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Correa, Gana, Pedro José

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GEOGRAPHY, DISASTERS, AND OPTIMAL TRANSPORT NETWORKS

Pedro José Correa Gana

Comisión

FELIPE ZURITA
HUGO SILVA

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By PEDRO JOSÉ CORREA GANA†
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Thesis Committee:
Hugo Silva and Felipe Zurita

Abstract

I study how transport network infrastructures should be allocated in economies where unexpected events diminish the network functionality. I develop a trade model with locations arranged to a graph, where goods are shipped through the transport network, and the trading cost endogenously depends on congestion produced by the available infrastructure and the number of goods transported. Each link in the road network has a certain probability of suffering the loss of a share of its capacity. The optimal network is the solution to a central planner's problem of maximizing the expected value of the consumer's welfare. I found that a disaster mainly affects the location that is isolated, but some non-isolated locations benefit. Also, the optimal road network reduces the expected welfare inequality between shocked and non-shocked regions. Finally, my simulations suggest that an efficient tax policy for shipping can reduce the necessity for a more significant alternative road to connect the isolated areas.

Keywords: Transport network, spatial equilibrium, disasters, economic geography, economic resilience.

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†Comments to pjcorrea1@uc.cl

1 Introduction

The transport network and its underlying geography are fundamental elements that shape the interaction between economic agents and the spatial distribution of economic activity. Transport networks allow intermediate and final goods to move across locations, determining trading costs, production, and consumption. One aspect of the transportation network that has become relevant in recent times has been the ability of the network to maintain its functionality when faced with shocks that affect its operability,[1] events that from now on I will call disasters. Road disruption due to natural hazards, such as hurricanes, floods, landslides, or man-made disasters, is a significant challenge when investing in transportation infrastructure.

Unexpected events can imply huge losses of road infrastructure that affect the overall network functionality. For example, the blockage of the Suez Canal in 2021 or Hurricane Katrina in 2005 disrupted, among other things, international and domestic trade routes, respectively, affecting not only the locations of the disasters.[2] It is not straightforward to quantify how losses in road operability affect the economy through the transport network. Depending on the number of goods transported, the substitute routes for those roads, and the spatial distribution of production, the disruption of one road can have little impact, while affecting another can cause severe losses in an economy. Thus, understanding how a disaster affects trade in an economy and the optimal allocation of roads in a geographic area subject to a given probability of disaster arise as primary public policy concerns. In this context, this paper responds to how disasters affect the spatial equilibrium of the economy and how optimal investment in transportation infrastructure should be made in geographic areas subject to the loss of road network functionality.

To answer this question, closely following Fajgelbaum and Schaal (2020a), I develop a static neoclassical model of trade with multiple goods and sectors, factors of production, and consumption distributed in geographic space. The spatial dimension

[1] In transport literature, this concept is well known as static resilience of a system (Rose & Liao, 2005).

[2] Around 12% of international trade passes through the Suez Canal. Some estimations quantify that the blockade could reduce annual trade growth between 0.2 and 0.4 percentage points (Russon, 2021). About Hurricane Katrina, Zhang, Wu, Martinez, and Gaspard (2008) estimates that there was approximately 3,220 km of roads in the New Orleans area that were submerged in floodwaters for five weeks.

of the model constraints trades only to be conducted through the transportation infrastructure. Transportation is costly, and the cost depends on road congestion resulting from the quantity shipped and the level of road infrastructure on the links. The model novelty is the inclusion of a stochastic element in the operability of the transport network due to unexpected events. Each stretch of infrastructure faces a probability of disruption such that the link becomes partially or entirely inoperative for the transport of goods, increasing congestion, and therefore, trading costs.

Thus, the fundamental timing of the model is summarized into three parts. First, a utilitarian central planner knows the probability of disruption of each span, so she chooses the infrastructure that maximizes the expected value of consumer's welfare given all possible disruption scenarios. Second, given the choice of infrastructure, nature is manifested, and the disruption of paths occurs. Finally, we got the competitive equilibrium for the interaction of agents given the operative transport network, production, consumption, and shipping flows.

The main contribution of this work is the development of a single framework that includes endogenous trading cost, optimal road network decision, and stochastic functionality of road infrastructure to study the economic effects of disruptions on trade. This work focuses on the first stage of this problem, where the planner evaluates the optimal network in the competitive equilibrium of all possible scenarios. The planner knows the risk distribution in the model and how road disruption and congestion affect the spatial equilibrium. This setting is more related to disasters that occur periodically in geographic areas and do not affect full production capacities, such as temporal shocks like local floods, road accidents, or land slices. Also, the model is static and excludes the dynamics of road infrastructure repairment, which restricts the model, but makes it more feasible to compute the optimum equilibrium.

I apply this framework in a economy with three locations, two tradable goods and one non-tradable good. Only one of the tradable goods require transportation to be traded. In this triangular economy, one of the locations has the comparative advantage in producing the tradable goods costly to transport. I assume that only one of the roads connecting the productive location to one of the other locations has a positive probability of disruption. In addition, I allow for the presence of a tax policy that corrects the congestion externality in each scenario. I show how a disaster affects this economy if the road infrastructure were built by a *naive* planner who does not consider disasters or a *sharp* planner who does consider disasters.

When the planner does not consider the disaster, disruption mainly affects the location that becomes isolated but can benefit some non-isolated regions through the comparative advantage of one of the goods traded. The optimal network reduces the expected welfare inequality between shocked and non-shocked regions. I found that the optimal road network can reverse the "benefits" for the disaster for the location not directly affected by the disruption, changing the comparative advantages compared to the economy with an isolated location. Finally, my simulations suggest that an efficient tax or toll policy for the flows of tradable goods reduces the necessity for a larger alternative road to connect the isolated region in the disruption scenario.

The rest of this thesis will proceed as follows. Section 2 reviews the related literature in geographic economics and the connection with disaster literature. Section 3 develops the general framework, with the competitive model, the planner's problem, and the description of the general spatial equilibrium. In Section 4, I present the main simulations of spatial risk distribution, highlighting the principal forces of this model. Section 5 analyzes how the road network affects the economy for different losses of operability. Lastly, Section 6 concludes.

2 Relation to the literature

There has been a substantial development of literature that seeks to explain the role of economic and physical geography in trade and spatial economics (Krugman, 1991a, 1991b; Hanson, 1997). The seminal work of Eaton and Kortum (2002) laid the foundations for the quantitative international trade literature that allows capturing the interaction between more locations and geographic complexities associated with the spatial dimension of trade. They develop a Ricardian model of international trade with a set of geographical factors, such as iceberg costs of trade, tariffs, and bargaining difficulties between agents. An advantage of this quantitative geographic model is the possibility of analyzing how the general equilibrium changes by studying counterfactuals with different trade costs.

Subsequent works have developed quantitative geographic models with an increasing level of spatial granularity.[3] Related to my work on the role of infrastructure, Redding (2016) analyzes how changes in trade cost associated with infrastructure

[3]For a review of different elements in quantitative models of economic geography, see Redding and Rossi-Hansberg (2017).

shift the equilibrium. Their model includes locations with differences in productivity, amenities, geographical location, and labor can move freely between locations, a more appropriate framework for intra-country trade. In the same line, Allen and Arkolakis (2014) develops a model suitable for many geographic features in a spatial equilibrium and studies under which conditions a unique and stable equilibrium exists. With this model, they calculate the welfare gains of a new interstate highway system in the U.S.

This work is also related to the literature that explains trade costs endogenously. Allen and Arkolakis (2019) incorporate a least-cost route problem in a quantitative general equilibrium spatial model where trade cost depends on traffic congestion and the infrastructure network. In relation to my thesis, one crucial insight of this paper is the relation between welfare gains and infrastructure improvements, which is mediated by congestion and the spatial distribution of economic activity. They applied this framework to empirically evaluate the welfare changes of transportation infrastructure improvements respecting an initial network.

Instead, I allow trade costs to change endogenously by congestion and the optimal road network decision in my thesis. Some works have modeled both congestion and road infrastructure. Fajgelbaum and Schaal (2020a) develop a quantitative spatial model where a social planner decides the optimal infrastructure between locations that consume and produce goods of different sectors. In this setting, the infrastructure level and the flow of goods endogenously determine the iceberg transport cost. In a different framework, Felbermayr and Tarasov (2015) models the trading cost depending on the level of road infrastructure. They develop a continuous space model where locations are positioned on a line, and welfare-maximizing national governments allocate infrastructure considering the competitive equilibrium. Nevertheless, this model only takes the infrastructure level and not the congestion on the determinants of trade cost.

This thesis closely follows the model develop in Fajgelbaum and Schaal (2020a). My model consists of locations on a map that produce tradable and non-tradable goods like the previous authors. One tradable good can be transported through the available road infrastructure, and the transport cost depends on the quantity of goods and the infrastructure. Also, the model is solved by a utilitarian central planner, but in this thesis, she only decides the road network, but not directly the quantities and prices of the equilibrium. In addition, in the previous work, the functionality of the paths is fixed and does not incorporate unexpected events that affect the network.

Even though the model in this thesis is based on Fajgelbaum and Schaal (2020a), there are a few similarities in the resolution method presented in Felbermayr and Tarasov (2015). On Felbermayr and Tarasov (2015) the consumption, production, and flows are the result of a decentralized equilibrium given a road network, and the social planner's problem is to choose the road network, which maximizes the competitive equilibrium welfare. In the model I present in this thesis, I follow the former approach of how the planner optimizes the road network.

This work is also related to a body of literature that analyzes how different shocks impact and propagate in a spatial framework. In the context of quantitative models of trade, Caliendo, Parro, Rossi-Hansberg, and Sarte (2018) show how productivity and infrastructure shocks propagate to other sectors of the economy through input-output linkages in the spatial equilibrium. They calibrate the model to a handful of cases, including the aggregate and disaggregate effect of hurricane Katrina in three states of the USA. My work contributes to this literature by incorporating the effect of shocks on the transport network.

Finally, this work is also related to applied literature that analyzes the indirect losses, propagation, and resilience of the economic network of shocks caused by natural and man-made disasters. These works use input-output and computable general equilibrium models to capture the supply chain dynamics of the economy.[4] Taking explicitly the transport network in general equilibrium Colon, Hallegatte, and Rozenberg (2021) use a dynamic firm-level input-output model framework with a transport network. They estimate the indirect losses from road disruption due to flooding in Tanzania and assess which roads increase the economy's resilience to natural hazards. This literature does not address the allocation of the optimal transport network, and transport costs are defined as exogenous to the model. However, they are insightful in the road network's dynamics behind disasters and operability losses.

3 Model

In this Section, I present the main model of this thesis. I begin presenting the model environment and the functional forms of consumption, production, road

[4] For some applications of indirect loss estimates from natural disasters see Tatano and Tsuchiya (2008); Henriet and Hallegatte (2008); Henriet, Hallegatte, and Tabourier (2012); Inoue and Todo (2019).

operability, and congestion. Subsequently, I define the competitive equilibrium given an available road network, and finally, the central planner's global equilibrium.

My general model closely follows Fajgelbaum and Schaal (2020a). There are three main differences. In the previous work, the road infrastructure does not face shocks that affect a share of its operation. In my model, each infrastructure link operability has two states: full operative or disrupted, following a Bernoulli process. Second, my model is restricted to three goods: a tradable good that is costly to transport, a tradable service with no transaction cost, and a non-tradable good. Lastly, in this model, the utilitarian planner only chooses the infrastructure that maximizes the competitive equilibrium's consumer expected value and not the overall quantities and prices in an omnipotent manner.

3.1 Environment

Preferences

Consider an economy with a discrete number of locations in the set $\mathcal{J} = \{1, ..., J\}$. In every location $j \in \mathcal{J}$ there is a fixed number $\overline{L}_j$ of workers. The total number of workers in the economy is L. The utility of workers depends on the consumption of traded good c that is expensive to transport, a tradable service s that does not need transport, that I will call the tradable service, and a non-traded good h. The service good and the non-traded good have a fixed supply S_j and H_j in each $j \in \mathcal{J}$, respectively. I assume that the utility of a single worker in j is a Cobb-Douglas,

$$u_j = u(c_j, s_j, h_j) = c_j^{\alpha}\, s_j^{\nu}\, h_j^{1-\alpha-\nu} \tag{1}$$

where α and ν are the share of the traded goods, and $\alpha + \nu \leq 1$. The expression $c_j = C_j/\overline{L}_j$ is the per capita consumption of the traded goods, and C_j and S_j is the aggregate demand of the traded good and the service good in location j, respectively.

Production

The production of tradable goods uses labor as the primary input. In every location j, there is a fixed supply of labor $\overline{L}_j$ that cannot be moved between locations. The production technology in location j is a function of the hired labor,

$$Y_j = F_j(L_j) = z_j(L_j)^a, \tag{2}$$

where z_j is the productivity of the firm in j, and L_j is the number of workers hired in the firm located in j. The parameter $a \in [0, 1]$ represent the returns to scale of the labor. Then, the production function F_j is either neoclassical when $a \neq 0$ – increasing and concave in it argument – or constant when $a = 0$ – endowment economy.

Underlying stochastic graph

The underlying graph is $G = (\mathcal{J}, \mathcal{E})$, where $\mathcal{J}$ is the set of J locations $\mathcal{J} = \{1, ..., J\}$, and $\mathcal{E}$ are the set of links connecting two locations. For every location, j exists a set $\mathcal{N}(j)$ of connected locations that I call neighbors. As is standard in the transport literature, tradable goods only can be shipped through connected locations. So, to ship goods from j to $k \notin \mathcal{N}(j)$, the goods will have to travel through a series of connected locations.

To make possible the transport of goods is also necessary a level of road infrastructure across locations. The level of built infrastructure from location j to k is I_{jk}. Although the infrastructure built is directed, in the subsequent simulations, I will assume that $I_{jk} = I_{kj}$, which means that the infrastructure construction is symmetric in both directions.

The key element of this model is the stochastic behavior of the road infrastructure. When the link jk is disrupted, the level of built infrastructure I_{jk} loses a known share of its functionality according to the random variable ψ_{jk}. The random variable ψ_{jk} follows a Bernoulli distribution. Then, ψ_{jk} takes value $\mu_{jk} \in [0, 1]$ with probability $\eta_{jk} \in [0, 1]$, and takes value 0 with probability $1 - \eta_{jk}$. The level of available infrastructure is defined by

$$I^A_{jk} = (1 - \psi_{jk}) I_{jk}, \tag{3}$$

which follow a Binomial distribution inherited from the distribution of ψ_{jk}:

$$I^A_{jk} = \begin{cases} I_{jk}(1 - \mu_{jk}) & \text{with probability } \eta_{jk} \\ I_{jk} & \text{with probability } 1 - \eta_{jk} \end{cases} \tag{4}$$

In Section 4 and 5, I will assume that the realization of the random variable ψ_{jk} is equal to ψ_{kj}. Then, both road directions will lose the same operability between the two locations in the disruption.

It is worth noting three assumptions in this stochastic setting. First, operability losses are independent across links. Although disasters are spatially correlated, this assumption allows us to focus on the role of uncertainty in its most basic dimension. Second, due to infrastructure failures, consumer's preferences and production do not change. Finally, in this static setting, road repairs are not allowed. This assumption is more related to settings in the short term, where repair takes time, and the road is still used. These simplifications allow isolating other model elements to focus on the impact of the stochastic element on the competitive equilibrium.

Definition of the scenarios

Let us define $\mathcal{E}^s \subset \mathcal{E}$ the set of links $jk \in \mathcal{E}$ that do not lose operability, and $\mathcal{E}^{po} \subset \mathcal{E}$ the complement of $\mathcal{E}^s$, which contain all the links jk that are disrupted. I define Ω_G as the set of all possible scenarios of operable and partial operable road network $G^s = (\mathcal{J}, (\mathcal{E}^s \cup \mathcal{E}^{po}))$. Then, the probability of occurrence of a scenario $G_s \in \Omega_G$ is

$$Pr(G^s) = \prod_{jk \notin \mathcal{E}^s} \eta_{jk} \prod_{jk \in \mathcal{E}^s} (1 - \eta_{jk}) \tag{5}$$

Transport Technology

As mentioned before, the tradable good can transit through locations for consumption. However, the shipping costs depend on the infrastructure and the flow of these tradable goods in the link. This cost will take the form of an iceberg cost. Denote Q_{jk} the quantity of tradable good shipped from j to $k \in \mathcal{N}(j)$, regardless of where it was produced, and τ_{jk} the iceberg cost of the good in the jk link. The iceberg cost means that to bring Q_{jk} goods from j to location k, the amount of goods that must leave from location j is $Q_{jk}(1 + \tau_{jk})$.

The iceberg cost τ_{jk} depends on the total flow of the tradable goods in the link and the available level of infrastructure. The iceberg cost is

$$\tau_{jk} = \tau_{jk}(Q_{jk}, I^A_{jk}) \tag{6}$$

Two assumptions are crucial about the iceberg cost of shipping. The per-unit cost of shipping increases in the quantity of good shipped,

$$\frac{\partial \tau_{jk}(Q_{jk}, I^A_{jk})}{\partial Q_{jk}} \geq 0, \tag{7}$$

and, the per-unit cost is decreasing in the level of infrastructure,

$$\frac{\partial \tau_{jk}(Q_{jk}, I^A_{jk})}{\partial I^A_{jk}} \leq 0, \tag{8}$$

where Q_{jk} is the total volume transported from j to k.

The equations (7) and (8) describe several elements of the transport dynamics. The increasing cost on the flow shipped captures the cost related to the intensity of road use, like congestion, time delays, or road damages. On the other hand, the decreasing cost of the infrastructure installed is related to quality measures of a road—for example, the number of lines, the construction material, availability of road services.

In the rest of the paper I parametrize the transport (6) technology with the following log-linear function,

$$\tau_{jk} = \delta^\tau_{jk} \frac{Q^\beta_{jk}}{(I^A_{jk})^\gamma} \tag{9}$$

with Q_{jk} the total volume transported from j to k, I^A_{jk} the available road infrastructure in the link jk, δ^τ_{jk} is parameter which capture other transport cost elements, as distance, slope of the path, and $\beta \geq 0, \gamma \geq 0$. As Fajgelbaum and Schaal (2020a) highlight, when $\beta > 0$, there is congestion in shipping. Also, when $\beta \geq \gamma$ the overall transport technology is decreasing.[5]

Flow Constraint

Each location $j = 1, ..., J$, must satisfy a flow constraint between consumption, production, intermediate factors, exports, and imports. The flow constraint is

$$\underbrace{C_j + \sum_{k \in \mathcal{N}(j)} (1 + \tau_{jk}) Q_{jk}}_{\text{Consumption + Exports}} \leq \underbrace{Y_j + \sum_{i \in \mathcal{N}(j)} Q_{ij}}_{\text{Production + Imports}} \tag{10}$$

where C_j is the total consumption of the tradable good in j, the export to neighbors Q_{jk}, and the transport sector cost defined by the iceberg cost $\tau_{jk} Q_{jk}$. The flows are bounded by the local production Y_j and the imports from the neighbors Q_{ij}.

[5]The relation between the goods flows and the road infrastructure plays an important role in the convexity of the problem. Fajgelbaum and Schaal (2020a) discussed the convexity properties in a non-stochastic central planner's problem and the conditions in which the optimization problem can be solved by dual methods.

Network-Building Technology

In this model there are two states of the transport network infrastructure: the built network infrastructure $\{I_{jk}\}_{j\in\mathcal{J},k\in\mathcal{N}(j)}$, and the available network infrastructure $\{I^A_{jk}\}_{j\in\mathcal{J},k\in\mathcal{N}(j)}$. The former is the level of infrastructure decided by the planner in every link $jk \in \mathcal{E}$. The available network I^A_{jk} is the level of the operative road after the realization of ψ_{jk}. There is a fixed supply of capital K that the utilitarian planner con only use for the road network. This capital can be moved at no cost between locations to build the network infrastructure.

The cost of building road infrastructure in a link jk is defined by $\delta^I_{jk} I_{jk}$ units of K and can vary across locations, allowing different costs of construction due to geographic heterogeneity. Then, the network building constraint is

$$\sum_j \sum_{k\in\mathcal{N}(j)} \delta^I_{jk} I_{jk} \leq K \tag{11}$$

3.2 Competitive allocation and planner's problem

I solve the problem of a utilitarian social planner with perfect information who maximizes the expected welfare of workers under immobile labor. The planner decides the infrastructure level $\{I_{jk}\}_{j\in\mathcal{J},k\in\mathcal{N}(j)}$ subject to the building constraint (11). Their decision takes into consideration two main features of the model. First, the infrastructure decision affects the decentralized competitive equilibrium through the cost of shipping goods across locations and then the spatial distribution of production and consumption. Second, given the stochastic road network operability, the planner anticipates the possible scenarios of the available road network $\{I^A_{jk}\}_{j\in\mathcal{J},k\in\mathcal{N}(j)}$, that also affects the cost of shipping.

As is standard in a backward induction problem, first I define the competitive equilibrium and then the planner's optimal problem.

3.2.1 Decentralized allocation

The decentralized economy is the competitive equilibrium where the consumers, the production sector, and the transport sector interact. The consumer maximizes her utility (1) subject to a budget constraint. The productive firms maximize their profit, paying the productive factors. Finally, the transport sector consists of one transport company that behaves as an arbitrator in each road link. These companies transfer goods from an origin o to a destination d, buying the tradable good at p_o^D and selling it at p_d^D. These firms are price takers and face a transport cost given according to (6), although the total flow endogenously determines the trade cost.

I allow the introduction of an ad valorem tax to shipments of the tradable good. The transport sector face a tax with the form of $t_{jk}^{\tau} = \varepsilon_{jk}^{\tau}\tau_{jk}$ on their value at j. Hence, to transfer q_{jk} units from j to $k \in \mathcal{N}(j)$ the company must pay a total cost of $p_j^D q_{jk}(1+\tau_{jk}) + p_j^D q_{jk}\varepsilon_{jk}^{\tau}\tau_{jk}$ in that link.[6] I will set the form of ε_{jk}^{τ} as,

$$\varepsilon_{jk}^{\tau} = \frac{\partial \log \tau_{jk}}{\partial \log Q_{jk}} = \beta, \tag{12}$$

which correct the externalities associated to congestion (Fajgelbaum & Schaal, 2020a). It is worth noting that this taxes policy can adjust perfectly to the state of nature. Then, the tax is flexible to the disruption scenario in each link $jk \in \mathcal{E}$

To close the economy, I assume that the returns of the non-tradable good H_j, the taxes, and firm's profits, are aggregated into a portfolio and transferred evenly to each worker.[7] I assume that the individuals in j are owners of S_j and the firms located in j in equal parts, and r_j is the corresponding part of the local firm's profit to the consumer. Finally, I assume a constant return to scale shipping technology, so I do not have to worry about the ownership of the transport company. In Definition 1, I describe the competitive setting deeply.

Definition 1: The decentralized equilibrium given the available road network without labor mobility consists of quantities $c_j, s_j, h_j, L_j, \{Q_{jk}\}_{k\in\mathcal{N}(j)}$, goods prices p_j^D, p_j^S, p_j^H and labor price w_j in each location j such that:

(a) the consumers maximize their utility such that c_j, s_j, and h_j are:

$$\{c_j, s_j, h_j\} = \underset{\hat{c}_j,\hat{s}_j,\hat{h}_j}{\arg\max}\, U(\hat{c}_j, \hat{s}_j, \hat{h}_j) = \hat{c}_j^{\alpha}\, \hat{s}_j^{\nu}\, \hat{h}_j^{1-\alpha-\nu},$$

[6] This tax implementation is equivalent to a per-unit toll $\theta_{jk} = p_j^D \varepsilon_{jk}^{\tau}\tau_{jk}$, as is demonstrated in Fajgelbaum and Schaal (2020b).

[7] Redding and Rossi-Hansberg (2017) summarize how in quantitative spatial literature land rents as H_j have been distributed among individuals. I follow Fajgelbaum and Schaal (2020a), which uses a global portfolio that aggregates the land rents and distributes them into shares to agents. Another standard option is distributing land rents locally to the residents (Redding, 2016), but inefficiencies can arise. Lastly, an uncommon option use Caliendo et al. (2018), which combine the two option with a share of land rents to the government and the other to residents.

s.t.

$$p_j^D \hat{c}_j + p_j^S \hat{s}_j + p_j^H \hat{h}_j = e_j \equiv w_j + r_j + t$$

where e_j is the expenditures per worker in j, p_j^D is the price of the tradable good, p_j^S is the price of the tradable service good, p_j^H is the price of the non-tradable good, and r_j is

$$r_j = \frac{\pi_j}{\overline{L}_j} + \frac{p_j^S S_j}{\overline{L}_j}$$

with π_j the profits of a firm in location j, and S_j is the aggregate endowment of the service in location j. The expression $p_j^S S_j$ are the profits for providing the service good of location j. And, t is a transfer per worker located in location j. The transfers satisfy

$$t = \frac{\Pi}{L}$$

where $L = \sum_j L_j$, and Π is the aggregate returns to the portfolio of H,

$$\Pi = \sum_i p_i^H H_i + \sum_i \sum_{k \in \mathcal{N}(i)} t_{ik}^\tau p_i^D Q_{ik};$$

(b) the firms of the transportable good maximize their profits such that L_j is:

$$\{L_j\} = \arg\max_{\hat{L}_j,} p_j^D F_j(\hat{L}_j) - w_j \hat{L}_j;$$

where w_j are the wages to labor.

(c) the transport companies in the link jk optimize:

$$\{\hat{Q}_{jk}\} = \max_{\hat{Q}_{jk}} p_k^D \hat{Q}_{jk} - p_j^D \hat{Q}_{jk} \tau_{jk} - p_j^D \hat{Q}_{jk} t_{jk}^\tau - p_j^D \hat{Q}_{jk}$$

where τ_{jk} is the iceberg cost and t_{jk}^τ is the ad valorem taxes.

Also, in equilibrium, flows constraints and non-negativity constraint must be satisfy:

(d) availability of service, and non-traded goods satisfy,

$$\sum_j s_j \overline{L}_j \leq \sum_j S_j;$$

$$h_j \overline{L}_j \leq H_j \quad \text{for all } j;$$

(e) the balanced-flows constraint,

$$C_j + \sum_{k \in \mathcal{N}(j)} (1 + \tau_{jk}(Q_{jk}, I_{jk}^A)) Q_{jk} \leq Y_j + \sum_{i \in \mathcal{N}(j)} Q_{ij} \quad \text{for all } j;$$

(f) local labor-market clearing,

$$L_j \leq \overline{L}_j \quad \text{for all } j;$$

(h) non-negativity constraints on consumption, and flows,

$$\begin{aligned} c_j, s_j, h_j \geq 0 \quad & \text{for all } j \in \mathcal{N}(j), \\ Q_{jk} \geq 0 \quad & \text{for all } j, k \in \mathcal{N}(j), \end{aligned}$$

3.2.2 Planner's stochastic problem

The planner's problem is written as the maximization of the aggregate expected value of the indirect utility $\hat{u}$ of the consumers. The indirect utility is associated with the competitive equilibrium of the decentralized problem given an available road infrastructure. Definition 2 formalizes the planner's problem,

Definition 2: The planner's problem is

$$W = \max_{\{I_{jk}\}_{k \in \mathcal{N}(j)}} E\Big[\sum_j \overline{L}_j \hat{u}(c_j(\{I_{jk}\}), s_j(\{I_{jk}\}), h_j(\{I_{jk}\}))\Big]$$

subject to

(i) the network-building constraint,

$$\sum_j \sum_{k \in \mathcal{N}(j)} \delta^I_{jk} I_{jk} \leq K$$

(ii) the quantities $c_j, s_j, h_j, L_j, \{Q_{jk}\}_{k \in \mathcal{N}(j)}$, goods prices p^D_j, p^S_j, p^H_j and labor price w_j in each location j of the competitive equilibrium of Definition 1 given the available road network $\{I^A_{jk}\}$ in each scenario.

Then, the model can be solved with backward induction in two separate stages: the competitive equilibrium given an operative road network and the planner maximization of the expected welfare of the economy.

3.3 Model resolution

In this Section, I present some properties derived from the model resolution. I highlight the main equations that determine the competitive and overall equilibrium. Also, I discuss the numerical implementation and the algorithm used to solve the model.

3.3.1 Competitive allocation given the network

Given a particular scenario of the available infrastructure network, the consumers, firms, and transport sector interacts as mentioned in Definition 1 and shape the competitive equilibrium.

Production and labor market

According to (b) in Definition 1, the firm's problem is to choose the labor quantity to maximize its profits. The first-order condition of the firm is :

$$[\hat{L}_j] \quad p_j^D z_j a(\hat{L}_j)^{a-1} = w_j \tag{13}$$

With only one productive sector in each location, no labor mobility, and with the local labor-market equilibrium condition, all labor $\overline{L}_j$ in location j goes to the tradable good sector in j. Therefore, there are fixed endowments $\overline{L}_j$ in each city of labor for the tradable good sector, and labor market equilibrium is,

$$\overline{L}_j = L_j \equiv \left(\frac{w_j}{p_j^D z_j a} \right)^{\frac{1}{a-1}} \tag{14}$$

With the equation (14), I can get the equilibrium wages of location j based on the prices of the tradable good in j:

$$w_j = a p_j^D z_j \overline{L}_j^{a-1} \tag{15}$$

Then, the production of a firm located in j is $Y_j = z_j \overline{L}_j$, and the utilities of the local firm in j is,

$$\pi_j = (1-a) p_j^D z_j (\overline{L}_j)^a \tag{16}$$

It can be noted that the utility of the local firm is independent of how much is exported or imported. This property derives from the fact that everything produced is consumed since the transportation firms are in charge of arbitraging prices such that the equilibrium condition is met throughout the economy.[8]

[8] To ease notation, from now on, I will use indistinctly the expression L_j to denote $\overline{L}_j$.

Transport sector

In the transport sector, following (c) in Definition 1, the transport firms act as arbitrators of prices transporting goods in every link jk. Since the transport firm had constant return to scale, and using tax equation (12), in equilibrium we can derive the following non arbitrage condition,

$$p_k \leq p_j(1+(1+\beta)\tau_{jk}) \quad j \in \mathcal{N}(k) \text{ for all } k, \tag{17}$$

This condition implies that in equilibrium, the price in location k cannot be greater than the price in location $j \in \mathcal{N}(k)$ plus the sum of transport iceberg cost and taxes between jk. If this condition does not hold, there will be a transport firm that will have profits taking goods on j, paying the iceberg cost τ_{jk} and the taxes t^{τ}_{jk}, and purchasing the tradable good on a price $p_j(1+(1+\beta)\tau_{jk})$. Then, if the flow between jk is greater than 0, this condition is fulfilled with equality, which implies that $p_k = p_j(1+(1+\beta)\tau_{jk})$.[9]

Consumer's problem

The consumer's problem, according to (a) in Definition 1, is the maximization of her utility subject to the budget constraint, which includes the wage w_j, the corresponding part of the local firm's profit r_j, and the government transfer t_j of the return of H. To obtain the demands for each good, we maximize the utility subject to the budget constraint. Then the demands for the traded good and the non-traded good are:

$$c_j = \frac{\alpha e_j}{p_j^D} \tag{18}$$

$$s_j = \frac{\nu e_j}{p_j^S} \tag{19}$$

$$h_j = \frac{(1-\alpha-\nu)e_j}{p_j^H}, \tag{20}$$

[9]In the alternative per-unit toll θ_{jk} specification, equation (17) can be written as,

$$p_k \leq p_j(1+\tau_{jk}) + \theta_{jk} \quad j \in \mathcal{N}(k) \text{ for all } k,$$

where $\theta_{jk} = p_j\beta\tau_{jk}$, which maintains the interpretation of the non-arbitrage condition.

where e_j is the total expenditure. Using equations (15) and (16), it can be written as a function of prices and flows,

$$e_j = p_j^D z_j(\overline{L}_j)^{a-1} + \frac{\sum_i p_i^H H_i + \sum_i \sum_{k\in\mathcal{N}(i)} t_{ik}^{\tau} p_i^D Q_{ik}}{L}, \tag{21}$$

Tradable service market equilibrium

There is a fixed endowment S_j of the tradable service in every location j. Then, using (19), the traded service market-clearing condition is,

$$\sum_j S_j = \sum_j L_j s_j \equiv \sum_j L_j \frac{\nu e_j}{p_j^S} \tag{22}$$

This equilibrium condition is met even if one of the locations is isolated with no possibility of trade.

Non-tradable market equilibrium

There is a fixed endowment H_j of non-traded in every location j. Then, using (20), the non-traded goods market-clearing condition is,

$$H_j = L_j h_j \equiv L_j \frac{(1-\alpha-\nu)e_j}{p_j^H} \tag{23}$$

Tradable market equilibrium

Finally, to characterize the equilibrium, the tradable market has to be in equilibrium. For every location j, the constraint of flows of goods must be met,

$$L_j\left(\frac{\alpha e_j}{p_j^D}\right) + \sum_{k\in\mathcal{N}(j)} \left(1 + \delta_{jk}^{\tau} \frac{Q_{jk}^{\beta}}{(I_{jk}^A)^{\gamma}}\right) Q_{jk} \leq Y_j + \sum_{i\in\mathcal{N}(j)} Q_{ij} \tag{24}$$

3.3.2 Competitive equilibrium equations system

At this point, we can express non-arbitrage condition (17), the tradable service equation (22), the non-tradable good equation (23), and the tradable good flow constraint (24) as functions of prices p_j^D, p_j^S, p_j^H, flows Q_{jk}, and the exogenous parameters and endowments defined in this model. Therefore, I can form a system with $3 \times J + \sum_j \sum_{k\in\mathcal{N}(j)}$ variables, and $2 \times J + 1 + \sum_j \sum_{k\in\mathcal{N}(j)}$ equations.

I got $J-1$ more variables than equations if we do not address the price dynamic of the tradable service. If all the locations j in $\mathcal{J}$ are connected by some level of road infrastructure I_{jk}^{A}, there is only one price for the tradable service because this service is costless to transport. Then, I add to the system of equation $J-1$ equations with the form of,

$$p_j^S = p_k^S \quad \text{for all the connected par } jk \in \mathcal{J}$$

In the extreme case when the available road I_{jk}^{A} is zero for all the links jk in $j \in \mathcal{N}(k)$ for some locations j, this location are isolated form the other. To complete the system, I add equation (22) to met for each isolated market separately,

$$S_j \geq L_j s_j \quad \text{for all the isolated location } j \in \mathcal{J}$$

With these extra equations, I can get a perfectly-identified system of equations that solve the prices of the competitive allocation given an available infrastructure network and then recover the amounts using the demands.

3.3.3 Numerical implementation

To solve the competitive equilibrium given the network, I implement a MatLab algorithm that iterates on the prices and the flow between locations to meet the equations system described in the previous Section. This system is defined by the non-arbitrage restriction (17), the flows constraints (24), the tradable service equilibrium (22), the non-tradable good equilibrium (23), and the non-negativity restrictions. Since there are many vectors of prices that solve the system, I restrict the price of the tradable service in the first location in $j=1$ to be $p_1^S = 10$.

The overall equilibrium, where the planner chooses the optimal network infrastructure, follows the same process, allowing the infrastructure level in each link to be a decision variable in a maximization problem of the total expected welfare. The central planner then can indirectly choose the prices and flows that satisfy the competitive equilibrium in every possible scenario through the election of the road network and the consequently available infrastructure.

As I cannot assure the convexity of the overall maximization problem, I implement a scatter-search method to find a global optimum. Broadly speaking, the scatter-search method generates multiple trial points that use a local solver's initial guess. The algorithm stores local solutions and returns the solution vector that achieves the maximum value for the objective.[10]

4 Disasters and road network infrastructures

In this section, I present how disasters that disrupt the road network affect the overall welfare of the economy and how should be the optimal road network in this context. I begin by showing an economy with no probability of disaster and describe the main characteristics of this equilibrium. The infrastructure distribution corresponds to the optimal network optimization of a *naive* planner that does not consider disasters. Then I show how the spatial distribution of this economy changes when a disaster occurs in this economy. An interesting aspect is what the planner would choose if she knew ex-ante the risk probability. I allow a *sharp* planner to choose the optimal infrastructure that maximizes the expected utility from the welfare at each location, and I compare it with the symmetric infrastructure of the previous case.

4.1 Triangular economy and parametrization

To understand the main elements of this model, I assume an economy with three productive locations. The geography $\mathcal{G}$ of the economy will be defined by location $\mathcal{J} = \{1, 2, 3\}$, and three roads $\mathcal{E} = \{12, 13, 23\}$ that can be used in both directions. All locations are neighbors. I assume that locations are equally separated by a distance normalized to 1 and δ^{τ}_{jk} is constant for all roads $jk \in \mathcal{E}$. All locations have the same amount of labor L_j. The productivity parameter z_j is 0.05 in all locations except location 1, which I will call the productive location, with $z_1 = 10$. The endowment of the tradable service good is 1 in all locations except in the productive location 1 that has a lower total endowment of $S_1 = 0.05$. Lastly, all locations have an endowment of 1 non-tradable good.[11] This productive distribution allows locations to gain from the bilateral trade, given their comparative advantages.

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[10] For a detailed description of the algorithm and the scatter-search method, see Ugray et al. (2007).

[11] This context can be understood as an economy with an industrial good, an agricultural good, and housing. The industrial good would be c, which is costly to move and produced mainly by the capital location. The agricultural good would be s, with moving costs normalized to 0, produced by the outer locations. And the good h is housing, with a fixed endowment in each location.

Table A.1 summarizes the parameter's values and the fixed endowments for this model. I assume that $1 - \alpha - \nu$ equals 0.25, consistent with the constant housing expenditure share estimated in the U.S. with Cobb-Douglas preferences (Davis & Ortalo-Magné, 2011). I also assume that $\alpha = 0.65$ and $\nu = 0.1$ I assume that firms have decreasing returns to scale with $a = 0.8$. I use the estimates of Couture, Duranton, and Turner (2018) with data from U.S. the ratio of congestion and road infrastructure. So I use $\beta = 1.3$ and $\gamma = 1$, which implies decreasing returns to scale. Finally, the planner weights the total utility of the locations equally.

In this triangular economy, the path connecting location 1 to location 2 has a probability of disruption of $\eta_{12} = 0.3$, while all other paths have a probability of $\eta_{13} = \eta_{23} = 0$. I also assume that the disaster decreases the functionality of this path by 100 percent ($\mu_{12} = 1$). This setting implies two scenarios. In the first scenario, with a probability of 0.7, there is no disaster, and the built infrastructure is equal to the available infrastructure. I will call this scenario the "non-disaster scenario" or "non-disruption scenario" indistinctly. In the second scenario, with probability 0.3, the disaster occurs, and the built infrastructure I_{12} will be useless for the transport of the tradable good. This scenario will be called "disaster scenario" or "disruption scenario" indistinctly.

4.2 The *naive* planner road network

I begin by presenting the equilibrium of this economy by a *naive* planner who does not consider risk. The solution of the *naive* planner in this model is equivalent to assuming that there is no loss of operability or that there is no probability of disaster occurrence in any link. This exercise allows us to benchmark the economy's infrastructure distribution and study the welfare effects.

If the planner does not consider that disasters exist, he wants to maximize the total welfare of the non-disruption scenario, with $\mu_{12} = 0$. I have assumed that locations other than the productive location are the same in characteristics and that the productive location has the comparative advantage in producing the tradable good. If there is no road network, the price of the tradable good p_1^D in the productive location will be too low. The planner knows that if she built a road that connects the productive location with the other two locations, trade could be made through the arbitrator's transport firms that buy the cheap tradable good in $j = 1$ and sell it on the other locations. The non-productive locations can purchase the tradable good in exchange for the tradable service. The trade gains are given by the higher consumption of the tradable service used as exchange currency in the productive location and the consumption of the tradable goods in the other two locations.

The planner, anticipating where the trade flows will be, constructs two symmetrical roads that connect the productive locations with the outside locations. As the total amount of asphalt for build construction is $K = 10$, half of the asphalt for road construction is used for each road, which means that $I_{12} = I_{23} = 5$.

If the disaster does not happen, the available network is the same that the built network. The aggregate welfare gains for trade is 55.15 percentage points respectively to the autarkic economy. The left panel of Figure 1 shows the distribution of infrastructure networks in the economy. The red circle represent the productive location $j = 1$, the white circle in the right is location $j = 2$, and the circle above is location $j = 3$. The thickness of the link represents the level of infrastructure built in the link. The key element to consider is that with equal outer locations and symmetric geography, the optimal network does not consider a route that connects the locations $j = 2$ and $j = 3$. As highlighted in the work of Fajgelbaum and Schaal (2020a), the optimal road network reflects the spatial distribution of comparative advantages. Therefore, there is no need for this path in this context. The outer locations do not have comparative advantages in producing tradable goods. The planner faces the opportunity cost of building an alternative route that connects the outer locations, which is the improvement of the routes used for trade, which lowers the cost of transportation.

In the right panel of Figure 1, the arrows show the amount and direction of the tradable good flows. Trade flows leave the productive location and reach the other two locations. The flow is also symmetric, delivering a final quantity of 0.955 goods from the productive location to every location. Table A.2 in Appendix A shows the detailed results of the percentage of the built infrastructure in each road, trade flows, prices, consumption, and welfare. As mentioned before, I normalize the price of the traded service good of the productive location to be $p_1^S = 10$. The price of the tradable good is higher in the non-productive locations, while the opposite is true for the non-tradable good prices. It is essential to highlight that the difference between the tradable prices is the different iceberg cost of transporting this good across locations. Wages are higher in the productive location. The tradable service flow is the opposite of the tradable good because it is used as an exchange currency

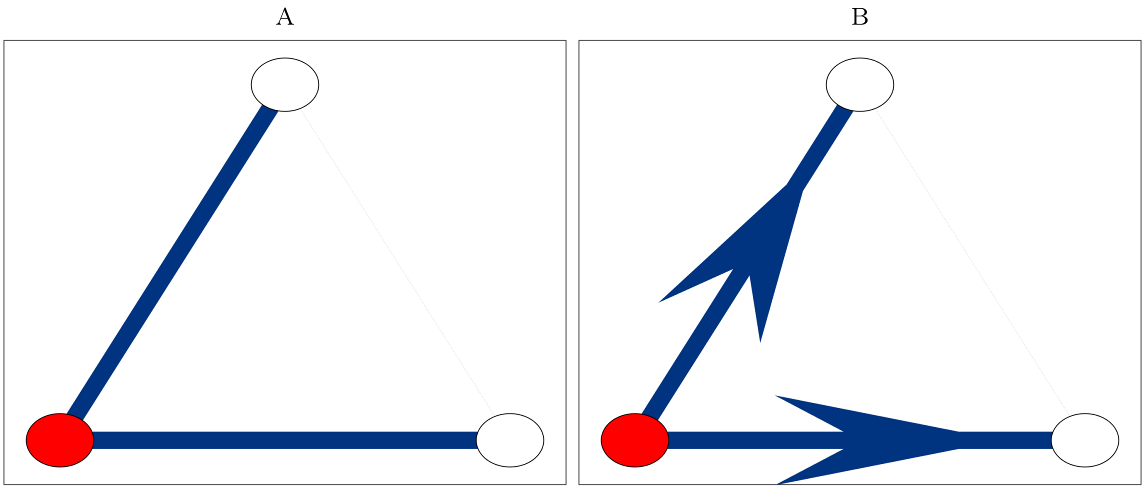

FIGURE 1. AVAILABLE INFRASTRUCTURE AND TRADE FLOWS WITHOUT DISASTER

for the tradable good c.

I show the same economy with taxes t^{τ}_{jk} to the shipping flow of goods in column (3) of Table A.2. The main difference with the non-tax economy is that the tax reduces the trade flows from the productive location to nearly 7 percent of the total flow. This tax implies a slight increase of the total welfare in a 0.2 percent respect the case with no taxes in the non-disaster scenario. This effect is caused by the negative externalities that produce congestion in the iceberg transport cost. Transport firms are price takers, so they do not internalize the congestion of transporting goods in their decisions.

The primary winner from taxation is the productive location. The productive location without taxes was trading through transportation firms at a higher than optimal level. One way to understand this negative externality is as follows. Since the shippers do not internalize the congestion they produce, they buy a larger quantity of tradable goods. The iceberg cost implies that those goods cannot be sold at location 2 or $j = 3$ for the proper return the productive location would have sold it. Then in equilibrium, the marginal utility of the last tradable goods that the productive location sells to the transportation firm is smaller than consuming those goods domestically. The tax solves this problem by adding a cost to transportation, which aligns the marginal utility of consuming the tradable good with the marginal utility of selling it. The aggregate welfare gains of taxes concerning the non-tax

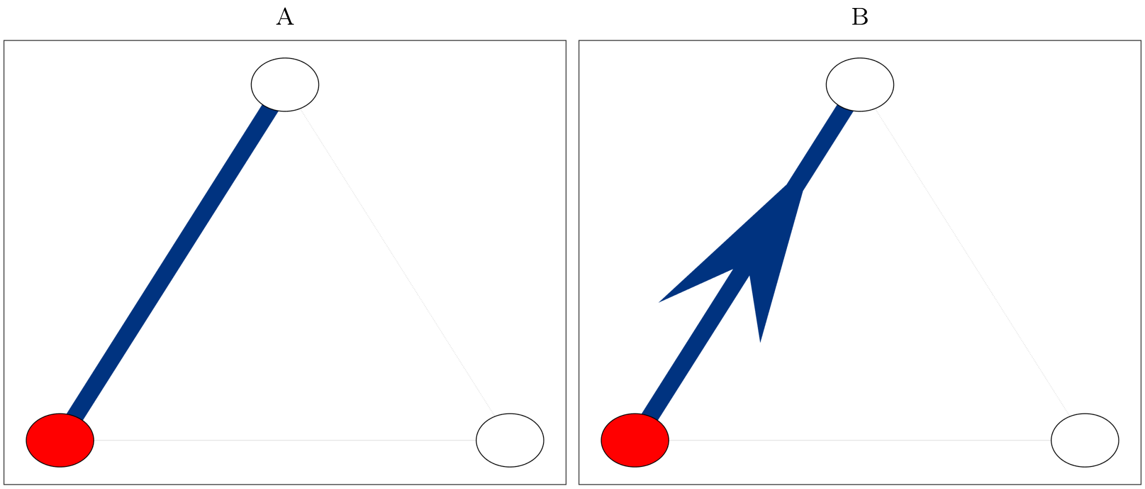

Figure 2. Available infrastructure and trade flows with disaster

economy are 0.23 percent, which means an improvement of 0.29 percentage points regarding the gains for trade with respect to autarky.

4.2.1 Disruption scenario in the symmetric network

Nevertheless, what happens if disruption affects this symmetric road network economy? It is not straightforward how a disaster affects the economy. If the disruption scenario manifests, the available infrastructure is $I^A_{12} = 0$. Since there is no possibility to trade on the $1-2$ route, and there is no route connecting location 2 with $j = 3$, location 2 is entirely isolated and must consume only its endowment goods.[12]

The left panel of Figure 2 shows the level of infrastructure available in the disaster scenario, and the right panel shows the direction of trade. The only possible trade is between the productive location and the third location. The total endowment of the tradable service is reduced because the second location cannot trade with the others. The tradable service appreciates respect to the tradable good, as seen in the reduction of p^D_1 and p^D_3 with respect to the non-disruption scenario. It increases the profits of the $j = 3$ location firm and increases the total expenditure of the third location. Then, the demand for the tradable goods increases by $j = 3$, and the transportation firms produce a greater flow of goods from the productive location to the third location. The increase in the bilateral trade between is 43 percent.

[12]However, it still receives part of the transfers t resulting from the spatial price difference in the non-tradable good, but these transfers do not affect their consumption basket.

The aggregate welfare losses when location 2 is isolated is 11.47 percent with respect to the non-disaster scenario, which implies a reduction of 17.5 percentage points of the trade gains. However, as the trade flows and prices of tradable goods show, not everyone is worse off with the disaster. The new context benefits location 3, which increases its comparative advantage of tradable service. Hence, its welfare increases by 23 percent, while the productive location hardly changes, and location 2, isolated, has a welfare fall of 83.8 percent.

Another relevant result is the effect of the tax policy in the disaster. I assume that the optimal tax can adjust perfectly to each scenario, so the optimal tax can also be implemented in the disaster. Column (4) of Table A.2 presents the results for the economy impacted by disruption with optimal taxes. The tax reduces the flow trade in the $1-3$ road, and again the beneficiary of this policy is the productive location. In the disaster case, the congestion in the link $1-3$ is more significant than the congestion in the non-disaster economy. Then, the tax reduces the inefficient amount of trade and impacts the aggregate welfare more than there is no loss of functionality of the road network.

In summary, if the network implementation does not consider risk in the road network, the welfare losses are considerable if the disaster involves isolating a location. Nevertheless, not everyone loses in this economy. Isolation of location 2 means that the third location, which is not affected by the disaster directly, gains the comparative advantage of the tradable service, which improves its terms of trade and increases its welfare. In addition to isolation losses on the second location, the productive location loses a share of the tradable good demand, reducing its welfare. Finally, taxes play a role in preventing excess congestion when reducing the adverse effects of the disaster.

4.3 Optimal road network in an economy with disruption

In the previous section, I study how the optimal infrastructure by a *naive* planner is affected by disruption and the consequences on the economic activity distribution of the economy. Then, the relevant question that arises in this context is which infrastructure network should the *sharp* planner choose that has perfect information of the probabilities of the non-disaster scenario and the disaster one.

In this section, I assume the same distribution of risk described in the previous section. The probability of the disaster scenario is $\eta_{12} = 0.3$, and in the disaster scenario, the only affected road is the path that connects location 1 with location 2. The infrastructure losses are $\mu_{12} = 1.0$. The productive characteristics of this triangular economy are the same as Section 4, where location 1 is the productive location in the tradable good, and the other two locations have the same characteristic between them. In this problem, the planner considers the probability of disruption in her objective function and the construction of the optimal road infrastructure network.

I begin by describing the two main forces faced by the planner. First, as I showed with the *naive* planner, in the non-disaster scenario, the planner would prefer a symmetric infrastructure network from the productive location, which allows reducing the iceberg cost τ_{jk} of the congestion resulting from the trade. However, the *sharp* planner is aware of the cost of the disaster scenario. In this case, the planner would prefer to have a route that allows trade between location 2 and $j = 3$. In this way, location 2 would not be completely isolated and would generate trade advantages with the rest of the locations. In short, if the planner increases the infrastructure on the alternative route, the cost of trade between the productive location and the rest increases. However, if she does not build the alternative route, there is a probability that location 2 will be isolated.

4.4 The *sharp* planner optimal road network

When the *sharp* planner chooses the optimal road considering the disruption probability, the assignation of road infrastructure is no longer symmetrical. The left panel of Figure 3 shows the network built infrastructure by the planner. The percentage of infrastructure invested in the link with a probability of disaster is now 24 percent of the total asphalt. The road that connects the productive location and location 3 increases the infrastructure level to 63.3 percent of the total available asphalt. However, the most important result in this setting is that the planner uses a small part of the infrastructure, 11.7 percent, on the alternative route connecting locations $j = 2$ and $j = 3$.

Comparing the expected aggregate welfare – which weights the welfare of each scenario by the probability of occurrence – between the *naive* and *sharp*, we can see that welfare increases by 0.54 percent, which implies a 1.7 percent increase in the gains from trade. This improvement is mainly driven by the increase in the expected

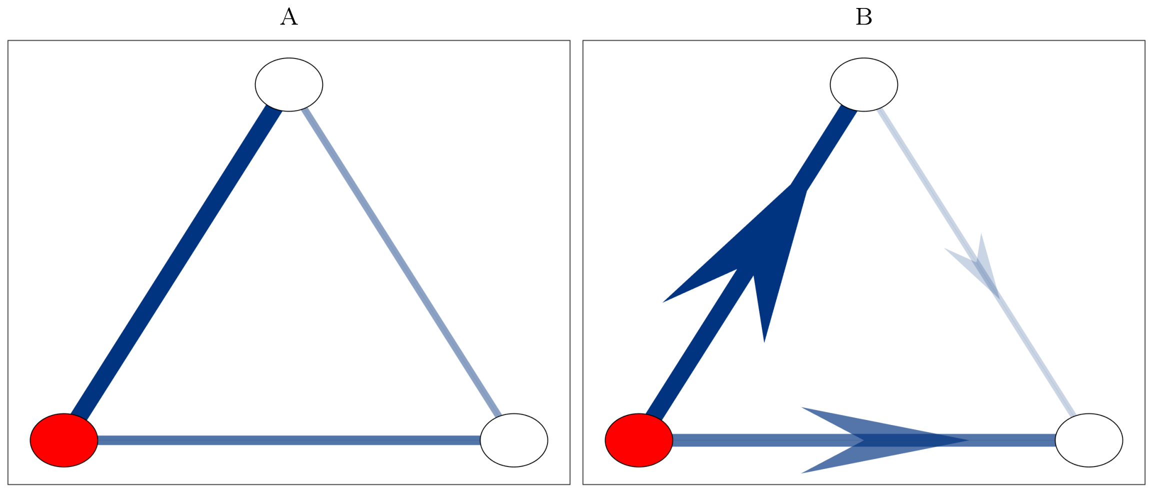

Figure 3. Infrastructure and trade flows no disaster

welfare of location 2 in the disruption scenario.

It is possible to identify two effects of risk in this economy. First, it is observed that there is a distribution of infrastructure towards roads with higher expected functionality. As operability is sure on the $1-3$ road, asphalt on that stretch increases. However, the redistribution of infrastructure investment does not only involve the most used infrastructure in the most likely scenario, but it increases the infrastructure on the $2-3$ path, which we will call the alternative road.

In the right panel of Figure 3, I show the trade flows of the tradable good when there is no loss of functionality. The trade is no longer symmetrical. The reduction in the possibly affected road and the increase of the quality of the other two roads change trade and generate that the tradable good has two options to arrive at the second location. The first is directly through the $1-2$ road, but it is expensive since the road is now of lower quality. And the second, through the third location and the alternative road. The existence of this alternative route implies that with symmetrical infrastructure and disasters, the weighted gain of redistributing infrastructure and allowing trade on the alternative route is greater than the cost in congestion resulting from the poorer quality of the main routes.

Table A.3 shows all the relevant variables of the *sharp* infrastructure design. The first two columns present the non-disaster and the disaster scenario for the economy without taxes. The last two columns show the equilibrium with optimal taxes. When nature does not manifest the disruption, the equilibrium generates more trade flows

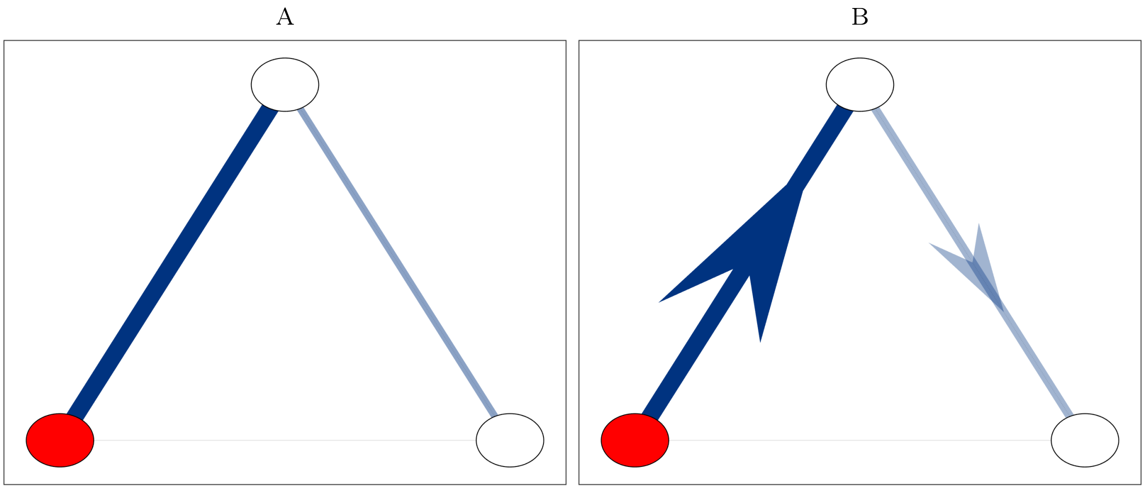

Figure 4. Infrastructure and trade flows with disaster

of the tradable good than the *naive* infrastructure, increasing 3.4 percent. However, this economy has more congestion, even in the non-disaster case. The average loss of tradable goods per iceberg cost for each unit transported is 0.38 tradable goods in the symmetric network since this loss is 0.41 in the *sharp* network in the non-disaster scenario. This result agrees with the fact that the aggregate welfare of this economy in the non-disaster scenario is somewhat lower than in the previous section.[13]

How does this road infrastructure work in a disaster situation? I show the available infrastructure I^A_{jk} and the trade flows Q_{jk} in the disruption scenario in Figure 4. Overall trade increases, and the available roads permit tradable goods to be sold in the second location. The possibility of trade with location 2 increases the aggregate welfare of the disaster scenario by 5.2 percent with respect to the symmetric infrastructure. With the implementation of taxes, this difference is more significant, reaching 5.6 percent.

Lastly, taxes affect the distribution of the *sharp* planner's infrastructure. Panel A of Table A.3, I present the percentage of built infrastructure in each link. Comparing column (1) and column (3), it can be seen that in the equilibrium with taxes, the alternative road is smaller, a 7.9 percent of the total asphalt, and the distribution of infrastructure between the others roads also changes. The $1-2$ increase its size and $1-3$ road reduces compared to the no-tax economy. This fact suggests that with

[13]Aggregate welfare cannot be higher in the good scenario than when the infrastructure is symmetric. Otherwise, symmetric infrastructure would not be the optimal road network in the risk-free economy.

an optimal tax policy, the gains for a large alternative road can be smaller than the economy without taxes. I will go into more deeply on this subject in Section 5.

4.4.1 Winners and losers with the *sharp* planner road network

As I mentioned earlier, the expected aggregate welfare is higher with the *sharp* planner infrastructure network. However, not all locations are improving in the two possible scenarios. In Table 1, I present welfare gains in each scenario across locations when the road network changes from the *naive* planner to the *sharp* planner. Each panel shows the economy without taxes and with taxes, respectively. Column (3) and column (6) report the percentage difference between the welfare of the *naive* and the *sharp* economy in each scenario. Three primary insights arise about the welfare distribution of this triangular economy.

TABLE 1
WELFARE GAINS ACROSS LOCATIONS

	(1)	(2)	(3)	(4)	(5)	(6)
	Non-disaster scenario			Disaster scenario		
	Naive	*Sharp*	percent diff.	*Naive*	*Sharp*	percent diff.
	Panel A. Without taxes					
u_1	3.812	3.812	−0.00	3.725	3.812	2.32
u_2	0.883	0.825	−6.66	0.143	0.59	313.51
u_3	0.883	0.89	0.76	1.087	0.81	−25.48
Total Welfare	5.579	5.527	−0.94	4.955	5.212	5.18
	Panel B. With taxes					
u_1	3.875	3.879	0.09	3.826	3.937	2.90
u_2	0.855	0.809	−5.33	0.143	0.489	242.55
u_3	0.855	0.872	2.08	1.015	0.839	−17.32
Total Welfares	5.585	5.561	−0.43	4.984	5.265	5.64

Notes: Naive is the symmetrical infrastructure network when the planner do not considers the disaster probability. *Sharp* is the infrastructure network when the planner considers the disaster probability.

The most direct result is that location 2 is better off if there is an alternative road in the disaster scenario. The gains are evident: in the non-tax economy, passing from autarky to free-trade implies an increase of 313 percent. However, when the disruption did not happen, the second location lost 6,6 percent of welfare by re-assigning the road infrastructure.

A paradoxical result appears in the third location. The third location is not the productive location, and neither is it directly affected by the disaster. Despite that, the consequences of the new network in this location are not obvious. While the disaster benefited the third location in the symmetric infrastructure, the disaster decreases the welfare of this location when there is a disaster with the optimal *sharp* infrastructure. This is explained because the complete isolation of location 2 is convenient for the third location since it gains the comparative advantage of producing the tradable service. This lowers the prices of the tradable good and increases the total expenditure of this location.

Related to the point, Table 1 shows that the third location is better off with the non-symmetric infrastructure in the disaster scenario. The welfare gains are associated with the reduction in trade cost with the productive location and the consequent reduction in the price of the tradable good. This comparative advantage would be expected to hold in the disaster, but the optimal network does not allow complete isolation. However, the high-quality road across $j = 1$ and $j = 3$ does not prevent the location 2 from losing part of the comparative advantage in producing the tradable service. Then, is a more significant reduction in the consumption of the tradable good for the third location.

Lastly, I present the welfare gains in each scenario across the *sharp* road network locations in panel B of Table 1 if there are taxes in the economy. The results are in line with those presented above. Congestion in the links primarily affects the locations from which the tradable goods are shipped. Since the third location also ships tradable goods to location 2, the tax increases the expected welfare of location 3 with respect to the non-tax economy.

This section's overall exercise of comparing the *naive* road network economy with the *sharp* network economy led to various relevant insights. First, the most mechanical result is that when the infrastructure decision is made under uncertainty, the distribution of infrastructure changes to ensure that disaster loss does not affect the connectivity of all locations. This means building routes that would not exist in a deterministic context. Taxes change this distribution of infrastructure somewhat. Reducing congestion means that the alternative route does not have to be so large, and the infrastructure network shifts towards a slightly more symmetrical one.

The other important insight is that the total isolation of the second location benefits the third location, which is not directly affected by the catastrophic event, as it gains the comparative advantage of producing the tradable service in this economy. Thus, with symmetric infrastructure, the third location benefits from moving from non-disaster to disaster. However, this trend is reversed when the planner builds the infrastructure that connects all locations. The third location is disadvantaged in this road network when a disruption happens relative to the non-disaster scenario.

of

5 Alternatives roads and taxes

In the simulations in Section 4, I have assumed that the disruption of route $1-2$ has a loss of operability of $\mu_{12} = 1$, which implies the total loss of that route and the total disconnection of location $j = 2$. However, cases where disasters only decrease part of a route's operability are more common than complete route cutoff. Even in events where roads cease to function, such as bridge closures or significant landslides, repair work generally includes the creation of alternatives that allow flow, albeit at a much lower level. In this way, studying the partial loss of operability also allows capturing some aspects of road repair.

In this Section, I conduct a sensitivity analysis to understand how different levels of operational loss and the presence of an alternative route affect welfare and trade in this economy, looking exclusively at the disaster scenario. This analysis also allows studying who would pay for a more significant alternative route and whether a disaster-adjusted tax policy is a complementary or substitute policy to creating an alternative route.

I assume the same economy described in Section 4, where there are three goods, two tradable and one non-tradable, and location $j = 1$ has the competitive advantage in producing the tradable good that is costly to transport. I will assume that the initial distribution of infrastructure is the same symmetric distribution given by the *naive* planner. Therefore, the amount of installed infrastructure is symmetric from the productive location, with $I_{12} = I_{13} = 5$. To analyze the impact of the disaster and the size of this alternative route, I change the risk distribution. I allow the loss of operability μ_{12} to change on a grid of values between $[0, 1]$, and the level of the alternative route I_{23} to take values on a grid between $[0, 4]$. It is important to note that the infrastructure built on the remaining roads does not change in the face of changes to the new route and that the new alternative route implies increasing the amount of K in the economy. Also, the distribution of the road network is not the decision of the central planner.

5.1 Sensibility analysis of the optimal network

Figure 5 shows how the total welfare of the economy changes with different disaster impacts on the road and the alternative path. In the figures above, the x-axis is μ_{12}, and each line takes a fixed level of infrastructure in the alternative road. The figures below are the same, but the x-axis is I_{23}, and each line is the grid of μ_{12} values. Finally, in the left figures, the economy is not using taxes for congestion, and in the right, the economy has taxes. I standardized the values to see the percentage change with respect to the welfare of the symmetrical infrastructure economy with $\mu_{12} = 0$ and $I_{23} = 0$.[14]

Regardless of the infrastructure level, all lines start from the same point in the figures above. If the disruption does not affect the road functionality, a sizeable alternative route has no value in this economy. Since the initial scenario is symmetric, and the outer locations are equal in characteristics, the non-productive locations have no incentive to exchange goods. Only when the available infrastructure is not symmetric, do the advantages of trading the tradable good arise.

The loss of operability of this economy reduces aggregate welfare on an increasing rate. The drop in welfare in this scenario is close to 2 percent when μ is close to 60 percent. Moreover, in the extreme case, when μ tends to 1 and location $j = 2$ is isolated, the aggregate welfare of the economy drops about 11 percent. The alternative path improves welfare the larger μ is. When the asphalt level of I_{23} is 4, the alternative path can reduce the welfare loss nearly 5 percent in the disaster scenario.

Figure 5 shows that in this setting, while there is always a gain from obtaining an alternative route and this gain is increasing in the level of μ, the welfare gain can be very small for low levels of μ. As the figures below present, the gain from moving from

[14]Figure B.1 in the Appendix B presents the non-normalized figures of the aggregate welfare.

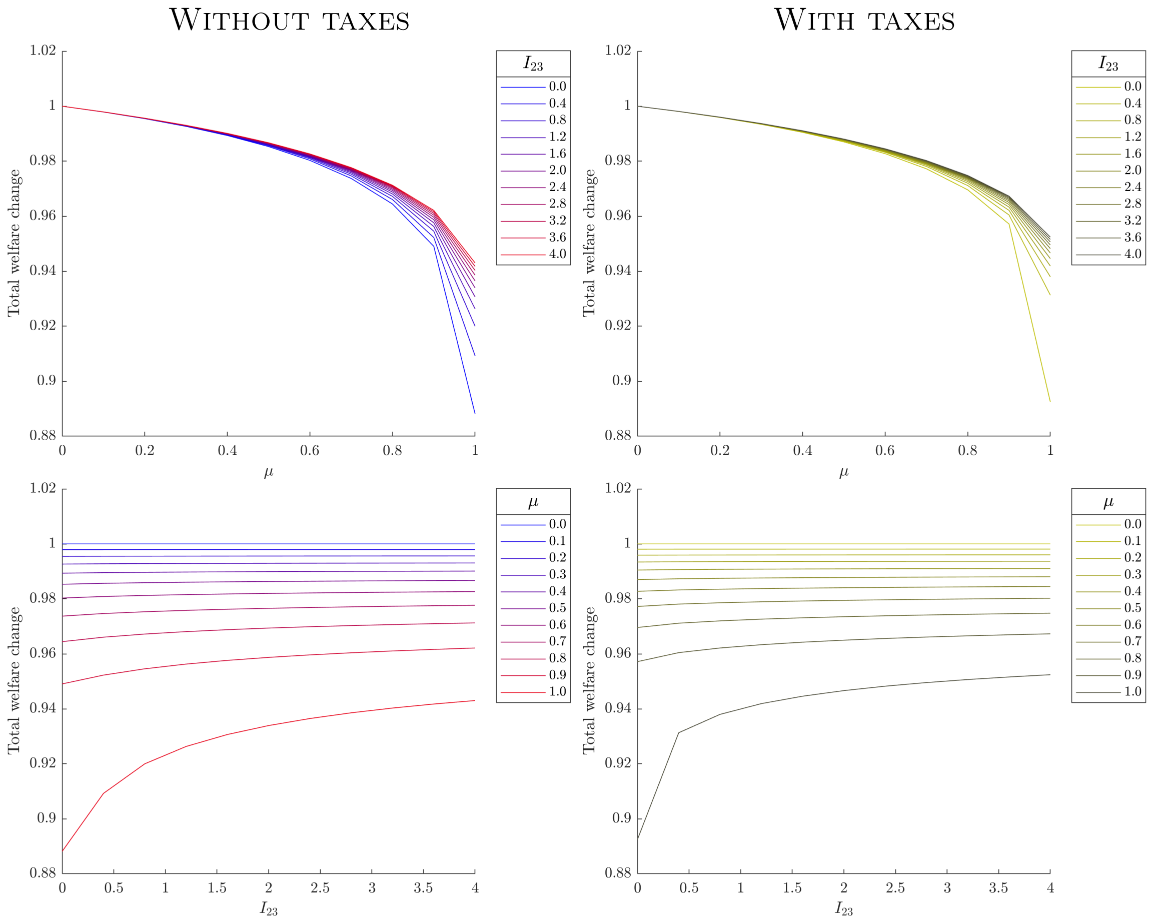

Figure 5. Aggregate welfare's percentage change

an $I_{23} = 0$ route to an $I_{23} = 4$ route – a 28.5 percent increase in total infrastructure – is 6 percent of welfare. Furthermore, these simulations are the welfare loss in the disruption scenario. If the probability of occurrence η_{23} of the disaster is very low and the construction cost δ^I_{23} is high, it may not be desirable to build the alternative route.

The comparison of the left panel without transportation taxes to the right panel with taxes in Figure 5 confirms the intuition that taxes can alleviate the congestion externalities when a disaster forces a rerouting of transportation, concentrating the flow on fewer routes. The drop in welfare is smaller with taxes for all levels of μ. Nevertheless, it seems that the gains from moving from $I_{23} = 0$ to some infrastructure are different with and without taxes. When the loss of functionality is high, the gain from making an alternative route with $I_{23} = 0.4$ is higher when there are taxes. When building the alternative route of $I_{23} = 0.4$, aggregate welfare rises by 4% when there are taxes and without taxes less than 2%.

This result answers whether or not taxes are a complementary policy to creating an alternative route. The graphical evidence in Figure 5 suggests two patterns. When no infrastructure is installed on the alternative route, the pass-through gain from not having a small route appears more critical when a tax policy is in place. However, when there is some level of the alternative road, an improvement of the alternative road does not appear to impact aggregate welfare differently, whether there are taxes or not. Then, taxes and the alternative route are no longer complementary for a high level of infrastructure.

5.1.1 Who wins with an alternative road?

In this Section I analyze who gains and loses from the alternative route and, consequently, who would be willing to pay for a more significant route in the disaster scenario. Figure B.2 and Figure B.3 in the Appendix B I present how total welfare changes with different disaster impact on the road and the alternative path for each location. I begin with the second location, which has the most direct relationship between the disaster and the alternative route. The higher the μ, the lower the welfare. The opposite is true for the alternative route infrastructure. The higher the I_{23}, the higher the welfare.

An interest pattern arises in location $j = 1$. In the no-tax economy, neither infrastructure nor the size of the $1 - 2$ path disruption affects the productive location. However, when location $j = 2$ is isolated – when $j = 1$ and $I_{23} = 0$ – the productive location loses about 2 percent of its welfare. If the second location is not completely isolated, the productive location can trade with both locations, albeit indirectly through location $j = 3$ and the alternative route. Nevertheless, total isolation implies that the tradable service becomes very expensive because almost half of the endowment of this good, which the second location has, is lost. With taxes, the same logic applies, but with a difference: when μ increases, the welfare of this location increases.

One mechanism behind this increasing relationship of μ with the welfare of the productive location is the distribution of taxes. When there are no taxes, the location μ affects the gain from trade with the second location. However, this loss is compensated by the demand increase for the tradable good in the third location, which through the alternative route, sells the tradable good to location $j = 2$. The same happens when there are taxes, but with a small different detail: the equal distribution of taxes. Even though congestion affects more location $j = 2$ – because of the difficulties to trade the tradable good – the taxes are distributed in equal parts, so both the productive location and the third location gain from taxes.

At the third location, a distinct pattern also develops in the relationship of the alternative path and μ. In panel E of Figures B.2 and B.3, location $j = 3$ only benefits from disruption if there is no infrastructure on the alternative route, a repeated result from the previous Section. With some positive infrastructure level on the $j = 3$ road, the third location loses the comparative advantage of tradable service, which implies lower overall spending and welfare. Therefore, for each value of μ, the increase in the alternative path reduces the welfare of this location.

However, taxes change these results somewhat. In panel F of Figures B.3 welfare continues to decrease with the level of infrastructure I_{23} for each value of μ. Nevertheless, there is now a positive level of I_{23} where the location can gain for the alternative road. Correcting for the congestion externality is one of the reasons why the alternative road affects the welfare of this location less. The taxes reduce trade, which means that the loss of comparative advantage in the tradable service at location $j = 3$ is not as significant as when there is a larger route.

What can be learned from this exercise? I can conclude that the productive location and location $j = 2$ win with the alternative route. However, there is a difference between how large the alternative route should be. When the catastrophe is significant, the best choice for the productive location is the smaller infrastructure that prevents the isolation of location $j = 2$. Conversely, the second location always benefits from the alternative road. Furthermore, these simulations suggest that an efficient tax policy for shipping goods can reduce the necessity for a more significant alternative road to connect the isolated region in the disaster scenario, which can be relevant if the cost of implementing a tax policy or poll is lower than the construction of the substituted road.

tradabk

6 Conclusion

In this thesis, I develop a spatial model of trade, where goods are shipped through the transport network, and the trading cost depends on the available infrastructure and the flow of goods transported. I extend the model including a stochastic element in the operability of the road network, where each link has a certain probability of suffering a loss of its capacity share. This framework allows studying the impact of a disaster in the competitive equilibrium and the optimal infrastructure network of a planner that knows the disaster probability and maximizes the expected aggregate welfare of the economy. The model allows the inclusion of different degrees of operational losses and disaster probability in the spatial model.

I apply this framework in a triangular economy where one of the road connecting locations has a positive probability of a total loss of their capacity. I study the optimal road network under two cases: one if the planners do not consider the disaster, and the other if the planner has a perfect knowledge of the probability of disruption.

I found that disruption affects mainly the location that becomes isolated when the planner does not consider the disaster, and benefits some non-isolated regions if they gain the comparative advantage of one of the goods traded. The optimal road infrastructure that considers the disruption probability distributes the infrastructure investment to roads not used in the non-disaster scenario, but prevents the isolation of locations when the disaster occurs. This optimal network reduces the expected welfare inequality between shocked and non-shocked regions. I found that the optimal road network reverses the "benefits" for the disaster for the non-shocked location, changing the comparative advantages in comparison to the economy with an isolated location. Finally, my simulations suggest that an efficient tax policy for shipping goods can reduce the necessity for a more significant alternative road to connect the isolated region in the disaster scenario.

The goal of this thesis has been to provide a framework linking general spatial equilibrium with the disaster literature through the road network. I do not include in this model dynamics of road repair, disaster migration, or shocks in other relevant infrastructures rather than the road network. However, this work has the potential to serve as the basis of future work for several questions, including: What investments can increase the resilience of the infrastructure network? What is the optimal redundancy of roads in a geographic area? How empirically estimate the gains of a highway network under the uncertainty of disasters? Or more political economy questions as the feasibility of especial tax policies for disasters. I hope that future research can address these relevant questions.

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A Tables

Table A.1

Parameters and Endowments

Parameters	Value	Explanation
α	0.65	arbitrary choice
ν	0.1	arbitrary choice
$1 - \alpha - \nu$	0.25	Estimates of housing expenditure in Davis and Ortalo-Magné (2011).
β	1.3	Ratio of congestion and road infrastructure
γ	1	from Couture et al. (2018).
ε_{jk}	1.3	Optimal tax from Fajgelbaum and Schaal (2020a).
L_j	1	arbitrary choice
H_j	1	arbitrary choice
K	10	arbitrary choice
a	0.8	arbitrary choice
δ^I_{jk}	1	symmetry
δ^τ_{jk}	1	symmetry
ω_j	1/3	symmetry

Table A.2

Triangular naive equilibrium

	(1)	(2)	(3)	(4)
	Without taxes		With taxes	
	Non-disaster	Disaster	Non-disaster	Disaster
	Panel A. Available infrastructure and trade flows			
I_{12}	50	0	50	0
I_{13}	50	50	50	50
I_{23}	0	0	0	0
Q_{12}	0.955	0	0.889	0
Q_{13}	0.955	1.369	0.889	1.207
Q_{32}	0	0	0	0
	Panel B. Tradable good prices and consumption			
p_1^D	13.144	6.771	12.145	6.256
p_2^D	18.098	682.5	21.729	812.882
p_3^D	18.098	10.844	21.729	13.606
c_1	7.37	7.808	7.613	8.176
c_2	1.005	0.05	0.939	0.05
c_3	1.005	1.419	0.939	1.257
	Panel C. Tradable service good prices and consumption			
p_1^S	10	10	10	10
p_2^S	10	5.25	10	6.253
p_3^S	10	10	10	10
s_1	1.49	0.813	1.422	0.787
s_2	0.28	1	0.314	1
s_3	0.28	0.237	0.314	0.263
	Panel D. Non-tradable good prices and consumption			
p_1^H	37.256	20.333	35.56	19.672
p_2^H	6.997	13.125	7.845	15.632
p_3^H	6.997	5.917	7.845	6.578
h_1	1	1	1	1
h_2	1	1	1	1
h_3	1	1	1	1
	Panel E. Wages and firm's utilities			
w_1	105.152	54.166	97.159	50.044
w_2	0.724	27.3	0.869	32.515
w_3	0.724	0.434	0.869	0.544
π_1	26.288	13.542	24.29	12.511
π_2	0.181	6.825	0.217	8.129
π_3	0.181	0.108	0.217	0.136
Taxes	0	0	9.628	5.015
	Panel F. Welfares			
u_1	3.812	3.725	3.875	3.826
u_2	0.883	0.143	0.855	0.143
u_3	0.883	1.087	0.855	1.015
Total welfare	5.579	4.955	5.585	4.984
Expected welfare	5.392		5.405	

Notes: this table present the spatial general equilibrium when a *naive* planner, who do not considers the disaster probability, chooses the optimal road network. The first two columns shows each scenario in the economy without taxes. The third and fourth columns shows each scenario in the economy with taxes.

Table A.3

Triangular sharp equilibrium

	(1)	(2)	(3)	(4)
	Without taxes		With taxes	
	Non-disaster	Disaster	Non-disaster	Disaster
	Panel A. Available infrastructure and trade flows			
I_{12}	24.046	0	32.93	0
I_{13}	64.309	64.309	59.218	59.218
I_{23}	11.645	11.645	7.852	7.852
Q_{12}	0.716	0	0.759	0
Q_{13}	1.122	1.646	0.974	1.402
Q_{32}	0.138	0.488	0.053	0.339
	Panel B. Tradable good prices and consumption			
p_1^D	13.135	13.047	12.086	11.159
p_2^D	20.211	34.847	23.878	59.958
p_3^D	17.881	20.801	21.16	24.61
c_1	7.37	7.376	7.627	7.863
c_2	0.904	0.538	0.862	0.389
c_3	1.017	0.879	0.968	0.901
	Panel C. Tradable service good prices and consumption			
p_1^S	10	10	10	10
p_2^S	10	10	10	10
p_3^S	10	10	10	10
s_1	1.489	1.481	1.418	1.35
s_2	0.281	0.288	0.317	0.359
s_3	0.28	0.281	0.315	0.341
	Panel D. Non-tradable good prices and consumption			
p_1^H	37.232	37.013	35.456	33.745
p_2^H	7.023	7.206	7.914	8.973
p_3^H	6.994	7.031	7.88	8.532
h_1	1	1	1	1
h_2	1	1	1	1
h_3	1	1	1	1
	Panel E. Wages and firm's utilities			
w_1	105.076	104.374	96.691	89.268
w_2	0.808	1.394	0.955	2.398
w_3	0.715	0.832	0.846	0.984
π_1	26.269	26.094	24.173	22.317
π_2	0.202	0.348	0.239	0.6
π_3	0.179	0.208	0.212	0.246
Taxes	0	0	10.134	17.437
	Panel F. Welfares			
u_1	3.812	3.812	3.879	3.937
u_2	0.825	0.59	0.809	0.489
u_3	0.89	0.81	0.872	0.839
Total welfare	5.527	5.212	5.561	5.265
Expected welfare	5.421		5.4704	

Notes: this table present the spatial general equilibrium when a *sharp* planner, considers the disaster probability, chooses the optimal road network. The first two columns shows each scenario in the economy without taxes. The third and fourth columns shows each scenario in the economy with taxes.

B Sensitivity analysis figures

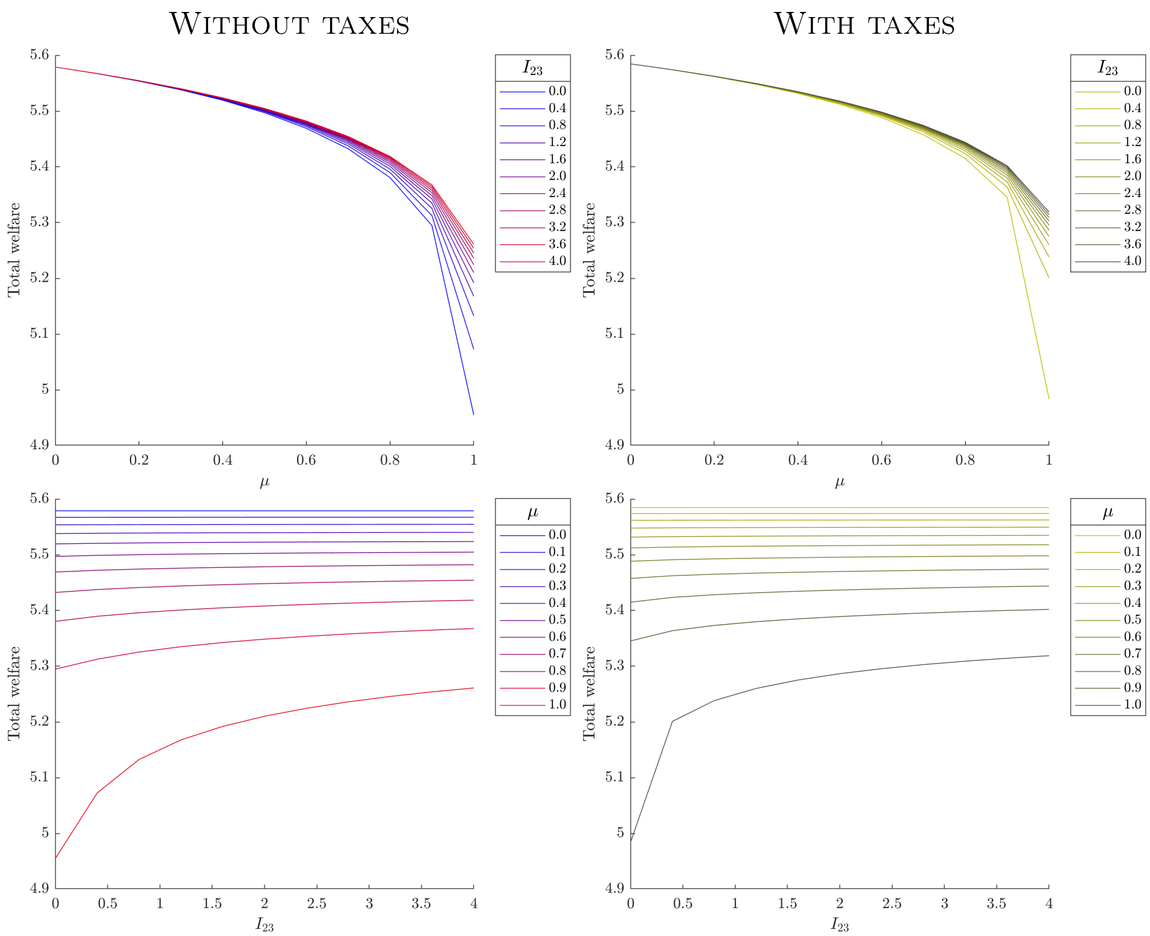

Figure B.1. Aggregate welfare's change

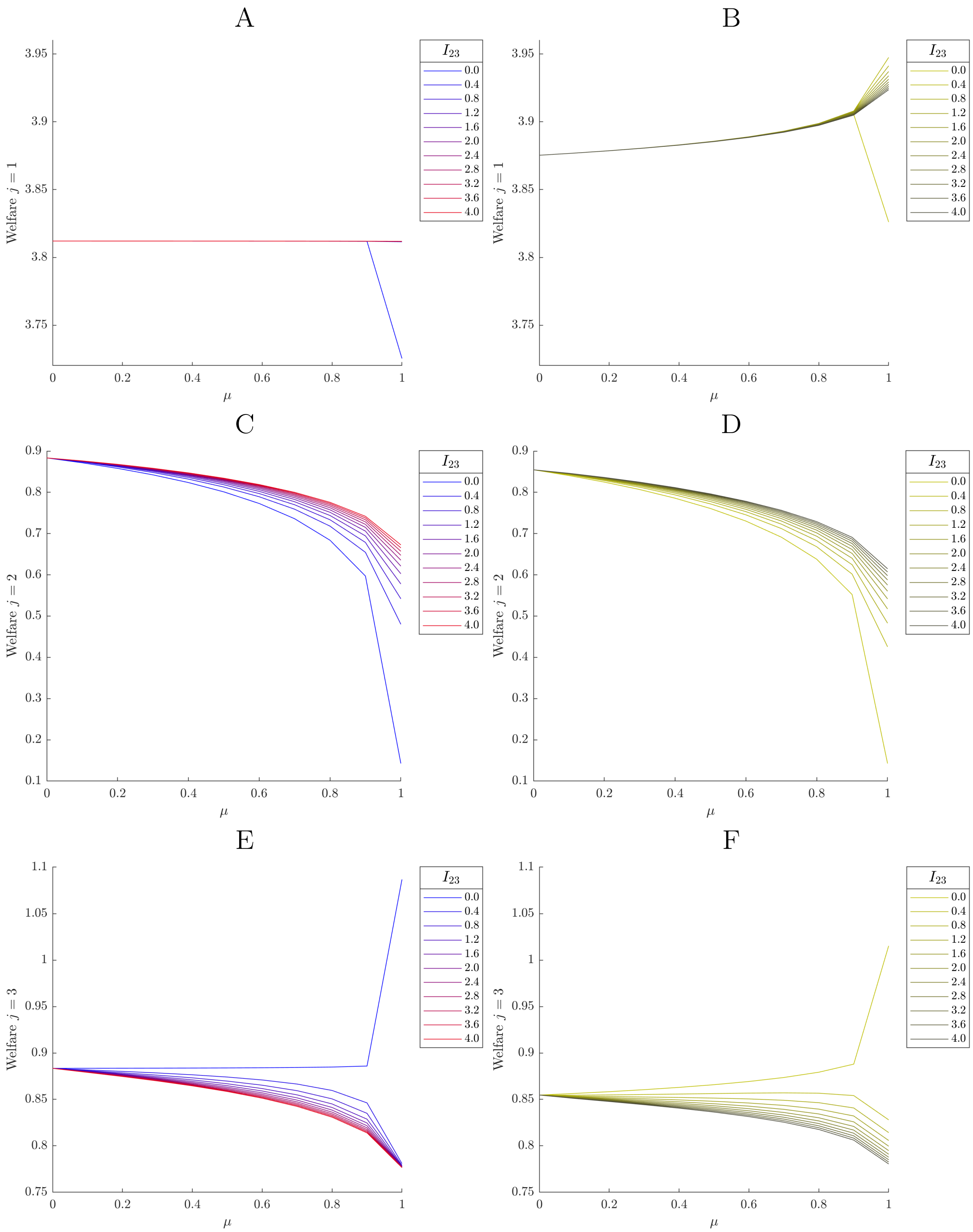

FIGURE B.2. WELFARE'S CHANGE ACROSS LOCATIONS

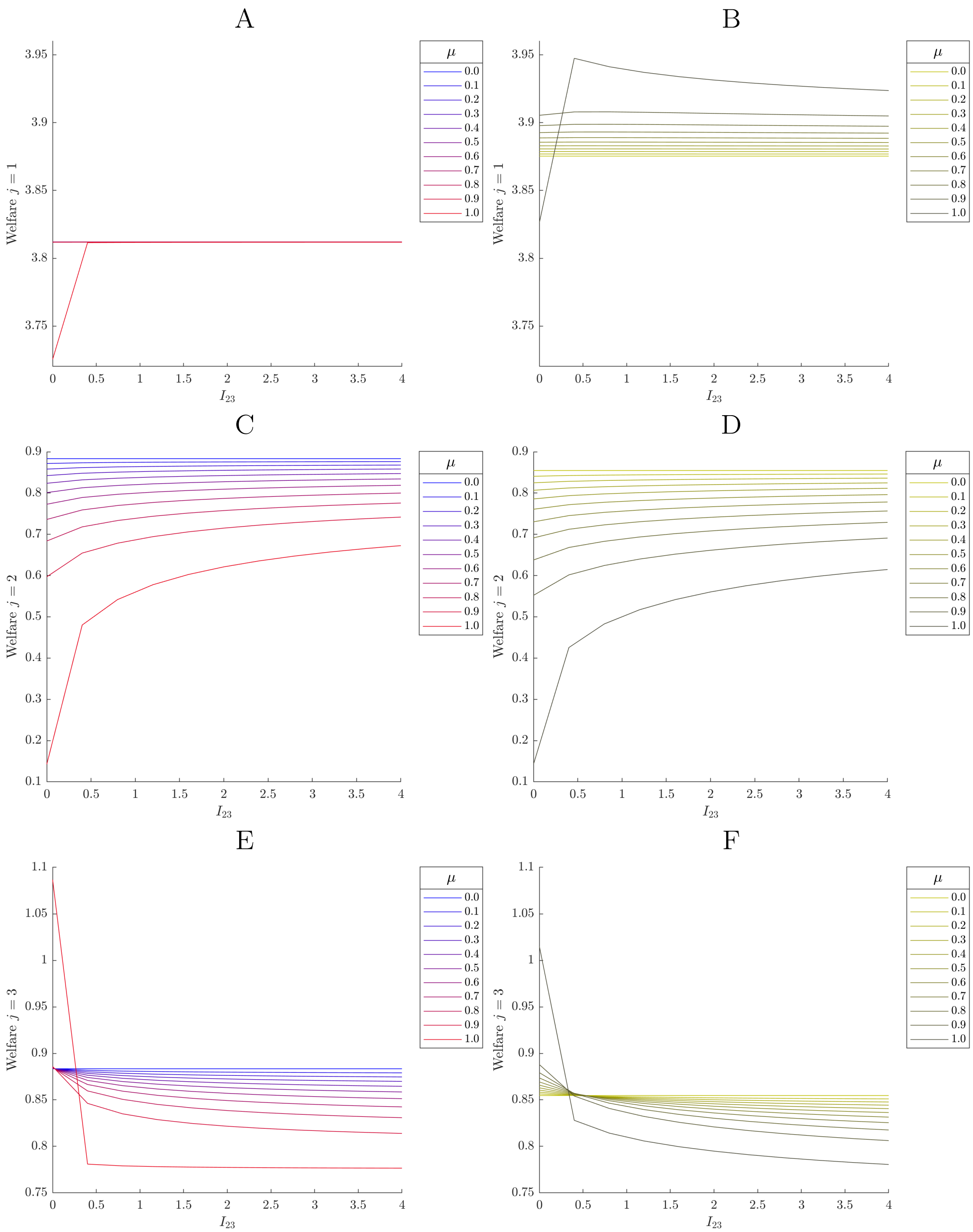

FIGURE B.3. WELFARE'S CHANGE ACROSS LOCATIONS

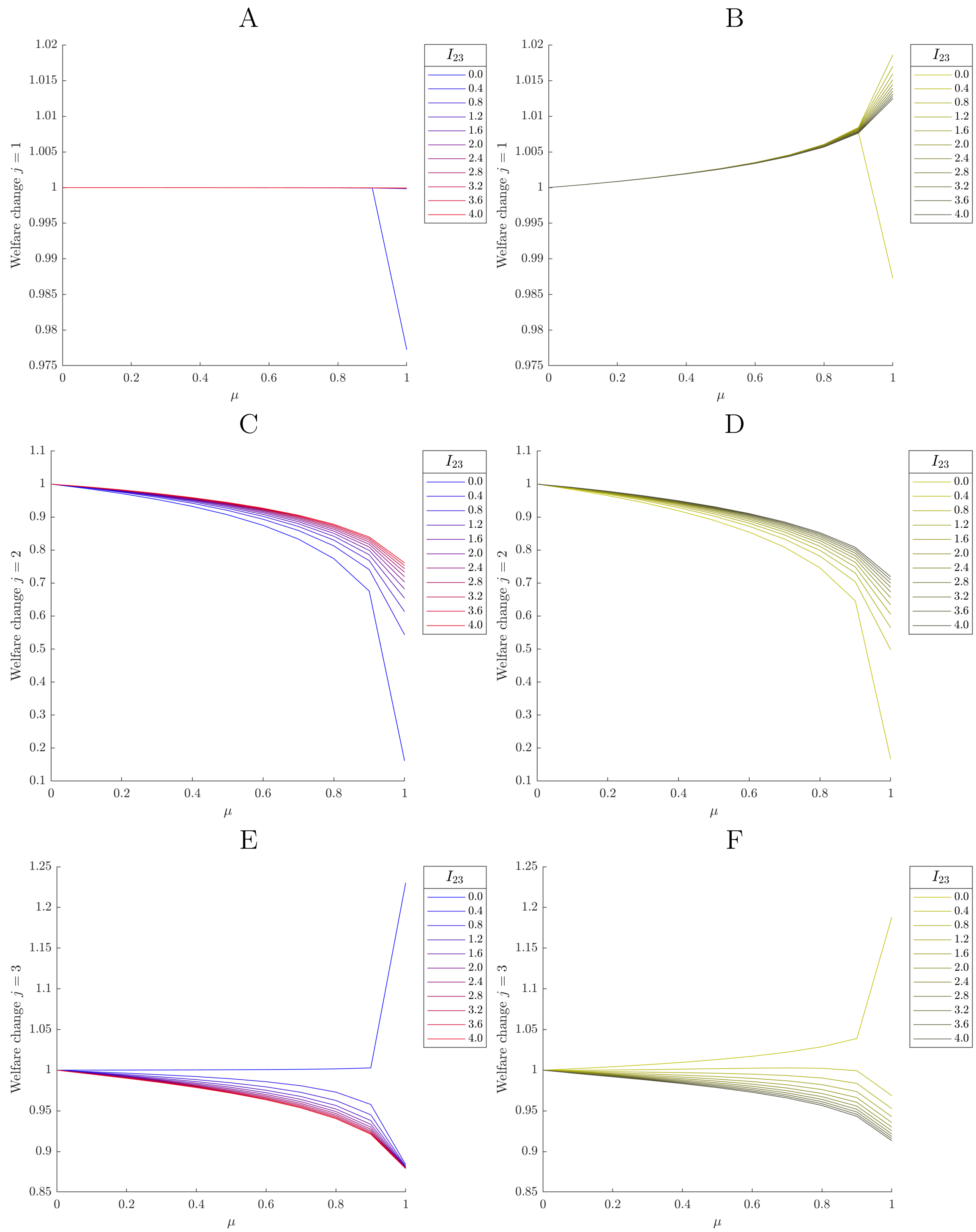

FIGURE B.4. WELFARE'S PERCENTAGE CHANGE ACROSS LOCATIONS

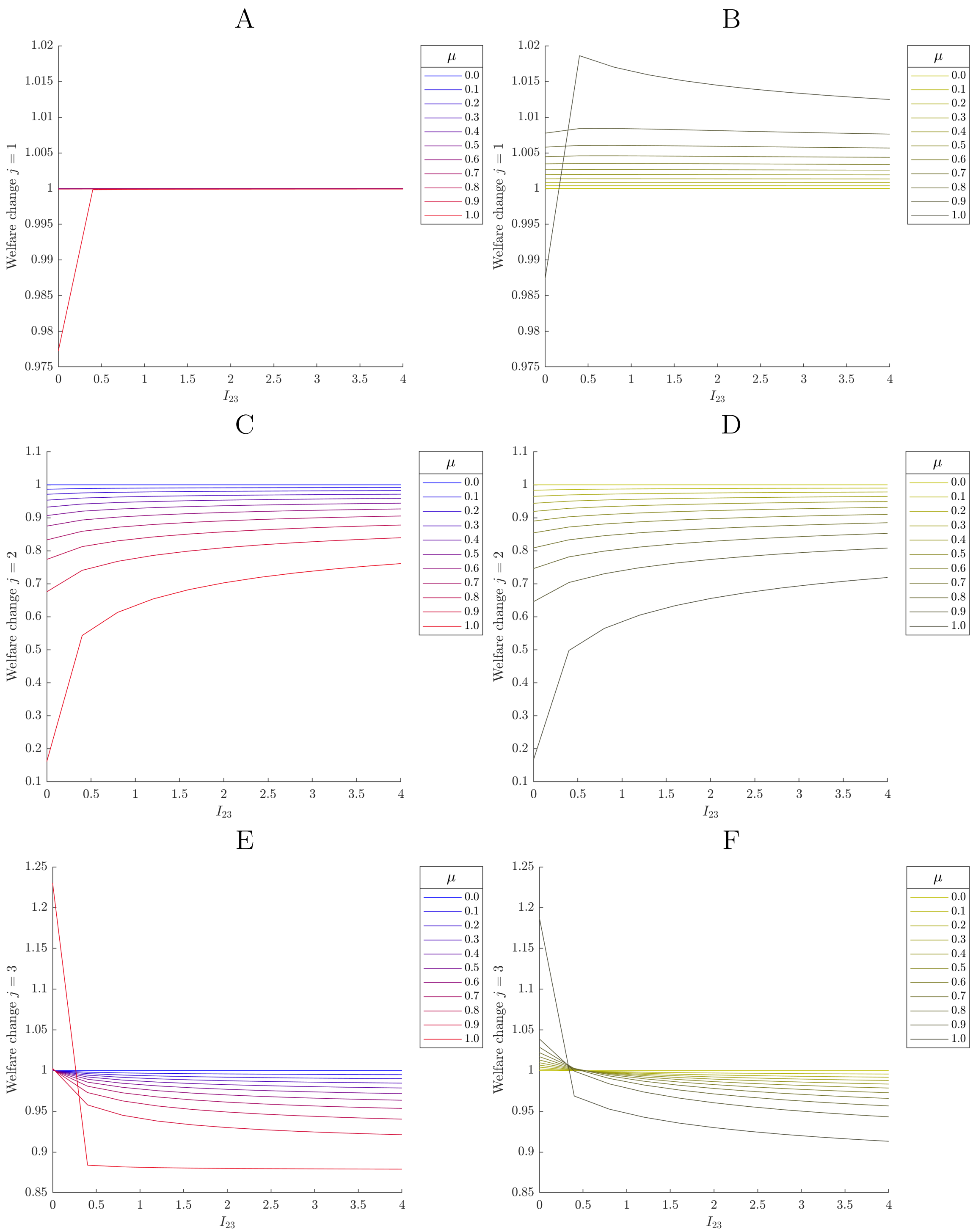

FIGURE B.5. WELFARE'S PERCENTAGE CHANGE ACROSS LOCATIONS