The Trans-Sumatra Toll Road and Economic Geography in Indonesia*

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Abstract

We develop and calibrate a quantitative spatial equilibrium model of Indonesia to analyze the potential impact of the Trans-Sumatra Toll Road project on the country's economy. The estimated aggregate welfare gains vary from 1.33 percent of the country's output if there is only trade in final goods to 3.59 percent if sectoral linkages and trade in intermediates are allowed, and they further increase to 4.15 percent if labor mobility is considered. About 86.5% of gains result from improved product market integration and 13.5% from easier worker migration. Finally, the welfare effect concentrates on Sumatra, whereas the overall national inequality declines.

Keywords: Transport infrastructure, economic geography, trade in intermediates, migration, Indonesia

JEL Codes: F10, R11, R13

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1 Introduction

Indonesia, whose more than 17,500 islands make it the largest archipelago country in the world, is the fourth most populous country in the world and the largest economy in Southeast Asia. The country has achieved remarkable economic growth since the Asian Financial Crisis, becoming an upper-middle-income country. However, poor transport connectivity has increasingly become a barrier hindering its economic performance and limiting convergence across the archipelago. In response, the Indonesian government has set ambitious goals to bridge the infrastructure gap, exemplified by a series of projects in Sumatra, its second-largest island both in population and economic importance.

The Trans-Sumatra Toll Road is an expressway project aiming to improve Sumatra's connectivity. The project, launched in 2013, is designed to span 2,818 kilometers, interlinking Banda Aceh in the north of the island with Bakauheni in the south and effectively bridging the island's eastern and western shores. Its development is divided into four phases, with over 500 kilometers already operational by 2023. This paper explores the potential effects of this enormous undertaking on the economic development of Sumatra and other parts of Indonesia in a spatial general equilibrium model.

Our quantitative framework builds on that of Caliendo and Parro [2015], which stresses sectoral linkages with the following innovations. First, our model replicates the Indonesian labor market's mobility challenges by extending the basic framework to an economy with frictional labor mobility across geographic units (Ahlfeldt et al. [2015], Bryan and Morten [2019]). In the model, better road connectivity helps facilitate labor mobility and thus fosters internal migration. It is then possible to disentangle welfare enhancements attributed to the integration of goods and labor markets, respectively. Second, as time has been considered a critical determinant of trade and migration barriers in the literature (e.g., Hummels and Schaur [2013], De Soyres et al. [2020]), we calibrate the corresponding reduction in trade cost for goods and cost of migration for labor due to faster travel speeds, a significant effect of the toll road.[1] In particular, we use detailed road network data to estimate the traffic times between Indonesian provinces before and after the road construction to overcome the issue of imprecisely measuring the toll road's impact based on travel distance.[2] In the calibration, trade and migration costs are parameterized by travel times instead of travel distances, relying on model-implied structural equations and trade and migration flow data.

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[1] For instance, Hummels and Schaur [2013] quantify that a single-day delay in shipping corresponds to an ad-valorem tariff of approximately 5 percent.

[2] Sumatra is extremely rich in flora and fauna, and the alignment of the Trans-Sumatra Toll Road has been thoughtfully selected to avoid wildlife sanctuary areas, with many segments being designed to parallel the existing roads. Therefore, computing change in travel distance cannot capture the improved connectivity brought by the Tans-Sumatra Toll Road.

The impact of the toll road is then simulated by estimating the reductions in travel times and generating subsequent exogenous variations in the costs of trading goods and migration.

Our quantitative model has multiple locations and sectors. Geographically, it covers eight provinces of Sumatra, the other 26 Indonesian provinces, and the rest of the world. There are primary, industry, and service sectors on the production side. Each Indonesian province imports intermediate goods subject to trade costs from the lowest-cost suppliers offered by firms from all provinces and from the rest of the world. Intermediate goods imported into a given sector are used to produce final goods in that same sector, which are then consumed or used as materials in the production of intermediate goods for all sectors. On the household side, each worker decides where to work and live based on the expected utility obtained from all potential destinations. The housing sector includes residential land use that is determined exogenously. A worker's utility calculation further depends on wages, prices of consumption goods and housing, migration costs, and idiosyncratic tastes. In equilibrium, labor distribution and factor prices are jointly determined such that all markets in all locations clear. Sectoral and regional linkages in our model are crucial to capturing how the reduction in trade and migration costs due to better road connectivity may have a differential impact across regions and sectors.

We calibrate our model to the equilibrium of the Indonesian economy in 2016. The key parameters are the shares of intermediate goods in production and sectoral interrelations, and inter-province trade in goods and services, both of which are drawn from the Indonesia inter-province Input-Output (I-O) table, and inter-province migration flows constructed from the Indonesia National Socio-Economic Survey. The model-implied structural equations are used to estimate the elasticity of trade and migration costs with respect to travel times. The remaining utility and production technology parameters are estimated using various macro data sources, or are drawn from the literature. In calibrating trade and migration elasticities, the entire network of existing roads in Indonesia is digitized to compute the travel times matrix between provincial capital cities for the scenario without the project. The road speed assumptions are chosen to match the travel times closely with those based on Google Maps. For policy evaluation, the planned segments of the toll road are digitized, relying on official documents, and incorporated into the existing road network to compute the travel times matrix for the project scenario. The differences between the two matrices constitute travel time reductions reverted to trade and migration cost reductions as policy shocks, using the estimated elasticity.

This quantitative exercise reveals that the construction of the Trans-Sumatra Toll Road has considerable effects on Indonesia's economy, driven by product market integration and trade. The aggregate welfare gains are about 4.15 percent. Dissecting the sources, we find that aggregate welfare gains vary from 1.33 percent of the country's output if there is only trade in final goods, to 3.59 percent if sectoral linkages and trade in intermediates are allowed. The gains further increase to 4.15 percent if migration cost reductions due to the project are considered. Overall, about 86.5 percent of gains are estimated to result from improved product market integration and 13.5 percent from easier migration for workers. Gains in trade value, including both intra-provincial and foreign exports, exhibit a similar pattern, at 1.20 percent if restricting to trade in final goods, approaching 3.61 percent after allowing sectoral linkages and trade in intermediates, and reaching 4.23 percent when considering the changes in migration costs as well.

Our results on aggregate welfare gains are consistent with those of recent evaluations of transport investments. For instance, Morten and Oliveira [2018] find that highway improvements in Brazil in the 1960s led to 2.8 percent aggregate welfare gains, and Coşar et al. [2022] show that public investment in roads in Türkiye in the 2000s resulted in a 3 percent increase in welfare. Baum-Snow et al. [2016] estimate the welfare contribution of the national highway system in China at around 5 percent, and Egger et al. [2023] reach a similar conclusion, determining that the welfare contribution of China's highway improvements between the years 2010 and 2013 is around 5.68 percent.

The toll road also leads to the reallocation of economic activities, with substantial economic improvements in most provinces of Sumatra. Seven out of the eight provinces in Sumatra experience an increase in welfare, with the exception of Lampung, which sees a welfare loss of 4.43 percent. Among the seven "winners", Riau, West Sumatra, and Jambi gain the most in terms of absolute value (47 trillion rupiah, 18 trillion rupiah, and 15 trillion rupiah), while Bengkulu experiences the highest percentage gain (93.54 percent). In contrast, among the 26 provinces outside Sumatra, only two provinces emerge as winners: Banten with a welfare gain of 1.95 percent, and Maluku with a gain of 1.15 percent. The remaining 24 provinces provinces see losses in welfare ranging from -0.28 percent to -4.06 percent.

Our quantitative findings are robust to alternative model assumptions. First, average driving times are used to compute travel times instead of the peak-hour travel duration. Second, exploring trade deficits in the real economy results in a smaller welfare change of 2.67 percent. Accounting for a five-year construction period for the road project leads to a slightly reduced aggregate welfare gain of 3.70 percent.

This paper contributes to several strands of the literature. First, it is closely related to other work exploring the welfare effects of transportation infrastructure investments in developing countries (Haughwout [2001, 2002], Allen and Arkolakis [2022]). For instance, in the context of China, Banerjee et al. [2020] study how highway networks affect regional economic outcomes. They find a positive and causal relationship between proximity to transportation networks and per capita GDP levels across different sectors. Similar research is limited in the context of Indonesia, a large country with significant transport infrastructure needs. This study takes a step toward addressing this gap. Indonesia's road network accounts for approximately 85% of passenger transport and 90% of freight traffic. The Trans-Sumatra Toll Road emerges as a pivotal link connecting Sumatra's regions. Our exploration helps to augment our understanding of how improved connectivity and better-integrated markets within Indonesia's unique economic and geographic context may impact its economic geography.

This paper also aligns with previous works applying the quantitative spatial equilibrium model to evaluate project or policy reforms, such as Bird and Venables [2019], Bird et al. [2020], De Soyres et al. [2020], Heblich et al. [2020]. While sharing many features with the existing studies, our approach has the advantage of depending less on model parameters in inferring equilibrium outcomes. Following Caliendo and Parro [2015], the solution method considerably simplifies the data requirements and estimated parameters needed to evaluate the connection to the Trans-Sumatra Toll Road. The model solution only depends on estimates of a few sets of parameters, regardless of the number of geographic units and sectors. These parameters include the share of input factors in production, the consumption share across sectors, the dispersion of productivity in trade, and the dispersion of amenities in migration. Notably, our approach deviates from the dynamic trade model employed by Caliendo et al. [2019] as we do not aim to capture the transition between two equilibria.[3] Additionally, we face constraints in accessing longitudinal migration data in Indonesia, which prevents us from estimating the dynamic transitions.

Finally, this paper is related to a growing literature that disentangles the underlying mechanisms of the welfare effect of better connectivity. Notable studies, such as Redding [2016], Lall and Lebrand [2020], Coşar et al. [2022], Morten and Oliveira [2018], attribute welfare gains to lower transportation costs, while others, such as Lall and Lebrand [2020], focus on the mobility of labor. Redding [2016] highlights that welfare gains depend on both the change in goods market integration and the re-allocations of population across locations. Morten and Oliveira [2018] are pioneers in systematically investigating the relative importance of goods and labor mobility in generating gains from better road connectivity. They explore the impact of an exogenous shock of highways in Brazil on both goods markets and labor markets and find that the road improvement increased welfare by 2.8 percent, of which 76% was due to reduced trade costs and 24% to reduced migration costs. Our findings

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[3] Caliendo et al. [2019] develop a dynamic trade model with spatially distinct labor markets facing varying exposure to international trade. They take a similar approach to ours, capturing the role of labor mobility frictions, goods mobility frictions, geographic factors, and input-output linkages in determining equilibrium allocations.

in Indonesia are consistent with those of Morten and Oliveira [2018] in that the main source of welfare gain is linked to trade, and more specifically, trade in intermediates.

The paper continues as follows. Section 2 provides background for the Trans-Sumatra Toll Road project and describes data used in the analysis. Section 3 sets up the quantitative spatial equilibrium model to study the effects of road improvements. Section 4 explains how key model parameters are calibrated and policy experiments are carried out. Section 5 presents the quantitative results concerning the effects of the Trans-Sumatra Toll Road. Section 6 conducts robustness checks. Concluding remarks follow in section 7.

2 Background and Data

In this section, we provide background information for the Trans-Sumatra Toll Road project, present key economic patterns for Sumatra, and summarize various data used for analysis.

2.1 Trans-Sumatra Toll Road Project

The government of Indonesia is prioritizing the development of transport infrastructure to improve intra- and inter-island connectivity and their economy's competitiveness. Indonesia ranked 72 out of 141 countries for infrastructure in the 2019 World Economic Forum Global Competitiveness Report. Its ranking by the Logistics Performance Index has also decreased due to poor infrastructure, becoming one of the worst within the Association of Southeast Asia Nations (ASEAN).

As in other parts of Indonesia, Sumatra ("Sumatera" in Indonesian) relies heavily on its road infrastructure. Sumatra is the largest island fully within Indonesian territory and the sixth-largest island in the world, encompassing over 470,000 km^2 in land area. It is elongated along a diagonal northwest-southeast axis, bordering the Indian Ocean from the northwest, west and southwest, located close to Malaysia and Singapore across the Malacca Strait in the northeast, and separated from Java ("Jawa" in Indonesian) by the narrow Sunda Strait in the southeast. Sumatra is also the second-largest island in Indonesia in terms of population and economic importance. It is a vital and natural migration destination and a potential economic powerhouse, second only to Java in economic dynamism. The government plans to transform Sumatra into a manufacturing hub specializing in natural resource processing. As a trade-oriented island, Sumatra trades domestically with other Indonesian islands and internationally through its ports, which aggregate goods through land transportation to achieve higher shipping efficiency. The ports in Sumatra have the potential to further benefit from their strategic locations on the Indian Ocean, Malacca Strait, and Sunda Strait. Tapping into this potential depends highly on intra-island road connectivity [4].

However, the existing national road network in Sumatra faces several challenges. The road network is mostly narrow, with residential constructions on either side of the right of way. The network has also been largely damaged by heavy rainfalls and severe droughts and typically exhibits slow or congested flow conditions.[5] The government has recognized these challenges and included enhancing transport infrastructure, particularly roads, among its priorities in planning documents, such as the Medium-Term National Development Plan (RPJMN) for 2020-2024. The Committee for Acceleration of Priority Project Delivery of Indonesia (KPPIP) has selected infrastructure projects linking to areas with high economic potential as priority projects, with more than 60 percent of projects in the road sector and two-thirds of them in Sumatra, including the Trans-Sumatra Toll Road.

The Trans-Sumatra Toll Road is a tolled expressway under development, which consists of 24 main sections with a total length of 2,818 km extending from Sumatra's northern tip, Banda Aceh, down to its southern tip, Bakauheni, as well as supporting sections connecting Sumatra's east and west coasts. The toll road aims to link Sumatra's key industrial areas and major cities, thus improving the island's economic connectivity and access to services. The toll road directly connects ports in Sumatra, including two international ports: the Kuala Tanjung Port in North Sumatra province and the Panjang Port in Lampung province. About a fifth of Sumatra's port-connected exports in 2020 flowed through these two ports. In addition, the alignment of the Trans-Sumatra Toll Road has been thoughtfully selected to avoid wildlife sanctuaries and other environmentally sensitive areas because Sumatra is extremely rich in flora and fauna . Some segments are designed to parallel the existing national road connecting these areas and will pass primarily through plantations and less environmentally sensitive lands. The toll road has been integrated into national and regional spatial plans.

Due to its large scale, the toll road development is being carried out in four phases. Phase I consists of 10 main segments and three supporting segments connecting several provincial capitals (Banda Aceh, Medan, Pekanbaru, and Palembang) with a total length of 1,064 km. Around 500 km are already operational. Phase II is currently under development and consists of three main sections with a total length of 574 km, connecting Pekanbaru to Palembang and providing important missing links in the middle of Sumatra. Phase III and Phase IV have been under preparation. This study focuses on the impact of the uncompleted segments of the toll road, treating the operational segments of Phase I as part of the existing road network.

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[4] Central Statistics Bureau. Inter-regional trade in Indonesia 2020. March 2021.

[5] BAPPENAS. Draft of RKP 2022.

The implementation and financing of the Trans-Sumatra Toll Road involve multiple stakeholders, with the scheme of each section selected depending on its economic returns and financial feasibility. The total cost of the project is estimated to be around 500 trillion IDR or 33 billion USD.[6] Less financially viable sections are directly assigned to state-owned enterprises or require sovereign financing support, including borrowing from multilateral development banks and other international financial institutions.[7] Commercially attractive sections are offered to the private sector under the Build-Operate-Transfer scheme with possible government support in the form of Availability Payments. Understanding the overall economic benefits of the toll road is critical for its financing and implementation.

2.2 Data and Economic Activities

In order to implement a quantitative spatial economic model and simulate the potential impact of the planned segments of the Trans-Sumatra Toll Road, we obtained provincial-level socio-economic characteristic variables for the Indonesian economy from 2016 and 2017, when the most recent data are available for all variables.

Data. The data sources and processing are briefly presented below, followed by a description of the distribution of key economic activities across provinces in Indonesia that are being captured by these data.

Geography: The impact simulation focuses on the 34 Indonesian provinces. Eight provinces make up the island of Sumatra: Aceh, North Sumatra (Sumatera Utara), West Sumatra (Sumatera Barat), Riau, Jambi, South Sumatra (Sumatera Selatan), Bengkulu, and Lampung, following the diagonal northwest-southeast axis. The digitized boundaries of all provinces are based on the official source. To complete the model, we include the rest of the world as a distinct geographic location.

Output, trade, and input-output linkages: The annual provincial-level sectoral value added from 2010-2020, the inter-provinces I-O table in 2016, and the provincial-level sectoral foreign exports in 2016 are from the Central Bureau of Statistics (BPS), which was accessed for this paper in November 2022. The national imports of services reported by the I-O table are distributed proportionately to provinces by their income levels. For imports of primary and industrial sectors, the provincial-level information is calculated from the Microdata – Import Statistical Data Compilation from the BPS, relying on the World Trade Organiza-

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[6] https://www.pwc.com/id/en/media-centre/infrastructure-news/july-2020/toll-road-funding-trans-sumatra-needs-breakthrough.html.

[7] The Asian Infrastructure Investment Bank will support the construction of 136.9 km of toll road from Cinto Kenang to Sentjalang, within the Jambi-Rengat section of Phase II. The China EXIM Bank will support part of the Jambi-Rengat section and the entire Betung-Jambi section of Phase II.

tion's classification of primary and industrial goods. All data are available for 17 sectors, aggregated into the three broader categories of primary, industry, and service, as detailed in Appendix, Table D.1. The sectoral value added of the rest of the world is computed as the difference between the sector-specific value added of the world and that of Indonesia in 2016, using the World Bank's Open Data. The annual average exchange rate published by the Central Bank of Indonesia is used to convert all data series between Indonesian rupiahs and US dollars in 2016, with one Indonesian rupiah valued at 0.000075 USD.

Population and migration: The annual provincial-level population data from 2010-2020 are drawn from the World Bank's Indonesia Database for Policy and Research. The migration data are sourced from the National Socio-Economic Survey 2017. Migration flows are computed as the number of people born outside the province where they were surveyed. The population data of the rest of the world are drawn from the World Bank Open Data. For simplicity, migration flows between Indonesian provinces and the rest of the world are assumed to be zero.

Land use: Land cover and land use data are sourced from the CCI Land Cover data compiled by the European Space Agency.[8] The settlement category as classified by the data source is used to define residential land use. This data is available as consistent global land cover maps created annually from 1992 to 2020 with a 300-meter spatial resolution. The data from 2010-2020 were accessed for this paper in November 2022 and overlaid with the boundaries of Indonesian provinces to obtain the amount of residential land available at the provincial-level.

Regional Distribution. Indonesia's population is highly concentrated on the island of Java (Figure 1). The world's most populous island, Java comprises four provinces (Banten, West Java (Jawa Barat), Central Java (Jawa Tengah), East Java (Jawa Timur)) and two special regions (Special Capital Region of Jakarta, Special Region of Yogyakarta), and was home to 147 million people, or about 57 percent of the national population in 2016. Their population densities averaged around 1104 persons per km^2 when defined as the ratio between population and land areas. Sumatra is the second most populous island in Indonesia, with 53 million people, or nearly 20 percent of the national population, residing in its eight provinces in 2016. Its average population density was about 114 persons per km^2, significantly lower than Java's.[9]

Inter-provincial migration is a notable feature of Indonesia's economy, even though the nation consists of 17,000 islands with straits and oceans as natural barriers. Total inter-

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[8] Refer to Defourny et al. [2023] and see website: https://maps.elie.ucl.ac.be/CCI/viewer/download.php

[9] The population displayed the same regional distribution in 2020.

Figure 1: Population across Provinces in 2016

provincial migration was about 22 percent of the population in 2017. Both Java and Sumatra are important destinations and origins of domestic migration, with inflow accounting for 10 percent and 12 percent of the islands' populations, respectively (Figure C.1; C.2). The most important flows are inter-provincial movements of people within each island, with a scale of 11 million people in Java (or 8 percent of the island's total population) and 3.4 million people in Sumatra (or 6 percent of its population) in 2017. Migration flows between Java and Sumatra are also considerable, with 1.5 percent of Java's residents born in Sumatra and 6 percent of Sumatra's residents born in Java.

Java is the economic powerhouse and the most dynamic economic center of Indonesia (Figure 2). With a total output of 554 billion USD, Java accounted for nearly 58 percent of the national GDP in 2016, with Sumatra in second place for economic importance, accounting for 20 percent of the national GDP. The leading provincial-level economic hubs are Jakarta, East Java, and Central Java in Java, and Riau and North Sumatra in Sumatra. The primary sector plays a pivotal role in Sumatra, representing an average of 36 percent of the provincial GDP, compared to 11 percent in Java (Figure C.3). The industry sector makes up an average of 38 percent of GDP at the provincial-level in Java and 24 percent in Sumatra (Figure C.4). The service sector holds a crucial position in both Java's and Sumatra's GDPs as well, contributing an average of 51 percent and 40 percent of the provincial GDP, respectively (Figure C.5). The relative importance of different sectors varies considerably across provinces within the two islands, though. [10]

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[10] From the sectoral perspective, both industry and service sectors are highly concentrated in Java, reflecting economies of scale in technology, with the outputs in Java amounting to 68 percent and 66 percent of national production in 2016. Outside of Java, North Sumatra and Riau stand out as additional important industry centers, both contributing to 5 percent of national production in 2016. The production of primary

Figure 2: GDP across Provinces in 2016

Inter-provincial trade is another remarkable feature of Indonesia's archipelago economy, with goods and services exchanged for final consumption and as inputs for production. In 2016, total inter-provincial trade in final goods amounted to 54 percent of the national GDP, while inter-provincial trade in intermediate inputs accounted for 37 percent of the national GDP. Both Java and Sumatra play pivotal roles as exporters and importers, with exports constituting a significant 16 percent and 10 percent of the islands' GDPs, respectively. The majority of exports are intra-island, at the scale of 48 billion USD in Java (9 percent of GDP) and 6 billion USD in Sumatra (3 percent of GDP). Trade flows between Java and Sumatra are also considerable, with Java's exports to Sumatra representing 3 percent of Java's GDP and Sumatra's exports to Java representing 5 percent of Sumatra's GDP in 2016. Bali, Borneo, and Sulawesi Islands are other notable destinations for Sumatra's exports. Both the industry and service sectors play pivotal roles in both Java's and Sumatra's exports, with the industry sector contributing 9 (6) percent and the service sector contributing 6 (3) percent to Java's (Sumatra's) GDP.

Income level varies significantly between islands and across provinces within an island (Figure 3). Java stands out with the highest island GDP per capita, but the provincial value ranges from 2216 USD in Yogyakarta to 15756 USD in Jakarta in 2016. Following closely, Sumatra has the second-highest GDP per capita, although the value varies from 2014 USD in Aceh to 7865 USD in Riau. Among provinces of other islands, GDP per capita spanned

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industries is driven more by the endowment of natural resources and spread across Borneo (Kalimantan), Java, and Sumatra. In Sumatra, Riau, as the largest producer of palm oil in Indonesia, is the most important production area, accounting for 13 percent of national production in 2016, followed by North Sumatra, which contributed 5 percent of national production.

from 1207 USD to 10901 USD.

Figure 3: GDP per capita across Provinces in 2016

2.3 Travel Time Reduction

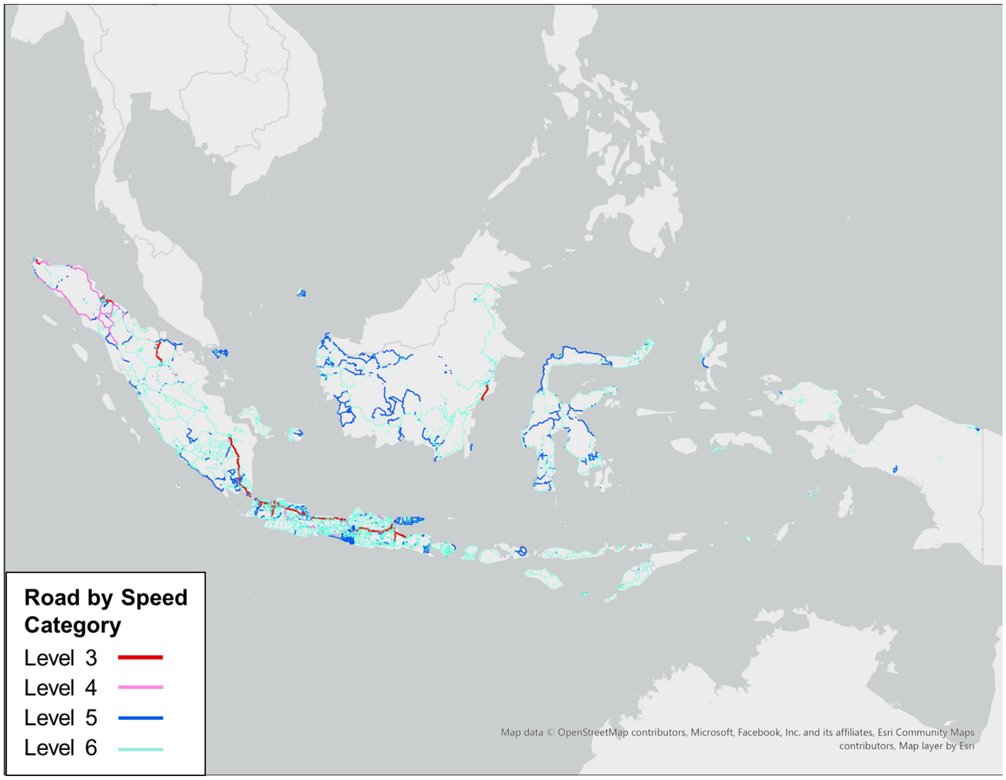
To estimate the reduction in travel times caused by the construction of the Trans-Sumatra Toll Road, we digitized the planned segments of the Trans-Sumatra Toll Road and added them into a digitized network of existing roads in Indonesia.

Road Network and Project Route. The original road network data for Indonesia are obtained from HERE Technologies, a map data provider that creates detailed road GIS data. The data reflect Indonesia's roads as of 2020/2021 and include digitized routes of all types of roads in the country and supplementary data tables with road-specific features such as direction, speed assumption, and points of interest along the road. A digitized road network is created by combining this input information. Peak-hour travel speed assumptions are applied for the baseline analysis, whereas average travel speed assumptions are used in a sensitivity check. Table 1 presents the details of the road network. About 135,000 km of roads with a design speed above 30 km/hour are captured. These roads have an estimated average speed of 37 km/hour during peak hours and 46 km/hour otherwise. They form the main skeleton of the road network, largely determining the computation of travel speed. Figure 4 displays roads with moderate- to high-speed traffic, where a smaller number indicates faster speed. An additional 1,080,000 km of low-speed roads are also covered. Importantly, more than 73,000 km of ferry routes with an estimated 11 km/hour speed are incorporated into the road network to connect islands, as displayed in Figure 5.

Table 1: Road Network Assumption

Speed Category	Peak Hour Speed (km/hour)	Average Speed (km/hour)	Number of links	Length (km)
Part (a): Roads				
3 (fastest speed)	91	95	12,584	5,888
4	71	80	25,739	3,298
5	51	60	67,732	16,404
6	31	40	903,142	109,399
7	11	20	3,650,681	790,170
8 (lowest speed)	5	5	1,923,192	290,422
3 to 6 (moderate- and high- speed)	37	46	1,009,197	134,988
7 to 8 (low-speed)	9	16	5,573,873	1,080,593
3 to 8 (overall)	12	19	6,583,070	1,215,581
Part (b): Ferry Lines				
1	11	11	31	5,773
2	11	11	183	5,601
3	11	11	101	10,942
4	11	11	43	4,922
5	11	11	1,228	45,789
1 to 5 (overall)	11	11	1,586	73,027

Figure 4: Distribution of Roads with Different Travel Speed



Map data © OpenStreetMap contributors, Microsoft, Facebook, Inc. and its affiliates, Esri Community Maps contributors, Map layer by Esri

Figure 5: Distribution of Ferry Lines

The road network allows the calculation of optimized routes between any two points connected by roads. In cases where the two points are on two islands not connected by roads or bridges, the ferry route with the shortest travel time is used. To assess the reliability of the digitized network, we compare the computed travel times (distances) between 63 pairs of randomly picked origin/destination locations with results generated by Google Maps for the same pairs of locations. The estimated travel times (distances) based on the road network match closely with those based on Google Maps (See Appendix Figure C.6). The digitized existing road network is used to compute the travel time Original-Destination (O-D) matrix for the scenario without the project.

The planned segments of the Trans-Sumatra Toll Road are digitized, relying on public documents. The exact routes and locations of exit points of the planned sections are identified using project documents provided by PT Hutama Karya, the major construction company of the toll road.[11] For the sections where exit road information is not available, the toll road is assumed to include one exit road connecting to every major town alongside it. In total, over 2,300 km length of new road segments are digitized (Figure 6). The digitized segments are then incorporated into the previous road network by taking the highest speed assumption,

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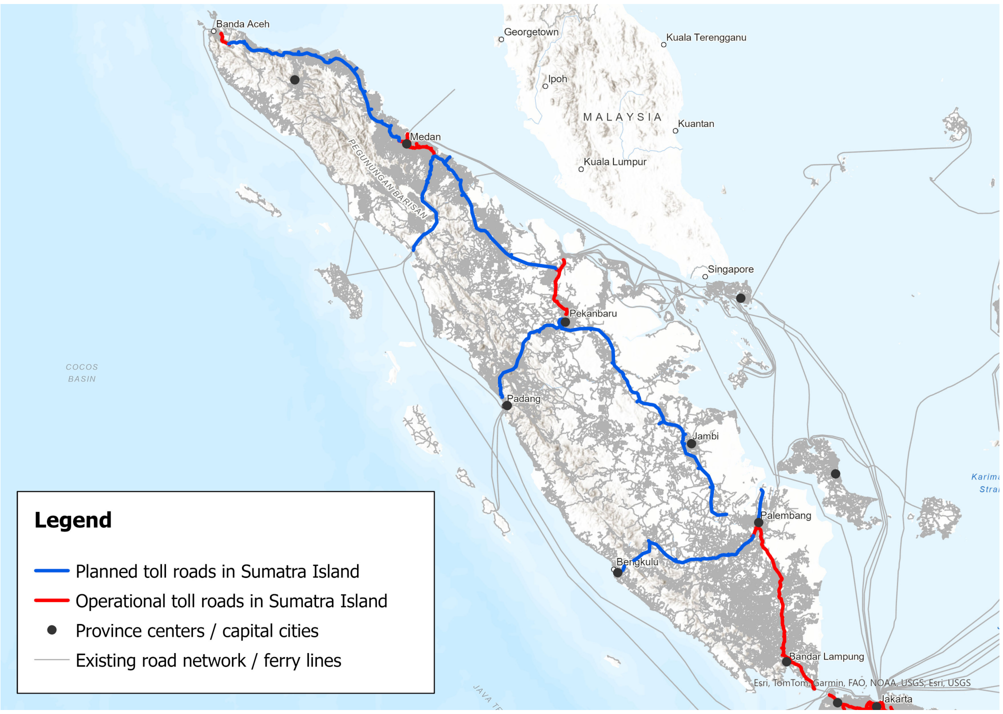
[11] https://www.hutamakarya.com/en/hutama-in-sumatera-island (Trans Sumatra Toll Road - PT Hutama Karya (Persero) Website.)

i.e., 91 km/hour. The resulting new road network is used to compute the travel time O-D matrix for the project scenario.[12]

Figure 6: Digitized Sumatra Toll Road



Travel Time Reduction across Regions This paper focuses on the impact of improved connectivity on Indonesia's 34 provinces. To that end, the travel time O-D matrix is computed as the matrix of road driving times on the fastest route (shortest time) between all pairs of provincial capital cities in Indonesia. The differences between the with- and without-project travel time matrices are used as travel time reductions due to the construction of the planned segments of the toll road.

Figure 7 presents the average travel time reduction between each province and all other provinces, as defined above. Aceh, North Sumatra, and Riau will see their travel times to other places fall the most if the toll road is constructed: by 22 percent, 25 percent, and 22 percent, respectively. They are located in the northwest part of Sumatra and are thus more distant from Java and other islands than other Sumatran provinces. At the same time, their travel times to other Sumatran provinces also decline the most. Aceh's travel times

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[12] Note that some parts of the Trans-Sumatra Toll Road (for example, in the southern part of the island) are already part of HERE road network data because these roads were already in operation prior to the creation of this map.

to other Sumatran provinces will be reduced by 32 percent, North Sumatra's by 40 percent, and Riau's by 46 percent. Inter-provincial travel times for other Sumatran provinces will also fall, ranging from 6 percent to 16 percent. As anticipated, inter-provincial travel times for provinces on other islands will not experience as significant a decrease, varying from 4 percent to 6 percent in Java and less than 1 percent for provinces on the island of New Guinea (Papua Barat and Papua).

Figure 7: Average Travel Times Reduction across Provinces

3 Quantitative Framework

This section builds a spatial general equilibrium model with multiple locations and sectors to quantify the economic impact of the Trans-Sumatra Toll Road. There are $J+1$ sectors, which are broadly defined, including the primary goods, industry, service, and housing sectors. To capture the economic geography of Indonesia, geographic units of the model include provinces within Sumatra, the rest of the provinces excluding Sumatra, and the rest of the world. We denote geographic units as i and n, and sectors as j and k. Our model is based on Caliendo and Parro [2015] with trade in intermediate goods and Input-Output linkages. Following Ahlfeldt et al. [2015] and Bryan and Morten [2019], we also introduce frictional labor mobility across geographic units to capture the effect of better labor mobility due to road connectivity.

3.1 Household

In each location n, there is a measure of L_n representative households (or workers) who have chosen to reside and work in the location. Originally, there is a measure of $\bar{L}_i$ households who were born in location i. Then L_{in} households maximize utility by moving from i to n and choosing final consumption C_n^j. Let U_{inh} denote the utility level of the worker h, originally from location i and living in location n. The preferences of households are given by

$$U_{inh} = z_{inh} \prod_{j=1}^{J+1} \left(\frac{C_n^j}{\alpha_n^j} \right)^{\alpha_n^j}, \quad \text{where} \quad \sum_{j=1}^{J+1} \alpha_n^j = 1 \tag{1}$$

where C_n^j denotes the consumption goods of sector j in location n. The utility also depends on an idiosyncratic shock (z_{inh}) that is specific to the individual worker and varies with the worker's birthplace and place of work. This idiosyncratic shock captures the idea that workers may have idiosyncratic reasons for migrating to different regions. Following Ahlfeldt et al. [2015], we assume $\{z_{inh}|n = 1, 2, ..., N\}$ are drawn from the Fréchet distribution that are independent across the birth regions (i) and individuals (h). In particular, we allow that the individual-specific component in workers' tastes is correlated across regions: some people may like living in cities more than others. Specifically, the vector of idiosyncratic taste shocks for any given worker is generated from the following $c.d.f$ of Fréchet (we denote $z_{nh} = z_{inh}$ for ease of notation):

$$F\left(z_{1h}, z_{2h}, \ldots, z_{Nh}\right) = \exp\left[- \left(\sum_n z_{nh}^{-\epsilon} \right)^{1-\rho} \right] \tag{2}$$

where ϵ measures the extent of taste dispersion (dispersion increases as ϵ decreases), and ρ reflects the inter-region correlation of taste draws.[13] If $\rho = 0$, taste shocks are uncorrelated across regions, while if $\rho = 1$, the taste shocks are perfectly correlated to that person.

3.2 Production Sectors

Following Caliendo and Parro [2015], the production of goods and services are separated into intermediate goods and composite intermediate goods. The latter can either be consumed as final goods or used as materials for producing intermediate goods.

Intermediate Goods A continuum of intermediate goods $\omega^j \in [0, 1]$ is produced in sector j, and its production function in location n is Cobb-Douglas using labor, and composite intermediate goods (as materials):

$$q_n^j(\omega^j) = z_n^j(\omega^j) \left[\frac{l_n^j(\omega^j)}{\beta_n^j} \right]^{\beta_n^j} \prod_{k=1}^{J} \left[\frac{m_n^{kj}(\omega^j)}{\gamma_n^{kj}} \right]^{\gamma_n^{kj}} \tag{3}$$

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[13] The parametric assumption on distribution is also used by Ahlfeldt et al. [2015], Bryan and Morten [2015], and Hsieh et al. [2019].

where $l_n^j(\omega^j)$ is labor input and $m_n^{kj}(\omega^j)$ is the composite intermediate goods from sector k used for the production of intermediate good ω^j. The parameter $\gamma_n^{kj} \geq 0$ captures the share of materials from sector k used in producing intermediate goods ω^j in sector j, with $1 - \beta_n^j = \sum_{k=1}^J \gamma_n^{kj}$, and β_n^j captures the share of value added. Finally, $z_n^j(\omega^j)$ captures the idiosyncratic productivity shock in producing intermediate goods of sector j in location n allowing production efficiency to vary across locations.

As the production of intermediate goods is constant return to scale, and the market is perfectly competitive, the unit cost of ω^j is $c_n^j/z^j(\omega^j)$, where c_n^j is the cost of an input bundle, which is expressed as

$$c_n^j = w_n^{\beta_n^j} \prod_{k=1}^{J} \left(P_n^k\right)^{\gamma_n^{kj}} \tag{4}$$

where P_n^k denotes the price of a composite good of sector k in location n.

Composite Intermediate Goods Producers of composite intermediate goods in sector j and region n supply Q_n^j at minimum cost by purchasing intermediate goods ω^j from the lowest-cost suppliers across locations. The production of Q_n^j is governed by the CES aggregator:

$$Q_n^j = \left[\int_0^1 \bar{q}_n^j(\omega^j)^{(1-1/\sigma_j)} d\omega^j\right]^{\sigma^j/(\sigma^j-1)} \tag{5}$$

where $\sigma^j > 0$ is the elasticity of substitution across intermediate goods within sector j, and $\bar{q}_n^j(\omega^j)$ is the demand of intermediate goods ω^j from the lowest-cost supplier. The solution to the profit maximization problem of firms in the composite intermediate good producer gives the following demand for good ω^j:

$$\bar{q}_n^j(\omega^j) = \left[\frac{p_n^j(\omega^j)}{P_n^j}\right]^{-\sigma^j} Q_n^j \tag{6}$$

where P_n^j is unit price of the composite intermediate good:

$$P_n^j = \left[\int p_n^j(\omega^j) d\omega^j\right]^{1/(1-\sigma^j)} \tag{7}$$

where $p_n^j(\omega^j)$ denotes the lowest price of intermediate good ω^j across location n. Composite intermediate goods from sector j are used as materials for the production of intermediate good ω^k in amount $m_n^{jk}(\omega^k)$ in all sectors k and as final goods in consumption C_n^j.

Trade Costs and Prices Trade in goods and services is costly and is subject to iceberg trade costs. One unit of tradable intermediate good in sector j supplied from i to region n requires producing d_{in} units in i, and it is assumed that $d_{in} \geq 1$ and $d_{nn} = 1$. After taking trade costs into consideration, a unit of a tradable intermediate good ω_j produced in country i is available in country n at unit prices $c_i^j d_{in}/z_i^j(\omega^j)$. The lowest possible price of intermediate good ω^j in country n is given by

$$p_n^j(\omega^j) = \min_i \left\{ \frac{c_i^j d_{in}}{z_i^j(\omega^j)} \right\} \tag{8}$$

As in Eaton and Kortum [2002], the productivity shock $z_i^j(\omega^j)$ is assumed to follow i.i.d. Fréchet distribution, with CDF being $F(z) = \exp(-T_i^j z^{\theta^j})$, where T_i^j captures the aggregate production efficiency of sector j in location i, or absolute advantage, and θ^j is the sector-specific technology dispersion parameter, which measures comparative advantage. The parameters satisfy that $1 + \theta^j \geq \sigma^j$. The price index for the composite intermediate good in sector $j = 1, 2, ..., J$ is then given by

$$P_n^j = A_j \left[\sum_{i=1}^{N} T_i^j (c_i^j d_{in})^{-\theta^j} \right]^{-1/\theta^j} \tag{9}$$

where $A_j = \Gamma\big(\frac{1-\sigma^j}{\theta^j} + 1\big)^{1/(1-\sigma^j)}$.

3.3 Housing Sector

The $J+1$th sector is the housing sector, which we introduce as in Redding and Turner [2015], Redding and Rossi-Hansberg [2017]. C_n^{J+1} denotes the residential land use in location n, which is interpreted as housing. For simplicity, the residential land is treated as a primitive of the model, although it could, in principle, depend on equilibrium population density (e.g., if a higher population density increases the housing supply). Expenditure on housing in each location is redistributed as a lump sum to workers residing in that location. Trade balance at each location implies that per capita income v_n of region n equals wage rate w_n and per capita expenditure on residential land $\alpha_n^{J+1} v_n$, namely,

$$v_n L_n = w_n L_n + \alpha_n^{J+1} v_n L_n = \frac{w_n L_n}{1 - \alpha_n^{J+1}} \tag{10}$$

Land market-clearing condition implies that land supply, H_n, equals land demand, $L_n C_n^{J+1}$. Combining land market-clearing condition with the first-order condition of consumer problem, we can derive the land rental rate in location n, P_n^{J+1}, as

$$P_n^{J+1} = \frac{\alpha_n^{J+1} v_n L_n}{H_n} = \frac{\alpha_n^{J+1}}{1-\alpha_n^{J+1}} \frac{w_n L_n}{H_n} \tag{11}$$

Provided with prices for composite goods in sector $j = 1, ..., J$ as shown in 9, Cobb-Douglas preferences in 1 implies that the consumption price index in region n is

$$P_n = \prod_{j=1}^{J+1} (P_n^j)^{\alpha_n^j} \tag{12}$$

3.4 Total Expenditure and Trade Balance

Total expenditure on sector j goods in location n is given by $X_n^j = P_n^j Q_n^j$. X_{in}^j denotes the expenditure in location n of sector j that is from i. It follows that location n's expenditure share of goods from i is $\pi_{in}^j = X_{in}^j / X_n^j$. Based on the property of Fréchet distribution, expenditure shares are functions of technologies, prices, and trade costs:

$$\pi_{in}^j = \frac{T_i^j (c_i^j d_{in})^{-\theta^j}}{\sum_{i=1}^N T_i^j (c_i^j d_{in})^{-\theta^j}} \tag{13}$$

Total expenditure on goods j is the sum of the expenditure on composite intermediate goods by firms and the expenditure by households. Then, X_n^j is given by

$$X_n^j = \sum_{k=1}^J \gamma_n^{jk} \sum_{i=1}^N X_i^k \pi_{in}^k + \alpha_n^j I_n \tag{14}$$

where $I_n = v_n L_n = w_n L_n / (1 - \alpha_n^{J+1}) + D_n$, which denotes the final absorption in region n, as sum of labor income, transferred income from the housing sector, and trade deficit. Particularly, location-specific deficits are the summation of sectoral deficits, $D_n = \sum_{j=1}^J D_n^j$, whereas sectoral deficits are defined by $D_n^j = \sum_{i=1}^N X_n^j \pi_{in}^j - \sum_{i=1}^N X_i^j \pi_{ni}^j$. Aggregate trade deficits in each location are exogenously determined, while sectoral trade deficits are endogenously solved in the equilibrium.

According to the definition of expenditure, for each location n, trade balance implies that

$$\sum_{j=1}^J \sum_{i=1}^N X_n^j \pi_{in}^j = \sum_{j=1}^J \sum_{i=1}^N X_i^j \pi_{ni}^j + D_n \tag{15}$$

The above condition reflects that location n's total expenditure equals the sum of all locations' total expenditure on tradable goods and services from location n, plus the trade deficit of location n.

3.5 Migration Decisions

Migration is modeled as a once-in-life choice. Each worker has an idiosyncratic preference for living in certain regions, and decides where to work, taking into account the destination-specific component in the indirect utility, as well as the migration cost that they will incur. The migration cost, denoted as e_{in}, is source-destination specific and is similar to the iceberg cost assumption used for trade costs. Taking the idiosyncratic tastes for regions defined in the section 3.1 as given, a worker h born in region i chooses to live in region n to maximize welfare:

$$\max_{n \in \{1,2,..,N\}} \left\{ \frac{z_{inh} V_n}{e_{in}} \right\} \tag{16}$$

where $V_n = v_n / P_n$ denotes the price-adjusted real per capita income in region n.

According to the assumption that $\{z_{inh} | d = 1, 2, ..., N\}$ are drawn from the Fréchet distribution (2) that are independent across the birth regions (i) and individuals (h), the probability that a worker from origin i moves to destination n is:

$$\delta_{in} = \left(\frac{V_n}{e_{in}} \right)^{\epsilon} / \sum_n \left(\frac{V_n}{e_{in}} \right)^{\epsilon} \tag{17}$$

Then the number of workers moving from i to n is $L_{in} \equiv \delta_{in} \bar{L}_i$, and we derive the supply of labor in region n as

$$L_n = \sum_i L_{in} = \sum_i \delta_{in} \bar{L}_i \tag{18}$$

For given $\bar{L}_n$, H_n and T_n^j, an equilibrium under policy variables $\{d_{in}\}$ and $\{e_{in}\}$ is a wage vector $\{w_n\}$ and prices $\{P_n^j\}$ that satisfy various conditions for all j and n, which are provided in Appendix A.

4 Calibration and Policy Experiments

Before employing the model for counterfactual policy experiments, we calibrate it to the equilibrium in Indonesia for 2016. This section outlines the data used and describes the steps involved in calibrating the main model parameters.

4.1 Modeling the Impact of Policies

Within the theoretical framework set up in the previous section, this section applies the exact hat algebra method (Allen et al. [2020]) to model the effects on equilibrium outcomes from changes in the policy variables (i.e., trade and migration costs).

Let $\{w_n, P_n^j\}$ be an equilibrium under $\{d_{in}, e_{in}\}$, and let $\{w_n', P_n^{j\prime}\}$ be an equilibrium under new policy variables $\{d_{in}', e_{in}'\}$. Define $\{\hat{w}_n, \hat{P}_n^j\}$ as the equilibrium under $\{d_{in}, e_{in}\}$ relative to $\{d_{in}', e_{in}'\}$.[14] The equilibrium conditions with relative values satisfy:

$$\hat{c}_n^j = \hat{w}_n^{\beta_n^j} \prod_{k=1}^{J} \left(\hat{P}_n^k\right)^{\gamma_n^{kj}} \tag{19}$$

$$\hat{P}_n^j = \begin{cases} \left[\sum_{i=1}^N \hat{T}_i^j (\hat{c}_i^j \hat{d}_{in})^{-\theta^j} \pi_{in}^j\right]^{-1/\theta^j} & j = 1, ..., J \\ \frac{\hat{w}_n \hat{L}_n}{\hat{H}_n} & j = J+1 \end{cases} \tag{20}$$

$$\hat{L}_n = \sum_i \hat{\delta}_{in} \hat{\bar{L}}_i \left(\frac{\delta_{in} \bar{L}_i}{L_n}\right) \tag{21}$$

$$\hat{\delta}_{in} = \left(\frac{\hat{w}_n / \prod_{j=1}^{J+1} \left(\hat{P}_n^j\right)^{\alpha_n^j}}{\hat{e}_{in}}\right)^{\epsilon} \Bigg/ \sum_n \delta_{in} \left(\frac{\hat{w}_n / \prod_{j=1}^{J+1} \left(\hat{P}_n^j\right)^{\alpha_n^j}}{\hat{e}_{in}}\right)^{\epsilon} \tag{22}$$

$$\hat{\pi}_{in}^j = \frac{\hat{T}_i^j (\hat{c}_i^j \hat{d}_{in})^{-\theta^j}}{\left(\hat{P}_n^j\right)^{-\theta^j}} \tag{23}$$

$$X_n^{j\prime} = \sum_{k=1}^J \gamma_n^{jk} \sum_{i=1}^N X_i^{k\prime} \pi_{ni}^{k}{}' + \alpha_n^j \left(\frac{\hat{w}_n \hat{L}_n w_n L_n}{1 - \alpha_n^{J+1}} + D_n\right) \tag{24}$$

$$\sum_{j=1}^J \sum_{i=1}^N X_n^{j\prime} \pi_{in}^{j}{}' = \sum_{j=1}^J \sum_{i=1}^N X_i^{j\prime} \pi_{ni}^{j}{}' + D_n \tag{25}$$

It is worth noting that the general equilibrium conditions with relative values can be solved without full knowledge of the model parameters that are difficult to estimate, such as productivity T_i^j.

4.2 Calibrating to the Base Year

Before we perform policy experiments, we match the model to the Indonesian economy in the base year, 2016, when the planned segments of the Trans-Sumatra Toll Road were not

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[14] A variable with a hat $\hat{x}$ represents the relative value of the variable, namely $\hat{x} = x'/x$.

constructed, and the relevant economic data were available. In the calibration, most of the relevant variables and parameters are computed based on national and provincial data of Indonesia described in section 2.2. They include bilateral inter-provincial migration shares δ_{in}, bilateral inter-provincial trade shares for each sector π_{in}^{j}, the share of value added in production for each sector at the provincial-level β_{n}^{j}, value added $w_n L_n$ at the provincial-level, the share of intermediate goods in production at the provincial-level γ_{n}^{kj}, and the share of each sector in final demand at the provincial-level α_{n}^{j}.

The rest of the parameters are drawn from previous literature. The trade elasticities for primary and industry sectors, θ^A and θ^M, are set at 8.11 and 8.41, respectively, following Caliendo and Parro [2015], and the trade elasticity for the service sector is drawn from Kucheryavyy et al. [2016] and set at 5.00. The migration heterogeneity, ϵ, is 6.83, following Ahlfeldt et al. [2015]. As a summary, panel (c) of Appendix Table D.2 provides an overview of variables and parameters that are calibrated, and Appendix Table D.3 presents the parameter values drawn from the literature.

4.3 Estimating Cost Reductions

In addition to calibration to the base-year economy, the changes in policy variables (i.e., trade and migration costs) are required to simulate the impact of applying the general equilibrium conditions with relative values. Following the literature, it is assumed that travel time changes due to the toll road will directly affect trade and migration costs.

Travel time has been shown to hinder trade and influence the movement of people. Hummels and Schaur [2013] quantify that a single-day delay in shipping corresponds to an ad-valorem tariff of approximately 5 percent. Djankov et al. [2010] estimate that each additional day that a product is delayed between the factory gate and the ship reduces trade by more than 1 percent. Sorek [2009] shows that travel time reduction significantly affects workers' decision between commuting and migration. Using Indonesian data, Bryan and Morten [2019] find that a 10 percent reduction in travel distance leads to a 7 percent increase in domestic migration, whereas travel distance and travel time are highly correlated. In addition, the impact of the Trans-Sumatra Toll Road is more evident in travel time than in distance because it is designed to avoid environmentally sensitive areas with segments of the toll road in parallel with the existing national road.

This section thus estimates the elasticity of trade cost (or migration cost) with respect to travel time within a model-induced gravity framework and uses the observed data of the base year.

We define the elasticity of trade cost with respect to travel time, β_1, to satisfy

$$\ln d_{in} = \beta_0 + \beta_1 \ln(times_{in}) + u_{in} \tag{26}$$

With the expenditure share in equation (40), location n's relative expenditure share of sector j that is from i to the domestic expenditure share is

$$\frac{\pi^j_{in}}{\pi^j_{nn}} = \frac{T^j_i (c^j_i d_{in})^{-\theta^j}}{T^j_n (c^j_n d_{nn})^{-\theta^j}} \tag{27}$$

where d_{nn} is normalized to be one. Taking the log of (27) and substituting d_{in} by (26), a regression function in the form of a gravity equation of trade can be derived as

$$\ln \pi^j_{in} - \ln \pi^j_{nn} = -\beta_1 \theta^j \times \ln(times_{in}) - \beta_0 \theta^j + \delta^j_i - \delta^j_n + \tilde{u}^j_{in} \tag{28}$$

where $\delta^j_i = \ln T^j_i - \theta_j \ln c^j_i$, $\delta^j_n = \ln T^j_n - \theta_j \ln c^j_n$, and $\tilde{u}^j_{in} = -\theta^j u_{in}$. Therefore, β_1 can be estimated by regressing $\ln \pi^j_{in} - \ln \pi^j_{nn}$ on the interaction between $-\theta^j$ and travel time $\ln(times_{in})$, where $\beta_0 \theta^j$ can be treated as sector fixed effect, δ^j_i can be treated as the origin-sector fixed effect, and similarly δ^j_n as the destination-sector fixed effect.

We define the elasticity of migration cost with respect to travel time, γ_1, to satisfy

$$\ln e_{in} = \gamma_0 + \gamma_1 \ln(times_{in}) + \omega_{in} \tag{29}$$

With the migration share in equation (17), the migration share from birth region i to destination n, normalized by the the share of individuals born in i who stay in i, becomes:

$$\frac{\delta_{in}}{\delta_{ii}} = \left(\frac{V_n}{e_{in}}\right)^{\epsilon} / \left(\frac{V_i}{e_{ii}}\right)^{\epsilon} \tag{30}$$

where e_{ii} is normalized to be one. Taking the log of (30) and proxy e_{in} by (29), a regression function as a gravity equation of migration can be derived as

$$\ln \delta_{in} - \ln \delta_{ii} = -\gamma_0 \epsilon - \gamma_1 \epsilon \times \ln(times_{in}) + \delta_n - \delta_i + \tilde{\omega}_{in} \tag{31}$$

where $\delta_n = \epsilon \ln V_n$, $\delta_i = \epsilon \ln V_i$, and $\tilde{\omega}_{in} = -\epsilon \omega_{in}$. Therefore, γ_1 can be estimated by regressing $\ln \delta_{in} - \ln \delta_{ii}$ on the interaction between $-\epsilon$ and distance term $\ln(times_{in})$, where δ_i can be treated as the origin fixed effect, and similarly δ_n as the destination fixed effect.

Column (1) of Table 2 reports the estimation from the trade gravity equation (28), using the inter-provincial bilateral trade shares for the primary, industry, and service sectors in 2016, and travel times from the O-D matrix of the existing road network. The point estimation of the elasticity of trade cost with respect to travel times, $\hat{\beta}_1$, is 0.27, which is statistically significant at the 1% level with a regression R-squared of 0.66. The migration gravity equation (31) is estimated with the inter-provincial bilateral migration shares in 2016, and travel times based on the existing road network. The result is reported in column (2). The estimated elasticity for migration cost with respect to travel times, $\hat{\gamma}_1$, is around 0.23, statistically significant at the 1% level.

Table 2: Elasticity of Trade & Migration Costs With Respect to Travel Times

	$\ln \pi^j_{in} - \ln \pi^j_{nn}$	$\ln \delta_{in} - \ln \delta_{in}$
Indepdent var:	(1)	(2)
$-\theta^j \times \ln times_{in}$	0.270***	
	(0.015)	
$-\epsilon \times \ln times_{in}$		0.232***
		(0.008)
Destination-Sector FE	Y	-
Origin-Sector FE	Y	-
Destination FE	-	Y
Origin FE	-	Y
Observations	3,241	1,028
R-squared	0.655	0.679

Notes: Robust standard errors are reported in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

After the toll road is in operation, the trade cost becomes $\ln d'_{in} = \beta_0 + \beta_1 \ln(times'_{in}) + u'_{in}$. Therefore, the trade cost in relative value can be estimated by

$$\ln \hat{d}_{in} = \hat{\beta}_1 \ln(\widehat{times}_{in}) \tag{32}$$

Similarly, the migration cost in relative value can be estimated by

$$\ln \hat{e}_{in} = \hat{\gamma}_1 \ln(\widehat{times}_{in}) \tag{33}$$

Table 3 reports the estimated average reductions in travel times for all provinces, along with the aggregate reductions in trade and migration costs for all provinces, with weights being the trade and migration shares of the partner provinces. [15]

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[15] In certain provinces, the reductions in trade or migration costs are negligible, nearing zero. This is

Table 3: Reductions in Travel Times, Trade Cost, and Migration Cost

Province	Travel Times	Trade Cost	Migration Cost
Aceh	-22.28%	-6.05%	-0.34%
Sumatera Utara	-25.00%	-2.30%	-1.76%
Sumatera Barat	-16.20%	-8.92%	-2.17%
Riau	-21.77%	-3.99%	-0.80%
Jambi	-11.61%	-5.75%	-0.54%
Sumatera Selatan	-8.17%	-0.73%	-0.37%
Bengkulu	-12.44%	-4.75%	-0.51%
Lampung	-6.43%	-0.19%	-0.15%
Kep. Bangka Belitung	-1.51%	-0.40%	-0.02%
Kep. Riau	-7.38%	-0.60%	-0.27%
DKI Jakarta	-5.62%	-0.43%	-0.10%
Jawa Barat	-5.29%	-0.63%	-0.04%
Jawa Tengah	-4.83%	-0.02%	-0.12%
DI Yogyakarta	-4.54%	-0.44%	-0.13%
Jawa Timur	-4.34%	-0.26%	-0.06%
Banten	-5.80%	-0.30%	-0.03%
Bali	-3.50%	-0.19%	-0.01%
Nusa Tenggara Barat	-3.17%	0.00%	-0.02%
Nusa Tenggara Timur	-1.79%	0.00%	-0.01%
Kalimantan Barat	-2.08%	-0.11%	0.00%
Kalimantan Tengah	-2.33%	0.00%	0.00%
Kalimantan Selatan	-2.46%	-0.01%	0.00%
Kalimantan Timur	-2.08%	-0.01%	-0.01%
Kalimantan Utara	-1.73%	-0.01%	-0.01%
Sulawesi Utara	-1.39%	-0.08%	0.00%
Sulawesi Tengah	-1.71%	0.00%	0.00%
Sulawesi Selatan	-2.08%	-0.01%	-0.01%
Sulawesi Tenggara	-1.76%	-0.37%	0.00%
Gorontalo	-1.49%	0.00%	0.00%
Sulawesi Barat	-1.76%	0.00%	0.00%
Maluku	-1.18%	-0.10%	0.00%
Maluku Utara	-1.22%	0.00%	0.00%
Papua Barat	-0.92%	0.00%	0.00%
Papua	-0.76%	0.00%	0.00%

4.4 Quantifying Welfare Impact

In the theoretical model, a utility-based measure is used to assess welfare. As an alternative approach, "compensating variation" is applied in what follows to quantify the welfare impact, which represents the additional amount of money an agent would require to maintain their initial utility level after experiencing changes in economic conditions (Borraz et al. [2012], Felbermayr et al. [2019]). This concept is often interpreted as the maximum amount

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because there is minimal trade or migration activity between these areas and Sumatra, where the toll road project is underway.

a consumer is willing to pay to bring about the economic change in question.

Define v_n^* as the counterfactual amount of money that an agent would need to preserve their original utility level after policy changes; it satisfies the following relationship:

$$\frac{v_n^*}{P_n} = \frac{1}{1-\alpha_n^{J+1}} \frac{w_n'}{P_n'} = \frac{1}{1-\alpha_n^{J+1}} \frac{w_n}{P_n} \frac{\hat{w}_n}{\hat{P}_n} \tag{34}$$

The welfare change or compensating variation, ΔV_n , becomes:

$$\Delta V_n = v_n^* L_n' - v_n L_n = \frac{w_n L_n}{1-\alpha_n^{J+1}} (\frac{\hat{w}_n}{\hat{P}_n} \hat{L}_n - 1) \tag{35}$$

where ΔV_n is computed as the difference between the counterfactual real income level ($v_n^* L_n'$) that workers in province n would require after economic changes and their initial real income level ($v_n L_n$). By effectively capturing the change in aggregate real income in province n, compensating variation offers a meaningful and practical evaluation of the road project's impact on the well-being of the population.

5 Impact of the Toll Road

In this section, with estimated parameters, we use the model as the laboratory to study the aggregate and distributional effects of the Trans-Sumatra Toll Road.

5.1 Aggregate Impact

First, we quantify the aggregate impact of the Trans-Sumatra Toll Road, integrating the steps set up in the previous sections. To better understand the mechanisms, in the first with-project scenario, we focus on the contribution of trade in final goods, excluding the effects of sectoral linkages and trade in intermediates, as well as the effects of migration cost reductions. To do so, we set $\gamma_n^{kj} = 0$ so that the sectoral linkage effect is nullified. The migration cost reductions are assumed away by setting $\hat{e}_{in} = 1$. In the subsequent scenario, the sectoral linkages and trade in intermediates are introduced by replacing zeroes with the calibrated values of γ_n^{kj}. As the final scenario, the reductions in migration costs are incorporated as an additional policy shock, implemented by replacing ones with the calibrated values of $\hat{e}_{in}$.

The first two columns of Table 4 summarize the simulated welfare gains stemming from the Trans-Sumatra Toll Road project, following the three scenarios. Column (1) reports the welfare changes in trillion rupiah, while column (2) presents the corresponding percentage change in welfare. The project is projected to increase total welfare by 29 trillion rupiah, corresponding to a 1.33 percent gain in welfare when only considering trade in final goods.

After we include sectoral linkages in production and trade in intermediates, the welfare gains increase significantly to 73 trillion rupiah, or 3.59 percent. Further inclusion of migration cost reductions leads to a slight rise in overall welfare gains to 84 trillion rupiah, or 4.15 percent. This progression in estimated gains resulting from our three scenarios–first using trade of final goods, second incorporating trade in intermediates, and third adding migration cost reductions–underscores the pivotal role of enhanced product market integration, accounting for nearly 86.6 percent of the aggregate welfare gains.

Table 4: Aggregate Impact on Trade and Welfare

	Welfare Gains		Trade Value Change	
	Trillion Rp	%	Trillion Rp	%
Scenarios:	(1)	(2)	(3)	(4)
Trade without sectoral linkages	26.85	1.33%	107.94	1.20%
Trade with sectoral linkages	72.76	3.59%	324.98	3.61%
Trade with sectoral linkages and migration cost reductions	84.02	4.15%	379.87	4.23%

Notes: This table presents the aggregate impact of the Sumatra Toll Road project in terms of changes in trade value and welfare gains. For each province, trade value is defined as the sum of exports to other provinces within Indonesia and exports to the rest of the world.

Gains in trade value exhibit a similar pattern as depicted in columns (3) and (4) of Table 4. Trade value is computed by summing both inter-provincial exports and exports to the rest of the world. The simulation suggests that the project results in a 108 trillion rupiah increase in trade, or a 1.2 percent gain when only considering trade in final goods. With the addition of sectoral linkages and migration cost reductions, increases in trade are much more significant, amounting to 325 trillion rupiah and 380 trillion rupiah, respectively. These increases represent a 3.61 percent and a 4.23 percent rise, respectively.

Our findings showing aggregate welfare gains align with recent evaluations of transport investments. Notably, Morten and Oliveira [2018] illustrate that highway improvements in Brazil during the 1960s resulted in a 2.8 percent increase in aggregate welfare. Similarly, Coşar et al. [2022] find that public investment in roads in Türkiye during the 2000s contributed to a 3.0 percent welfare increase. Moreover, Egger et al. [2023] estimate that China's transport network improvements from 2010 to 2013 contributed to an overall welfare increase of approximately 9.72 percent, with highway improvements accounting for 5.68 percent. A similar conclusion is reached by Baum-Snow et al. [2016], who estimate the welfare contribution of China's national highway system to be around 5.0 percent (see Appendix Table D.4 for a summary).

5.2 Regional Impact

To address the toll road project's impact on shaping the spatial distribution of Indonesia's economy, we delve into the distribution of the welfare effect across provinces. Table 5 presents the welfare change for each province. Columns (1)-(2) show the results for the scenario when trade in both final goods and intermediates are included, while columns (3)-(4) report the results when migration cost reductions are further included. The results are highly correlated across provinces. In what follows, the discussion will focus on the final scenario reported in columns (3)-(4).

The welfare gains are concentrated in Sumatra, while most other provinces witness a decline in welfare (Figure 8). Specifically, seven out of the eight provinces in Sumatra witness an increase in welfare, with the exception of Lampung, which sees a welfare loss of 4.43 percent. Among the seven "winners," Riau, West Sumatra, and Jambi gain the most in terms of absolute value (47 trillion rupiah, 18 trillion rupiah, and 15 trillion rupiah), while Bengkulu has the highest percentage gain (93.54 percent). In contrast, among the 26 provinces outside Sumatra, only two provinces emerge as winners: Banten, with a welfare gain of 1.95 percent, and Maluku, with a gain of 1.15 percent. The remaining 24 provinces incur losses in welfare ranging from -0.28 percent to -4.06 percent.

This finding is intuitive, and is partly driven by the geographic feature of Indonesia as a large archipelago country. The toll road project only connects provinces in Sumatra and hence reduces travel times to and from these provinces significantly. Meanwhile, travel times to and from other provinces are only improved indirectly and marginally because they are mainly connected to Sumatra via ferries.

This finding is also consistent with the results of Caliendo and Parro [2015], the foundation upon which our model is constructed. Their study quantifies the welfare impact of NAFTA's tariff reduction using a 31-country model (Mexico, Canada, U.S., and 28 other countries). Except for the three countries covered by NAFTA, most of the countries indirectly affected by the tariff are estimated to experience a welfare loss. A parallel pattern is evident in the study by Walter [2022], which also employs a model based on Caliendo and Parro [2015] to quantify the welfare effect of the free trade agreement between Japan and the United States. Their findings indicate that most countries indirectly affected by the policy shock experience a welfare loss.

It is also noteworthy that the relationship between trade cost reductions and welfare gains is not linear due to the complex sectoral linkages and trade and migration relationships across provinces. As noted in the data section, Aceh, North Sumatra, and Riau will see their travel times to other places fall the most. Hence, trade cost reductions for these three provinces will be higher than for Jambi and West Sumatra. However, trade value increases and welfare gains for Aceh and North Sumatra are not as large as those for Jambi and West Sumatra. Table 6 reports exports of the eight Sumatran provinces to other Sumatran provinces and to the rest of the country. Most notably, Aceh and North Sumatra see small declines in their exports to both groups of domestic trading partners while Jambi and West Sumatra see significant gains in trade values.

Figure 8: Regional Distribution of Welfare Impact

To achieve a comprehensive and visually intuitive understanding of the relative change in equilibrium across Indonesian provinces, Appendix Table **??** and Appendix Figures C.7 to C.11 represent the relative changes in housing prices, wage rates, population, nominal GDP, and trade values (encompassing sales to other provinces and the rest of the world) respectively. They further highlight the concentration of winners in Sumatra as well as the differences among the winners.

Finally, the Theil index and the Gini coefficient are computed to measure the changes in the overall cross-province inequality in real income (Appendix B). The results are presented in Table 7. These outcomes underscore a twofold impact of the Sumatra road project—augmenting aggregate welfare while simultaneously reducing initial regional inequality driven by the economic dominance of Java. As one moves from the scenario without sectoral linkages to the scenario allowing these linkages and, subsequently, to the one including migration cost reductions, there is a reduction in inequality. Overall, the Theil index declines significantly by 5.15%, and the Gini coefficient falls by 1.47%.

Table 5: Impact on Provincial Welfare Change

	Trade with sectoral linkages		Trade with sectoral linkages and migration cost reductions	
	Trillion Rp (1)	% (2)	Trillion Rp (3)	% (4)
Province:				
Aceh	2.76	15.01%	2.37	12.89%
Sumatera Utara	12.35	14.71%	8.50	10.12%
Sumatera Barat	15.98	53.67%	17.79	59.74%
Riau	31.51	39.59%	46.64	58.61%
Jambi	12.93	60.69%	15.40	72.30%
Sumatera Selatan	5.40	11.96%	3.83	8.47%
Bengkulu	6.40	73.71%	8.13	93.54%
Lampung	-1.17	-2.84%	-1.82	-4.43%
Kep. Bangka Belitung	-0.27	-2.37%	-0.32	-2.79%
Kep. Riau	-4.53	-7.47%	-2.03	-3.35%
DKI Jakarta	-0.16	-0.04%	-0.64	-0.18%
Jawa Barat	-1.21	-0.39%	-2.42	-0.78%
Jawa Tengah	-0.30	-0.18%	-1.56	-0.92%
DI Yogyakarta	-0.32	-1.43%	-0.52	-2.29%
Jawa Timur	-4.09	-1.17%	-6.02	-1.73%
Banten	1.67	2.07%	1.57	1.95%
Bali	-0.12	-0.30%	-0.21	-0.51%
Nusa Tenggara Barat	-0.29	-1.10%	-0.34	-1.30%
Nusa Tenggara Timur	-0.04	-0.32%	-0.04	-0.28%
Kalimantan Barat	-0.15	-1.01%	-0.15	-1.06%
Kalimantan Tengah	-0.32	-2.28%	-0.38	-2.68%
Kalimantan Selatan	-0.35	-1.75%	-0.41	-2.06%
Kalimantan Timur	-1.09	-1.89%	-1.28	-2.21%
Kalimantan Utara	-0.25	-2.22%	-0.29	-2.57%
Sulawesi Utara	-0.23	-1.15%	-0.26	-1.31%
Sulawesi Tengah	-0.17	-1.44%	-0.20	-1.66%
Sulawesi Selatan	-0.51	-1.07%	-0.51	-1.08%
Sulawesi Tenggara	-0.06	-0.49%	-0.08	-0.68%
Gorontalo	-0.04	-0.76%	-0.04	-0.85%
Sulawesi Barat	-0.08	-1.79%	-0.09	-2.01%
Maluku	-0.10	-1.64%	-0.12	-1.92%
Maluku Utara	0.06	1.34%	0.05	1.15%
Papua Barat	-0.24	-3.52%	-0.28	-4.06%
Papua	-0.21	-1.44%	-0.25	-1.66%

Table 6: Impact on Provincial Trade

	Change in Trade to Sumatra		Change in Trade to Other Provinces	
Province:	Trillion Rp (1)	Share (2)	Trillion Rp (3)	Share (4)
Aceh	-1.07	-1.63%	-0.14	-0.21%
Sumatera Utara	-11.67	-2.85%	-1.66	-0.40%
Sumatera Barat	6.68	5.94%	0.02	0.02%
Riau	48.34	12.45%	6.64	1.71%
Jambi	8.99	10.16%	0.42	0.48%
Sumatera Selatan	-6.30	-2.99%	-0.42	-0.20%
Bengkulu	6.52	19.41%	0.91	2.72%
Lampung	-2.04	-1.15%	-0.40	-0.23%
8 Provinces in Total	49.45	3.33%	5.39	0.36%

Notes: Columns (1) and (3) report the change in trade to Sumatra and to other provinces outside Sumatra for each province in Sumatra. Columns (2) and (4) represent the corresponding change in columns (1) and (3) as a share of provincial trade value. Provincial trade value is defined as the sum of exports to other provinces and to the rest of the world.

Table 7: Impact on Regional Income Inequality

	Theil		Gini	
Scenarios:	Change (3)	% (4)	Change (5)	% (6)
Trade without sectoral linkages	-0.0088	-1.12%	-0.0007	-0.11%
Trade with sectoral linkages	-0.0357	-4.54%	-0.0086	-1.34%
Trade with sectoral linkages and migration cost reductions	-0.0405	-5.15%	-0.0094	-1.47%

5.3 Sectoral Production

In this section, we explore the production redistribution effect of these policy changes. We utilize the Herfindahl-Hirschman Index (HHI) as a quantitative measure to assess the impact on production concentration. The HHI is calculated by summing the squared market shares of all provinces operating in each sector. The resulting HHI value ranges from 0 to 1, where a higher HHI indicates a higher level of market concentration. Table 8 reports the HHI by sector for all 34 provinces in Indonesia, as well as the results of HHI with specific focuses on the eight provinces within Sumatra. As depicted in Table 8, the industry sector experiences an increase in HHI, suggesting that production activities within the industry sector are becoming more centralized among fewer provinces. Conversely, the primary and service sectors show a reduction in HHI, indicating a shift toward a more diverse distribution of production activities across provinces within these sectors.

To formally investigate the relationship between the sectoral production distribution and the initial sectoral composition, we conduct a regression analysis to identify factors influencing the growth rate of sectoral output at the provincial-level. The explanatory variables encompass the initial sectoral composition, initial population, and the average reduction in travel times to other provinces. We conduct separate regressions for the primary, industry, and service sectors and present the results in Table 9. Columns (1)-(3) provide the regression results for the entire sample of 34 provinces, while columns (4)-(6) focus on the eight provinces in Sumatra.

Table 8: Market Concentration (HHI) by Sectors

	Primary		Industry		Service	
Samples:	Change	%	Change	%	Change	%
Indonesia, 34 provinces	-0.001	-1.23%	0.001	0.56%	-0.001	-0.73%
Sumatra, 8 provinces	-0.002	-1.70%	0.016	5.05%	-0.004	-2.15%

Notes: Market concentration is measured by the Herfindahl-Hirschman Index (HHI). The HHI is calculated by summing the squared market shares of all provinces operating in each sector. It can range from close to 0 to 1, with lower values indicating a less concentrated market.

Table 9: Regression of Impacts on Gross Output by Sector

	Part (a): Indonesia, 34 provinces			Part (b): Sumatra, 8 provinces		
	(1) Growth of Primary Output	(2) Growth of Industry Output	(3) Growth of Service Output	(4) Growth of Primary Output	(5) Growth of Industry Output	(6) Growth of Service Output
Initial primary share	-0.002			-0.693***		
	(0.050)			(0.142)		
Initial industrial share		0.003			0.196**	
		(0.030)			(0.055)	
Initial service share			-0.069			-0.694**
			(0.053)			(0.177)
Initial population	-0.011	-0.008	-0.009	-0.282***	-0.127***	-0.076**
	(0.008)	(0.005)	(0.007)	(0.045)	(0.020)	(0.025)
Reduction in travel times	0.308**	0.213**	0.258**	0.303	0.173	0.220
	(0.119)	(0.081)	(0.116)	(0.200)	(0.135)	(0.207)
Observations	34	34	34	8	8	8
R-squared	0.195	0.207	0.243	0.909	0.908	0.895

Robust standard errors are reported in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

First, columns (2) and (5) show a “siphon effect” pattern in the industry sector, indicating a tendency for the industry to gravitate toward provinces with a larger initial share of industry GDP. Conversely, the remaining columns in Table 9 demonstrate that the primary and service sectors exhibit a tendency to relocate to provinces with a smaller initial share of sector GDP. Secondly, provinces with a higher initial population tend to experience a lower growth rate of sectoral output, supporting our findings of a reduction in regional inequality resulting from road connectivity. Thirdly, it is evident from the table that a reduction in travel times increases the growth of sectoral output.

6 Sensitivity Checks

In this section, we study how sensitive our results are to values of key parameters and to some assumptions we have made.

6.1 Parameter Sensitivity

A critical factor influencing the equilibrium results in section 4.1 is the sectoral trade elasticity θ^j, which represents the dispersion parameter of the stochastic productivity shock $z_i^j(\omega^j)$ in equation (8). It plays a vital role in determining the bilateral trade share as indicated in equation (23). Additionally, we have the commuting heterogeneity parameter ϵ, which represents the dispersion of the stochastic taste shocks z_{odi} in equation (1). This parameter significantly affects the migration probability as given in equation (22). In this section, we explore how these parameters shape the relative change in equilibrium and discuss the robustness of our results concerning variations in θ^j and ϵ.

If productivity exhibits less dispersion, reflected in a larger value of θ^j, it indicates that goods are less substitutable. In this situation, production relies more heavily on specific countries with lower production costs. Consequently, when road connectivity reduces trade costs, the gains from trade are more substantial. Conversely, if productivity is more dispersed due to a lower θ^j, implying higher variability, road connectivity will have a comparatively smaller effect on equilibrium results. The same logic can be applied to changes in the commuting heterogeneity parameter ϵ. As ϵ increases, individuals are more likely to live in provinces with larger real income, and the reduction in migration costs due to road connectivity will make these provinces more attractive. As a result, these regions will experience a larger increase in GDP.

Table 10 presents a comprehensive comparison of the average change in equilibrium under alternative parameter values with the average change in the baseline scenario. To understand the relative impacts, we compute the ratio between the alternative parameter setting and the baseline setting, while normalizing the relative change in equilibrium as unity. The baseline parameter values are denoted as θ_0 and ϵ_0. In this analysis, we thoroughly investigate the effects of varying trade elasticities from $0.5\theta_0$, $0.8\theta_0$, $1.25\theta_0$, and $2\theta_0$. Additionally, we explore the impacts of changing commuting heterogeneity by considering different values of ϵ, such as $0.5\epsilon_0$, $0.8\epsilon_0$, $1.25\epsilon_0$, and $2\epsilon_0$. By examining the relative changes in equilibrium for wage rates, housing prices, population, and real GDP under these different parameter values, we find that as θ increases, the relative change in equilibrium becomes larger, and similarly, as ϵ increases, the relative change in equilibrium becomes larger as well. This sensitivity analysis is crucial in validating the robustness of our findings and understanding the variations in the economic impacts of the Trans-Sumatra Toll Road project under different trade elasticities and commuting heterogeneity scenarios.

Table 10: Ratio of Average Change under Baseline and Alternative Parameters

Average Change	θ (Sectoral trade elasticity)				ϵ (Commuting heterogeneity)			
to Origin	$0.5\theta_0$	$0.8\theta_0$	$1.25\theta_0$	$2\theta_0$	$0.5\epsilon_0$	$0.8\epsilon_0$	$1.25\epsilon_0$	$2\epsilon_0$
Wage Rate	0.636	0.859	1.182	1.767	1.099	1.028	0.981	0.987
Housing Price	0.689	0.873	1.178	1.887	0.758	0.904	1.114	1.409
Population	0.689	0.869	1.185	1.930	0.439	0.773	1.277	2.014
Real GDP	0.718	0.882	1.162	1.776	0.869	0.940	1.083	1.336

6.2 Alternative Model Assumption

In the benchmark model, we gauge bilateral travel times between provinces during peak hours. However, these travel times might vary during different hours of the day. To address this, we reevaluate bilateral trip duration using average driving times between provinces. Employing the average time measure could potentially lead to an understatement of the reduction in travel times, transportation costs, and migration costs. Our assessment, as reflected in the outcomes presented in Table 11, indicates a slightly lower estimate for aggregate welfare improvement. Specifically, when considering all sections, the overall welfare change is now calculated to be 69.97 trillion rupiah (3.45%). Meanwhile, the reduction in inequality, as measured by the Theil Index, decreases from 5.15% to 4.26%.

We then investigate the use of observed trade deficits in the real economy to solve the equilibrium, as opposed to the baseline assumption of a zero trade balance. The results obtained from this revised approach reveal a smaller welfare change compared to the baseline result. Specifically, the welfare change decreases from 84.02 trillion rupiah to 54.01 trillion rupiah when all sections are taken into account. Consequently, the percentage change in welfare also shifts from 4.15% to 3.45%. However, the reduction in inequality, as quantified by the Theil Index, increased from 5.15% to 5.97%. This adjustment is primarily attributed to the substantial modifications in the initial welfare conditions resulting from the inclusion of observed deficits in the real economy.

We are considering a five-year construction period for the road project. Over this duration, each province experiences growth in estimated birth rates ($\hat{\bar{L}}_i$), technological progress

($\hat{T}_i^j$), and land expansion ($\hat{H}_n$). The policy shocks come into effect 5 years later, once the road is fully constructed. Subsequently, we calculate the relative change in equilibrium to determine the percentage difference with and without the road project. It's important to note that, when considering the construction period, the aggregate welfare improvement is slightly reduced, amounting to 74.95 trillion rupiah (3.70%). Additionally, the reduction in the Theil index decreases to 4.89%.

Table 11: Robustness Results

	Welfare Gains		Theil		Gini	
Scenarios:	Trillion Rp (1)	% (2)	Change (3)	% (4)	Change (5)	% (6)
Policy shock based on average times	69.97	3.45%	-0.0335	-4.26%	-0.0077	-1.20%
Observed trade deficits	54.01	2.67%	-0.0469	-5.97%	-0.0136	-2.13%
Policy shock after 5-year construction	74.95	3.70%	-0.0384	-4.89%	-0.0090	-1.40%

7 Conclusion

The Trans-Sumatra Toll Road offers Sumatra the prospect of large improvements in connectivity, linking regions within the island to the rest of Indonesia and the international market. The tools of the quantitative spatial equilibrium model, as commonly used in international economics and economic geography, provide us with a way of evaluating the effects of such infrastructure investments, which the paper applies to study their regional impact and welfare consequences. We show that the toll road leads to substantial economic improvements in regions within Sumatra, as captured by greater nominal wages, enlarged populations, higher housing prices, and real GDP. The overall welfare gains are about 4.15 percent.

We shed light on the mechanisms at work–a novel contribution to the literature–by relating the integration of goods and labor markets to the aggregate and distributional effect driven by the planned toll road. Doing so requires a calibrated, spatial general equilibrium model with many regions and sectoral and regional linkages. We extend the work of Caliendo and Parro [2015] by introducing frictional labor mobility to capture the important feature of Indonesia's economy and structurally estimate the key parameters using the auxiliary model equations. Meanwhile, dissecting the sources, we find that the majority of welfare gains come from improved goods market integration.

Despite the growing number of studies on the goods shipping and people-moving transportation infrastructure in developing countries, little attention has been drawn to the context of archipelago countries. Our study addresses this gap by evaluating the potential economic impact of significant infrastructure investments in Sumatra. Nevertheless, this paper abstracts from some important aspects of the real world that could affect the impacts of toll road connections. For instance, allowing for the presence of agglomeration economies in the industry sector may further increase the possible gains from the toll road.

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A Model Equilibrium

$$c_n^j = w_n^{\beta_n^j} \prod_{k=1}^{J} \left(P_n^k\right)^{\gamma_n^{kj}} \tag{36}$$

$$P_n^j = \begin{cases} A_j \left[\sum_{i=1}^{N} T_i^j (c_i^j d_{in})^{-\theta^j} \right]^{-1/\theta^j} & j = 1, ..., J \\ \frac{\alpha_n^{J+1}}{1-\alpha_n^{J+1}} \frac{w_n L_n}{H_n} & j = J+1 \end{cases} \tag{37}$$

$$L_n = \sum_i \delta_{in} \bar{L}_i \tag{38}$$

$$\delta_{in} = \left(\frac{w_n / \prod_{j=1}^{J+1} (P_n^j)^{\alpha_n^j}}{(1-\alpha_n^{J+1}) e_{in}} \right)^{\epsilon} / \sum_n \left(\frac{w_n / \prod_{j=1}^{J+1} (P_n^j)^{\alpha_n^j}}{(1-\alpha_n^{J+1}) e_{in}} \right)^{\epsilon} \tag{39}$$

$$\pi_{in}^j = \frac{T_i^j (c_i^j d_{in})^{-\theta^j}}{\sum_{i=1}^{N} T_i^j (c_i^j d_{in})^{-\theta^j}} \tag{40}$$

$$X_n^j = \sum_{k=1}^{J} \gamma_n^{jk} \sum_{i=1}^{N} X_i^k \pi_{ni}^k + \alpha_n^j \left(\frac{w_n L_n}{1-\alpha_n^{J+1}} + D_n \right) \tag{41}$$

$$\sum_{j=1}^{J} \sum_{i=1}^{N} X_n^j \pi_{in}^j = \sum_{j=1}^{J} \sum_{i=1}^{N} X_i^j \pi_{ni}^j + D_n \tag{42}$$

B Measures of Income Inequality

We follow Boyce et al. [2016] and compute income inequality using the Gini coefficient and the Theil index. The Gini coefficient, is derived through the formula:

$$Gini = 1 + \left(\frac{1}{N}\right) - \left[\frac{2}{\bar{v} * N^2}\right] \sum_{i=1}^{N} \left[(N - i + 1) * v_i\right] \tag{43}$$

Here, v_i signifies per capita income in province i, and $\bar{v}$ denotes the average of v_i. The Gini coefficient lies in the interval between zero and one, with higher values indicating greater income inequality.

The Generalized Entropy measure, characterized as $GE(1)$ or the Theil index, is expressed as:

$$Theil = \sum_{i=1}^{n} \left(\frac{w_i}{N}\right) \left(\frac{v_i}{\bar{v}}\right) \log \left(\frac{v_i}{\bar{v}}\right) \tag{44}$$

In this equation, w_i denotes the weight assigned to province i, and $N = \sum_{i=1}^{n} w_i$. The Theil index values, encompassing a range from zero to $\log N$, offer insights with higher values signifying augmented inequality.

C Additional Figures

Figure C.1: Domestic Migration Inflow across Provinces in 2017

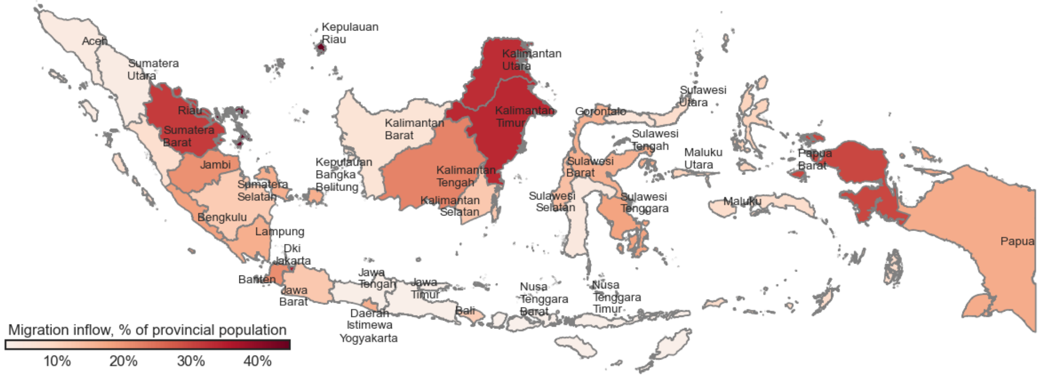

Figure C.2: Domestic Migration Outflow across Provinces in 2017

Figure C.3: Primary Sector Share of GDP within Provinces in 2016

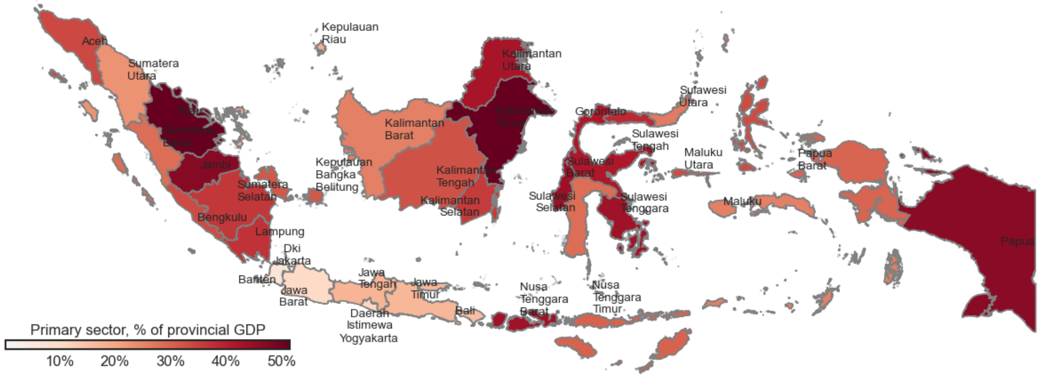

Figure C.4: Industry Sector Share of GDP within Provinces in 2016

Figure C.5: Service Sector Share of GDP within Provinces in 2016

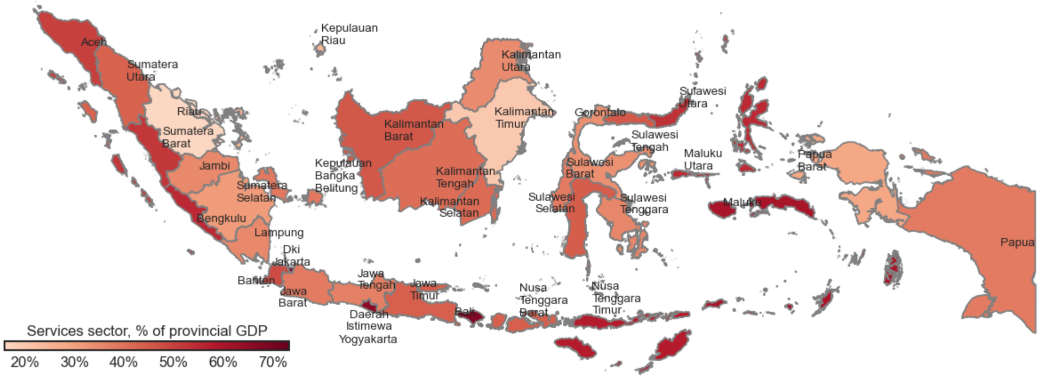

Figure C.6: Comparison of Travel Times between HERE and Google Map

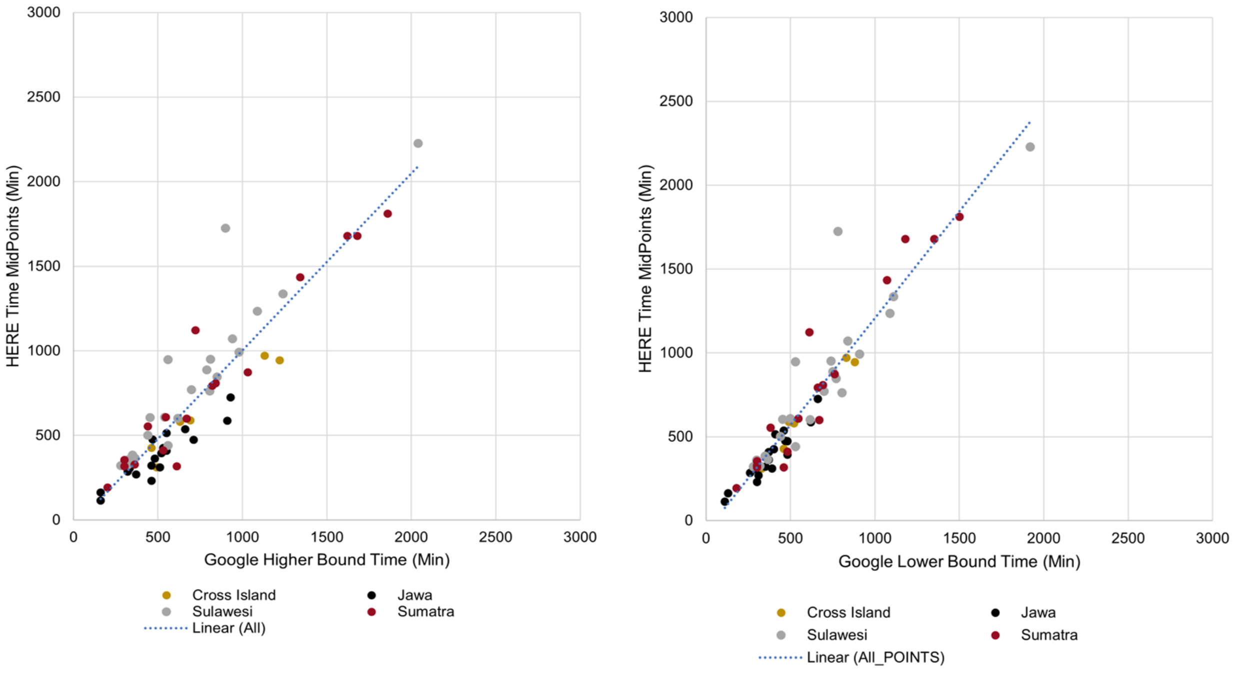

Figure C.7: Change in Housing Price with and without the Road

Figure C.8: Change in Wage Rate with and without the Road

Figure C.9: Change in Population with and without the Road

Figure C.10: Change in GDP with and without the Road

Figure C.11: Change in Trade Value with and without the Road

D Additional Tables

Table D.1: Sector Classification

Classification	Sectors
Primary	Agriculture, Forestry, Fishery
Primary	Mining
Industry	Manufacturing Industries
Industry	Electricity and Gas
Industry	Water and waste management
Industry	Construction
Service	Retail and Wholesale, Vehicle Repairment
Service	Transportation and Warehouse
Service	Accommodation, Food and Beverage
Service	Information and Communication
Service	Finance and Insurance
Service	Real Estate
Service	Business services
Service	Government administration, defense, and social security
Service	Education
Service	Health and Social
Service	Other services

Table D.2: Variables List

Variable	Description	Sources
Panel (a): Variables to be solved		
$\hat{w}_n$	Wage	
$\hat{P}_n^k$	Price index	
$\hat{c}_n^j$	Cost of input bundles	
$\hat{L}_n$	Supply of labor	
$\hat{\delta}_{in}$	Emigration rate	
$\hat{\pi}_{in}^j$	Bilateral trade shares	
$X_n^{j\prime}$	Total expenditure	
Panel (b): Exogenous policy changes		
$\hat{dist}_{in}$	Distance	Authors' own calculation
$\hat{d}_{in}$	Trade cost	Authors' own calculation
$\hat{e}_{in}$	Emigration cost	Authors' own calculation
$\hat{T}_i^j$	Technology	Per capita GDP growth, BPS Website, 2010-2020
$\hat{\bar{L}}_i$	Number of births	Population growth, Worldbank, 2010-2020
$\hat{H}_n$	Land supply	Urban area growth, European Space Agency, 2010-2020
Panel (c): Variables to be calibrated		
L_{in}	Initial migration	Socio-Economic Survey 2017
π_{in}^j	Initial trade share	2016 - BPS Website; Worldbank; MicroDataset; National's import in services
$w_n L_n$	Labor compensation	2016 - BPS Website
β_n^j	Share of value added in output	2016 - BPS Website; Worldbank
γ_n^{kj}	Inuput-Output Coefficient	2016 - BPS Website; World Input-Output Database
α_n^j	Share of each sector in final demand	2016 - BPS Website
θ^j	Trade elaticity	Caliendo and Parro (2015); Kucheryavyy et al. (2016)
ϵ	Migration heterogeneity	Ahlfeldt et al. (2015)
σ^j	Elasticity of substitution across intermediate goods	Not used in the equilibrium system

Table D.3: Parameter Calibration

Parameter	Description	Value
θ^A	Trade elasticity (dispersion parameter) in agricultural sector	8.11
θ^M	Trade elasticity (dispersion parameter) in manufacturing sector	8.41
θ^S	Trade elasticity (dispersion parameter) in service sector	5.00
ϵ	Commuting heterogeneity (dispersion parameter)	6.83

Notes:
(1) θ^A and θ^M are from Caliendo and Parro [2015]
(2) θ^S are from Kucheryavyy et al. [2016]
(3) ϵ are from Ahlfeldt et al. [2015]

Table D.4: Literature review on the welfare impact of transportation infrastructure

Reference	Objective	Welfare Gains	Distribution Effect
Bird et al. [2020]	Belt and Road Initiative in Central Asia	3.0%	up tp 12% in some areas, while other ares stagnate or decline
De Soyres et al. [2020]	Belt and Road Initiative	3.4%	-
Egger et al. [2023]	China's transport network improvements (2000-2013)	9.7%	-
Coşar et al. [2022]	Public investment in roads in Turkey (2000s)	3.0%	up tp 12.4% in some areas, and the median gains are 2.4%
Morten and Oliveira [2018]	Highway improvements in Brazil in 1960	2.8%	range from 1%-15%
Xu [2017]	High-speed railways (HSR) impact in China (2007-2015)	0.5%	-
Baum-Snow et al. [2016]	National highway system in China (1990-2010)	5.0%	-