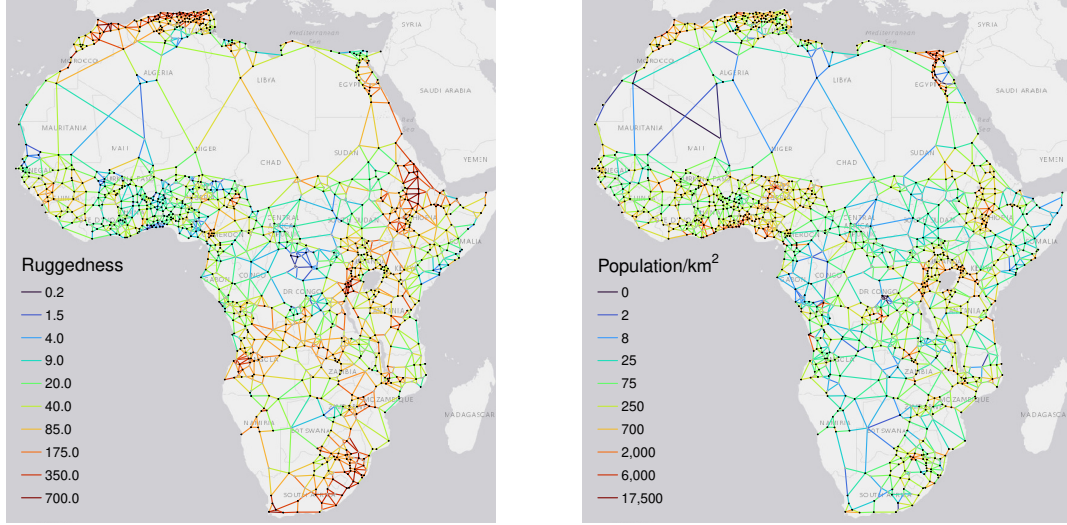
Notes: Figure shows average ruggedness and total population within a 3km (two-sided) buffer around (straight) links.

Appendix Figure A9 shows the corresponding cost estimates from applying Eq. 6.[23] I divide the cost of building Algeria-Morocco links by 3 as these are, to a large extent, already constructed. The distribution of costs is roughly consistent with African Development Bank (2014), whose 1st and 3rd quartile estimates, appropriately converted, are 386,000 and 987,500 USD'15/km. Reconstructing the total existing network comprising 315K km of roads is estimated to cost $186B USD'15, and the proposed extension of 104K km costs $56B. Figure A9 suggests that roads in unpopulated and relatively flat areas such as Congo and the Sahara are cheapest. This may be erroneous since both exhibit rather extreme weather conditions and human security risks. Collier et al. (2016) unfortunately don't consider temperature, humidity, and landcover variables. More research is thus needed to refine estimates of road construction costs in developing countries.

5.3   Cost-Benefit Analysis: Building New Links

Comparing the proposed extensions at cost of $56B to the total MA gain of 5.5% of $1.42B/m, amounting to $77.6M/m or $77.6B/km, yields a MA return of $1.4/km per USD invested—in short, $1.4/km/$. If border frictions are added, the MA gain from the network extensions is only 3.9% or $41B/km, implying a return of $0.76/km/$. If frictions are built into the network and agents optimize, the MA gain is 4% or $36.4B/km, implying a return of $0.65/km/$. Either way, current frictions reduce the gains from the proposed investment package by around 50%.
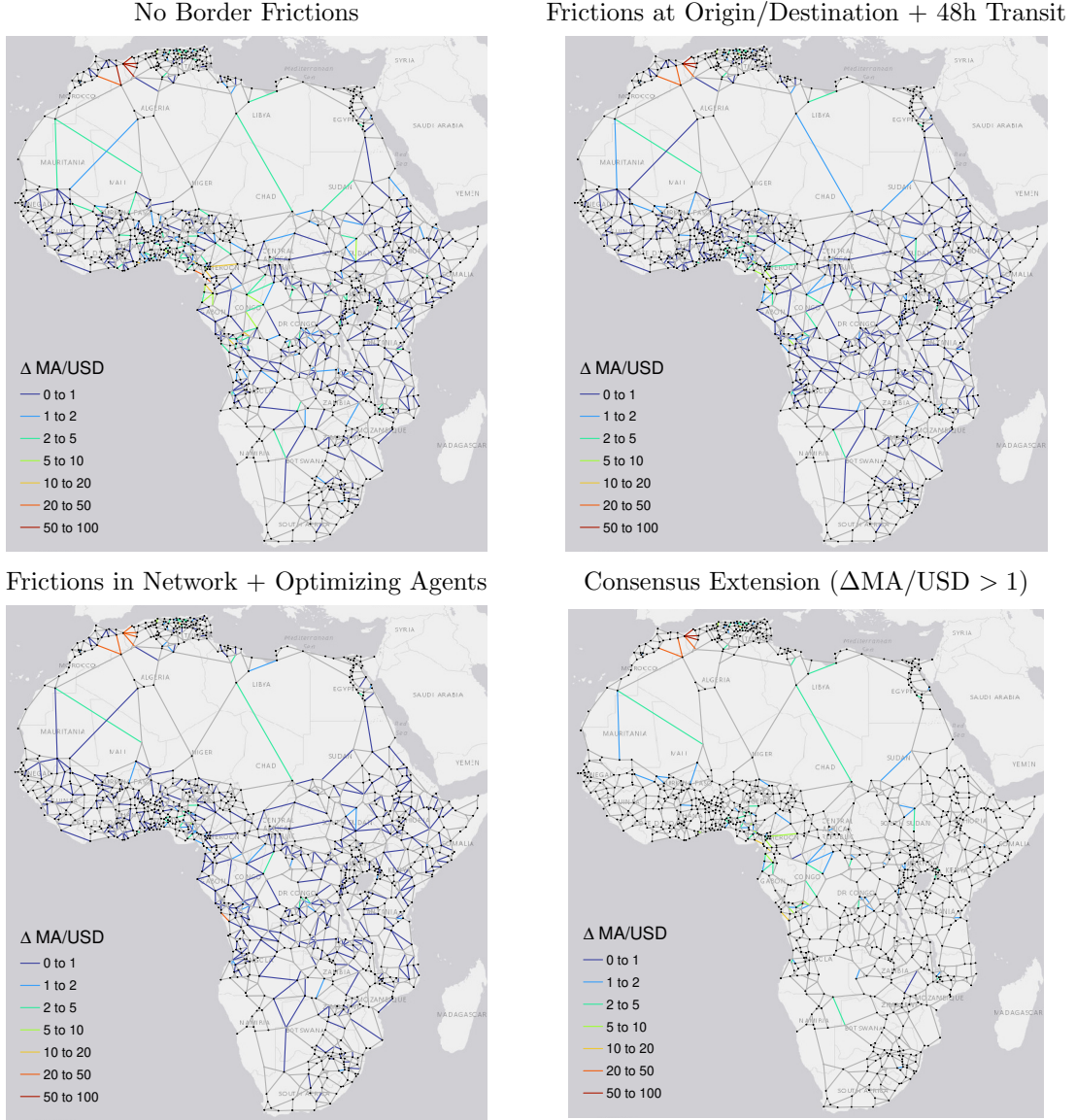
Since the total MA gains are below $1/km/$ under frictions, a limited investment package focusing on critical links is more sensible. Figure 18 shows the gain in $/km/$ of different links under the three assumptions about border frictions, and a consensus extension including only links above $1/km/$ in the frictionless case and at least one of the two scenarios with frictions.

Figure 18 indicates that, even without frictions, 66.5% of the proposed links yield a MA return of <$1/km/$, and only 19.5% of links yield MA returns >$2/km/$. Some links, especially in West Africa (Cameroon) and Congo (Kinshasa), yield up to $20/km/$ returns. Reopening the Morocco-Algeria border would yield even higher returns on any border-crossing link. The consensus extension combining at least break-even links in MA terms includes 105 links (21.8% of the proposed 481). This package's estimated cost is $12.1B. In the frictionless scenario, it yields a 4% MA gain amounting to $57.5B/km, implying a return of $4.75/km/$.[24] Excluding the 6 links bridging the Morocco-Algeria border still yields a 2.9% MA gain of $41.8B/km or $3.45/km/$. Under the most restrictive cumulative frictions scenario, the MA gain (excl. Morocco-Algeria links) drops to $22B/km (2.4%) or $1.82/km/$. Thus, this package, which includes 4 additional trans-Saharan links, is only sensible if MA gains generate high economic gains (more in Section 5.8).

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[23] Figure A12 provides the same information, including upgrading costs. Thus Figure A9 is in the Appendix.
[24] These returns are based on recalculating shortest paths and MA after adding all 105 links.

Figure 18: Cost-Benefit Analysis (USD/km MA Gain per USD Invested)

No Border Frictions   Frictions at Origin/Destination + 48h Transit

Frictions in Network + Optimizing Agents   Consensus Extension (ΔMA/USD > 1)

Notes: Figure shows MA returns in USD/km per USD invested in link building under different types of border frictions.

5.4 Upgrading of Existing Links

Since constructing new roads is expensive and the quality of African roads is low in many regions, upgrading the existing network is another vital policy option. While routing engines cannot perfectly consider road quality, OSM has an elaborate tagging system to indicate the surface and smoothness of roads, which is taken into account in OSRM routing and travel time estimates. Figure 19 shows the average travel speed in km/h along each link, indicating sizeable heterogeneity. The distribution of travel speeds is trimodal, with slow links around 40km/h, medium links around 65 km/h, and fast links around 85km/h. The three fastest links at travel speeds around 120km/h are in Libya, which satellite imagery reveals are newly asphalted straight roads through flat desert. The slowest link at a travel speed of 5km/h is in Gabon and connects the coastal cities of Libreville and Port-Gentil via a ferry (in absence of a viable road). Apart from these extremes, most links in populated areas have travel speeds ≥60 km/h. Slower links with travel speeds <60km/h, or even <40 km/h, are prevalent in central Africa (Congo, Central African Republic, Chad, (South-)Sudan) and around the Horn of Africa (Northern Kenya, Somalia, South-Sudan, peripheral Ethiopia). The three trans-Saharan links connecting Algeria and Libya to Mali and Niger also have average travel speeds around 50km/h. Thus, Figure 19 (and Appendix Figure A1) suggests that mainly roads connecting the different populated macro-regions in Africa need upgrading.

Figure 19: Average Link Speeds in Africa's Transport Network
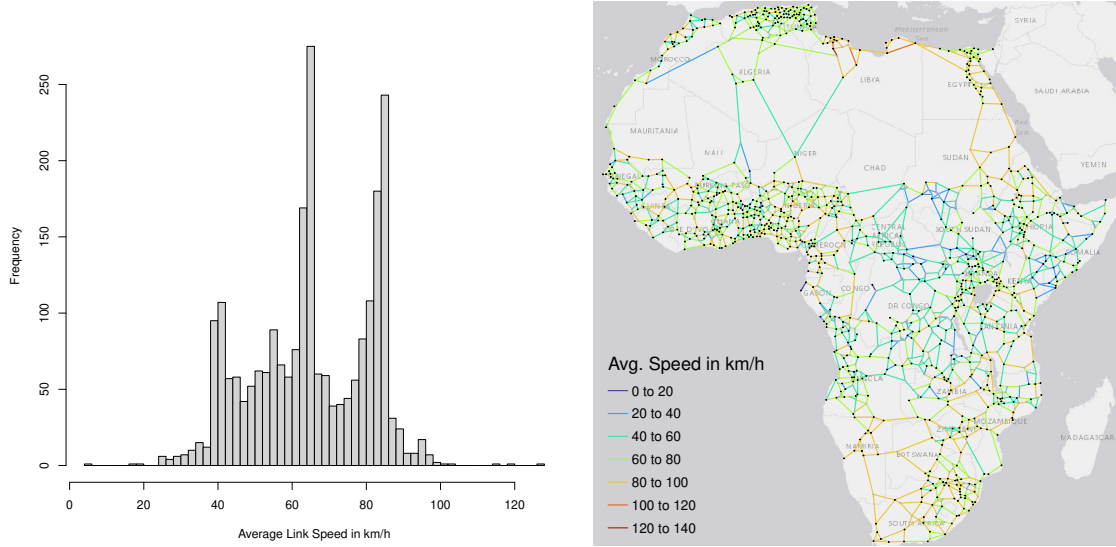
Notes: Figure shows average link speeds calculated at the link-level using the ORSM R API (accessed June 2024).

The MA measure implied by the current network speed is \$1.75T/min. Letting all links have a speed of ≥100km/h yields a MA of \$2.48T/m, a 42.1% increase.[25] This is dramatically higher than the 5.5% gain from adding all proposed links (disregarding speed). To determine whether this discrepancy is an artefact of the way of denominating MA, I also compute MA gains from the proposed links, assuming average speeds of either 100km/h or 65km/h, the median link speed in the existing network. Adding all new links at 65km/h yields a 5.7% MA gain - comparable to the 5.5% measured earlier - whereas assuming a speed of 100km/h yields a 14.1% increase. This highlights the importance of road quality considerations. Since new roads are typically high quality, the 100km/h assumption and associated 14.1% MA gain without border frictions may be more realistic. In total, eliminating all frictions, upgrading all existing links to ≥100km/h, and adding the proposed links at 100km/h, would increase MA to \$2.62T/min, a 50% improvement. This affirms that the largest gains (42%) can be reaped from improving existing roads. Gains from new roads are higher without improvements to existing roads due to optimizing behavior.

All of these scenarios can be simulated on a link-by-link basis. Figure 20 reports three scenarios that are policy relevant: upgrading existing links to ≥100km/h, building new links at 100km/h with the existing network unchanged, and building new links at 100km/h on an upgraded network. The final panel shows a ratio indicating the relative MA gains under the latter two scenarios.

Panel A signifies that improving major north-south/east-west roads and roads in metropolitan areas yields significant MA gains. Panels B and C are congruent to previous results that new high-speed north-south/east-west roads are most impactful, with lower average gains under the upgraded network. Panel D signifies that, whereas most links yield smaller returns under an upgraded network (ratio < 1), some links, including re-opening the Morocco-Algeria border and the two proposed north-west south-east oriented trans-Saharan connections, yield higher returns if the existing network is fully upgraded. Notably, these are also particularly high-value links from a pure route efficiency standpoint and included in the consensus extension of Figure 18.

Another major area of necessary improvement is border frictions. Applying current frictions, i.e., dividing border time by 4 and documentary time by 10 (Table 4) and adding a 48h transit through 3rd countries, yields a MA of \$982B/min, which is only 56.1% of the \$1.75T/min without frictions. When improving all links to a speed of ≥100km/h, total MA increases to \$1.24T/min, which is 50% of the \$2.48T/min without frictions and only 27% more than the \$982B/min under the current network, compared to a 42% increase without frictions. Figure 21 reports link-level gains and a comparison to frictionless gains (Panel A of Figure 20). The results are unequivocal: border frictions particularly diminish MA gains from upgrading remote and transnational links.
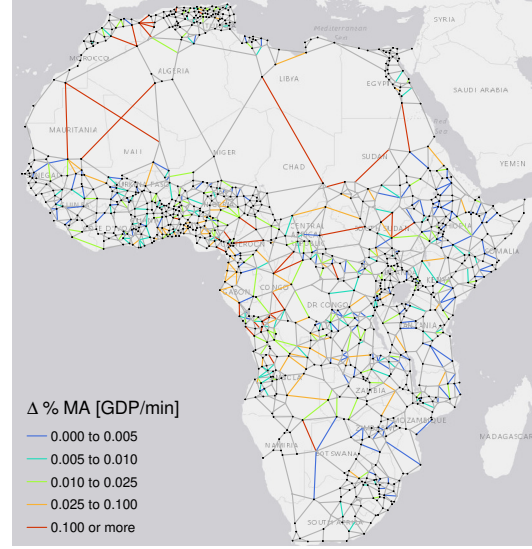
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[25]The Histogram in Figure 19 suggests 100km/h as a natural efficiency target for transport roads. This target is also sensible as different maximum speed regulations may exist beyond it.

Figure 20: MA Gains (GDP/min) from Upgrading Links and Adding High-Speed Links
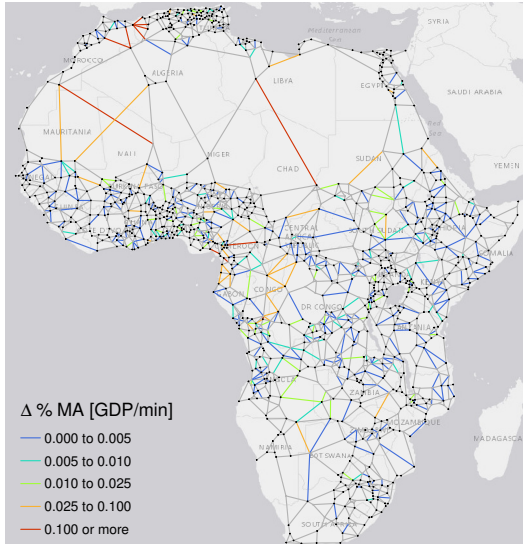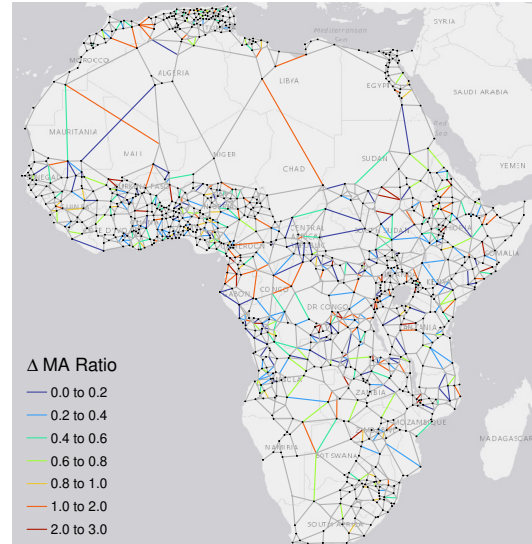

(A) Upgrading Link to Speed ≥ 100km/h
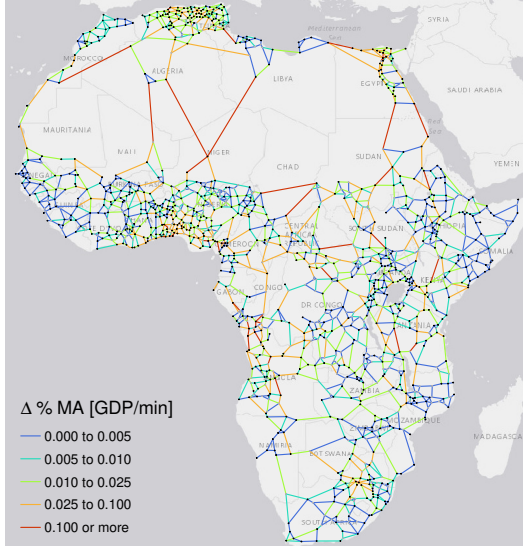
(B) Adding High-Speed (100km/h) Link

(C) Adding Links to Upgraded Network

(D) Ratio: C / B

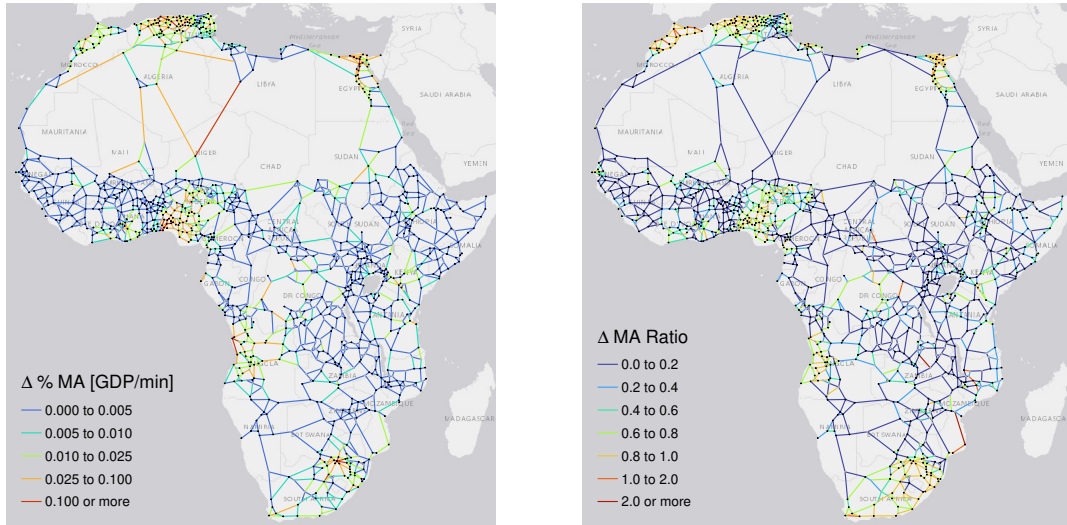*Notes:* Figure shows total MA gains from upgrading a link and building a new link before/after upgrading all links.

The exercise is again repeated by incorporating average export/import frictions into border-crossing links. This reduces MA to $820B/min, or 47% of the frictionless value. With all links upgraded to 100km/h, the MA is $1.04T/min, only 42% of the MA gain without frictions, but still 27.3% more MA than without road improvements. These numbers reflect an average 6x travel time increase under frictions, which rises to 8.6x with an upgraded 100km/h network. Figure 22 shows gains under the cumulative frictions case. The effects are similar and stronger than in Figure 21. Because of the optimizing behavior away from expensive links, the RHS of Figure 22 again includes a few links whose upgrading under frictions yields greater MA gains than without frictions.

Figure 21:   Percentage Gains in Market Access (GDP/min) under Border Frictions

%-Gain in MA from Improving Link   Ratio of Gains to Frictionless Network
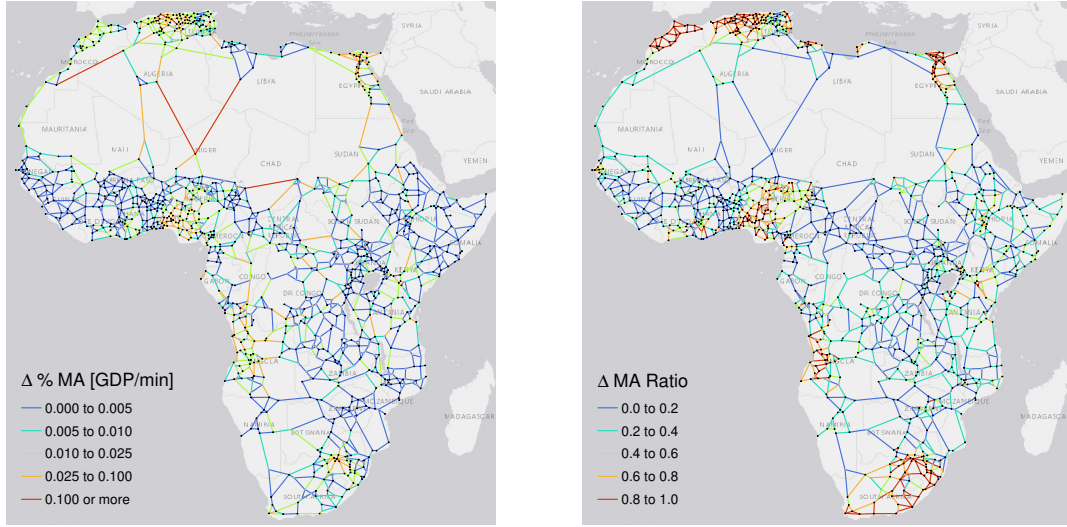
Notes: Figure shows absolute and relative MA gains from upgrading a link under trip-level frictions.

Figure 22:   Gains in MA (GDP/min) under Border Frictions with Optimizing Agents

%-Gain in MA from Improving Link   Ratio of Gains to Frictionless Network

Notes: Figure shows absolute and relative MA gains from upgrading a link under link-level frictions.

5.5   Road Upgrading Costs

For cost-benefit analysis, I also estimate the cost of upgrading roads. The ROCKS database distinguishes several types of road improvements. Table 6 summarizes the four most common ones: 'Upgrading', 'Reconstruction', 'Asphalt Mix Resurfacing', and 'Strengthening'. To obtain a summary statistics for the cost of upgrading, I compute a weighted average of the median costs/km across types, using the number of works (N) times the median length of the work in km as weights. This yields an average upgrade cost estimate of \$326M/km. Thus, upgrades are, on average, only about half as costly as new highways priced at \$611M/km (see Table 5). However, road upgrades in Africa are ∼ 60% more costly than the low- and lower-middle income country average of \$205M.

Table 6: Road Upgrading Costs: Road Costs Knowledge System (ROCKS) - 2018 Update

Work Type	N	Length (km)	Weight	Cost (M$'15)	Cost/km
Continental Africa					
Upgrading	28	103.5	2898	49.73	0.513
Reconstruction	27	33.0	891	20.20	0.116
Asphalt Mix Resurfacing	14	133.8	1874	16.93	0.143
Strengthening	11	110.0	1210	42.97	0.316
Weighted Average		104.0		35.77	0.326
All Low and Lower-Middle Income Countries					
Upgrading	68	61.8	4199	20.63	0.320
Reconstruction	53	73.0	3869	20.20	0.162
Asphalt Mix Resurfacing	35	143.9	5036	15.50	0.090
Strengthening	26	92.0	2392	20.89	0.316
Weighted Average		95.9		18.90	0.205

Notes: Statistics are aggregated across projects using the median. The 'Weight' column is the number of projects (N) times the median length (Length). This is used to compute a weighted average across different work types. Costs are in millions of 2015 USD. The raw costs in current USD were deflated at their project end date using the US GDP deflator with base year 2015.

These estimates are consistent with African Development Bank (2014), who report an average cost of 180,300 USD'06/lane-km for a category called 'Rehabilitation,' yielding 418,500 USD'15/km for 2-lane highways. Their 1st and 3rd quartile estimates translate to 254,900 and 673,100 USD'15/km, respectively. As mentioned earlier, African Development Bank (2014) lump together 'Upgrading' with new construction at a median price of 528,800 USD'15/km. Their estimate is thus between the 'Upgrading' estimate of $513K in Table 6 and new construction at $611K from Table 5.

Upgrading a link to allow speeds of 100km/h should require different types of road work depending on the existing condition of the road. It is unrealistic to assume that this is a continuous function of the distance of travel speed from 100km/h. For example, two roads with travel speeds of 85 and 90km/h likely both require a full asphalt resurfacing to bring them to 100km/h. Since the distribution of speeds in Figure 19 is trimodal, I propose the following three categories: (1) roads with a travel speed below 60km/h require a full 'Upgrade' at an average cost of $513K/km; (2) roads with travel speeds of 60-79km/h may require mixed works at an average cost of $326K/km; (3) roads with travel speeds of 80km/h and higher require an 'Asphalt Mix Resurfacing' at $143K/km on average. To introduce heterogeneity in these cost estimates, I use Eq. 6 and modify the intercept such that the median (across all routes, regardless of their upgrade type) is close to the respective category medians: For category (1), the intercept is ln(101,600), for category (2) it is ln(64,600), and for category (3), it is ln(28,400). In addition, I clip estimates at the 2.5th and 97.5th percentile to guard against outliers, such that, e.g., 'Asphalt Mix Resurfacing' costs remain between $94K/km and $206K/km. Figure 23 reports the classification and estimated unit costs.

The entire central-African network and trans-Saharan connections via Mali and Niger, as well as most of the network around the horn of Africa, is classified as requiring a full upgrade, at costs around $400K/km due to mostly flat terrain and small population density. The total cost of upgrading the entire 315K km transport network is thus estimated at $106B (in 2015 USD), comprising $57.8B full road upgrades, $35.6B mixed works, and $12.3B mixed asphalt resurfacing.

5.6 Cost-Benefit Analysis: Road Upgrading

Comparing this cost to the total MA gain of 42% or $701B/min implies a return of $6.6/min/$. With border frictions, the MA gain is reduced to 27% or between 214 and 253 billion USD/min in the two scenarios, implying a 2/2.4 $/min/$ return in the cumulative/simple frictions scenarios, respectively. Thus, road upgrades yield significantly higher average returns than fresh construction.

It remains to gauge the returns to upgrading individual links. Figure A11 shows estimates following the same schema as Figure 18, signifying that upgrading links in populated areas and critical trans-continental connections yields significant returns. The consensus package again

Figure 23: Estimated Network Upgrading Cost per Kilometer
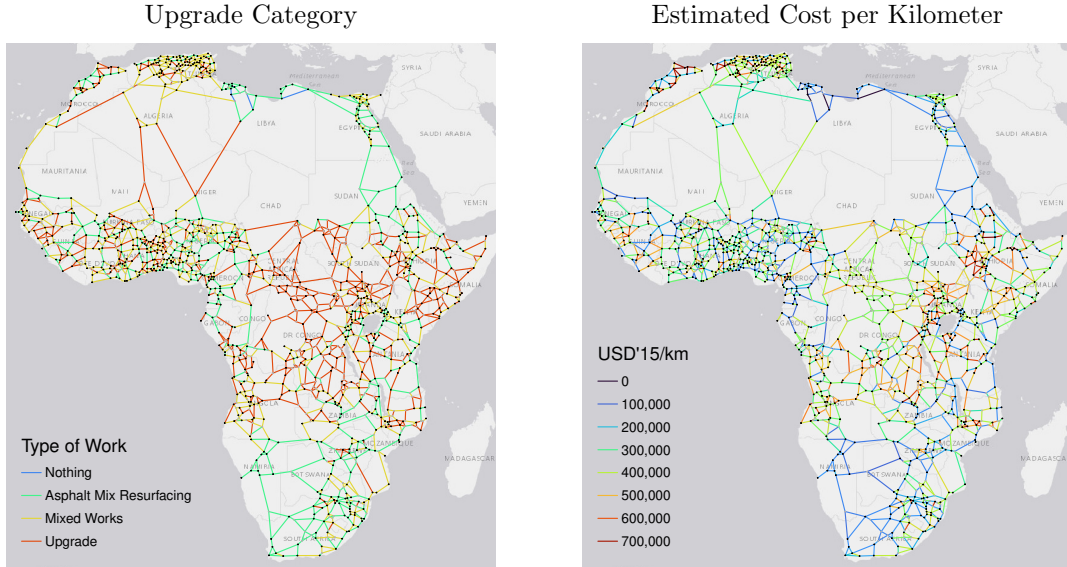
Notes: Figure shows stipulated work required to upgrade a link to speed ≥100km/h (LHS) and estimated cost/km (RHS).

includes links where the MA return in $/min/$ is grater than 1 in the frictionless case and at least one of the scenarios with frictions. It suggests prioritizing upgrading roads near urban centers and important trans-continental links. The package comprises 1255 links, 53.5% of all links, and costs $45B. It yields a frictionless 33.1% MA gain of $552B/min or 12.3$/min/$.

5.7   Cost-Benefit Analysis: Joint Scenarios

Combining road construction and upgrading costs (see Figure A12), I also perform cost-benefit analysis for joint scenarios where building new links and upgrading existing ones are part of the choice set. Due to the different intercepts in Eq. 6, the cost of building a new link is always greater than upgrading an existing one *ceteris paribus*.

All proposed road works combined cost 161 billion USD'15 (around 200 billion in current USD). They yield a frictionless MA gain of 50%, amounting to $831B/min or $5.2/min/$. The more restrictive cumulative frictions case yields a 31% MA gain, amounting to $241B/min or $1.5/min/$. Figure A13 provides the full link-level analysis, including three consensus packages with MA gains above 1, 2 and 4 $/min/$, at costs of 60.9, 36.6, and 17 billion USD'15, respectively:

- The > $1 package comprises upgrading 54% of links and building 30% of proposed links. It yields a 38% MA gain of $636B/min or $10.4/min/$ without frictions and 26.8% | $251B/min | $4.1/min/$ or 28% | $221B/min | $3.6/min/$ under simple or cumulative frictions.

- The > $2 package comprises upgrading 37% of links and building 18% of proposed links. It yields a 30.6% MA gain of $511B/min or $14/min/$ without frictions and 24%/ | $225B/min | $6.1/min/$ or 25.7% | $201.5B/min | $5.5/min$ under simple or cumulative frictions.

- The > $4 package comprises upgrading 22.4% of links and building 8.9% of proposed links. It yields a 20% MA gain of $340B/min or $20/min/$ without frictions and 19.5% | $182B/min | $10.7/min/$ or 21.3% | $167B/min | $9.8/min/$ under simple or cumulative frictions.

The first two packages are prone to generate a much greater developmental impact than the high-yield package, which primarily addresses low connectivity in the already large markets.

5.8   Macroeconomic Cost-Benefit Analysis

A critical question neglected so far is whether these investments are macroeconomically feasible. How do MA gains translate into medium-term economic gains, and are these gains large enough to justify such expenses, potentially even on a debt-financing basis?

The medium-term economic returns to increased MA are very difficult to estimate, especially on such a large scale. The only large-scale analysis I am aware of is Donaldson & Hornbeck (2016). The authors regress changes on the log of land values across 2,327 US counties between 1870 and 1890 on changes in the log of MA, and find an elasticity of 0.5, which is quite robust to different choices of θ. This suggests that in the medium run MA translates into economic activity at a ratio of 2:1. However, present-day Africa may be very different from the historical US.

I thus also run some regression similar to Donaldson & Hornbeck (2016), examining the effect of log(MA) on GDP per capita (Kummu et al., 2018) and the International Wealth Index (Lee & Braithwaite, 2022) using the dataset of 1379 nodes/cities. I control for country fixed effects and also for the log of port outflows in 2020Q1, adding one so that the log is zero in non-port cities. Since MA is endogenous to GDP, I apply the network finding algorithm from Section 4.2 (with EU parameters but not checking against OSM) to generate a hypothetical network with 2869 edges, shown in Appendix Figure A14, and use the MA measure based on this network as an instrument for MA. Table 7 reports the results for MA denominated in both road distance and travel time.

Table 7: Returns to Market Access in Africa ($N = 1379$ Nodes)

Dependent Variable:	log(GDP/Capita)		IWI		log(IWI)	
Estimator:	OLS	IV	OLS	IV	OLS	IV
Variables						
log(MA): Distance	0.3221**	0.3250**	10.44***	10.53***	0.3450***	0.3445***
	(0.1432)	(0.1451)	(2.258)	(2.425)	(0.0918)	(0.0934)
log(Outflows + 1)	0.0103**	0.0103**	1.390***	1.390***	0.0370***	0.0370***
	(0.0042)	(0.0042)	(0.1451)	(0.1456)	(0.0048)	(0.0048)
Fit statistics						
R^2	0.9709	0.9709	0.8079	0.8079	0.7602	0.7602
Within R^2	0.1399	0.1399	0.2465	0.2465	0.1676	0.1676
Wu-Hausman, p-value		0.5409		0.6842		0.9508
Wald (1st stage), p-value, log(MA)		< 0.01		< 0.01		< 0.01
Variables						
log(MA): Travel Time	0.3216**	0.3147**	11.33***	10.01***	0.3891***	0.3277***
	(0.1278)	(0.1379)	(2.044)	(2.177)	(0.0856)	(0.0835)
log(Outflows + 1)	0.0100**	0.0100**	1.383***	1.378***	0.0369***	0.0366***
	(0.0041)	(0.0041)	(0.1427)	(0.1421)	(0.0047)	(0.0046)
Fit statistics						
R^2	0.9714	0.9714	0.8140	0.8137	0.7684	0.7678
Within R^2	0.1541	0.1540	0.2703	0.2691	0.1962	0.1940
Wu-Hausman, p-value		0.3023		< 0.01		< 0.01
Wald (1st stage), p-value, log(MA)		< 0.01		< 0.01		< 0.01
Fixed-effects						
iso3c (49)	Yes	Yes	Yes	Yes	Yes	Yes

Clustered (iso3c) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

The coefficients in both MA denominations suggest that in Africa MA translates to GDP/Capita or household wealth with an elasticity of ~0.33, which is slightly lower than in the US. Using the IWI in level suggests that a doubling of MA raises the IWI [0, 100] by 10 points—a sizeable return.

The failure of the Wu-Hausman test of endogeneity in most cases indicates that the instrument is too strong and possibly itself endogenous. Since the network was constructed by intersecting routes between 453 (port-)cities, $1379 - 453 = 926$ nodes/cities were found by intersecting the optimal routes between these cities, and thus already reflect the existing road network.

However, repeating the exercise using just the original 453 (port-)cities and a hypothetical network between them gives the same gdp elasticity (around 0.3), with Wu-Hausman p-values all greater than 0.1, and partly insignificant IWI elasticities around 0.15-0.3. Thus, the cross-sectional IV approach using a hypothetical network in any case does not add much to the exercise.

The results are still useful in suggesting that in Africa the returns to MA may be up to 50% lower than in the US following Donaldson & Hornbeck (2016). A reason for this may be the prevalence of other market inefficiencies, often of a regulatory nature (Herrera Dappe et al., 2024). A prudent assumption is that in Africa MA gains translates into economic activity at a ratio of 4:1.

In the following, instead of computing exact returns, I determine the returns needed in order to break even. This will take the form of a reverse macroeconomic present discounted value (PDV) calculation. African GDP in 2022 was 2.81 trillion 2015 USD. The median growth rate in 2000-2022 was 4.1%. If we are pessimistic, let it be 3% going forward. I discount the future by 10%. This is a reasonable rate given that stock market returns are generally below this—the MSCI World has a long-term return rate of 8-9%. Emerging market bonds yield even lower returns, around 6%, according to the EMBI index by JP Morgan. So at the macroeconomic scale, it is very difficult to invest with more than 10% returns. I also assume that the horizon of policymakers is 30 years and disregard benefits accruing after 30 years. With these assumptions, I calculate the change in the macroeconomic growth rate of Africa needed to break even in PDV terms for each of the three scenarios proposed above as well as the full/consensus construction and upgrade scenarios considered in Sections 5.4 and 5.7. Table 8 reports these calculations.

Table 8: Break Even Changes in the Macroeconomic Growth Rate for Different Investments

Work Package	Cost	%ΔMA	BEG (4.1%)	BEG (3%)
Full Extension (↑RE)	$56.1B	$3.9 - 5.5$	$0.31\% \rightarrow 4.113$	$0.50\% \rightarrow 3.015$
Consensus Extension (↑RE)	$12.1B	$2.4 - 4.0$	$0.07\% \rightarrow 4.103$	$0.11\% \rightarrow 3.003$
Full Upgrade (↑TE)	$105.7B	$27.0 - 42.1$	$0.58\% \rightarrow 4.124$	$0.94\% \rightarrow 3.028$
Consensus Upgrade (↑TE)	$45.0B	$21.2 - 33.1$	$0.25\% \rightarrow 4.110$	$0.40\% \rightarrow 3.012$
All Links > $1/min/$	$60.9B	$26.8 - 38.1$	$0.33\% \rightarrow 4.114$	$0.54\% \rightarrow 3.016$
All Links > $2/min/$	$36.6B	$24.0 - 30.6$	$0.20\% \rightarrow 4.108$	$0.32\% \rightarrow 3.010$
All Links > $4/min/$	$17.0B	$19.5 - 20.4$	$0.09\% \rightarrow 4.104$	$0.15\% \rightarrow 3.005$

Notes: Table shows the cost in 2015 USD PPP of different investment packages, their MA %-gain under the worst frictions and frictionless scenarios, and the change in Africa's macroeconomic growth rate needed to break even after 30 years under realistic (4.1%) and pessimistic (3%) baseline growth.

I illustrate their interpretation using the largest consensus package containing all links with >$1/min/$ marginal returns. It costs $60.9B and yields a MA gain between 26.8% (worst frictions scenario) and 38.1% (no frictions). Under the 4.1% baseline growth scenario, the growth rate needs to change by 0.33% to 4.114% to yield a return of $60.9B in PDV terms after 30 years. Comparing the 26.8% lower bound to 0.33% yields a ratio of 81:1. Thus, if changes in MA translate to changes in the growth rate at 81:1 or higher, the package is macroeconomically feasible.

This appears very plausible given the 0.5 elasticity of Donaldson & Hornbeck (2016) and the ~0.33 elasticity of Table 7 suggesting a ratio of 3:1 (prudent estimate is 4:1). However, many things can go wrong. First, growth could be slower at 3%, requiring a 0.54% increase in the growth rate or a return ratio above 50:1. Then, the package could end up being more expensive for various reasons related to terrain, weather, corruption or delays. Assuming it turns out twice as expensive, this would require a ratio above 25:1. Finally, if the investment is financed through debt, it could adversely affect both the total costs and the macroeconomic growth rate by limiting fiscal space and worsening credit ratings. Such forces could lower the required return ratio to as low as 10:1. Nevertheless, this is still above 4:1. Thus, overall, these back-of-the-envelope calculations suggest that large-scale *optimal* investments in Africa's road network are macroeconomically feasible.

6 Optimal Network Investments in General Equilibrium

Having simulated many scenarios in partial equilibrium by modifying one link at a time or jointly adding/improving a selection of (high marginal value) links and computing MA returns, this section goes a bold step further and considers welfare-maximizing network investments in general equilibrium (GE). In particular, using a quantitative framework established by Fajgelbaum & Schaal (2020), I optimize over the space of networks after setting an infrastructure budget. The framework accommodates trade in multiple goods and requires exogenous productivities for the production of each good in each location. Cities must have different productive endowments to create incentives for trade. For my application to the African network, this is a strong limitation, firstly because such city-level productivity data is unavailable, and secondly because global optimization with many goods traded on a large network is computationally infeasible.

To remedy the lack of detailed productivity data, I follow Armington (1969), Fajgelbaum & Schaal (2020), and Graff (2024) and assume that products are differentiated by city of origin and each city produces just one good. To overcome the dimensionality problem, I create 22 traded products differentiated by origin, of which 17 are produced by selected mega-cities[26], and the remaining 5 are divided among large port-cities (population > 1M and outflows > 1M TEU), large cities (population > 2M), ports (outflows > 0), cities (population > 200K), and smaller cities/towns or unpopulated nodes (which do not produce traded goods).

In my model specification and parameterization, I largely follow Graff (2024). I set the existing level of infrastructure along each link from city j to city k, I_{jk}, to the average link speed in km/h

$$I_{jk} = \text{speed}_{jk} \quad \forall j, k. \tag{7}$$

I_{jk} is bounded from below by the present speed ($I_{jk}^{\min} = I_{jk}$), which is zero for proposed links. It is also bounded from above by the greater of 100km/h and the present speed, denoted by $I_{jk}^{\max} = \max(I_{jk}^{\max}, 100)$. I then calculate the (per km/h) infrastructure building cost δ_{jk}^{I} as

$$\delta_{jk}^{\text{I}} = \text{upgrade cost}_{jk}/(I_{jk}^{\max} - I_{jk}), \tag{8}$$

where upgrade cost$_{jk}$ corresponds to the cost per km of building each link or upgrading it to 100km/h from Figure A12, multiplied by the link length in km. Since in the model of Fajgelbaum & Schaal (2020) the lower bound on I_{jk} is simply a constraint on how a given infrastructure budget may be spent, I set the baseline budget equal to $\delta_{jk}^{\text{I}} \times I_{jk}$. I then consider social planners with \$20 billion, \$35 billion, and \$50 billion USD'15 in addition to the baseline budget, which is well below the theoretical total of \$162 billion cost of all proposed work (upgrading and construction). The planner can freely choose which links to build/upgrade at cost δ_{jk}^{I}.

In reality, most road upgrade/construction decisions are discrete, but the quantitative framework does not allow a discretization of optimal infrastructure investments. The results may instead be interpreted as 'partial' upgrades/completions. For example, suppose a road at 80km/h has a speed of 90km/h after the optimization. In that case, we may conclude that the planner decided to upgrade $(90-80)/(100-80) = 50\%$ of the road.[27] The model also features iceberg trade costs

$$\tau_{jk}^n(Q_{jk}^n, I_{jk}) = \delta_{jk}^{\tau} \frac{(Q_{jk}^n)^{\beta}}{I_{jk}^{\gamma}}, \tag{9}$$

such that traders need to send $1 + \tau_{jk}^n$ units of a good for one unit to arrive. Following Graff (2024), who averages estimates from Atkin & Donaldson (2015) for Nigeria and Ethiopia, I set

$$\delta_{jk}^{\tau} = 0.1159 \times \ln(\text{distance in miles}_{jk}). \tag{10}$$

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[26]Dakar, Casablanca, Abidjan, Kumasi, Algiers, Lagos, Kano, Yaounde, Luanda, Kinshasa, Cape Town, Johannesburg, Cairo, Khartoum, Nairobi, Addis Ababa, and Dar es Salaam.

[27]While this interpretation is plausible, the cost per km of building/upgrading segments decreases for roads longer than 50km (Eq. 6, following Collier et al. (2016)), and it is thus not realistic that the planner considers prices δ_{jk}^{I} inelastic to the quantity (length) constructed. In addition, if the planner partially builds a new links, we must assume that the remainder corresponds to a dirt road that can be constructed free of cost. Thus, the framework may slightly overstate the amount of infrastructure that can be constructed on a given budget.

The trade cost positively depends on the flow of good n across link $j \to k$, Q_{jk}^n, subject to an elasticity β, an effect Fajgelbaum & Schaal (2020) describe as 'congestion forces'. It also depends negatively on the level of infrastructure I_{jk}, subject to an elasticity γ. Following Graff (2024), I set $\gamma = 0.946$.[28] I would also follow him and set $\beta = 1.177$, however, due to the large size of the network, only the dual solution to the model which casts all variables as function of prices is viable, stipulating a maximum of $\beta = 1$ for strong duality (Fajgelbaum & Schaal, 2020). As also discussed at length by Fajgelbaum & Schaal (2020), the lagrangian objective of the model is only convex if $\beta > \gamma$, in which case a unique global solution to the network design problem can be computed. If $\beta < \gamma$, the problem becomes non-convex and yields a local optimum, which Fajgelbaum & Schaal (2020) further refine using simulated annealing methods. They denote this case as 'increasing returns to infrastructure' (IR) and show that the optimal network is more tree-like, with larger investments in fewer links. Graff (2024)'s parameterization implies $\beta > \gamma$. This may, however, not hold for large transnational networks; thus, I also examine the IR case assuming $\gamma' = 1.2$.[29]

Fajgelbaum & Schaal (2020)'s model has a normalized inequality-averse Cobb-Douglas utility function giving the utility of a single worker in location j in terms of consumption and housing

$$u_j(c_j, h_j) = \left[\left(\frac{c_j}{\alpha} \right)^\alpha \left(\frac{h_j}{1-\alpha} \right)^{1-\alpha} \right]^{1-\rho} / (1-\rho), \tag{11}$$

where ρ controls the level of inequality aversion. Following Graff (2024), I assume $\alpha = 0.7$, which is based on estimates by Porteous (2022), and $\rho = 0$ (no inequality aversion), but I also explore $\rho = 2$ (moderate inequality aversion). Following Graff (2024), I set $h_j = 1 - \alpha$, i.e., the local housing availability is proportional to the current population. Total consumption in location j is $C_j = L_j c_j$, which in turn is a CES aggregate over N traded goods with elasticity of substitution σ

$$C_j = \left[\sum_{n=1}^{N} (C_j^n)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}. \tag{12}$$

In line with the international trade literature, Fajgelbaum & Schaal (2020) and Graff (2024) use $\sigma = 5$, following recommendations by Atkin & Donaldson (2022). Both assume that the largest $N - k$ cities produce their own good and mostly conduct single-country simulations.[30] Since I have few cities per country, it is also plausible to interpret σ as an Armington (1969) elasticity, and here a meta-study by Bajzik et al. (2020) suggests a median value of 3.8. Since the network is very large, even $\sigma = 3.8$ yields equilibria with limited inter-city trade where optimal investments are quite localized around population centers. I thus also run simulations with $\sigma = 2$, which is at the low end of empirical estimates (Bajzik et al., 2020). Production of good n in node j is given by

$$Y_j^n = Z_j^n L_j^n. \tag{13}$$

Due to lack of better measures,[31] I set city productivity Z_j^n equal to the predicted International Wealth Index of Lee & Braithwaite (2022) (Figure A2). Since the original estimate is only available

[28] The value for γ is informed by estimates of the costs of road delays to African truckers by Teravaninthorn & Raballand (2009). The value of β is informed by estimates on the cost of traffic congestion by Wang et al. (2011). Fajgelbaum & Schaal (2020) use $\beta = 0.13$ and $\gamma = 0.1$, but their characterization of infrastructure (I_{jk}) in terms of road-lane km yields significantly larger values than the formulation in terms of km/h adopted from Graff (2024).

[29] Fajgelbaum & Schaal (2020) page 1439 simulate an IRS case by inverting the ratio of β and γ keeping β fixed, which, for $\beta = 1$, yields $\gamma' = 1.057$. This, however, yields very similar solutions to $\gamma = 0.946$, thus I set $\gamma = 1.2$ to induce stronger effects. There are, as far as I am aware, no studies or empirically accessible data on road congestion in inter-city or international transport.

[30] Graff (2024) sets $N = 6, k = 2$ (with one international good produced outside the country and one agricultural good produced by smaller cities) and conducts simulations for every African country. Fajgelbaum & Schaal (2020) set $N = 10, k = 1$ and conduct simulations for France, Spain, and Western Europe.

[31] Graff (2024) uses nightlights divided by city population to form the productivity measure. While this is a viable approach, the task of measuring differences in city productivity across countries encourages the use of richer data sources. Lee & Braithwaite (2022) combine daylight satellite imagery and OSM data in an iterative ML framework that has proven able to predict wealth within and across SSA countries reliably. As an attempt to verify, taking a city-population weighted average of the IWI by countries yields a correlation of 0.62 with the 2020 World Bank national GDP/capita estimate and a correlation of 0.73 with the log of GDP/capita. Using NASA's Black Marble nightlights, on the other hand, only yields a correlation of 0.15 between city-population weighted nightlights/capita and national GDP/capita. However, using the log of nightlights/capita yields a 0.58 correlation with GDP/capita and a 0.65 correlation with the log of GDP/capita. While this appears more promising, a visual comparison, provided in Appendix Figure A10 for the interested reader, shows that the IWI is higher in larger cities in richer countries - in line with much scientific evidence. The nightlights measure appears quite noisy and imprecise.

for SSA, I use the imputed version of Krantz (2023) (Figure A3) and compute the productivity of each city as the inverse-distance-weighted average of cells within 30km of the city centroid. I assume that average household wealth, aggregated at the city level, approximates worker productivity. Footnote 31 argues that national average urban wealth strongly correlates with GDP per capita.

I also calibrate the productivity of international ports so that overall production matches national accounts data. Averaging estimates from the UN National Accounts Main Aggregates database between 2020 and 2022 yields that imports were equal to 26.5% of African GDP. Since my network does not include foreign locations,[32] the imported goods will have to be produced by port cities. Assuming that port outflows in 2020Q1 are proportional to the inflows, multiplying outflows from the 52 largest ports by a factor of 37 yields (precisely) an imports measure summing to 26.5% of the total production volume using the IWI as productivity measure. These imports need to be divided by port city population to yield productivities. Since the framework of Fajgelbaum & Schaal (2020) endogenously allocates labor to different tasks, letting port cities produce both a domestic and international variety would obscure this calibration. Thus, I compound both tasks so that port cities use all labour to produce a mixed international variety at productivity

$$Z_j^{\text{intl.}} = \text{IWI}_j + \frac{37 \times \text{Outflow in TEU 2020 Q1}_j}{\text{City Population}_j}.$$ (14)

The median intl. productivity is 27 IWI points, but the mean is much higher at 2748, indicating high import volumes in some port cities with small populations. Top of the list is Egypt's Sokhna Port (towards the Red Sea), with a population of 1000 and intl. productivity of 134,656, followed by Egypt's Port Said, with a population of 894,850 (within a 30km radius) and intl. productivity of 1,264. Other ports with intl. productivity above 500 include Tanger Med and Walvis Bay. Since utility functions are mildly concave ($\alpha = 0.7$) and the planner maximizes utility, the comparatively small populations of these port cities downweight their importance for network optimization. The resulting increase in purchasing power also implies that a part of the equilibrium consumption of port cities is exported. For simplicity, I assume the export share is equal to the share of international productivity in total city productivity and adjust consumption and welfare accordingly.

Table 9 summarizes productivity and population by city type, indicating that the 17 megacities together account for 35.7% of population (159 million) and 46.5% of total domestic production.

Table 9: Productivity and Population by City Type

City Type	City/Node	City>200K	Port	City>2M	Port-City	Megacity
Count	1,022	286	32	13	9	17
Population						
Sum	48.5M	154.6M	20.7M	38.6M	23.2M	158.7M
Mean	47.4K	540.5K	645.4K	2.97M	2.58M	9.3M
Median	21.2K	390.7K	590.7K	2.69M	1.89M	6.9M
Production						
Total	1.50B	5.86B	3.32B	1.84B	3.88B	10.80B
Total Domestic	1.50B	5.86B	0.97B	1.79B	1.38B	10.01B
Productivity						
Domestic Mean	27.72	36.15	47.34	46.58	60.83	60.89
Domestic Median	23.74	32.41	47.88	46.92	60.37	59.65
International Mean	0	0	4,376	1.59	203.6	7.1
International Median	0	0	28.4	0	80.88	0

Notes: Table shows population and productivity (IWI) summarized for cities of different sizes and port-cities. International productivity (for imports) is the second term on the RHS of Eq. 14.

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[32] It would be difficult to add foreign markets to an already large network. In theory, this could be done by adding additional nodes for ports and separating the city from the port in this way, but for any goods to flow to these locations, they need to have populations. Since flows are an equilibrium outcome, they would have to be calibrated to match the data by reverse engineering the model, which is quite complicated solving for populations of multiple ports. The framework may also have difficulties computing optimal flows along zero-cost links.

Another implication of this calibration is that I am constrained to fixed labor scenarios. The mobile labor case, examined by Graff (2024) for national African road networks and by Fajgelbaum & Schaal (2020) for France, Spain, and Western Europe, lets workers reallocate to more productive and better-connected locations—implying potentially large changes in the production of imports. It does, however, not admit a dual solution and is thus also computationally infeasible. Figure 24 provides an overview of the calibrated network structure.

Figure 24: Calibrated Network for General Equilibrium Simulations
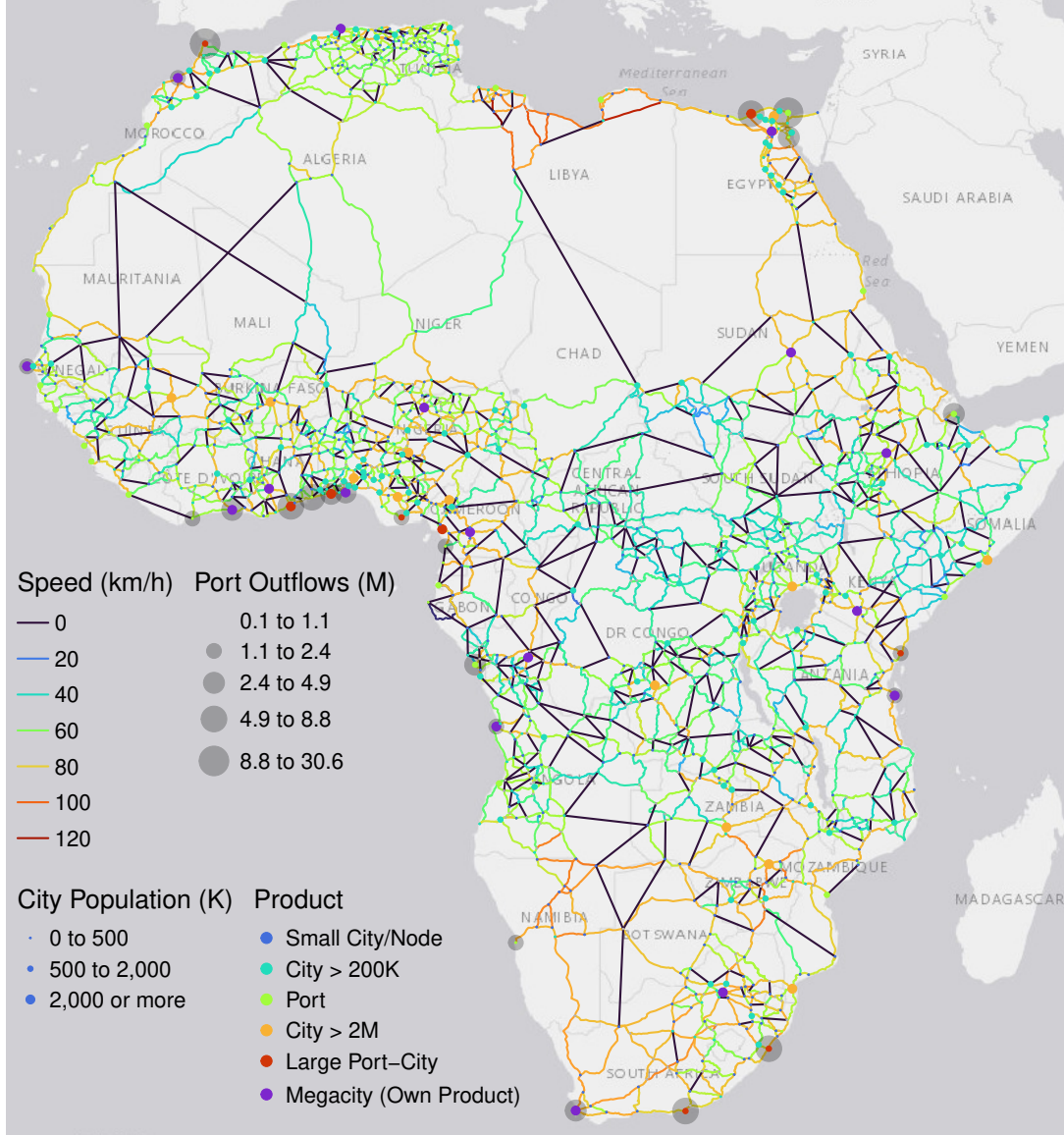
Notes: Figure shows network calibrated with speed, city population and productivity (IWI) and port outflows → Eq. 14.

6.1 Optimal Investments into Africa's Transport Network

Under decreasing returns (DRS) ($\gamma < \beta$), the \$35B social planner focuses on connecting high-productivity large cities and port cities to surrounding smaller cities, particularly where road connectivity is inferior. Fajgelbaum & Schaal (2020) find that, in equilibrium, more infrastructure is allocated to regions with lower levels of infrastructure, higher population, and greater worker productivity. Figure 25 visualizes the optimal allocation. The left panel shows network speed post optimization, the middle panel the speed difference to the current network, and the right panel the percentage to which the stipulated work on each link was completed. Thus, the right panel measures the extensive margin of road work, the middle panel the intensive margin.

Figure 25: Optimal Network Investments under Decreasing Returns

Final Network Speed   Investments in km/h   Investments in % Completed
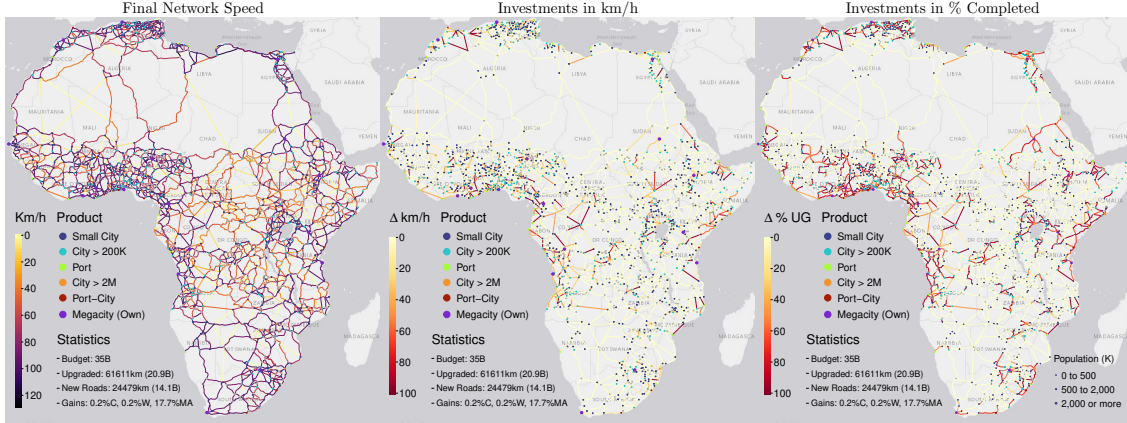
Notes: Figure shows the optimal spatial allocation of a $50B social planner. Investments in km/h are bounded above by 100km/h. The %-completed is the invested amount (speed) divided by the difference of the initial speed from 100km/h.

Overall, this planner commissions road activities equivalent to 86,090km of fully built/upgraded road segments, of which 61,611km are upgrades at a cost of $20.9B, and the remaining 24,479km are fresh construction at a cost of $14.1B. These activities induce a non-risk-averse model-implied utilitarian welfare gain of 0.18% and a market access gain of 17.7%. The welfare gain is proportional to a consumption gain of 0.2%. Both are spatially heterogeneous, with utility per worker gains ranging from a 26% loss (1st percentile) to a 22% gain (99th percentile), at a median gain of 0.33%. The gains are mildly negatively correlated with the IWI ($r = -0.05$), indicating that they are mildly redistributional. The MA gains are lower than the consensus packages of Section 5.8, where the second package at a cost of $36.6B yields a 30.6% MA gain. This difference is due to the welfare maximizing motive and also the trade elasticity of 3.8 (versus $\theta = 1$ for MA calculations). Notably, PE packages invest more in major markets and trans-African links connecting them.

To better understand the planner's optimal allocation, I also examine the flow of goods. Figure 26 visualizes the exports of 8 of the 17 selected megacities producing own goods. The scales are logarithmic, owing to significant differences in the magnitudes of flows.

Figure 26: Flow of Goods Following $35B Investments under Decreasing Returns
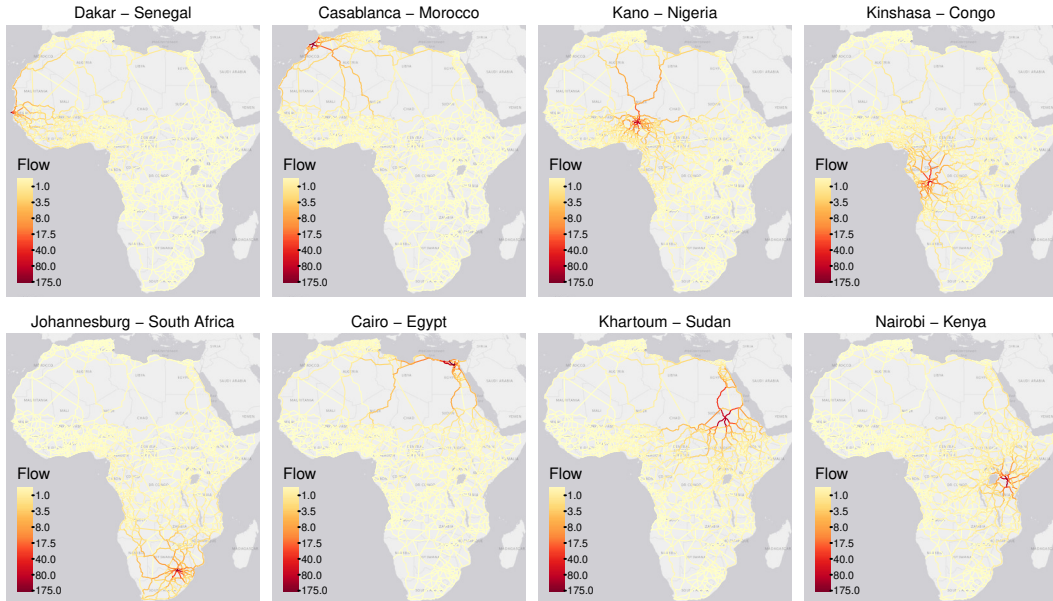
Notes: Figure shows the equilibrium flow of goods produced by difference (port-)cities on a logarithmic scale.

Ostensibly, the flows are quite localized within a radius of around 2000km, explaining why the planner mostly invests in better connecting these cities with surrounding ones. They are also small

relative to local consumption: all 17 megacities consumer more than 99% of their own produce. Thus, a lower trade elasticity and/or using the inequality-averse planning objective ($\rho = 2$) may be necessary to achieve more far-reaching outcomes. Figure 27 provides a comparison.

Figure 27: Optimal $35B Network Investments under Decreasing Returns: Different Scenarios
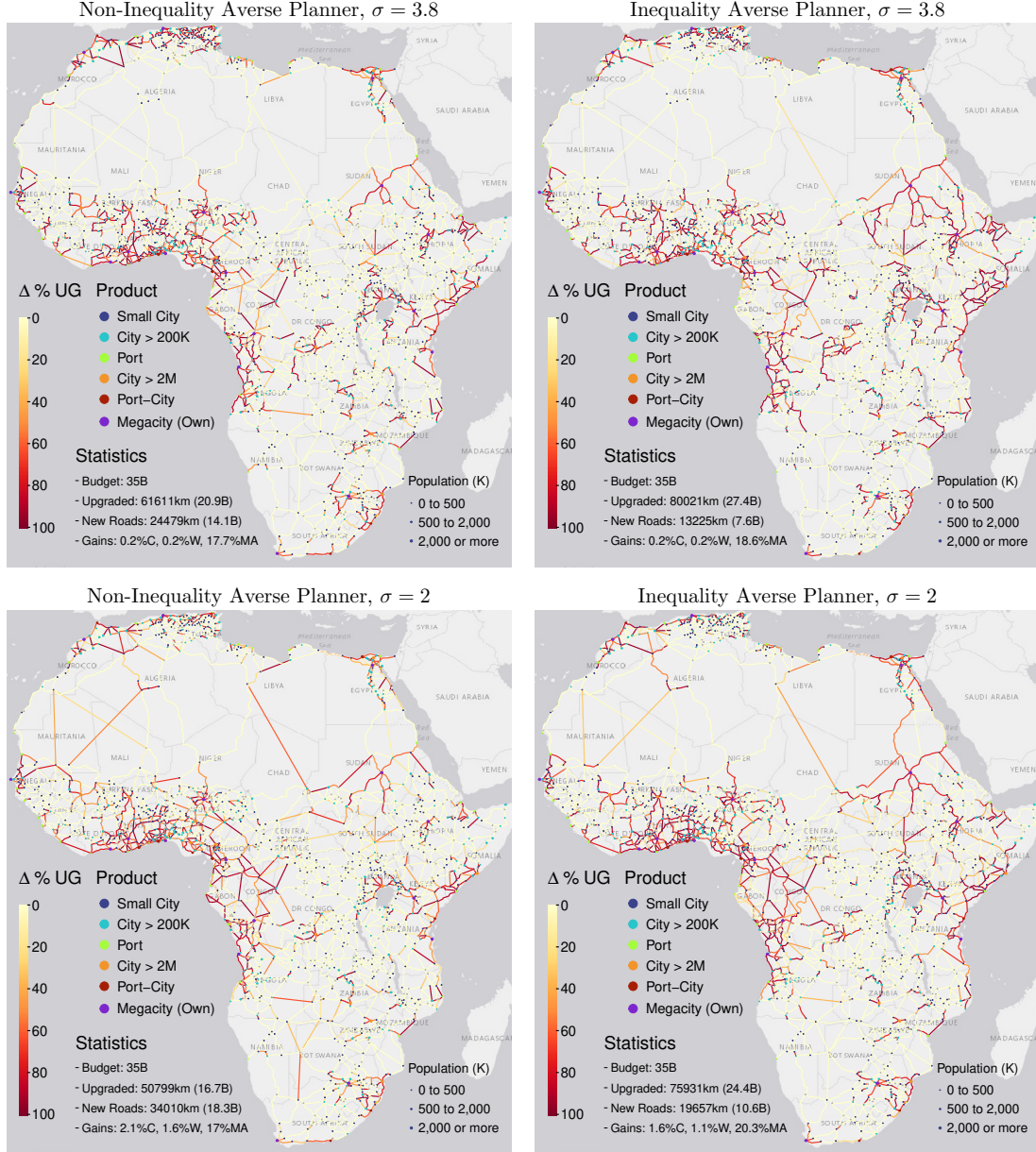
Notes: Figure compares optimal $35B allocations under DR with/without an inequality averse planner under different σ.

Indeed, both inequality aversion and $\sigma = 2$ yield more cosmopolitan outcomes, with more investments in poorer central and eastern African regions under inequality aversion, and more investments in remote links connecting major distant markets under $\sigma = 2$. However, the assumption that congestion forces are strong ($\gamma < \beta$), yields unrealistic outcomes under $\sigma = 2$, in that the planner chooses to build new trans-Saharan links without upgrading existing ones because of assumed congestion on trans-African roads. This is questionable given the presently very low volumes of trans-Saharan trade. Thus I also run simulations for the IR ($\gamma > \beta$) case with $\gamma = 2$.

Figure 28 shows the optimal $35B investments under IR. In stark contrast to the DR case, here planners almost exclusively spend on road upgrading. The only new construction is reconnecting Morocco to Algeria, which is an extremely high-yield road. Overall, these planners complete more than 110K km of road work, versus only around 85K km under DR due to the more expensive new

construction. Again, under inequality aversion ($\rho = 2$), more is invested in poorer populated areas in central Africa (Congo) and the Horn of Africa (Somalia). Under $\sigma = 2$, the planner upgrades one of the trans-Saharan roads, connecting well to Algeria, and also constructs a significant new link to better connect to Morocco. Overall, this scenario seems more reasonable than the DR scenario, given the presently low volume of trans-African and trans-Saharan trade.

Fajgelbaum & Schaal (2020) assume DR ($\gamma < \beta$) as their baseline drawing on a study of the determinants of driving speed in large U.S. cities by Couture et al. (2018). Graff (2024)'s calibration also implies DR, but his parameters are derived very indirectly from the literature (not from econometric estimates) and thus form a sparse evidential basis. It may thus well be that trans-African connections, much less prone to congestion than inner-city roads, exhibit IR.

Figure 28: Optimal $35B Network Investments under Increasing Returns: Different Scenarios
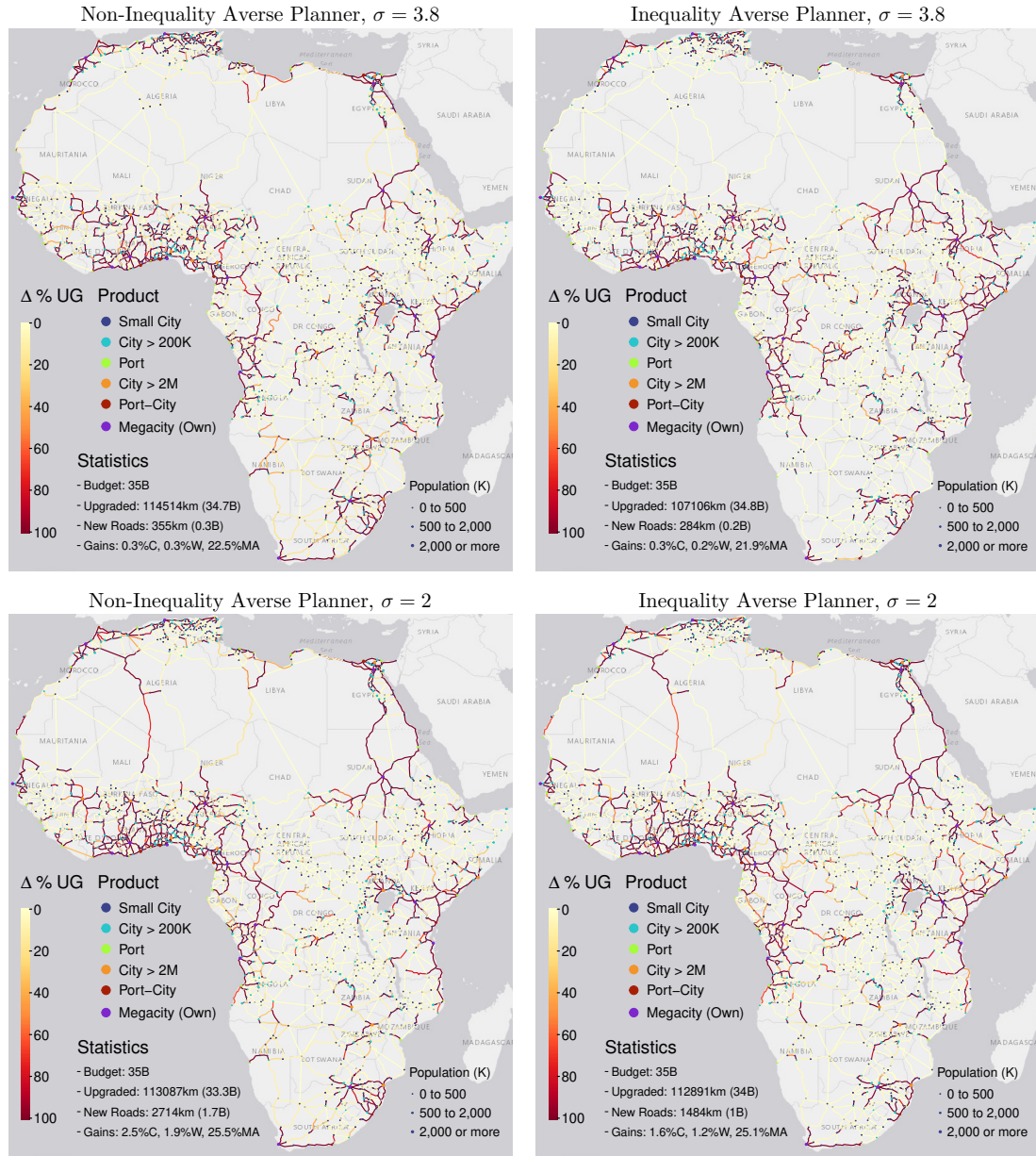
Notes: Figure compares optimal $35B allocations under IR with/without an inequality averse planner under different σ.

Figure 29 again shows the flows under IR for 8 megacities. Due to the lower trade costs, they are more than 2x larger than under DR (Figure 26). Appendix Figures A15 and A17 also show the optimal flows under $\sigma = 2$. Additionally, Appendix Figures A16 and A18 show optimal allocations of a standard planner with $20 and $50 billion under DR or IR, respectively. Lastly, Figure 30

Figure 29: Flow of Goods Following $35B Investments under Increasing Returns
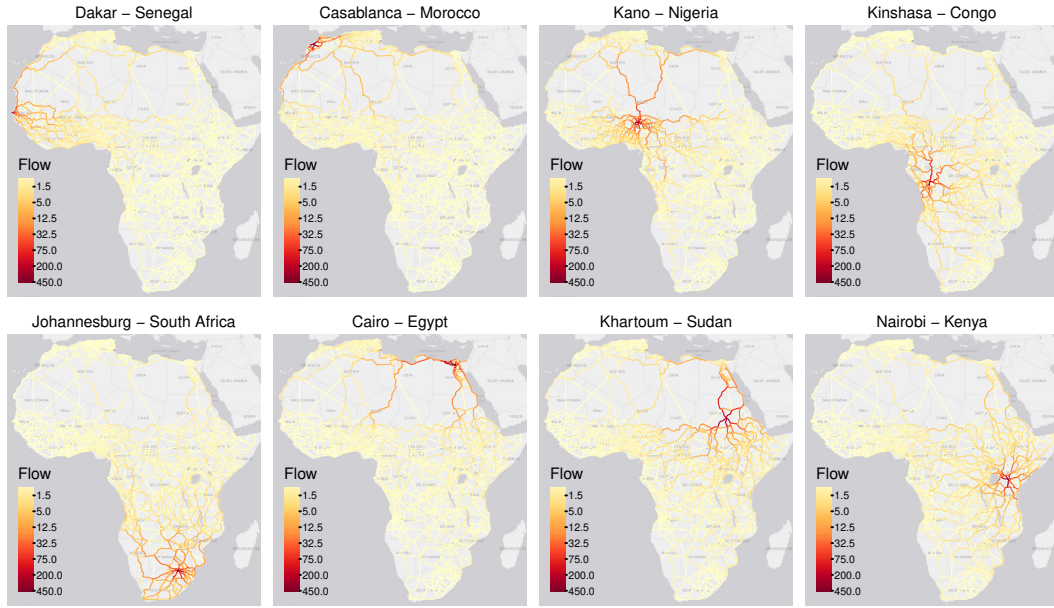
Notes: Figure shows the equilibrium flow of goods produced by difference (port-)cities on a logarithmic scale.

Figure 30: Optimal $35B Network Investments under Increasing Returns: Welfare Gains
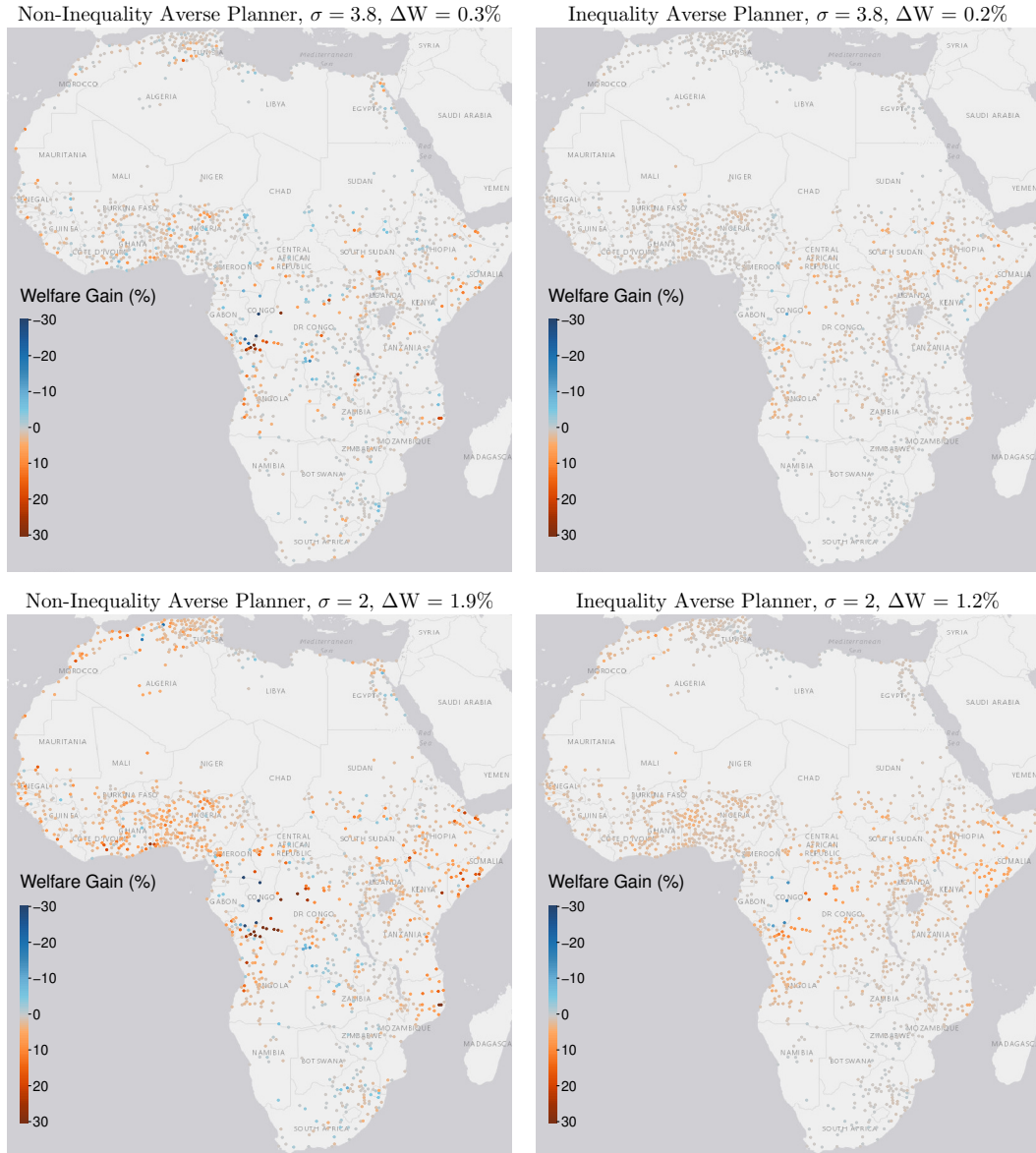
Notes: Figure compares welfare gains from optimal $35B allocations under IR − corresponding to Figure 28.

reports local welfare gains corresponding to the IR case (Figure 28). Ostensibly, under inequality aversion ($\rho = 2$), the variation in local gains is much smaller and few locations loose welfare.

What happens under border frictions? I investigate this by adding the distance-equivalent border frictions (Figure 7) to δ_{jk}^{τ} (Eq. 10) and computing the difference in % of work completed to the frictionless case. Figure 31 shows the results under IR/DR and moderate/low σ assumptions.

Figure 31: Optimal $35B Network Investments under Frictions: Difference
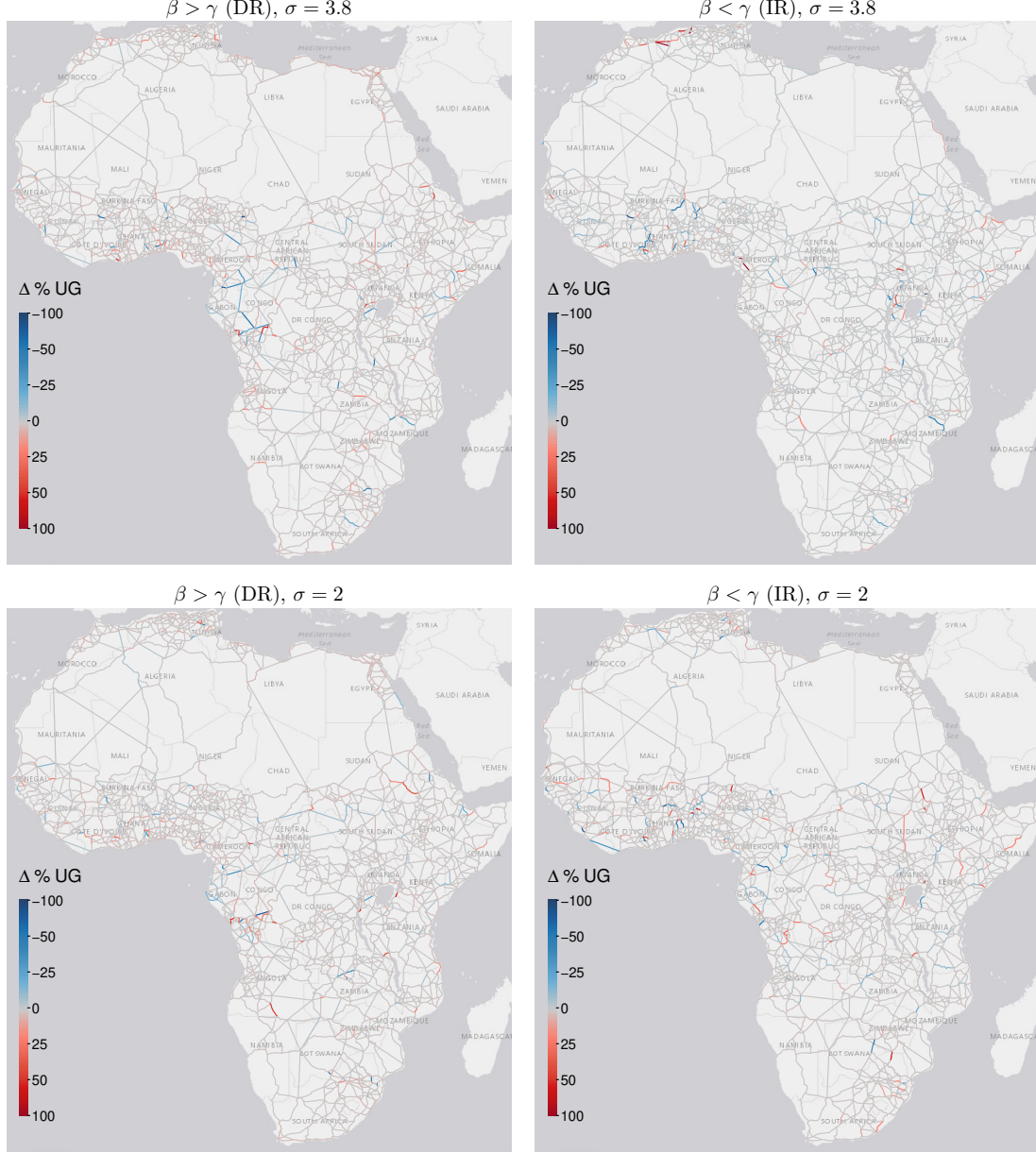
Notes: Figure compares optimal $35B allocations with/without border frictions as the difference in % of work completed.

Surprisingly, optimal network investments change very little; the planner slightly reduces investments on certain links, many of which are close to borders, and invests in others instead. Flows through expensive border-crossing links are redirected to less expensive border-crossing links. Overall consumption and welfare are reduced slighly under frictions, and particularly in remote cities which would trade more without frictions. Appendix Figure A19 shows, for the IR case, both the difference in welfare pre-investment (LHS) and the difference in welfare gains from optimal investments to the frictionless case (RHS), indicating that several locations loose up to 20% of their welfare/welfare gains because of the border frictions. In all cases, some locations also gain welfare of up to 10% due to distortions/trade diversion caused by the frictions.

6.2 Optimal Trans-African Network Investments

Of particular interest to trans-African policymakers and traders are important transport routes connecting major (port-)cities across the continent. To elicit these routes, I consider the subset of major agglomerations with >2 million inhabitants and ports with >1 million TEU in 2020Q1, yielding 47 major (port-)cities. I then compute fastest routes between them using the existing network and contract it, removing unnecessary intermediate nodes while summing distances and travel times and recalculating travel speeds along the edges. This yields a trans-African network graph with 212 nodes and 330 edges. Since the original graph optimally connects 453 (port-)cities, the reduced graph, shown in Figure 32, also optimally connects the 47 largest (port-)cities.

Figure 32: Trans-African Network Connecting Large Cities: Parameterization
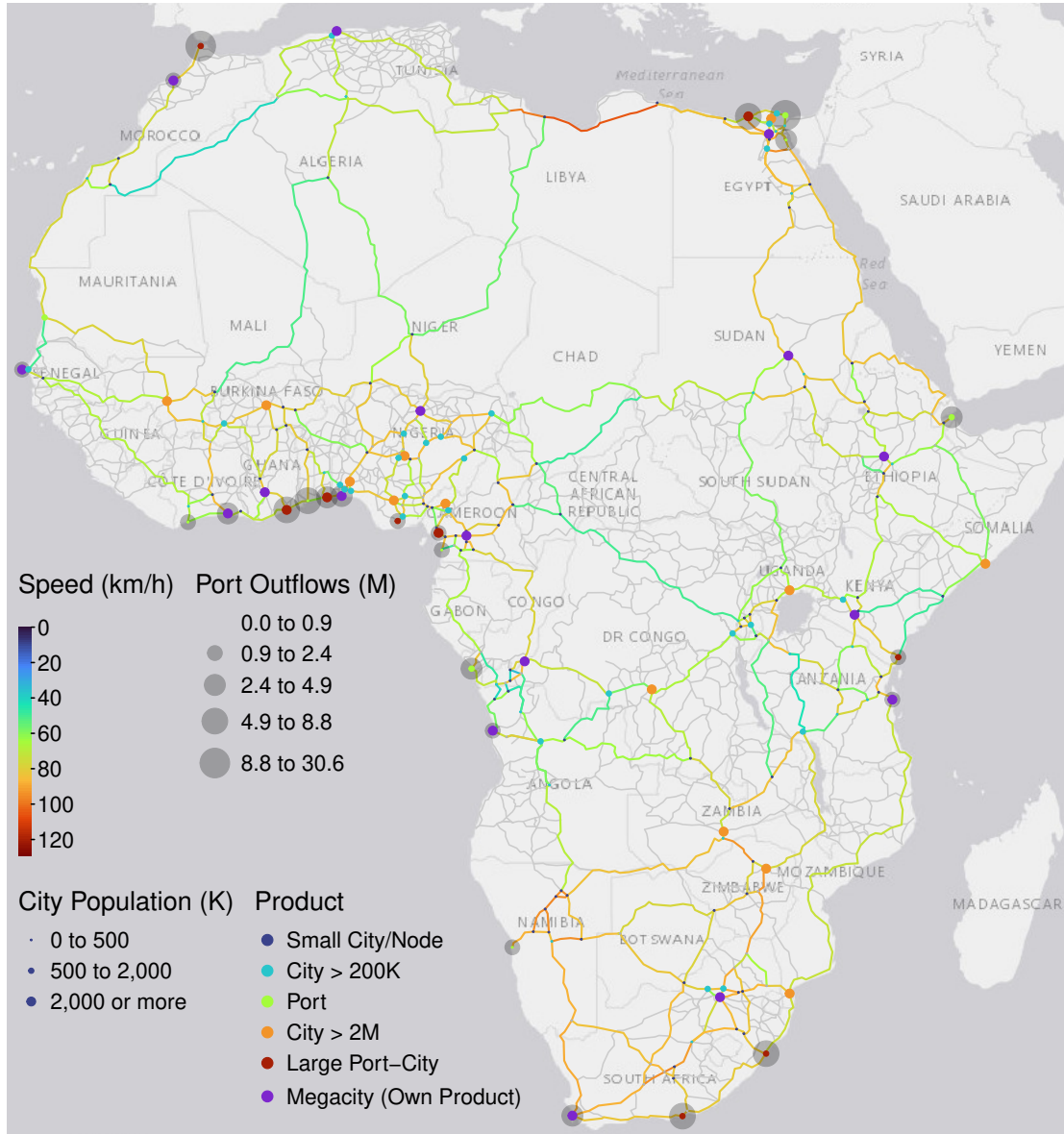
Notes: Figure shows fastest routes connecting 47 large (port-)cities. These are contracted to 212 nodes and 330 edges.

The reduced network admits a total upgrading investment volume of $33B. I assume the baseline planner has $15B to invest in trans-African roads, but also simulate planners with $10B and $20B. The parameterization otherwise exactly follows the previous subsection.

Figure 33 shows the optimal $15B investments under DR ($\gamma < \beta$). Ostensibly, the planner mainly invests in connections between large cities, megacities, and ports. This includes better connecting Khartoum to upper Egypt, Kampala to Mogadishu via Mombasa, Kinshasa to Mbuji-

Mayi, and improving connectivity in West Africa, particularly along the coastline between Abidjan and Yaounde and into the interior. With inequality aversion ($\rho = 2$) and the benchmark substitution elasticity ($\sigma = 3.8$), the planner builds a full corridor across populated central Africa, better connecting Kinshasa to Bukavu/Rwanda. With low $\sigma = 2$, however, trade and infrastructure investments largely concentrate on north-south connectivity, such as fully upgrading the passage from Cape Town to Lagos, and partially upgrading the road from Kampala up to Khartoum.

Figure 33:   Optimal \$15B Trans-African Network Investments under Decreasing Returns
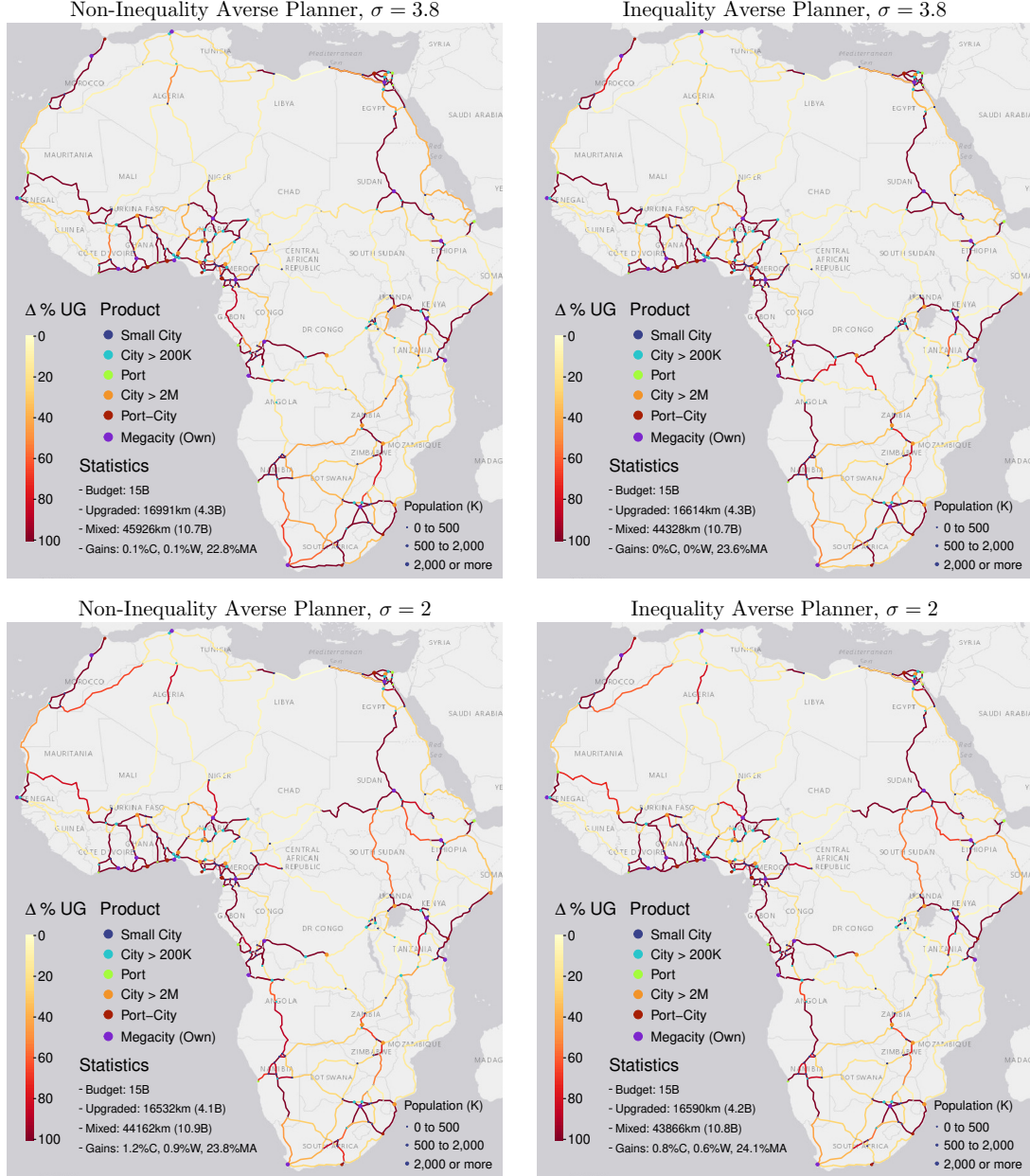
Notes: Figure compares optimal \$15B allocations under DR with/without an inequality averse planner under different σ.

Figure 34 shows the corresponding flow of goods for 8 selected cities. Due to the restricted network, they are much more wide-ranging than in Figure 26. Figure 35 also shows the optimal \$15B investments under IR. They are overall quite similar, indicating that on a sparse network congestion forces are not so important in guiding optimal investment decisions. Rather, the key parameters governing trans-African investments are σ and ρ. Border frictions again cause minor deviations away from expensive border-crossing links, as Appendix Figure A24 shows. Since in PE (Section 5), frictions had a significant impact on optimal allocations, this suggests that the iceberg formulation (Eq. 9) with logarithmic distance (Eq. 10) may not be the most appropriate way to include them. Better accounting for frictions in spatial models thus invites further research.

Figure 34: Flow of Goods Following $15B Investments under Decreasing Returns
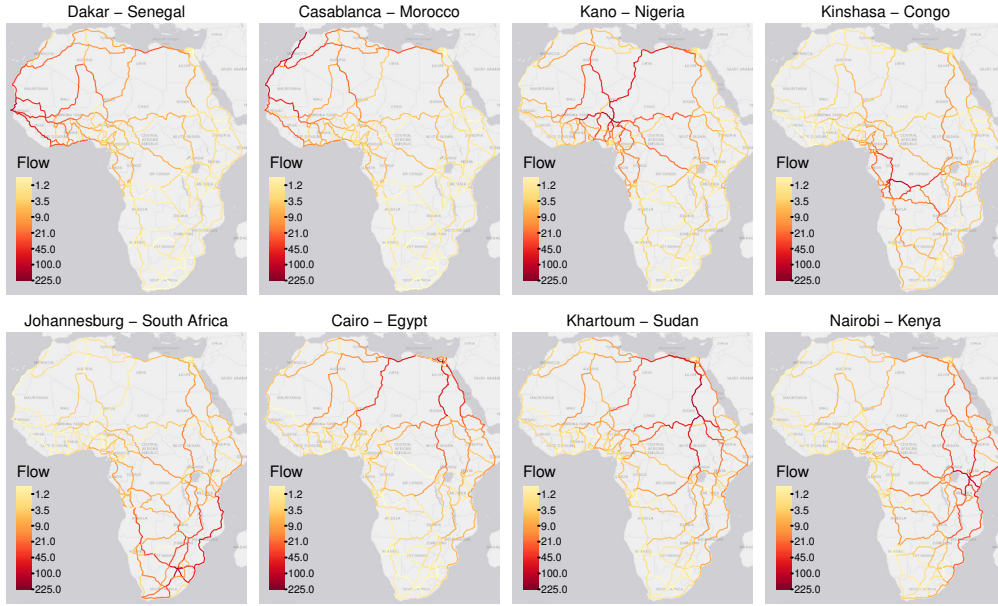
Dakar – Senegal	Casablanca – Morocco	Kano – Nigeria	Kinshasa – Congo

Johannesburg – South Africa	Cairo – Egypt	Khartoum – Sudan	Nairobi – Kenya

Notes: Figure shows the equilibrium flow of goods produced by difference (port-)cities on a logarithmic scale.

Figure 35: Optimal $15B Trans-African Network Investments under Increasing Returns
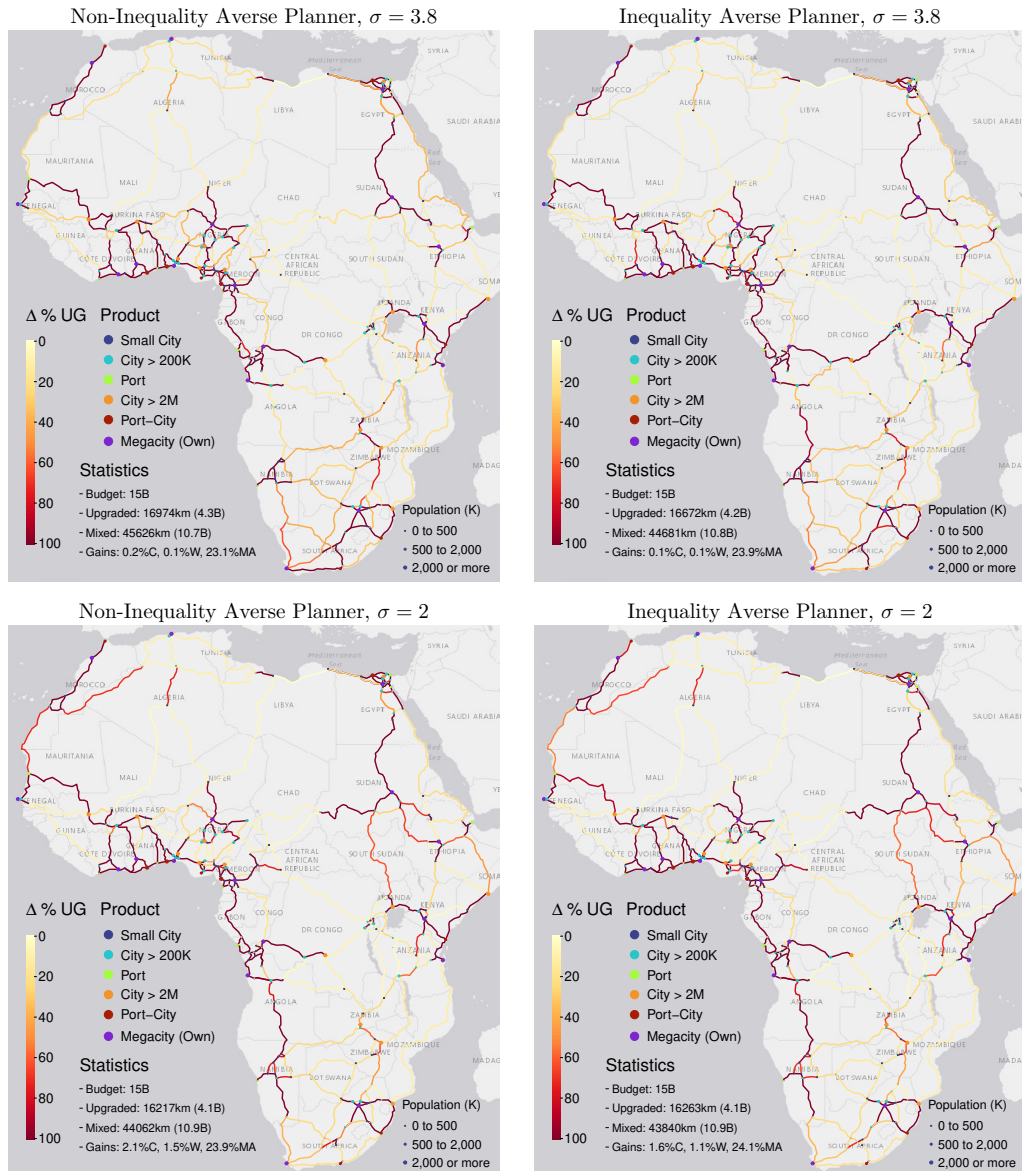
Non-Inequality Averse Planner, $\sigma = 3.8$ — Inequality Averse Planner, $\sigma = 3.8$

Non-Inequality Averse Planner, $\sigma = 2$ — Inequality Averse Planner, $\sigma = 2$

Notes: Figure compares optimal $15B allocations under DR with/without an inequality averse planner under different σ.

In all parameterizations considered so far, significant efforts to upgrade central African roads—the worst on the continent—are not a priority. This also still holds when increasing the budget to $20B, as shown in the bottom panels of Appendix Figures A21 (DR) and A23 (IR). This is primarily due to the high upgrading cost of these roads, coupled with high border frictions (if enabled). It is also reflected in existing trading patterns: Presently, trade between ECOWAS and the EAC + IGAD combined makes up only 0.2% of total inner-African trade and 0.7% of inner-African trade between different regional economic communities. Closing the central African infrastructure gap is likely to increase these shares significantly, but at a high construction cost.

This invites the question what would need to be the case for links crossing central Africa, e.g., the link from Goma in DRC to Bangui in CAR, to become a spending priority. It turns out that a combination of very low substitution elasticity ($\sigma = 1.5$) and inequality aversion ($\rho = 2$) does the job—as Figure 36 shows. However, $\sigma = 1.5$ is below practically all empirical estimates (Bajzik et al., 2020). It further turns out that if border frictions are activated, the planner reduces investments on the Goma-Bangui link by around 25%—as the bottom panels of Figure 36 illustrate.

Figure 36: Optimal Trans-African Network Investments to Close Gap (Increasing Returns)
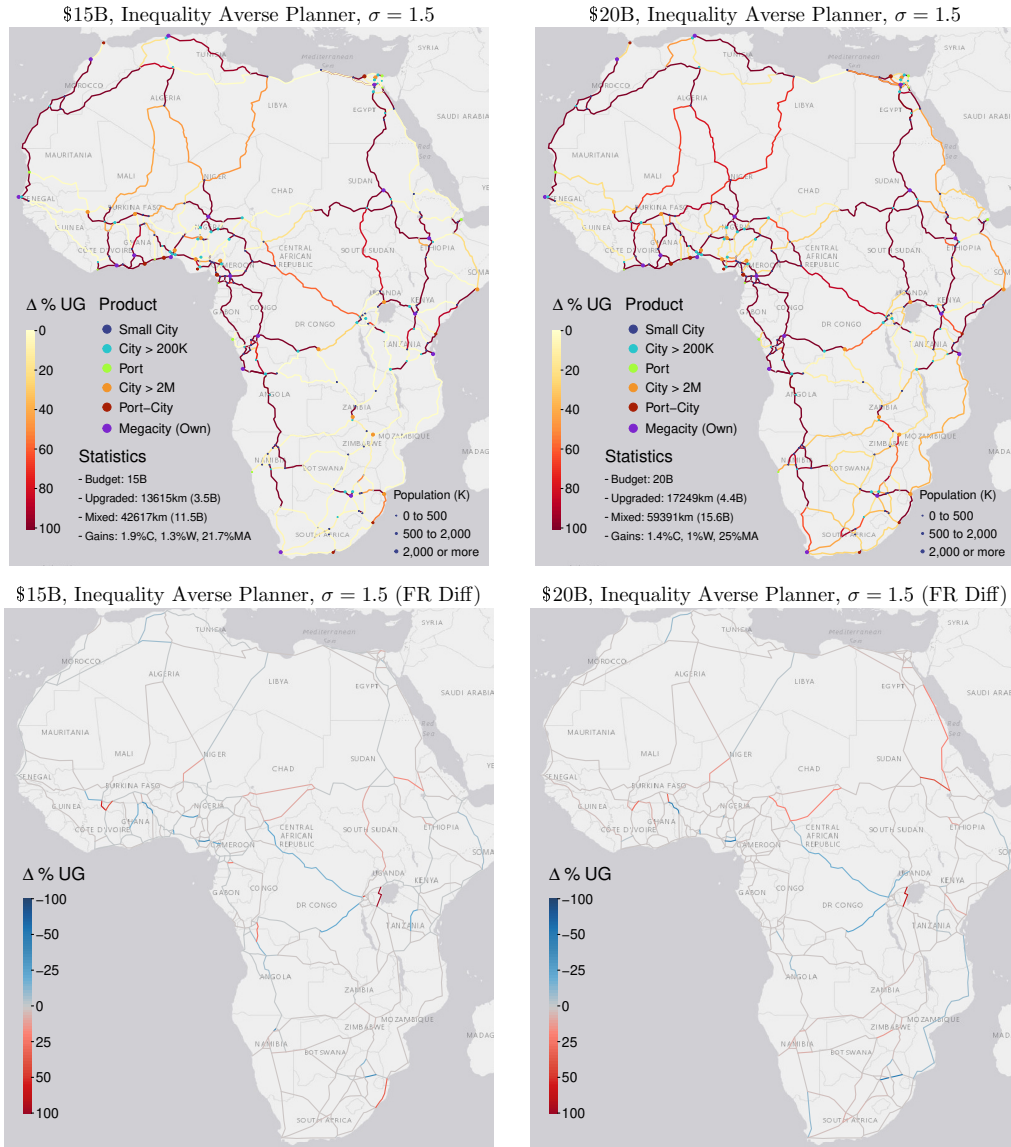
Notes: Figure compares optimal $15B allocations under DR with/without an inequality averse planner under different σ.

This overall suggests two broad policy implications for trans-African road investments: (1) most welfare can be gained from upgrading links in populated areas and links connecting markets within the same region, and (2) trade facilitation should precede major trans-African investments.

7   Summary and Conclusion

Using detailed routing data, large and accurate network graphs, and a rich economic geography including population, wealth/gdp, trade through ports, border frictions, road construction and upgrading costs, this paper rigorously examines Africa's full continental road network and characterizes optimal investments into it in partial and general equilibrium (PE and GE).

Presently, Africa has 1.6 million km of non-residential roads, around 30% of which are paved. This fraction differs significantly by country and road type. Particularly in Central Africa, the Sahara, and the Horn of Africa region, most roads are unpaved and rough, severely limiting trans-African connectivity. The network's overall route efficiency (RE) of 0.68 is acceptable but considerably lower than that of the US network at 0.84. The time efficiency and average travel speed along many roads is significantly worse than in other world regions. Particularly the aforementioned regions can only be traversed at speeds around 40km/h. In addition, cross-border frictions substantially impede continental market access (MA). Estimates suggest that crossing the median border in Africa is as costly as 1043km of road distance, and the time commitment is equivalent to 3.2 days of travel time. These frictions induce an aggregate MA loss between 26% and 78%. Locations across the border from major markets such as Nigeria suffer MA losses of up to 80%.

Given a detailed network and economic geography, optimal road investments still depend on the geographic scale and magnitude of the investment and the planner's objective (MA or welfare maximization with/without inequality aversion). Structural parameters such as the trade elasticity/elasticity of substitution and returns to scale in infrastructure also noticeably impact optimal spatial allocations, as do heterogeneous road construction costs and border frictions. The paper navigates this complexity via a graduated approach, starting with small-scale PE investments and gradually progressing towards GE simulations where social planners spend large amounts. This requires different network representations and methods.

To increase the scale of investments to entire roads or collections of segments, I build a detailed representation of the transport network connecting 447 important cities and 52 ports along the fastest routes. My network graph has 1379 nodes and 2344 edges (links), summing to 315K km. I apply a network finding algorithm and find 481 potential new links summing to 104K km. Building them all would raise RE by 7.1%, from 0.68 to 0.72, and MA (denominated in road distance) by 5.5%. The most valuable links increasing RE/MA by more than 0.1% are new trans-Saharan roads through Mauritania, Mali, and Chad and reopening the closed Morocco-Algeria border. Some new roads in Central and Southern Africa would also significantly increase RE/MA. When border frictions are activated, the MA gain drops from 5.5% to 3.9%, with particularly high losses on remote and border-crossing links. The median link yields a 50% lower MA gain under frictions.

According to the World Bank ROCKS database, the median 2-lane highway in Africa costs $611K 2015 USD per km. Using a heterogeneous road costs prediction model considering road length, terrain ruggedness, and population density, I estimate the cost of the existing transport network at $186B USD'15, and the proposed extension of $104K km at $56B, yielding an average MA return of $1.4/km per $ invested in new links, which drops to ~$0.7/km/$ if frictions are added.

Examining road quality measured by travel speed, I find that upgrading all links to ≥100km/h yields a time-denominated MA gain of 42.1%. New links yield a 14.1% MA gain if built at 100km/h on top of the existing (slow) network. Upgrading the entire network to fast links and also building the proposed ones could yield a 50% MA gain. There is significant heterogeneity in the value of upgrading links, with trans-Saharan links yielding the greatest MA gains. Applying border frictions lets the total MA gain from upgrading all links drop to 27%. Again, particularly peripheral and transnational links lose value. I estimate the cost of upgrading the entire network at $106B, comprising $67.8B full upgrades, $36.5B mixed works, and $12.3B asphalt resurfacing. Upgrading all roads yields average gains of $6/min per $ spent, which drops to $2.4/min/$ under frictions.

To raise average returns, I consider investment packages targeting high marginal gain links (both upgrades and new roads). I propose three packages with links at marginal gains >1, 2, or 4 $/min/$. They cost $60.9B/$36.6B/$17B, yield frictionless MA gains of 38.1%/30.6%/20%,

and 26.8%/24%/19.5% under frictions. These packages are globally macroeconomically feasible under frictions if they can raise Africa's aggregate growth rate (4.1%) by 0.33%/0.2%/0.09%. For the >\$1 (\$60.9B) package, this would require that growth in MA translates into economic growth at a rate of $\geq 81{:}1$. This is plausible in light of empirical results suggesting economic returns to MA gains as high as 3:1, but there are several factors that could raise the cost of these packages considerably and lower the macroeconomic returns, especially if they are financed through debt.

Calibrating a general equilibrium framework by Fajgelbaum & Schaal (2020) permitting global optimization over the space of networks, I also derive optimal investments in spatial equilibrium, letting a welfare-maximizing social planner spend a fixed infrastructure budget. My calibration accounts for trade in multiple goods and through international ports. I consider cases with/without inequality aversion, cross-border frictions, and increasing returns to infrastructure. I also simulate with different values for the elasticity of substitution (σ). Planners with a baseline budget of \$35B optimally connect large cities and ports with each other and surrounding smaller cities, focusing on populated/productive areas. An inequality-averse planner invests slightly more in the poorer Central African and the Horn of Africa regions. About 30% of the investments are new/proposed links, built particularly around major cities to limit congestion. With increasing returns to infrastructure (low congestion forces), the investments become less concentrated around large cities, and the planner upgrades more roads (building few new ones). This increases welfare gains. With inequality aversion, the gains again become more equitable at minor aggregate losses, and the planner upgrades more roads in Central Africa. Overall, due to concave utility of consumption, remote cities gain more welfare despite receiving less infrastructure.

To focus spending on important roads, I additionally consider a trans-African planner that optimally invests in continental transport roads connecting 47 major (port-)cities. The planner, endowed with \$15B, also mostly improves regional connectivity under standard assumptions of $\sigma = 3.8$. Much is invested along the West African coastline, but also in better connecting Dakar to Bamako, Khartoum to Egypt, Kampala to Mogadishu via Mombasa, and Kinshasa to Mbuji Mayi. An inequality-averse planner fully connects Kinshasa to Bukavu/Rwanda and further to Mombasa, Mogadishu, and Dar es Salaam. Thus, the planner upgrades a corridor crossing populated Central Africa. To include truly pan-African investments with roads across sparsely populated Northern Central Africa (e.g., Goma to Bangui) and the Sahara within an optimally spent \$15B budget would require an unrealistically low elasticity $\sigma = 1.5$ coupled with inequality aversion and increasing returns. Further, activating border frictions reduces equilibrium investments along these links again, indicating that such investments should be coupled with trade facilitation measures.

In conclusion, the paper characterizes optimality for road network investments at different spatial scales and economic objectives from a pan-African perspective. It thus provides broad guidance for policymakers interested in improving Africa's road infrastructure. An overarching finding is that trans-African roads are neither MA nor welfare maximizing compared to benefits from improved local connectivity in populated areas or between nearby cities and coastal ports. This is especially true under border frictions, which reduce the value of trans-African links. Yet, these links are essential for trans-African trade under AfCFTA to pick up. A general policy recommendation is thus to prioritize regional connectivity improvements, reduce border frictions, and invest in trans-African roads along specific high-yield links/corridors. The graphical results provided in the paper and appendix should be helpful in prioritizing continental and regional investments, with detailed data and results available on GitHub. The multi-level approach combining routing engines, PE, and GE analysis can also be adapted to examine specific regions/investments— such as, recently, for the CEMAC region as part of a World Bank regional infrastructure assessment program. Towards this end, the Julia library and reproducibility package are utile.

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Appendix

Figure A1: Average Network Speed and WorldPop Population Estimate

Average Network Speed (km/h)   WorldPop 2020 Total Population Estimate
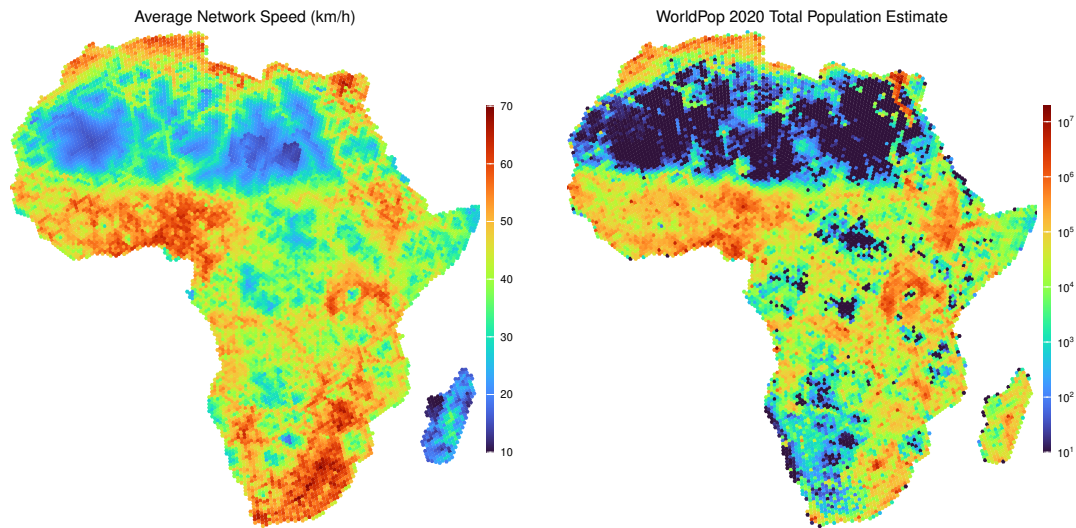
Figure A2: Gridded GDP and International Wealth Index

Gridded GDP PPP in 2015   International Wealth Index (2017+)
(Kummu et al., 2018)   (Lee & Braithwaite, 2022)
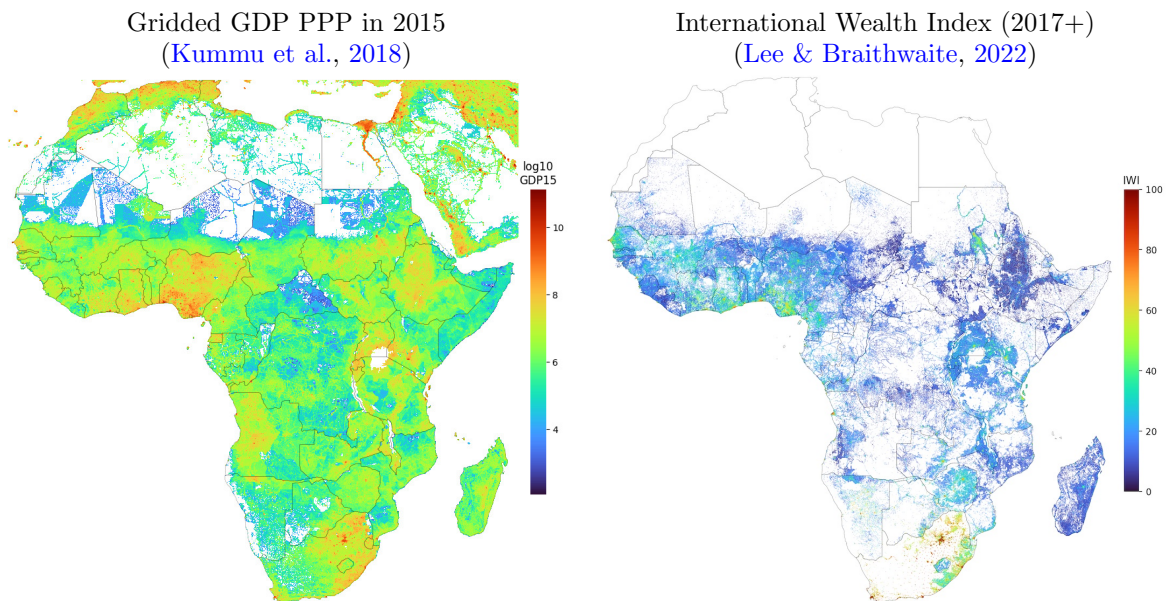
Figure A3: Imputed International Wealth Index using Database of Krantz (2023)

Predicted International Wealth Index: Imputed With MissForest, R-Squared = 0.970
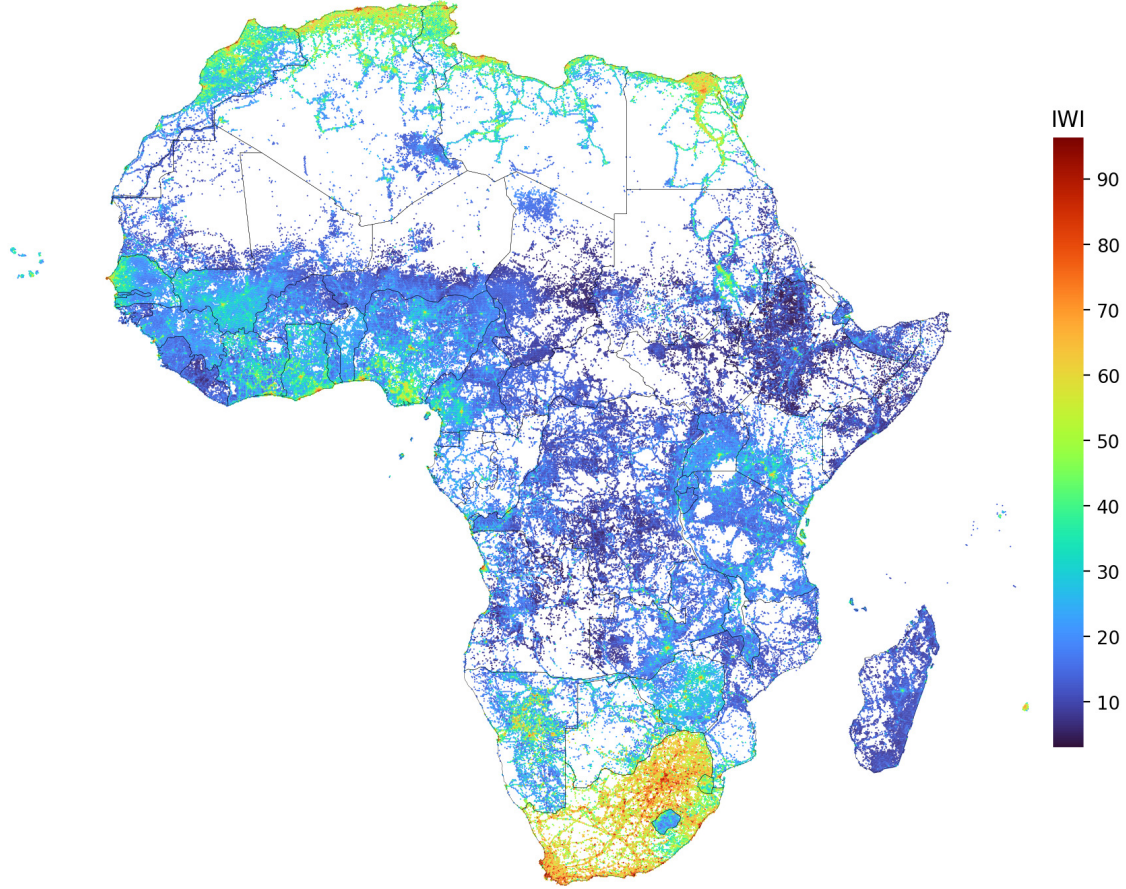
Notes: The high R^2 is not surprising as the estimates of Lee & Braithwaite (2022) also utilize many features from OSM in their methodology and Random Forests is very flexible. A concern with the imputation is that the relationship between infrastructure and wealth may be different south of the Sahara. Lee & Braithwaite (2022) mention the absence of (recent) DHS surveys in North Africa as an obstacle to extending their methodology to them. Their success in estimating cross-country models for all of SSA, including South Africa, however suggests that these models - approximated by *MissForest* - should also provide acceptable predictions in North Africa.

Figure A4: Market Access Maps using GDP in 2015 USD PPP: $\sigma = 3.8$

$\theta = 3.8$ (Jedwab & Storeygard, 2022), cor(MA, GDP) = 0.894-0.962

Market Access (Total 2015 GDP PPP per Road Hour to the Power 3.8) Market Access (Total 2015 GDP PPP per Road Km to the Power 3.8)
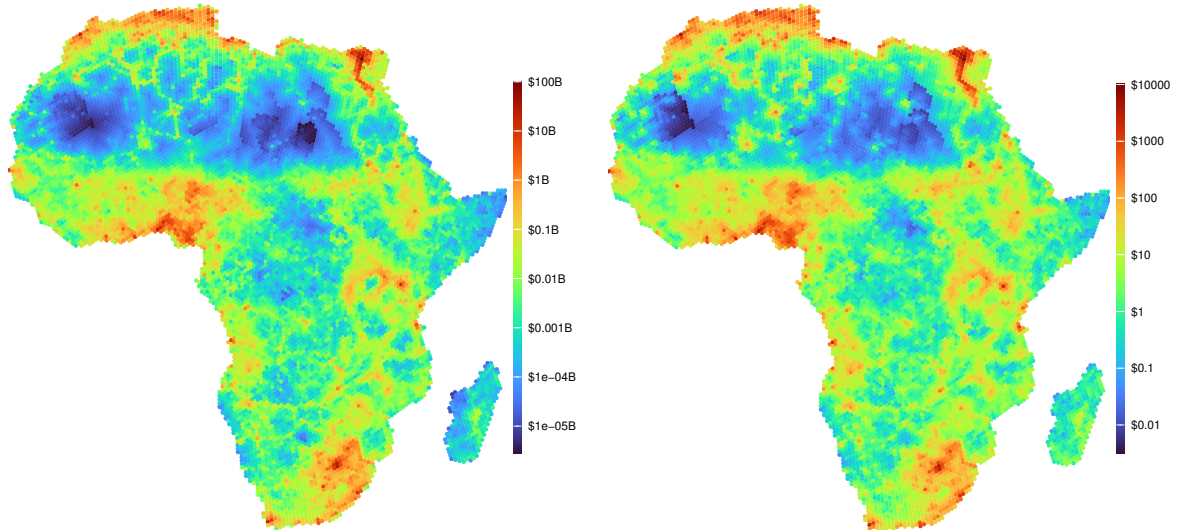
Figure A5: Market Access Maps using GDP in 2015 USD PPP: With Frictions

$\theta = 1$ (Peng & Chen, 2021), cor(MA, GDP) = 0.519-0.530

Market Access (Total 2015 GDP PPP per Road Hour)

Market Access (Total 2015 GDP PPP per Road Km)

$\theta = 3.8$ (Jedwab & Storeygard, 2022), cor(MA, GDP) = 0.894-0.962

Market Access (Total 2015 GDP PPP per Road Hour to the Power 3.8)

Market Access (Total 2015 GDP PPP per Road Km to the Power 3.8)
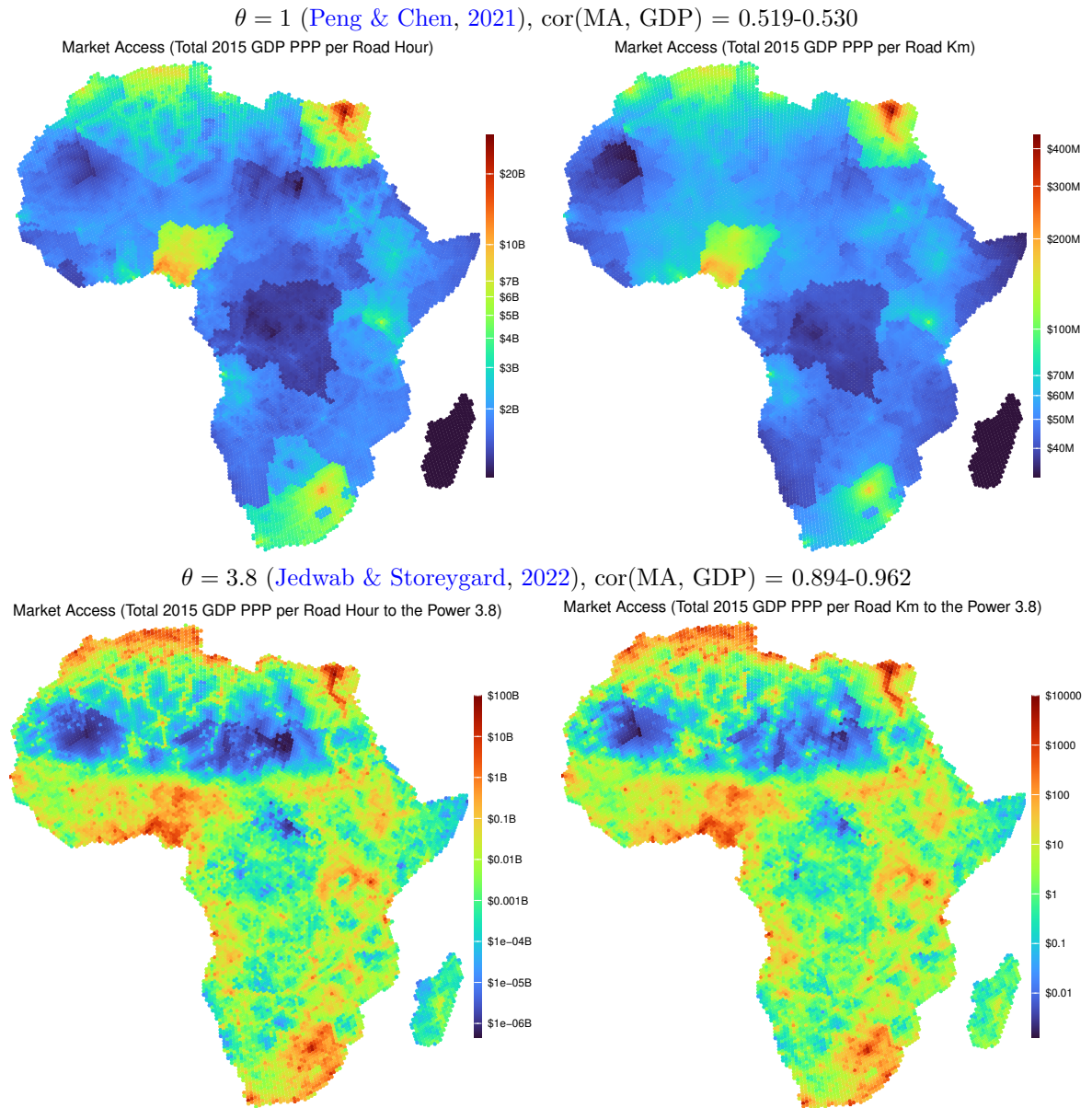
Figure A6: Market Access Loss (%) from Border Frictions under $\sigma = 3.8$

Travel Time

Road Distance
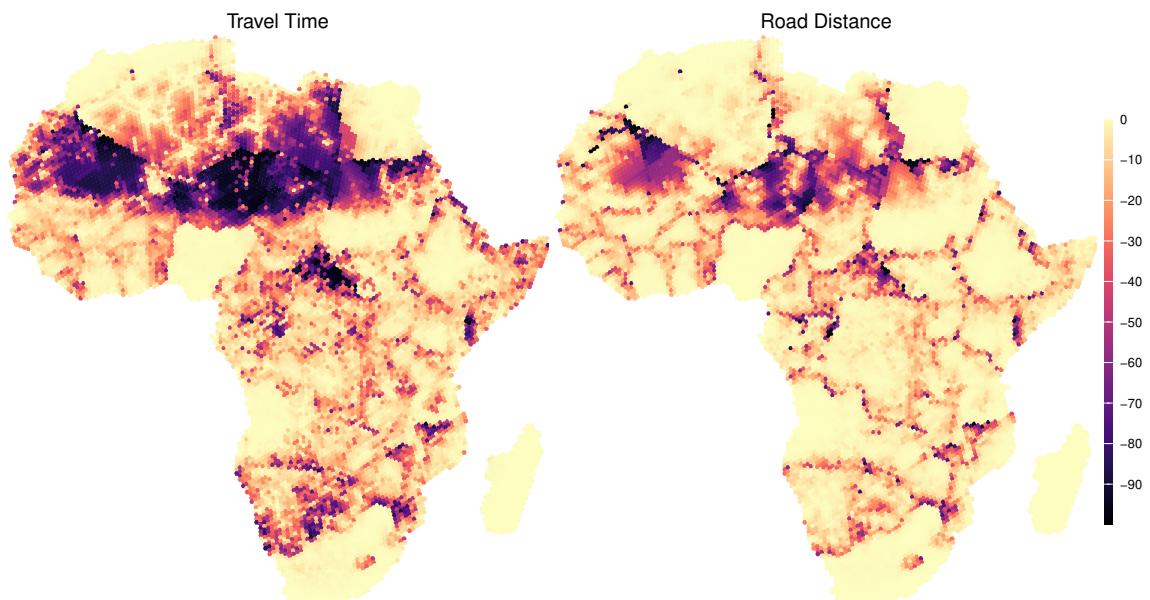
Figure A7: Discretized Trans-African Network Plus Original Routes

Sum of Gravity
— 0 to 5
— 5 to 25
— 25 to 125
— 125 to 625
— 625 or more
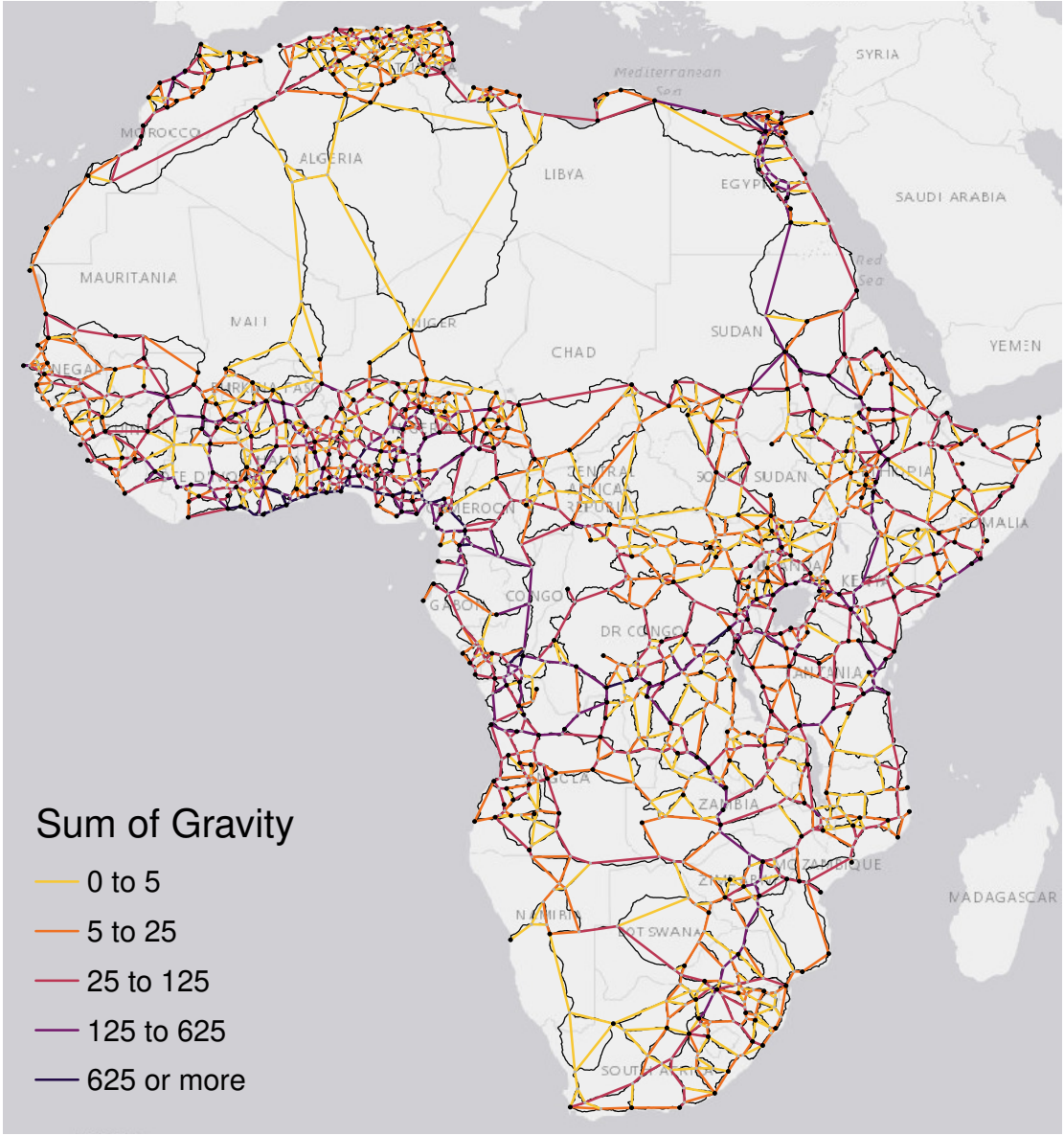
Figure A8: Discretized Trans-African Network and New Links for US Route Efficiency
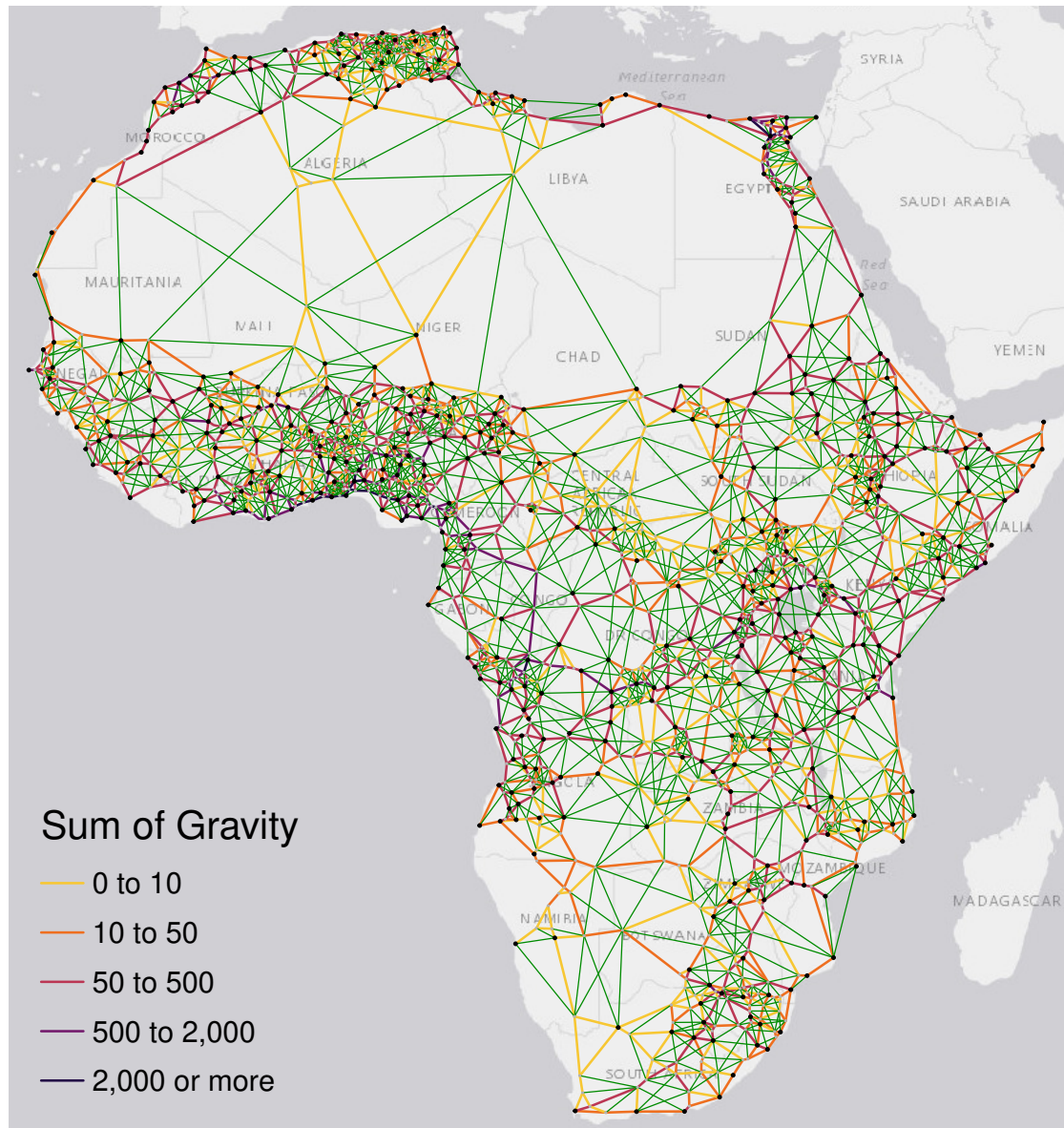
Figure A9: Estimated Network Building Cost per Kilometer

Total Network Building Cost Estimate
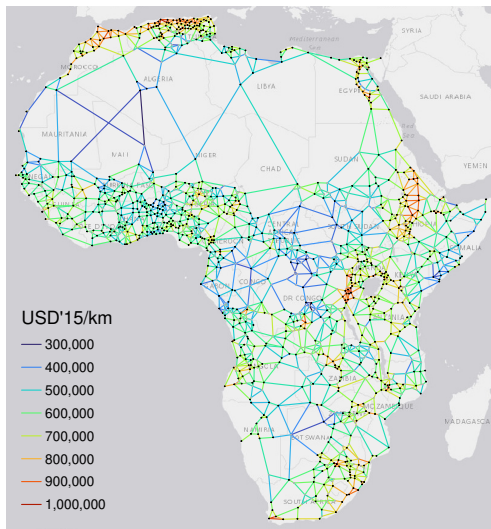
New Links + Algeria-Morocco 3× Cheaper
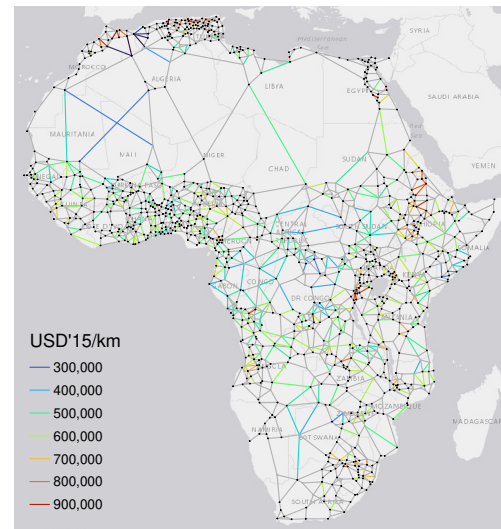
Figure A10: Nightlights vs. IWI to Measure City Productivity

Nightlights/Capita (20km Buffer)
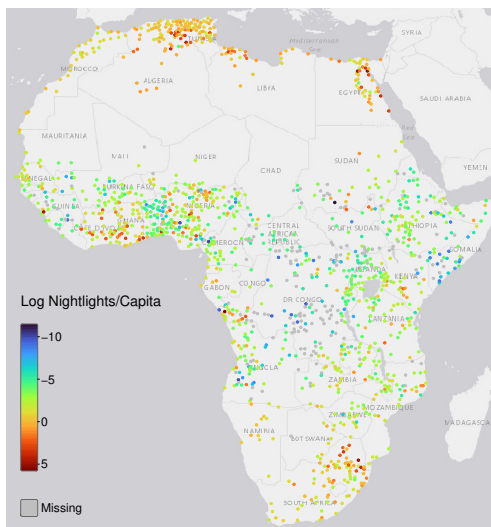
IWI by Lee & Braithwaite (2022)
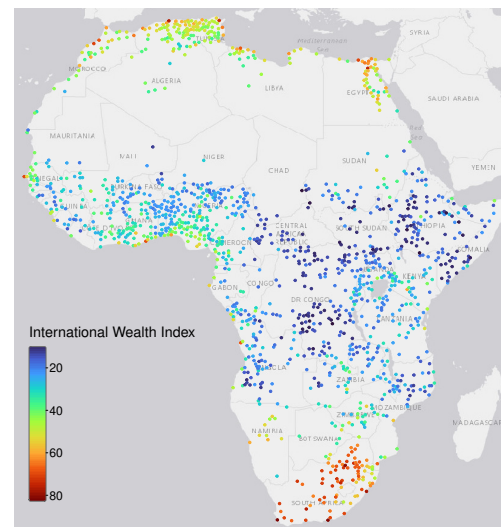
Figure A11:   Cost-Benefit Analysis (USD/min MA Gain per USD Invested)

No Border Frictions

Frictions at Origin/Destination + 48h Transit

Frictions in Network + Optimizing Agents

Consensus Upgrade (ΔMA/USD > 1)
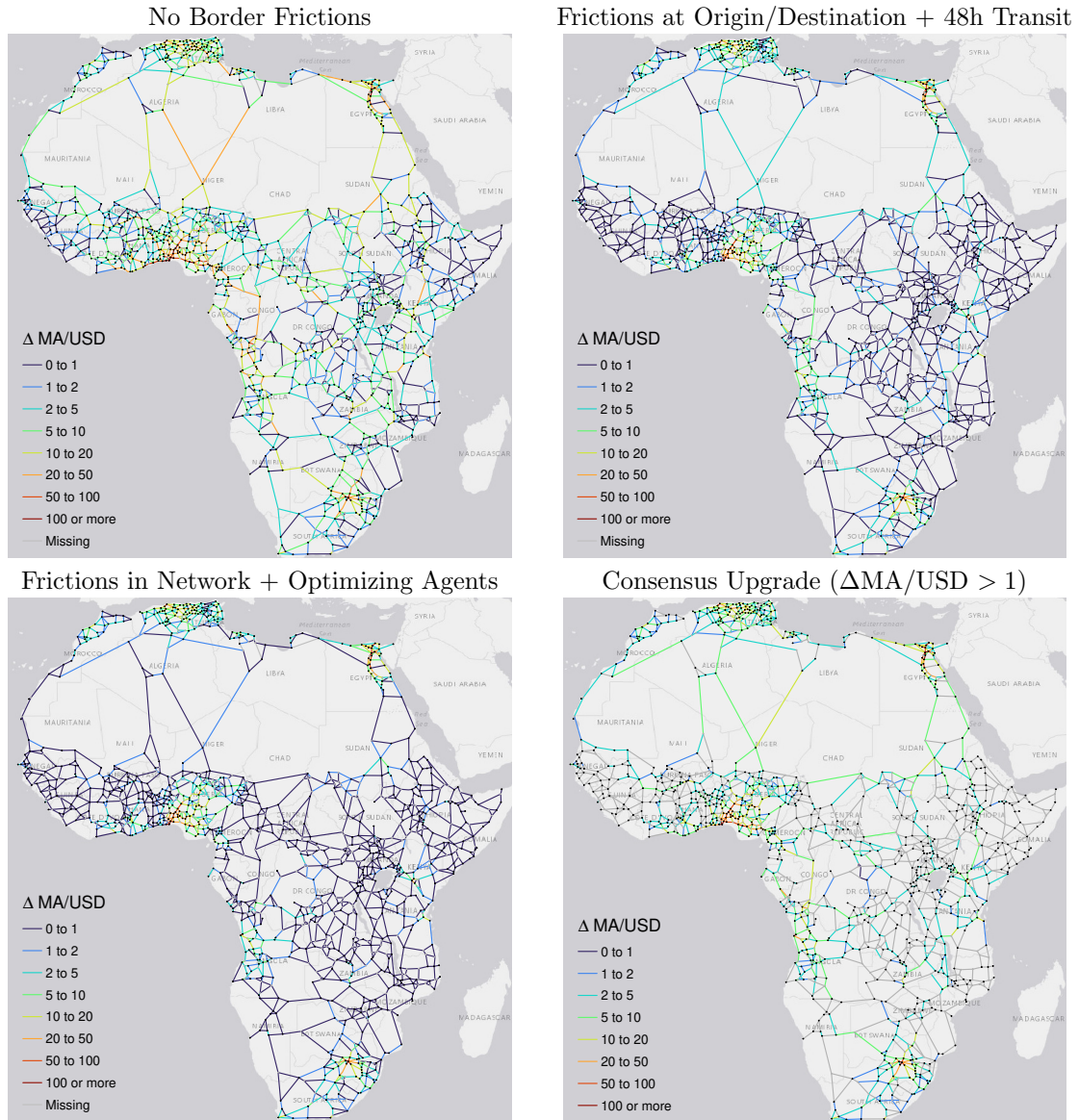
Notes: Figure shows MA returns in USD/min per USD invested in link upgrading under different types of border frictions.

Figure A12:   Estimated Network Building/Upgrading Cost per Kilometer
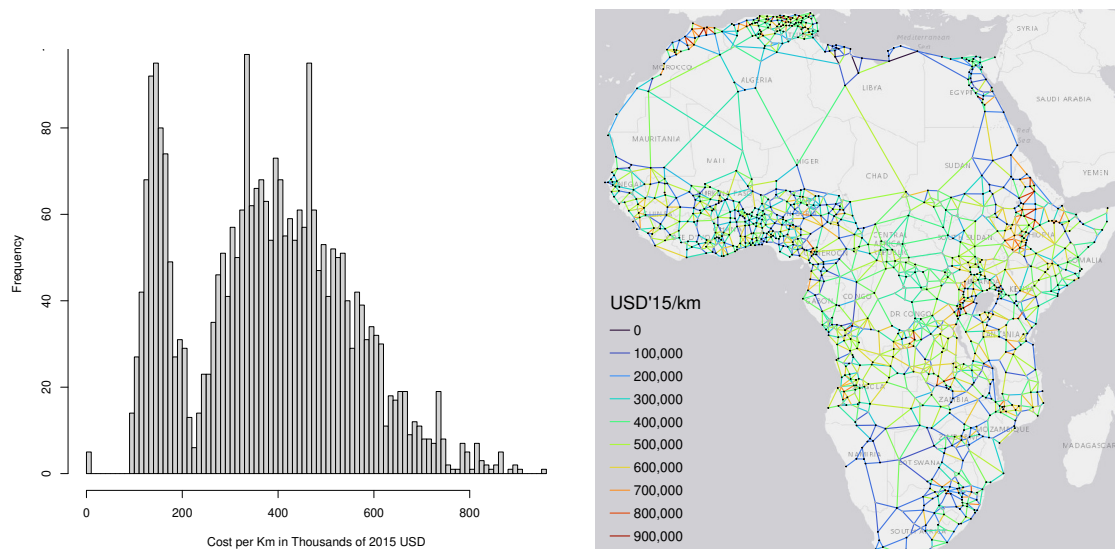
Notes: Figure shows combined cost/km of building new (fast) links and upgrading existing links to speed ≥100km/h.

Figure A13: Cost-Benefit Analysis: Joint Scenarios (USD/min MA Gain per USD Invested)
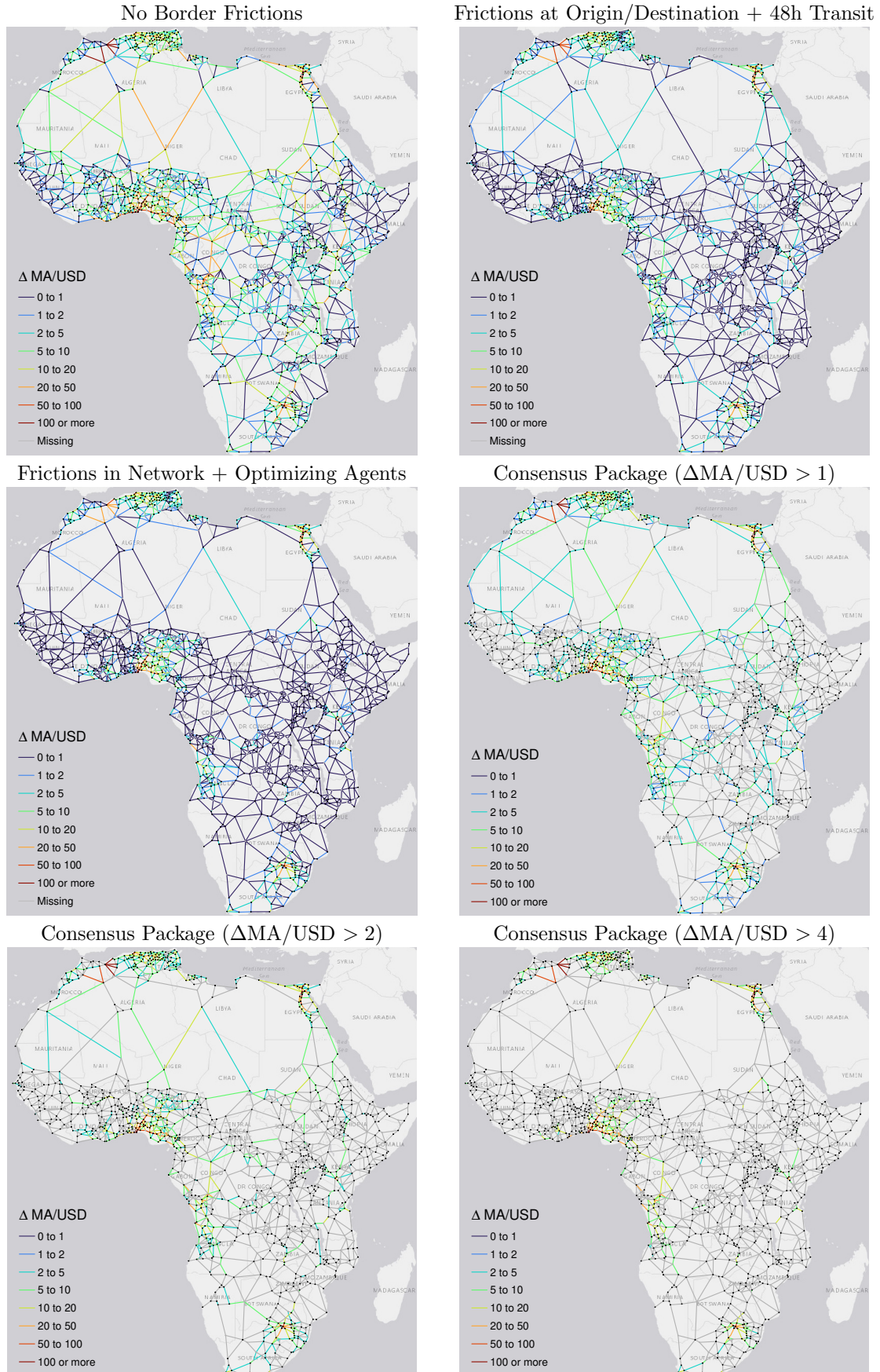
Notes: Figure shows MA returns in USD/min per USD invested in link building and/or upgrading under different types of border frictions. It also shows 3 different 'consensus packages' containing high-returns links with and without frictions.

Figure A14: Hypothetical Trans-African Network Connecting the 1370 Nodes with EU Route Efficiency
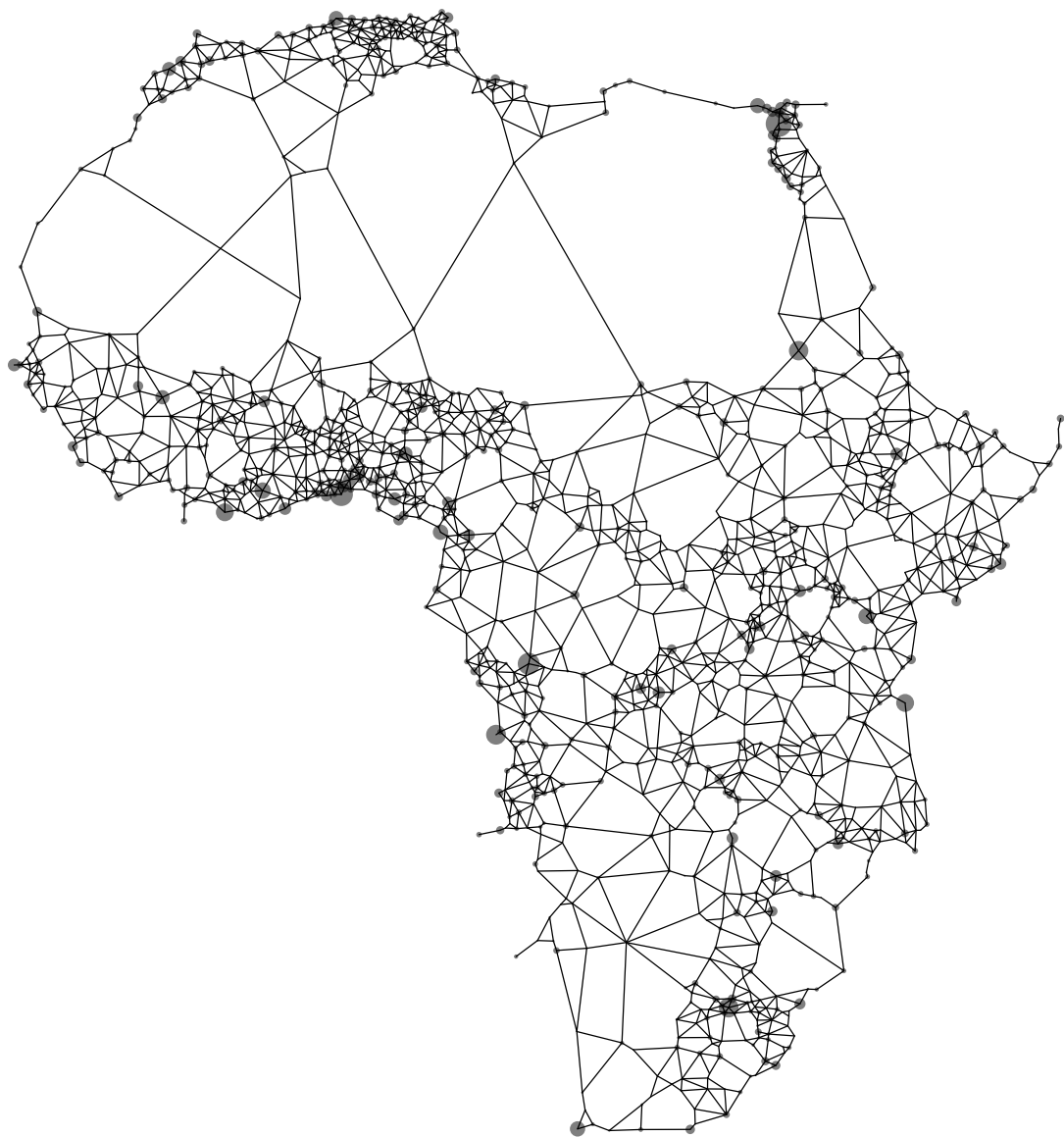
Figure A15: Flow of Goods Following $35B Investments under Decreasing Returns and $\sigma = 2$
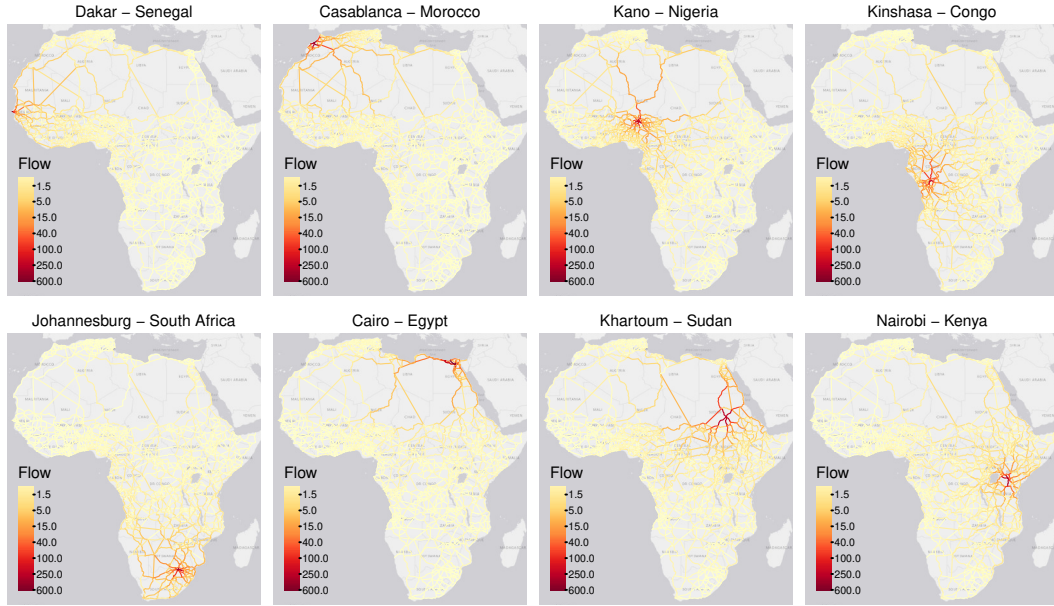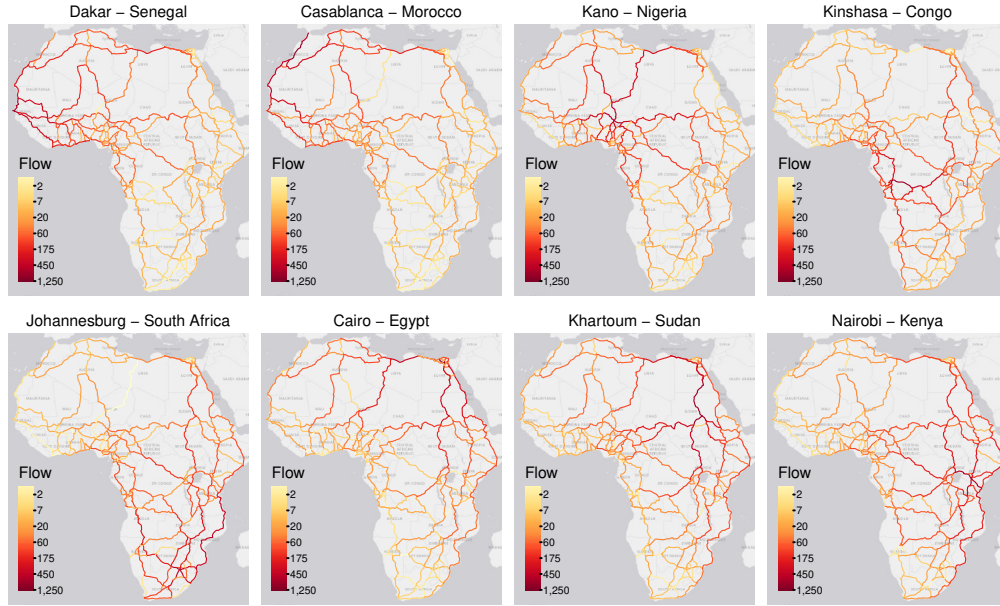

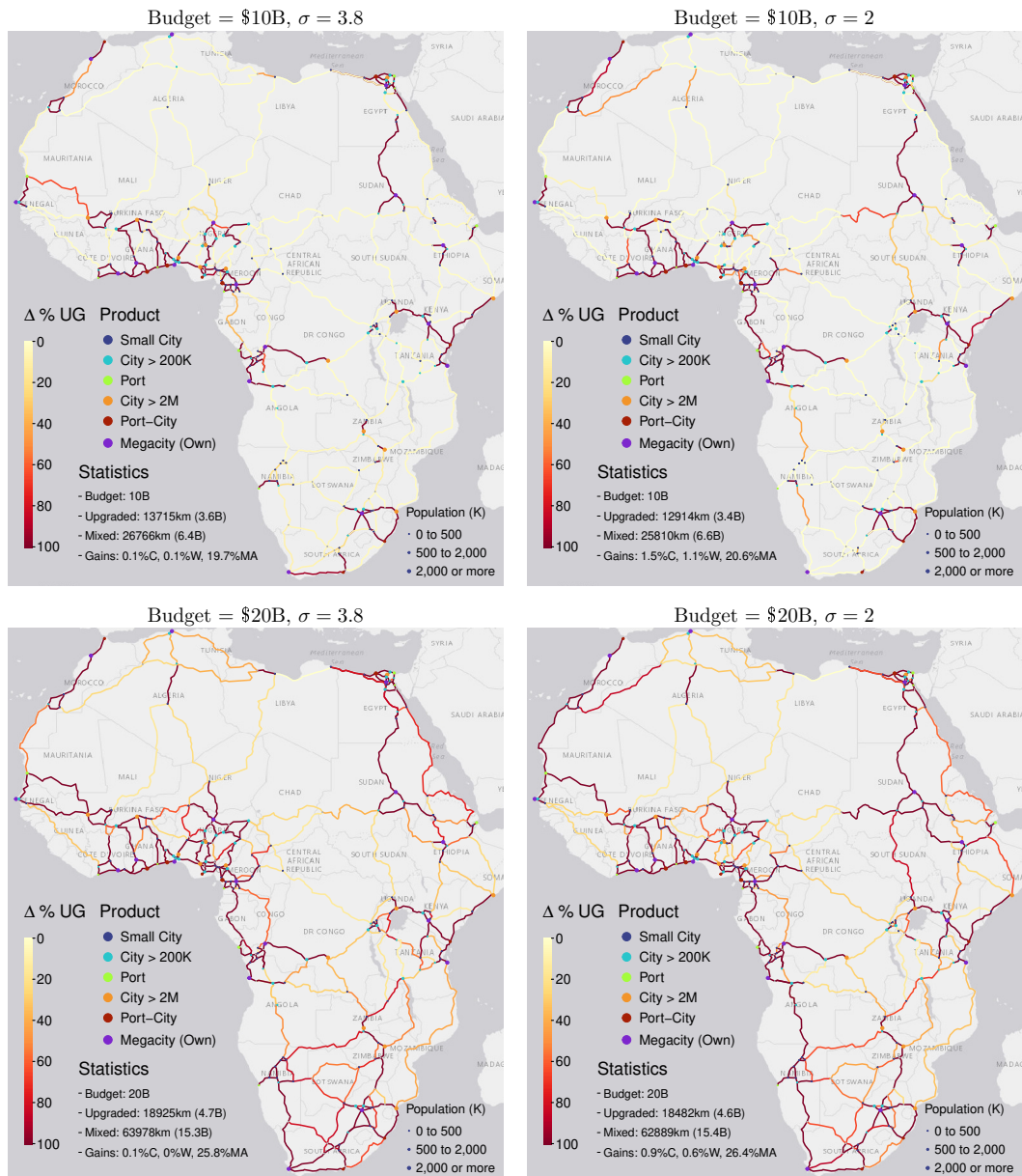Figure A16: Optimal Network Investments under Decreasing Returns: Alternative Budgets

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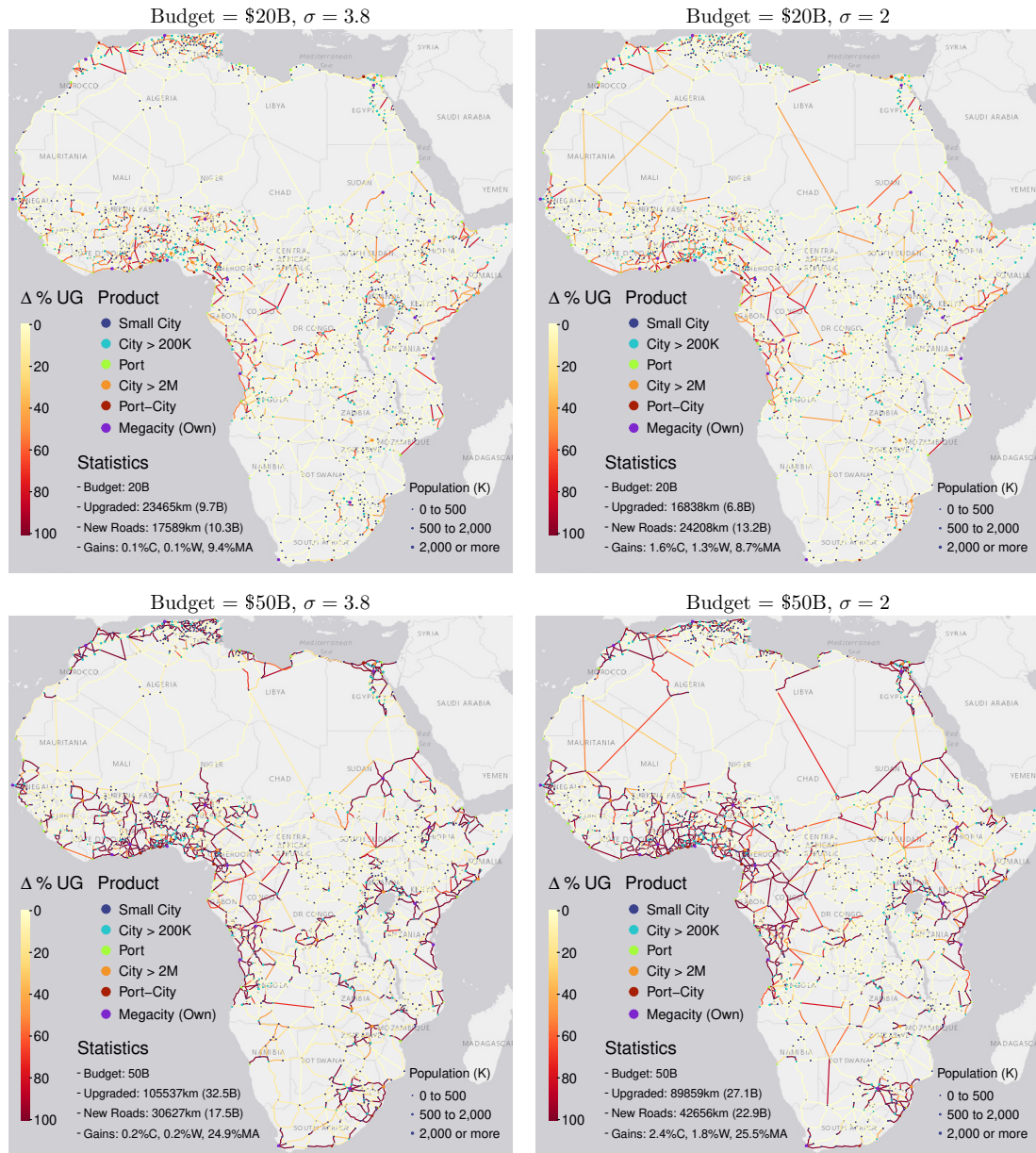
Figure A17: Flow of Goods Following $35B Investments under Increasing Returns and $\sigma = 2$
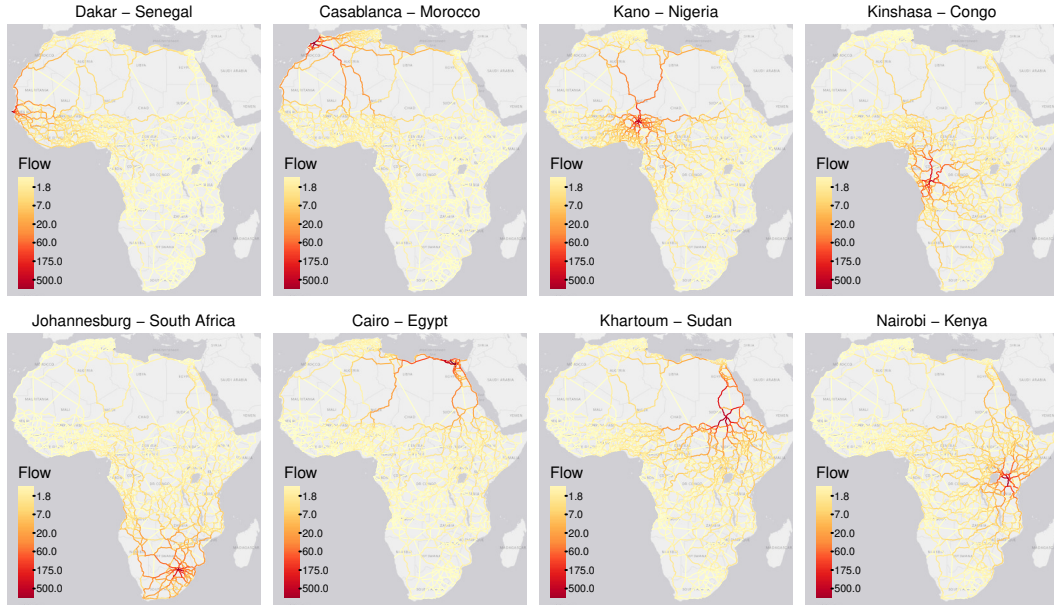
Figure A18: Optimal Network Investments under Increasing Returns: Alternative Budgets
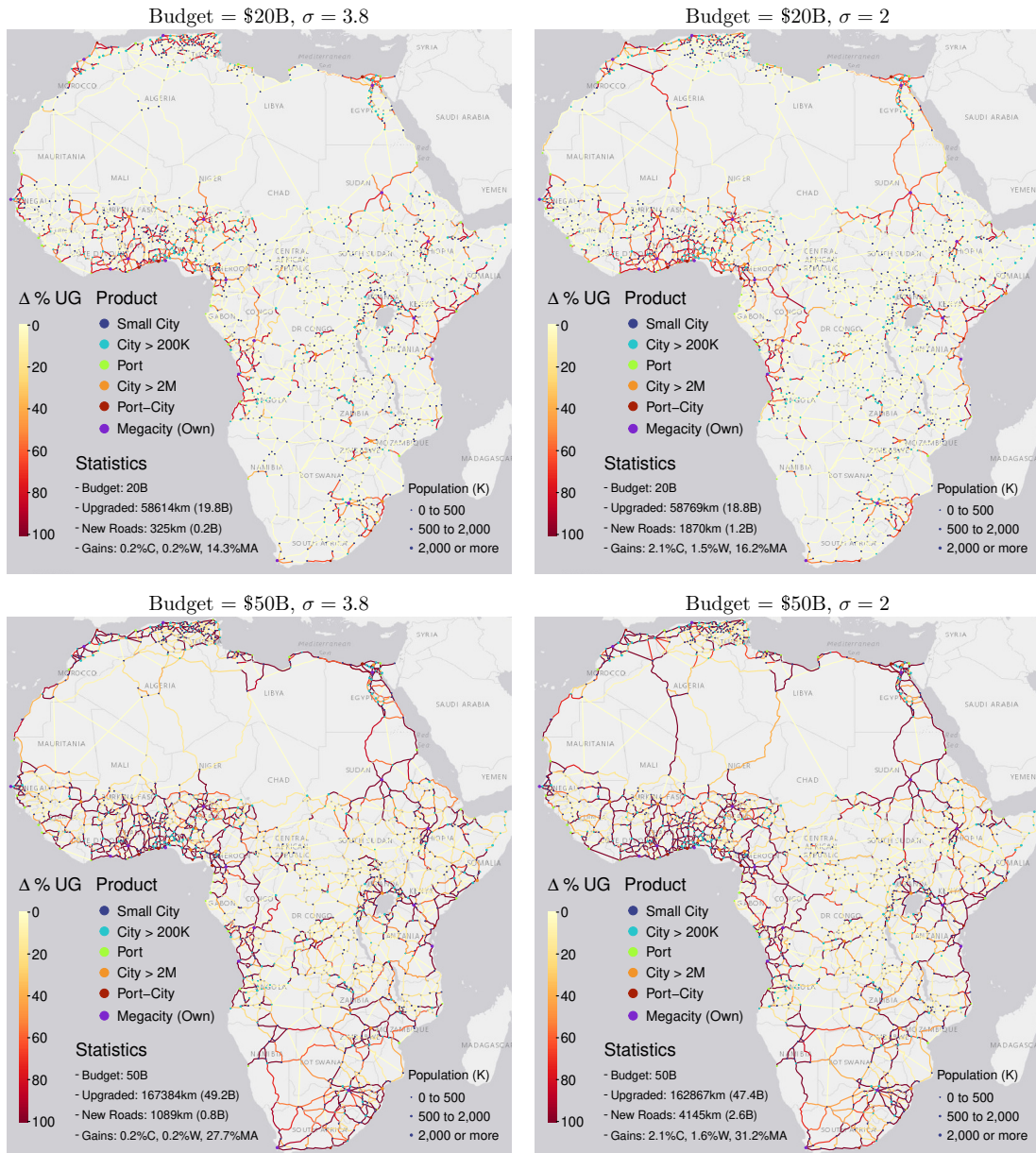
Figure A19: Optimal $35B Network Investments under Increasing Returns: Difference in Welfare (Gains) under Frictions

Figure A19: Optimal $35B Network Investments under Increasing Returns: Difference in Welfare (Gains) under Frictions
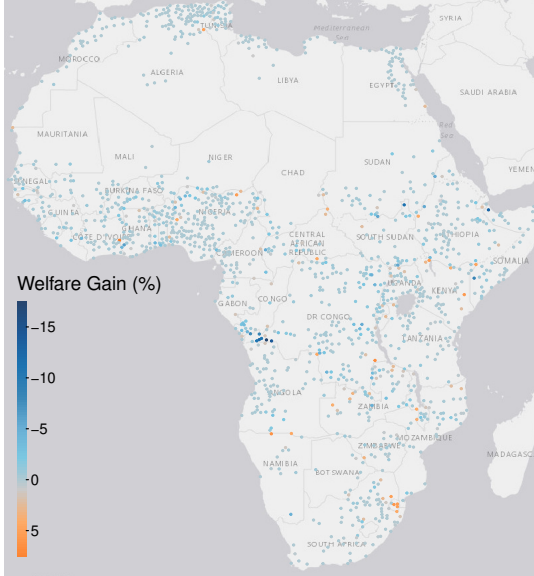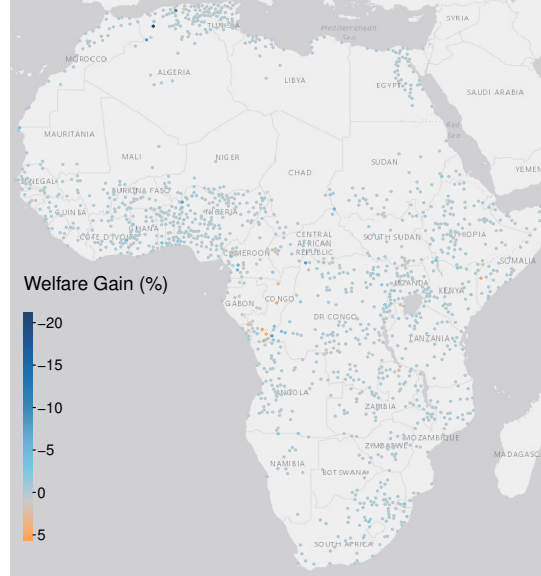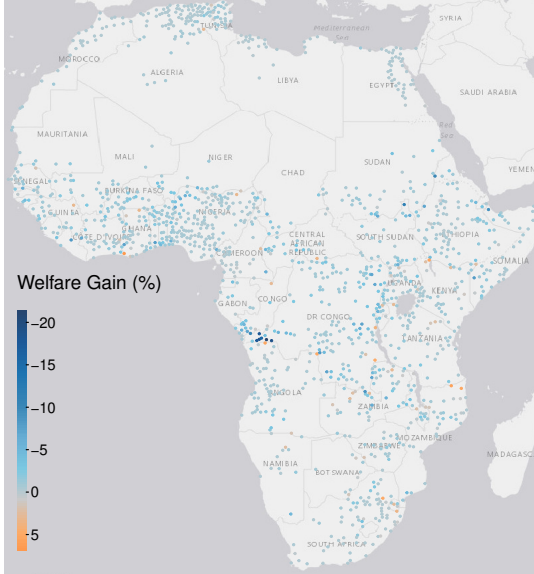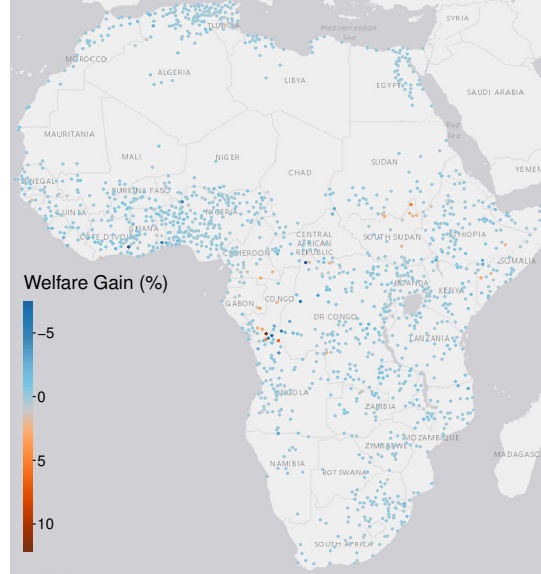
Notes: Figure compares the difference in welfare gains. The LHS maps provide the difference in % before the investment for different values of σ (i.e., the negative welfare loss ex-ante), and the RHS maps show the difference in (relative) welfare gains in % from optimal $35B investments. All differences are computed against the frictionless case.

Figure A20: Flow of Goods Following \$15B Investments under Decreasing Returns and $\sigma = 2$

Figure A21: Optimal Network Investments under Decreasing Returns: Alternative Budgets

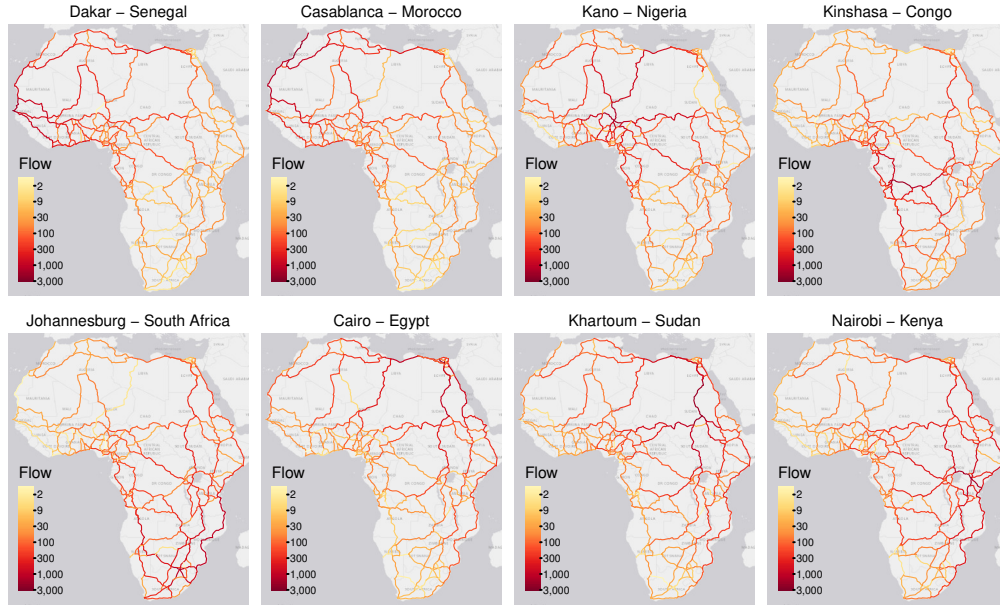Figure A22: Flow of Goods Following $15B Investments under Increasing Returns and $\sigma = 2$

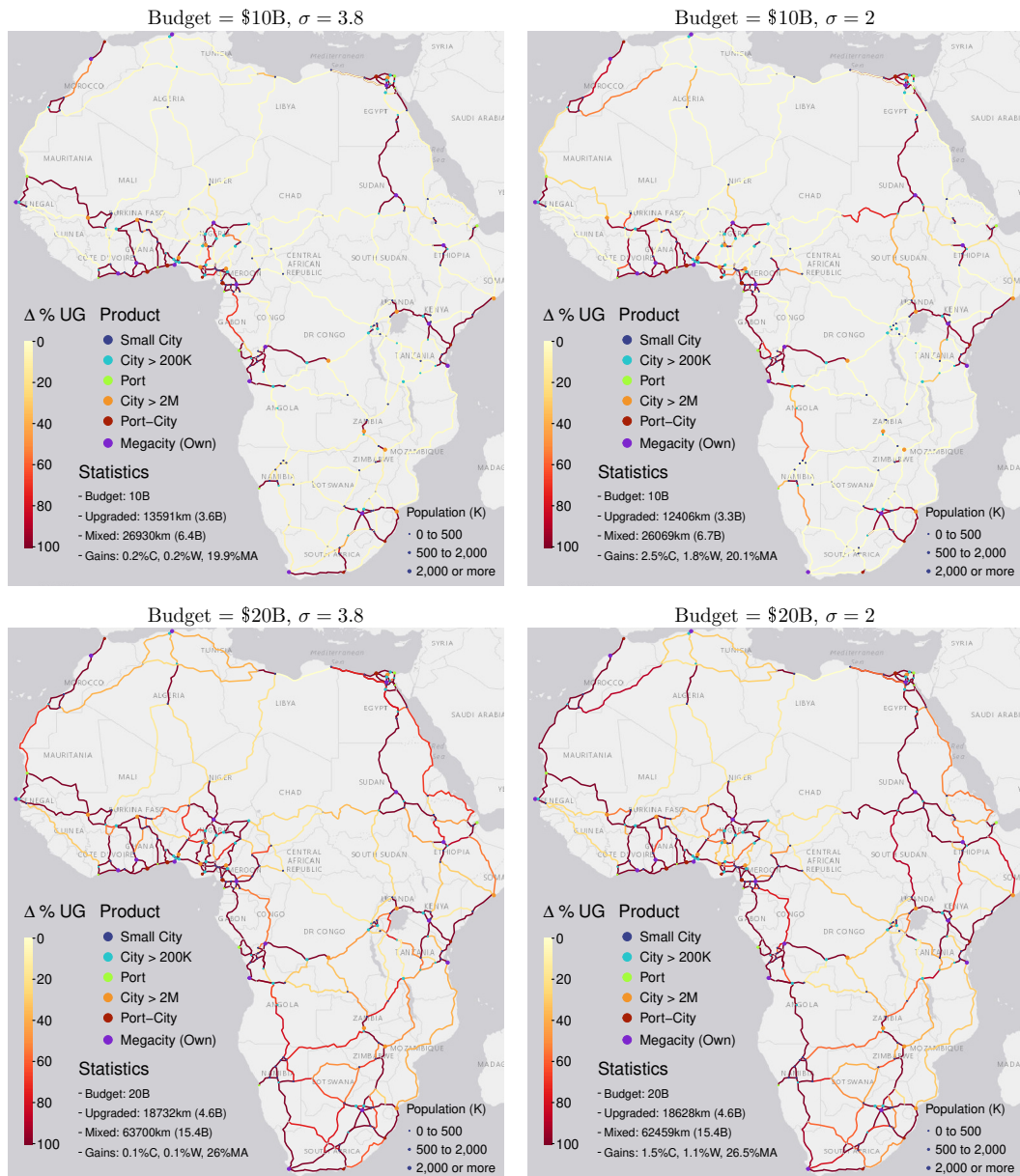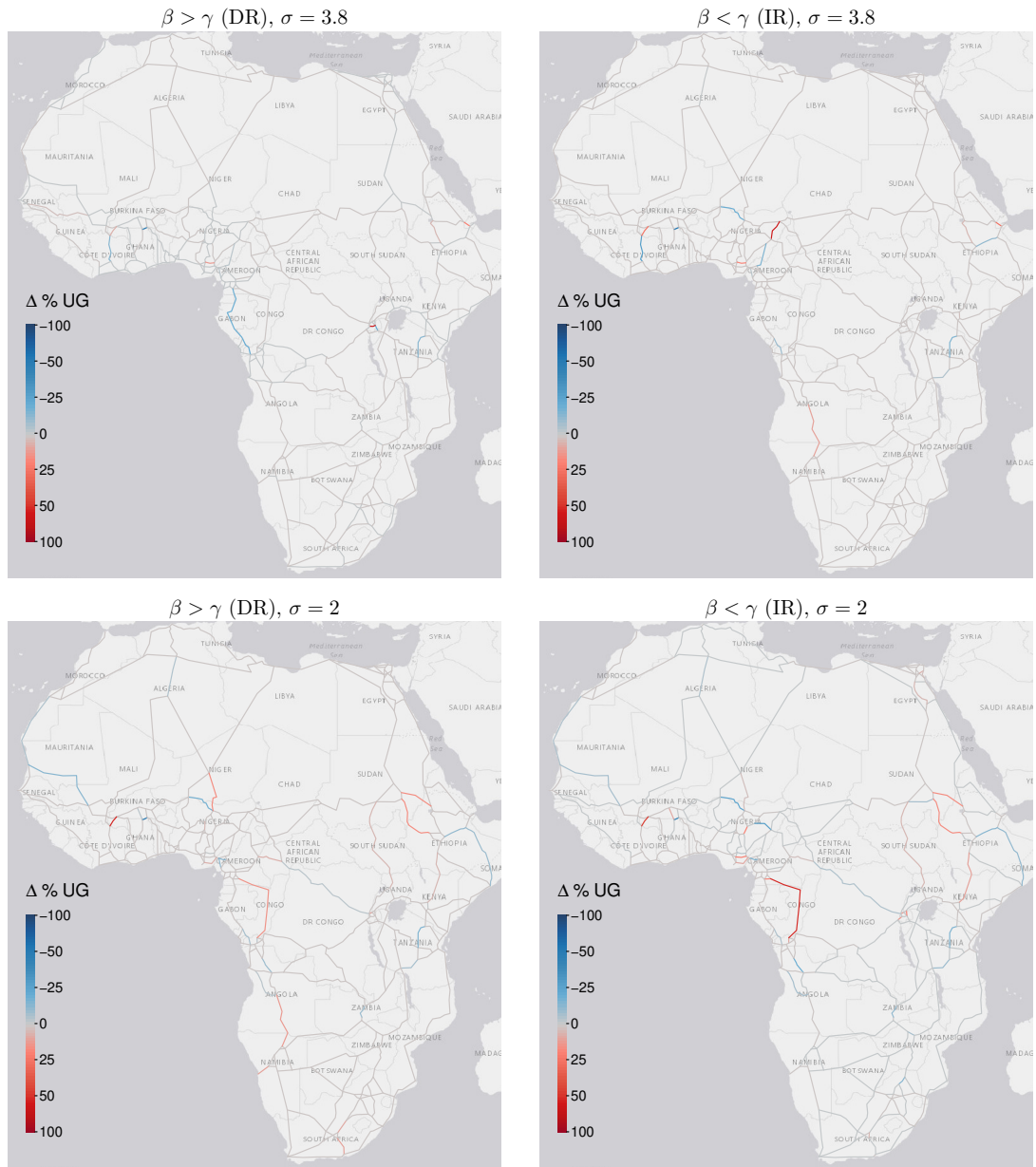Figure A23: Optimal Network Investments under Increasing Returns: Alternative Budgets

Figure A24: Optimal $15B Network Investments under Frictions: Difference