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CONGESTION, TAXES & WELFARE: THE EFFECTS OF CONGESTION EXTERNALITIES ON SPATIAL EQUILIBRIUM

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Congestion, Taxes & Welfare: The Effects of Congestion Externalities on Spatial Equilibrium

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Abstract

We study the effects of congestion externalities on spatial equilibrium. We develop a quantitative spatial trade model capable of characterizing a decentralized equilibrium in the presence of congestion externalities. This model contemplates a neoclassical economy with labor mobility in which locations are arranged on a graph, goods are shipped between locations through routes optimally chosen by a transport sector, and where transport costs depend on congestion, road infrastructure and other factors. We allow the possibility of internalizing the externalities by including a planner who imposes pricing on the transport network and redistributes taxes among consumers. We study different sets of corrective taxes on the transport network. We show that congestion externalities affect spatial distribution, evidencing the biases of the efficient equilibrium analysis. We show heterogeneous effects on trade flows, prices and consumption according to which cities show greater dependence on trade. We find that target pricing rises transportation costs of non-priced routes, as the trader compensates with more intensive use of alternative routes. We show heterogeneous effects on individual's welfare, concluding that pricing policies increase income and equality in utility distribution. We also show that externalities affect production intensity with heterogeneous effects on labor allocation in cities. Additionally, we find that congestion externalities affect labor distribution, increasing agglomeration in the most productive cities, and show that pricing policies increase welfare and homogeneity in labor distribution. Finally, we show that target pricing generates labor migration to cities less dependent on priced routes.

Keywords: Congestion Externalities, Spatial Equilibrium, Pigouvian Taxes, Trade, Transport Costs, Welfare Economics, Quantitative Spatial Model.

I Introduction

Trade models have shown that economies can benefit from exchanging goods with each other under certain conditions since they can gain greater efficiencies in terms of comparative advantages leading to higher levels of welfare. However, with the absence of

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correction mechanisms this exchange can sometimes be inefficient as trade flows directly affect the trade costs via congestion externalities.

These trade costs (or transport costs) directly affect the spatial distribution of economies in terms of prices, wages, population, trade flows, and decisions of investments on transport networks. Therefore, the public sector would have incentives to make the transport sector internalize the effects that congestion has on transport costs in the economies through taxes to that sector. The imposition of taxes could present methodological difficulties and rejection from individuals because the effects of congestion must be estimated accurately, and these taxes could be distorting and regressive in some cases. As a result, economies are likely to fall into inefficient spatial equilibria with active effects of congestion externalities due to suboptimal trade taxes that do not fully internalize the externality.

In dealing with general spatial equilibrium in trade models, much literature focuses on studying efficient equilibria that fully internalize congestion externalities via optimal taxes or establishing their allocations through the intervention of a central planner who internalizes the externalities (centralized equilibrium). However, the latter limits a complete understanding and leads to biases in analyzing the effects of congestion on the equilibrium, since efficient equilibria are assumed, and these may not be true in economies.

This thesis addresses this problem by studying the welfare effects of congestion externalities in a competitive general equilibrium spatial model under suboptimal taxation. In particular, this study develops a spatial model capable of characterizing a decentralized equilibrium with active externalities in order to study the associated mechanisms and the magnitude and sensibility of the effects of these externalities. The latter, to answer the question of how and in what magnitude the congestion externalities in the transport of goods affect the welfare of an economy.

This question is relevant given that these externalities affect the spatial distribution by affecting the optimal decisions of the agents because the effects on transportation costs, that impact directly on tradable goods prices and trade flows of the economy. Thus, the effects affect wages, income, prices of non-tradable goods, consumption levels, and labor mobility decisions as we will show.

This study is additionally important because disaggregating the effects of this externality by better understanding its associated mechanisms could be helpful for policymakers in order to optimize investment decisions in the transport network and develop better tax schemes for improving the welfare of individuals. Furthermore, this study of congestion externalities in a spatial general equilibrium with inefficiencies could be helpful to understand the biases of the planner's optimum analysis when this last is used as a predictive tool.

In addition, this study addresses the distributional consequences of internalizing the congestions externalities through taxes. Regardless of whether an externality is being corrected, the imposition of Pigouvian taxes will have adverse effects on specific individuals and positive impacts on others. Given this problem, it is necessary to structure an "optimal system" of redistribution and weightings that can reflect the relative importance of each individual in the economy and then explore the impacts of the externality with the imposition of corrective taxes.

This optimal path does not have a "correct answer," and each redistributive course will directly affect the equilibrium; so, determining this system is relevant to determine the impacts of congestion externalities.

On the other hand, this study of distributional consequences in economics faces the problem of being able to determine a methodology that allows making comparisons between individuals. Even so, this mechanism also enables evaluating the relative efficiency of public policies. In the sense that when faced with different combinations of weights and redistributions, the effectiveness of corrective policies is affected differently among separate individuals and in the aggregate. For example, there could be cases where the full internalization of congestion externalities might not be optimal if a social planner in an economy gives a sufficiently greater relative importance to the losers over the winners. Moreover, the imposition of Pigouvian taxes could be regressive if the losers of the correction are those with the lowest incomes. Thus, there is a trade-off of deciding between giving greater importance to economic efficiency or equality to individuals. In this thesis, we also study this distributional consequences problem as a proposal in section E of the Appendix, providing a methodology to determine optimal corrective policies with a planner who internalizes the trade-off between economic efficiency and inequality.

II Relation to Literature

The effects of congestion externalities have not been studied widely in the quantitative spatial economics literature due to the difficulties of incorporating congestion externalities without correction in spatial models. This can be seen in Kehoe, Levine & Romer (1992) who focus on characterizing equilibria of general equilibrium models with externalities and taxes, presenting a unifying framework to face the derived difficulties of solving the fixed point problem with multiple solutions.

Studies quantitative spatial economics have increased since Eaton & Kortum (2002) presented a Ricardian model of international trade that incorporates a role for geographic features in terms of trade costs, establishing a trade model capable of capturing the relationship between comparative advantages and trade costs. In this line, Allen & Arkolakis (2014) develop a general equilibrium framework capable of determining the spatial distribution of economic activity, providing sufficient conditions for existence, uniqueness, and stability of the equilibrium by establishing gravity equations that were better incorporated after Anderson & Wincoop (2003) demonstrate a better understanding of the applicability of these equations in spatial models.

Allen & Arkolakis (2016) guide understanding the components of trade models while Redding & Rossi-Hansberg (2017) and Redding (2020) review more recent research in quantitative spatial models that can characterize rich geography features and are tractable for applied use, analyzing the role of geography in shaping the distributional consequences of trade. However, in those models, slight attention is paid to equilibrium' efficiency or the congestion externalities caused by trade.

Redding (2016) develops a quantitative spatial model with rich geography of trade costs that incorporates labor mobility and heterogeneous workers preferences across locations. Following this paper came two major studies that characterize an equilibrium with the presence of congestion externalities. First, Fajgelbaum & Schaal (2020) study the optimal transport networks characterizing a spatial equilibrium in a neoclassical trade model with rich geographic features and the presence of congestion externalities due to the functional form of transport costs. However, the authors focus on characterizing an efficient equilibrium that assumes the existence of a social planner who fully internalizes the externalities through an optimal Pigouvian tax. Furthermore, Allen & Arkolakis (2019) incorporated congestion externalities into a quantitative general equilibrium to evaluate the welfare impact of investments on transport networks on U.S. highways and Seattle road networks. Unlike Fajgelbaum & Schaal (2020), they focus on characterizing a competitive equilibrium of the spatial model with the presence of congestion externalities without any internalization of the externality (absence of correction taxes), that is, an inefficient equilibrium.

Additionally, to understand the mechanisms of these externalities, Sullivan (1982) studies the distortionary effects of congestion externalities in a general equilibrium urban model comparing the market equilibrium city with the optimal city, which internalizes the externality. Similarly, Parry & Bento (2002) extend the analysis of congestion taxes by studying their effects on welfare, taking into account the presence of other types of distortions within the transport system. Duranton & Turner (2011) investigate the effects of increases in road provision on congestion, concluding that increasing the provision of roads is unlikely to relieve congestion. In terms of impact on production, Firth (2017) analyzes the effects of congestion externalities on the production sector in an applied study with traffic data from Indian Railways. Finally, Vickrey (1967) provides intuition for a better understanding of transport costs as well as characterization of functional forms that incorporate the flows and the transport network infrastructure.

Moreover, as we will see in later sections of this study, dealing with a decentralized spatial model leads to having to decide the ownership of land, as there is a non-tradable sector (land) in the economy. This ownership directly affects the spatial distribution of the economy as it affects and individual's income as well as prices through different locations. In this matter, Basso, Pezoa & Silva (2021) study various scenarios of land ownership in a monocentric city model, showing that different allocations are reached under different assumptions of land ownership and redistribution of rents. Specifically, they show that the discrepancy between a Rawlsian planner's allocation and the competitive equilibrium allocation increases as the planner's percentage of land ownership decreases.

This thesis continues as follows: Section III presents the specification of the extended decentralized spatial model to be used. Section IV presents a Quantitative Analysis where we calibrate the model and study three different applications to study the effects of congestion externalities, and Section V concludes.

III Model

In order to study the impacts of externalities, in this section, we present an extension of the spatial model formulated by Fajgelbaum & Schaal (2020). We make modifications and follow a different resolution method to determine the (inefficient) decentralized equilibrium. As mentioned earlier, this extension of the model enables characterizing a decentralized spatial equilibrium and can support the imposition of different levels of correction taxes, thus reflecting complete, partial, and null internalizations of the congestion externalities. This method permits us to determine the impact of congestion externalities on the spatial distribution of the economy because we can identify the efficient equilibrium of complete internalization through Pigouvian taxes and the inefficient equilibrium without the internalization of the externalities. Additionally, we specify a treatment for the land ownership and for the Welfare Economics, both regarding the social planner's decision on redistribution of land rents, taxes revenues, and weighting of individual utilities to determine the social welfare of the economy.

The economy will correspond to the interactions between cities that have consumers who maximize their utility given their budget, demanding tradable and non-tradable goods, firms that produce tradable goods subject to their production possibilities, a free entry transport sector that trades goods between cities maximizing its profits by choosing the least cost routes, and a planner who determines the distribution of land rents, congestion externalities corrective policies and taxes refund.

III.1 Spatial Setting

We consider a set of discrete locations $\mathcal{J} = \{1, ..., J\}$, with L_j^s workers and a fixed land supply (H_j^s) in location $j \in \mathcal{J}$. Each location will have a set of neighbors' locations $k \in \mathcal{N}(j)$. We understand cities as locations with a positive supply of workers and production of goods. In Figure 1 we show an example with six cities located in a 5x5 grid (25 nodes). As we can see in the figure, the blue arrows represent the directions and magnitudes of trade flows between cities. From this pattern, we can see that each city has neighboring nodes through which there are links that connects them. In this way, cities that are not neighbors to each other are still connected by paths that go through different nodes.

We assume two tradable sectors $n \in \{1, 2\}$ (two tradable goods), a non-tradable sector, and a fixed number of cities ubicated in certain locations along the space. With regard to worker mobility between locations, we allow and study both cases of mobility and immobility. Finally, we consider an exogenous road network for the entire economy. This could be extended by adding one more sector (constructor sector) that endogenously decides the transport network infrastructure I_{jk} between node j and node k.

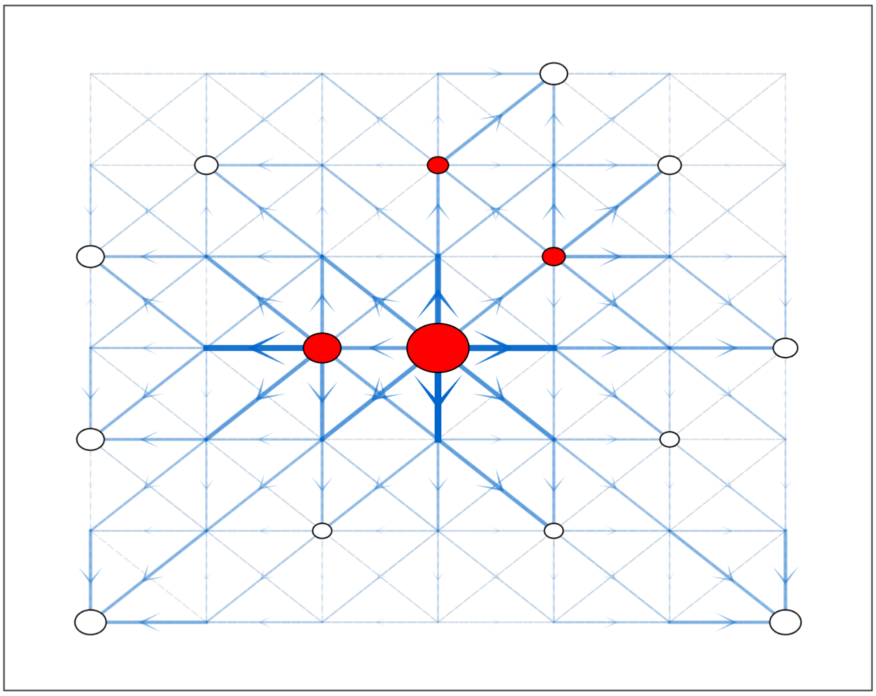

Figure 1: Spatial Setting. 49 locations with 15 cities represented as red and white circles
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III.2 Preferences and Consumers' Problem

Consumers optimize their consumption of traded (C_j^n) and non traded goods (H_j) given their budget (e_j). In every location, there are firms that produce tradable goods in the economy. Regarding the firm's ownership, we assume that the consumers from location j owns 100% of the firms from location j in equal share. Also, we assume the existence of a planner who transfers the land returns and redistribution of taxes to consumers.

Let w_j be labor income, T_j transfers from the government, and π_j^n profits from the firm of sector n located in location j. The planner's transfer system for land rents redistributions and taxes revenues will be discussed later in section III.7.

Consumers maximize:

$$\max_{\{\{C_j^n\}^n, H_j\}} U_j(\{C_j^n\}^n, H_j) \quad \text{s.t} \quad e_j \equiv w_j + \left[T_j + \sum_n \pi_j^n\right] \frac{1}{\sum_n L_j^n} = \sum_n p_j^n C_j^n + p_j^H H_j.$$

$U_j(\{C_j^n\}^n, H_j)$ assuming two tradable goods $n \in \{1, 2\}$ will take the Cobb-Douglas form:

$$U_j(\{C_j^n\}^n, H_j) = C_j^{1\,\alpha_1} C_j^{2\,\alpha_2} H_j{}^{\alpha_3}.$$

This will consider Cobb-Douglas elasticities α_1, α_2 and α_3 in the consumption of traded and non-traded goods where $\alpha_1 + \alpha_2 + \alpha_3 = 1$.

III.3 Production Sector

Firms from sector n and location j optimize profits subject to their production possibilities:

$$\max_{\{L_j^n\}} \pi_j^n = p_j^n z_j^n (L_j^n)^a - w_j L_j^n.$$

Where $0 < a < 1$ establishes diminishing returns and z_j^n corresponds to the firms from sector n productivity in location j. This enables us to analyze spatial heterogeneity in productivity across cities.

III.4 Transport Sector

The transport sector consists of a free entry market of price-taker traders who purchase tradable goods in location o (origin) and ship them to location d (destiny) $\forall\ (o,d) \in \mathcal{J}^2$.

III.4.1 Transport Costs and Network

For this economy, we assume that transportation costs are determined by iceberg costs (τ_{jk}). This means the cost of transporting one unit of good from j to k will be τ_{jk} units of that good. Then, in order for one unit of good to arrive at k, the trader will need to ship $1 + \tau_{jk}$ units from j. The functional form of this costs takes the form:

$$\tau_{jk} = \phi\delta_{jk} + \delta_{jk}\frac{(Q_{jk}^T)^\beta}{I_{jk}^\gamma}\ ;\ Q_{jk}^T = \sum_n Q_{jk}^n.$$

δ_{jk} represents the geographic frictions (such as distance) of the link between locations j and k that affects transports costs, β and γ corresponds to the elasticity from the transported quantity (Q_{jk}^T) and transport network (I_{jk}) to the variable component of transport costs respectively. As we can see, ϕ represents a fixed cost that makes transport costs non-zero when there is no flow on the link. Then, this cost could be interpreted as the minimum cost that would be incurred to transport through a link, such as non-Pigouvian tolls, driver's wage, truck rental, or gasoline.

Additionally, with this functional form of transport costs, we assume that transport costs are determined by the sum of the quantity of the n tradable goods that are being shipped through the link jk (Q_{jk}^T). This implies that each link shares the transport of the n types of tradable goods, which enables us to study how the transport of each type of tradable good impacts the aggregate transport costs in every link.

This form additionally permits us to incorporate congestion externalities into our problem so long as $\beta > 0$, in the sense that as the amount shipped by the trader through the link between location j and k increases, the transport costs over that link also increases, reflecting diminishing returns to the activity.

$$\frac{\partial \tau_{jk}}{\partial Q_{jk}^n} > 0.$$

Then, if there is congestion in shipping ($\beta > 0$), there will be an inefficient amount shipped as the trade sector take the transport cost τ_{jk} as given. They do not internalize the effects of flows on transport costs, so there is a congestion externality.

Moreover, as discussed earlier, we will assume an exogenous transport network $I_{jk} \ \ \forall j \in \mathcal{J}; k \in \mathcal{N}(j)$ in the economy. This network can be understood as the level of road infrastructure that generates reductions in transport costs such as levels of capacity, quality, and speed limits of the roads.

As appreciated, transport costs may vary between each link jk due to distance factors, trade flows, and level of road infrastructure. The implicit assumption in this situation is that transport of goods in one direction does not affect transport costs for the opposite direction of that same link. This could be understood as each link having two directions of flow independent of each other.

III.4.2 Pigouvian Taxes

Since there is an active congestion externality, as discussed in the previous section, we consider the possibility of correction policies in the economy in the form of Pigouvian taxes that would internalize the externality if the planner decides to carry out the policy. Taxes will take the ad-valorem form:

$$t_{jk} = \lambda_{jk} \frac{\partial \tau_{jk}}{\partial Q^T_{jk}} Q^T_{jk} \ \ ; \ \lambda_{jk} \in [0, 1].$$

We added the parameter λ_{jk} to be able to analyze corrective policies with different levels of internalization of the externalities for every link between nodes j and k. λ_{jk} would reflect the "ratio" of selected taxes to the Pigouvian taxes that would fully internalize the externality. Then we have the following cases:

(i) $\lambda_{jk} = 1$: Pigouvian taxes, full internalization of the externality in link "jk".

(ii) $\lambda_{jk} \in (0, 1)$: Suboptimal taxes, partial internalization of the externality in link "jk".

(iii) $\lambda_{jk} = 0$: No taxes, null internalization of the externality in link "jk".

This enables to control the internalization of the congestion externalities as we use suboptimal taxes to analyze the impacts of congestion.

III.4.3 Route Optimization

In this economy, as discussed, a transport network enables traders to optimize shipping through locations by selecting the least cost route. This selection of routes will consist of choosing the combinations of neighboring locations that minimize transport costs for each set of origin-destination cities. Using Fajgelbaum & Schaal's (2020) notation, traders select the least cost route from $r = (j_0, ..., j_\rho) \in \mathcal{R}_{od}$ where $(j_0, ..., j_\rho)$ is a sequence of locations that connects the cities o and d. The optimal route r_{od} then maximizes the per-unit profits:

$$\pi_{od}^{TS} = \max_{r=(j_0,\ldots,j_\rho)\in\mathcal{R}_{od}} p_d^n - p_o^n - \sum_{k=0}^{\rho-1} p_{jk}^n \tau_{jkjk+1} - \sum_{k=0}^{\rho-1} p_{jk}^n t_{jkjk+1} \leq 0.$$

Figure 2 shows the trader problem graphically in a simple example with two cities, “o” and “d” and only three routes available between them:

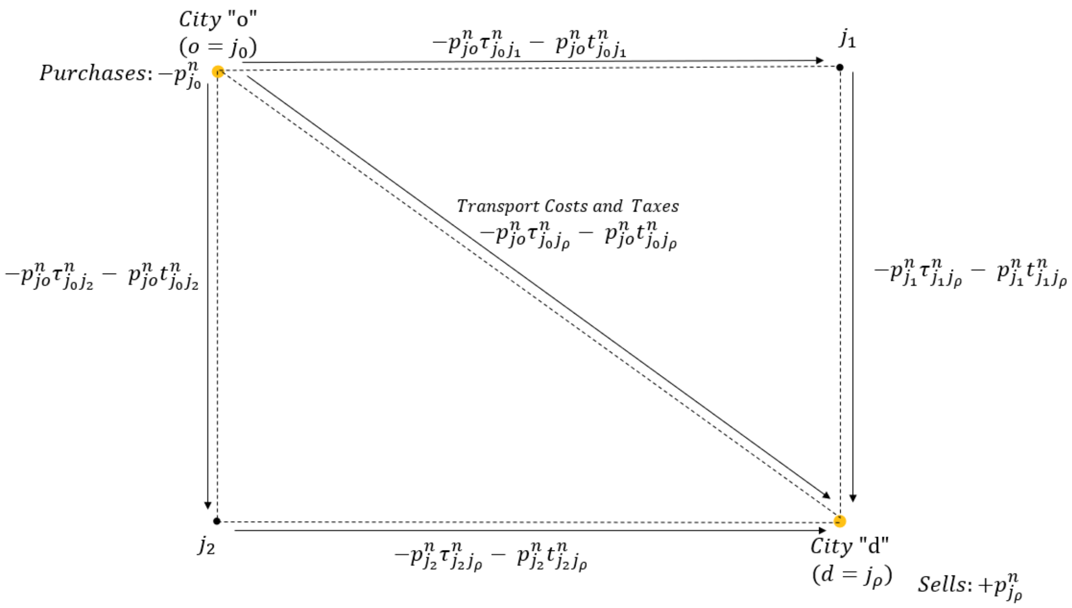


Figure 2: Simple example of trader problem of choosing the optimal route with the least cost to ship goods from city “o” to city “d” with only three routes available.

III.5 No-Arbitrage Condition and Flows Conservation

From the traders cost optimization, we can derive the following no-arbitrage condition for prices:

$$\frac{p_k^n}{p_j^n} \leq 1 + \tau_{jk} + t_{jk}.$$

From this condition, we can determine that, as the transport sector is a free-entry market, the ratio of prices will be determined exclusively by the transport costs (τ_{jk}) and taxes (t_{jk}) taken by the transport sector, as the traders can not obtain positive profits from their activity (free-entry). This means that the price ratio between locations k and j must be less or equal to the marginal transport cost of shipping from j to k.

From the previous sections, we can now characterize the flows of goods conservation along the economy. Each city produces and consumes a certain amount of tradable goods, having the possibility of exporting and importing goods from other cities through the transport sector. The conservation of flows for each location j takes the form:

$$\underbrace{Y_j^n}_{\text{Production}} \geq \underbrace{C_j^n + \sum_{\kappa \in \mathcal{N}(j)} (1+\tau_{jk})\, Q_{jk}^n - \sum_{\kappa \in \mathcal{N}(j)} Q_{kj}^n}_{Consumption+Exports-Imports} \quad \forall j \in \mathcal{J}.$$

III.6 Labor Mobility and Land Market Equilibrium

In the case of immobile labor between locations, we have the following equilibrium conditions for the labor market:

$$L_j^s = \sum_n L_j^n \quad \forall j \in \mathcal{J}.$$

This last condition allows workers to have mobility between sectors of the same location but not between locations.

In the case of labor mobility between locations, we have the following conditions:

$$\sum_j L_j^s = \sum_j \sum_n L_j^n.$$

$$u = U_j(\{C_j^n\}^n, H_j) \quad \forall j \in \mathcal{J}.$$

This condition of mobility between locations allows consumers to choose where to locate based on their utility maximization, which implies that in equilibrium the consumers of each location will have the same level of utility.

Finally, with respect to the market equilibrium of the non-tradable good (land), we have the following condition:

$$H_j^s = H_j \quad \forall j \in \mathcal{J}.$$

III.7 Income, Land Rents and Taxes Redistribution

In the previous sections we specified the consumer's income e_j as an aggregate of labor income (w_j), firm profits (π_j^n) and government transfers (T_j). If we decompose the government transfers the income for consumer located in j takes the form:

$$e_j = [\sum_n w_j L_j^n + \sum_n \pi_j^n + \ \psi_j^H \underbrace{\sum_j p_j^H H_j}_{\text{Land Rents}} + \psi_j^t \underbrace{\sum_n \sum_j \sum_{\kappa \in \mathcal{N}(j)} t_{jk} p_k^n Q_{jk}^n}_{\text{Taxes Collected}}] \frac{1}{\sum_n L_j^n}.$$

We treat the above as the income of the representative consumer for city j. The parameter ψ_j^H represents the proportion of the total land rents that is transferred from the government to the consumers from location j. At the same time, ψ_j^t corresponds to the proportion of the government's total corrective taxes collection transferred to these consumers. The described weights imply the following:

$$\sum_j \psi_j^H = 1,$$

$$\sum_j \psi_j^t = 1.$$

These weights affect the income distribution of the economy. Therefore the decision on these is relevant for analyzing the magnitude of the impact of congestion externalities.

Additionally, in section E of the Appendix, we develop as a proposal, a methodology for determining optimal externality correction policies. This methodology considers a planner who endogenously chooses the level of internalization of the externality for each link (λ_{jk}) and the weights of tax redistribution (ψ_j). This methodology is highly relevant because it assumes a planner who internalizes, in his decisions, the trade-off between economic efficiency and inequality.

III.8 Resolution: Decentralized Equilibrium

As discussed in the previous sections, the decentralized equilibrium will correspond to a competitive equilibrium of a neoclassical economy consisting of quantities $[C_j^n, H_j, L_j^n, \{Q_{jk}^n\}_{k\in\mathcal{N}(j)}]$, prices of goods $[p_j^n, p_j^H]$ and factor prices $[w_j]$ in every location j.

The resolution method for computing the decentralized equilibrium of the economy implies an iterative algorithm whose objective function is to minimize the transport costs of the trader, complying with the first order conditions (FOC's) system derived from the Consumers Problem, Production and Transport Sectors, the No-Arbitrage Condition, Conservation of Flows, and the Labor and Land Markets Equilibriums. This system is detailed in section A of the Appendix.

IV Quantitative Analysis

In this section, we present three numerical implementations of the decentralized spatial model studied. First, we analyze the mechanisms and effects of congestion externalities on trade flows, transport costs and trader's least cost route optimization problem in a reduced economy with four cities. Second, we analyze the effects of congestion externalities on the spatial distribution of the economy with immobile labor in a mid scale economy with 15 cities. Finally, we analyze the effects of congestion in the spatial distribution of a large scale economy with mobile labor.

In each application, we analyze the effects of congestion externalities by studying the spatial equilibrium of three different congestion scenarios. For our analysis we take the spatial distribution of the economy in the case of null internalization of the externalities ($\lambda_{jk} = 0 \ \forall j, k$) as our conterfactual (inefficient equilibrium), so we study the effects of corrective policies in a spatial equilibrium of an economy with active externalities. We analyze these effects under two cases of internalization: first, under a full internalization of the externality through Pigouvian taxes for every type of road ($\lambda^H_{jk} = 1, \lambda^s_{jk} = 1 \ \ \forall j, k$); and second, under a restricted internalization of the externality where it is only possible to impose taxes in the highway ($\lambda^H_{jk} = 1, \lambda^s_{jk} = 0 \ \ \forall j, k$).

IV.1 Spatial Setting

For this implementations, we establish various economies in terms of the number of cities, labor endowments, productivity distributions, spatial grid, and assumptions discussed in their respective sections. For all three applications, we assume 100% route availability for exchange, and we establish two types of routes in the transport network of the economy, a highway that connects the central city with two others and local streets. Figure 3 shows the spatial setting of an economy with six cities as an example.

For applications I and II, we assume immobile labor and for application III, we assume mobile labor. In each application, we assume an equal land supply $H_j = 1$ in each city. Additionally, in all applications we assume two tradable goods (industrial and agricultural) that can be traded between cities and one non-tradable good (land).

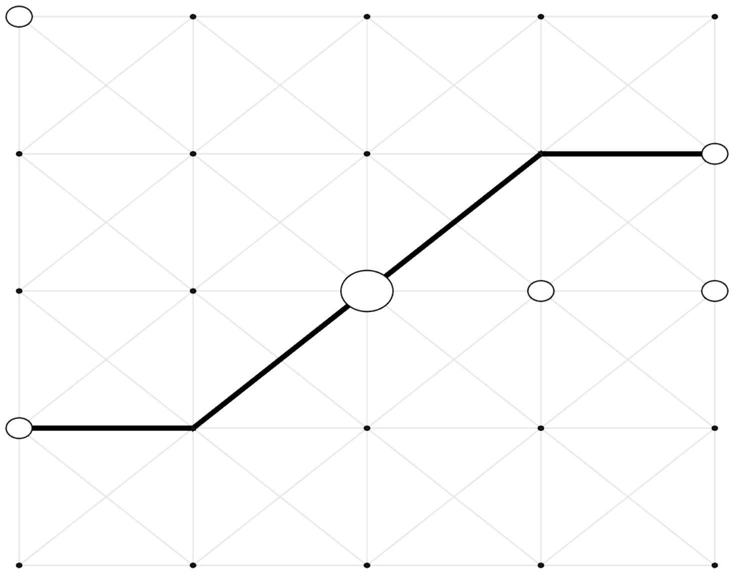


Figure 3: 25 locations with six cities represented as white circles, highway in black and local streets in light gray. The circle's width represents the productivity of the city (in this example the central city is more productive).

IV.2 Calibration

In this section, we make assumptions and determine parameters based on empirical literature to calibrate the model.

IV.2.1 Preferences and Production Technology

For preferences, we assume a Cobb-Douglas form with two tradable goods and one non-tradable good, with a elasticity parameters α. For the non-tradable good elasticity (α_3), we assume an expenditure share of land consumption of $\alpha_3 = 0.24$ based on the housing expenditure share reported in Davis & Ortalo-Magné (2011). We also assume equal expenditure share for industrial and agricultural good consumption of $\alpha_1, \alpha_2 = 0.38$.

We assume decreasing returns to scale in both production sectors with a production technology $a = 0.8$. This assumption of diminishing returns enables us to study the effects of the firms' ownership on individual's income by having positive firm profits $\pi_j^n > 0$. Finally, to determine the equilibrium, we will assume in each application that the wage in the central city is $w_c = 1$.

IV.2.2 Transport Technology and Network

We define δ_{jk}^{τ} as the Euclidean distance between location j and its set of neighbors $\mathcal{N}(j)$, where we normalize the horizontal and vertical distance between each neighbor to 1.

For fixed transportation cost ϕ, we assume that the transport sector pays commission wages to drivers as a percentage of the quantity shipped and that this wage is not spent in the economy. This assumption is made as we are dealing with iceberg costs in our problem, which are a proportion of the good being shipped that then is lost to the economy. To determine this parameter, we develop a guess and verify method to incorporate the results obtained by Persyn, Díaz-Lanchas & Barbero (2020) where they estimate the average generalized transport costs (GTC) in Europe, including a decomposition of cost components. They estimate that the 42.2% of the average GTC corresponds to drivers' wages. To incorporate this estimate into our model, we determine a fixed value of ϕ that meets the following:

$$\frac{\phi}{\bar{\tau}_{jk}} \approx 42.2\%.$$

$\bar{\tau}_{jk}$ is the average transportation costs in the economy. We determine ϕ in the case where there is no internalization of the externality $\lambda = 0$; so, for the case of full internalization, the proportion of the drivers' wage in the total transport costs may change as we are maintaining a fixed value for ϕ and the transportation costs would vary with the introduction of corrective taxes. For example in Application III, we assume a fixed value of $\phi = 0.012$, which would represent 1.2% of the quantity shipped that is given as commission to the driver. This value of ϕ in our model generates a participation of 42.09% of the drivers' wage on total transport cost.

Regarding the transport network, we assume that the level of infrastructure (I_{jk}) will be given by the number of lanes of the road.

$$I_{jk} = lanes_{jk}.$$

We assume that the highway will have two lanes and each local street only one lane. Hence, the highway will have twice the level of infrastructure as local streets ($I_{jk}^H =$

$2; I^s_{jk} = 1$). These assumptions are made in the spirit of Fajgelbaum & Schaal (2020) where they formulate a discretization of the road network and assume an infrastructure index as a function of average lanes and type of road (national and non-national). Our assumptions for infrastructure are consistent with the range of average infrastructure index that they report (0.28 - 2.61). We also assume that the infrastructure is the same for both directions of transit, this is $I_{jk} = I_{kj}$. Finally, for the elasticity of transport infrastructure, we assume $\gamma = 1$.

On the other hand, for the elasticity of quantity shipped, because we scale our base economy to certain levels of endowments that would require trade flows in the range of 0 - 1, we choose the elasticity range that best fits the economy in terms of relative transportation costs. If we assume a range of $\beta < 1$ (non-convex transport cost), the transport costs are high relative to the quantity shipped, generating very low or zero levels of trade flow in the economy. This range of elasticity of quantity shipped is consistent with those used by Allen & Arkolakis (2019) and Fajgelbaum & Schaal (2020) to estimate trade costs (0.092 and 0.13 respectively).

In contrast, if we assume $\beta > 1$ (convex transport costs), the relative transport costs are better adjusted to the scale of the economy, with positive trade flows between cities. This range for the congestion elasticity is commonly used to determine the transport costs in urban spatial models as is detailed in Vickrey (1969) wich assumes a particular functional form for speed under traffic volumes in the range of 0.5 - 0.9 and congestion elasticity equal to 1. Vickrey affirms that if considerable congestion exists for this specification, this elasticity is likely to be in the range of 3 - 5. Our model's transportation costs are similar to Vickrey's specification, and our economy scale resembles the detailed flow range. Thus, the literature would also justify the use of elasticity greater than 1. Therefore, we will assume a conservative congestion elasticity of $\beta = 2$.

Finally, in these applications, we are assuming the following assumptions discussed in previous sections:

(i) Consumers from j owns the 100% of the firms from location j in equal share.

(ii) The planner owns the 100% of the lands and land rents are equally redistributed among consumers.

(iii) The planner redistribute the collected taxes equally among consumers.

IV.3 Application I: Trade Flows, Transport Costs and Distribution of Prices

The objective of this application is to analyze the effects of congestion externalities on the prices distributions of the economy. As discussed, prices are determined by transport costs that depend directly on trade flows, so in this application, we analyze the effects that corrective policies have on trade flows, transport costs, and road use under different congestion scenarios. This application enables us, to decompose the mechanisms associated and effects of congestion on the trader's least cost problem and how this trader decision affects the economy.

We chose a small-scale economy with four cities in a 5x5 grid to better analyze the effects on transport flows and route optimization. As we will see later in larger-scale economies, the graphic effects on transport flows and route optimization lose clarity.

For this application, we assume a central city more productive in the industrial sector (red circle) and three cities more productive in the agricultural good (white circles) distributed away from the center of the economy. A highway will connect the central city with two other cities. We assume labor and land supplies of $L_j^s = 1$ and $H_j^s = 1$ in each city.

In Figures B.1 and B.2 from the Appendix we show the spatial distribution of the economy under active congestion externalities reflected in heatmaps. We present the highway marked in black to demonstrate a clear analysis in these figures.

On the other hand, in Figure 4 we show the levels of trade flow, transport cost, and tax for this economy. Panel (a) of Figure 4 details the magnitude of the trade flows of the industrial good (Q_{jk}^1) for each link based on the intensity of the color blue and the width of the link. At the same time, the flow direction is determined by the direction of the arrow. If we observe the industrial good trade flows, we note that by starting from the central city and using any route to the outside cities, the link wideness decreases from one link to another.

This wideness (the magnitude) decrease is explained by two causes: one is the form of transport costs that we assumed for this economy in terms of iceberg costs. We see that trade flows decrease because transport costs take a proportion of the goods being shipped. Another way of looking at it is that the good "melts" along the way (iceberg costs). The second reason is that the trade flows separate, and go through different routes along the way to reach their destinations in the cheapest way possible. We can understand the above, as we see that the trade diversifies the transport flows to the same destination through different routes with the aim of reducing transport costs. Also, as we can see, routes without trade flows exist due to the fixed transportation costs (ϕ) in the functional form of transport costs, which implies a minimum transport cost regardless of flow level.

For the interpretation of transport costs and taxes, the magnitude of the transport costs (taxes) is represented by the intensity and wideness of the link relative to the levels of transport costs (taxes) in the economy. The arrow represents the direction of the link, and this reflects the previous assumption, that transport costs would be different depending on the direction of the link. Thus, a wider link represents that transport costs (taxes) in that specific link are higher relative to the level of transport costs (taxes) in the economy.

As we can see in Panel (a) of Figure 4, trade flows of industrial goods are shipped from the central city because the central city presents an absolute competitive advantage in the production of the industrial goods, as the only city that is intensive in that sector. So, as we can see in Figure B.1, the lowest prices in the economy of the industrial goods are located in the central city. Hence, this city acts as the exporter of the industrial goods, and less productive cities in that sector benefit from the exchange, acquiring tradable goods from the more productive city, and improving economic efficiency relative to the autarky case.

On the other hand, in Panel (b) of Figure 4 we see that the non-central cities are the exporters of the agricultural good, and observe that the flows from the three agricultural cities are shipped to the central city. Given this, trade, we can determine that the exchange occurs due to heterogeneity in productivities of tradable goods. In this way, the more productive cities in a given good will exchange that good as a means of exchange to acquire other goods where they are less productive.

In addition, as discussed in previous sections, transport costs will be different depending on the directions of trade flows. In this economy, we have different transport costs regarding the goods being shipped from the agricultural cities to the central city (Center Direction) and goods being shipped from the central city to the agricultural cities (Outskirts Direction). We interpret this as the existence of two-way streets where one-way flows do not affect transportation costs of the other direction.

In Panel (c) and (b) of Figure 4 we see the transport costs (τ) of each direction, and note that transport costs to the center are relatively higher due to a greater intensity of agricultural good flows being shipped to the central city as we observed in Panel (a) and (b). This differential is explained because, in this economy, the industrial good is relatively scarcer and therefore more valued (higher relative price), so that the agricultural cities are sacrificing a greater quantity of the agricultural good to acquire the industrial good. This prices can be seen in Figure 5 where Panel (c) and (d) present the distribution of prices in the economy.

In addition, Panel (e) and (f) of Figure 4 show the respective taxes for each direction of flows. In this case of null internalization, there are no corrective taxes in the economy so that prices will be only determined by the transport costs (τ). Later, we will analyze the effects of the imposition of taxes in the economy that will affect transport costs and, therefore, the trader's routes and prices.

As a result of the above, the trader will be seeking to trade from the cheapest location to cities where it can sell the good at higher prices, all, by minimizing transport costs by choosing the least cost routes. Also, the assumption of a free entry transport sector implies that the difference in prices from location will be determined by the transport costs of shipping between these locations (no arbitrage condition).

In Figure 5 we observe the above by comparing the total per unit transport costs reported in Panels (a) and (b) with the distribution of prices of the industrial good and agricultural good in the economy in Panels (c) and (d) respectively. As we can see in Panels (a) and (c), industrial prices are higher in the northwest city because transport costs of shipping from the central city to that location are relatively higher. This results from two main reasons regarding the functional form of transport costs. First, because this city is at a greater distance from the central city than the others and transportation costs depended directly on it. The second reason is because this city is not connected by the highway, and is far from it, implying that this city does not benefit relatively much from the cost reduction that the highway provides.

Further, we see that prices of the industrial goods increase differently as we move away from the central city. This increases, are explained by factors of distance, proximity to the highway, trade flows, and spatial competition in terms of differences in local aggregate demands. The latter is the sense that cities that have other nearby cities demanding the same good will increase the local demand for it, increasing exchange flows and, therefore, the transport costs of local routes (higher local prices). This phenomenon is more thoroughly explained, observed and analyzed in applications II and III where we study larger economies.

Moreover, regarding the transport costs and price distribution of the agricultural good, in Panels (b) and (d) of Figure 5 we can observe that prices are higher in the central city as it is more productive in the industrial good, and in that city the agricultural good will be more scarce and therefore, more valued. Additionally, we can see that the lower agricultural good prices will be in the northwest agricultural city, because in this city the industrial good is relatively more scarce than in the other agricultural cities given the higher transportation costs. Therefore, this city will be willing to give relatively more quantity of agricultural good for the acquisition of industrial good with respect to the other cities, implying lower prices of agricultural good in that city.

Next, we will analyze the effects of two cases of corrective policy. The first case with a global tax policy targeting all routes and the second case with a restricted correction policy, where only the highway can be priced.

Figure 4: Trade Flows, Taxes and Transport Costs ($\lambda_{jk} = 0$)

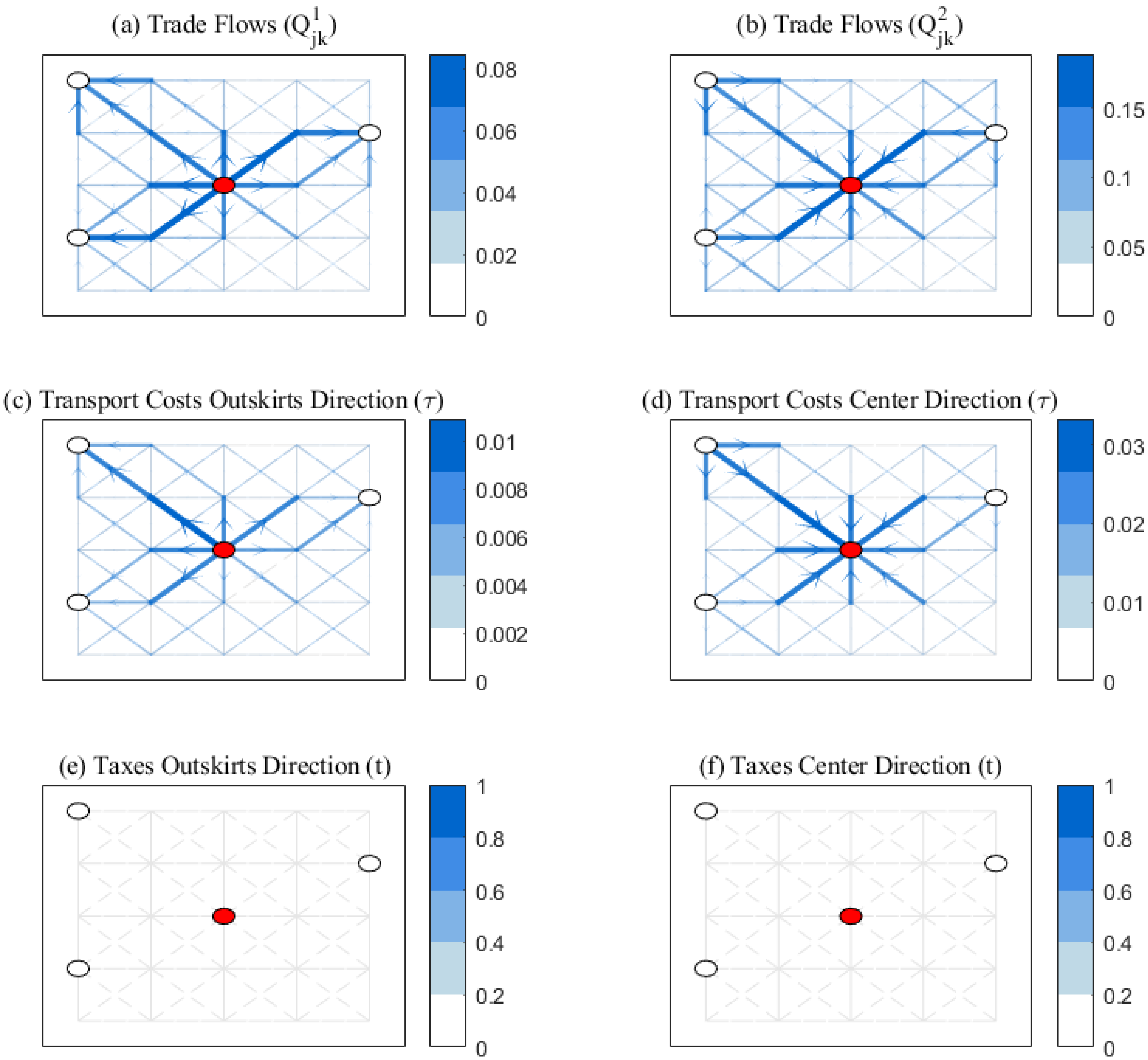
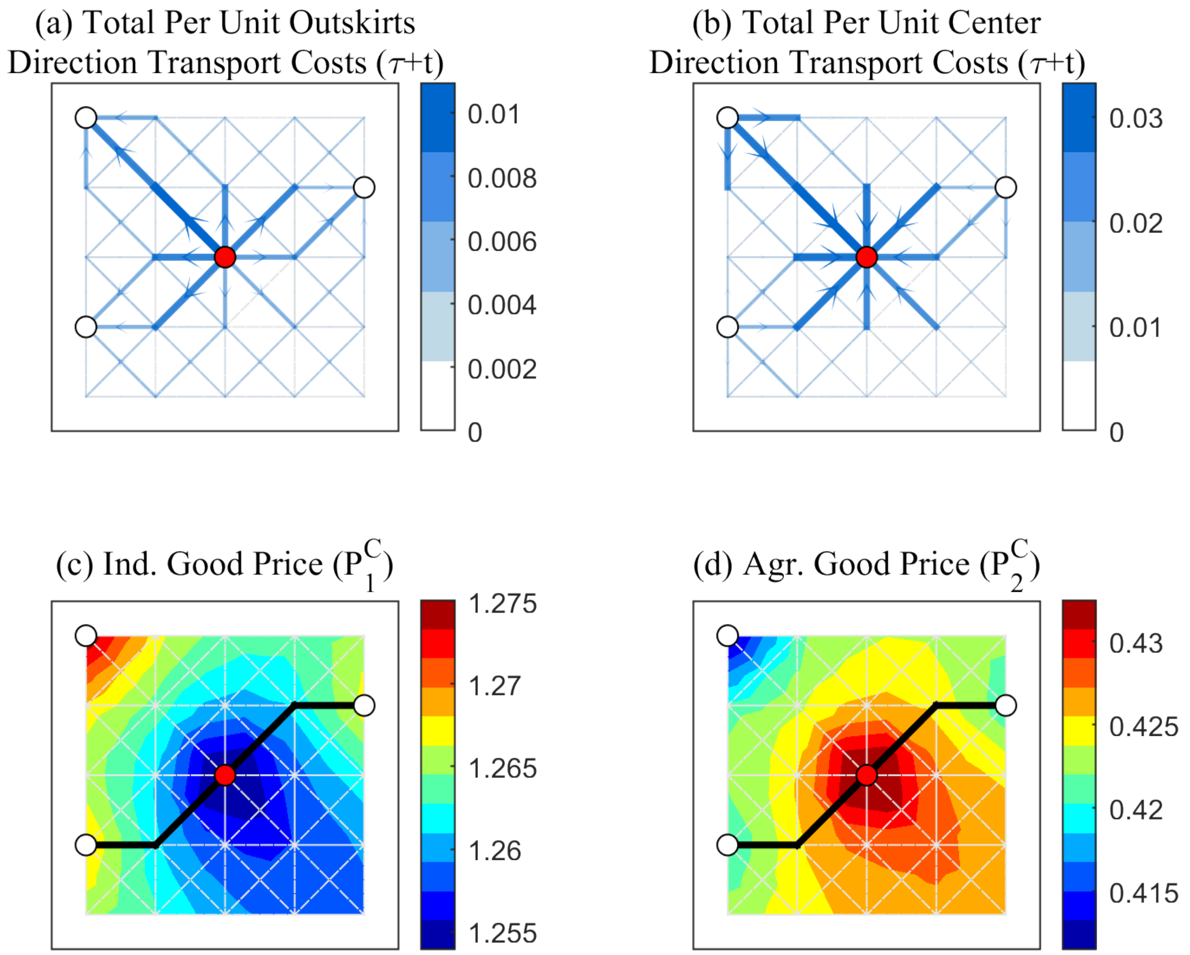


Figure 5: Total Per Unit Transport Costs and Distribution of Prices ($\lambda_{jk} = 0$)



IV.3.1 Case I: Global Corrective Taxes

In this section, we study the effects of a full internalization of the congestion externalities through Pigouvian taxes to the transport of goods in the highway and local streets ($\lambda^H_{jk} = 1, \lambda^s_{jk} = 1 \;\; \forall j, k$). In Figures B.3 and B.4 of the Appendix we show the levels of trade flows, taxes, transport costs of and prices distribution of the economy under a full internalization of the externality. In Figure 6 we show the effects of the internalization of the externality on trade flows and transport costs. As shown in Panel (e) and Panel (f), the economy is in the presence of corrective taxes in every route; so, the transport costs will be relatively higher leading to reductions on trade flows.

In Figure 6 we present the changes in trade flows, taxes, and transport costs caused by the internalization of the externality. In this figure, we show the positive changes in blue and negative changes in red, with the magnitude of the change determined by the wideness and color intensity of the link in order to improve understanding of the effects of congestion on trade flows and transports costs. We directly analyze the substitution of trade routes generated by changes in the transport costs. The magnitude presented is relative to the changes and not to the magnitude of trade flows or transport costs from the counterfactual scenario. Additionally, in Panels (c) and (d) of Figure 7 we show heatmaps that represent changes in the spatial distribution of prices from a scenario with active congestion externalities to one with full internalization through taxes. For example, in Panel (c) we show the percentages of change in the distribution of the industrial good price resulting from the corrective policy.

We first analyze the effects of the internalization on the trade flows and transport costs of the economy. In the Panel (e) and (f) of Figure 6 we observe that the taxes collected for each link are now positive in the links with active trade flows, meaning an increase in the total per unit transport costs ($\tau + t$) in the economy as we see in Panel (a) and (b) in Figure 7. From this increase in transport costs, the transport sector has no choice but to reduce the trade flows in more congested links and start trading through other relatively less congested routes to distribute the trade flows in a more diversified way, in order to minimize their costs of transport.

The latter can be seen in Panel (a) of Figure 6 where we observe that the transport sector reduces trade flows on the more direct routes (red links), substituting them for longer routes (blue links) that presented lower and null levels of trade flows in the case without internalization. As we can observe in Panel (a), the trader sends a higher level of industrial goods flow to southeast routes that previously did not have as much flow, to compensate for the increased costs caused by taxes. On the other hand, if we look at the northwestern city, we can see in Panel (b) that the trader now uses the northern and southern routes with greater intensity relative to the case with no internalization to transport agricultural goods to the central city.

To reduce transport costs, the transport sector is now using new routes that were not used before, partitioning trade flows in more routes and increasing the trade flows in non-direct routes. The effects of this behavior can be observed directly in Panel (c) and (d) of Figure 6 as it details the changes in transport costs (τ) derived from a reduction (or increase) in trade flows. We can see that the transport costs in the main routes are reduced and that there is an increase in transport costs in the non-direct routes to cities.

The changes are explained by the transportation sector seeking at least to partially compensate for the increase in total transport costs ($\tau + t$) derived from imposition of corrective taxes. The transport sector reacts by reducing trade flows on direct routes and increasing flows on less direct routes (route substitution).

This discussion emphasizes the presence of congestion externalities; there was an excess of trade flows in the economy caused by the carrier not internalizing the externality. Then, with internalization, we observe that this inefficiency is corrected by reducing trade flows in the economy, which directly affects the consumption, welfare of individuals, and price distributions in the economy, as will be seen in Applications II and III.

Next, we analyze the effects of the internalization on the distribution of prices in the economy. If we observe the effects in the distribution of the industrial good price in Panel (c) of Figure 7 we determine a global increase in the level of prices. This is directly explained by the increases in total per unit transport costs generated by the imposition of corrective taxes, as shown in Panel (a). The transport sector is unwilling to maintain the same level of trade flows for the same prices; so, with the internalization, there are fewer trade flows at higher prices resulting from the mechanisms discussed earlier. Regarding the magnitude of the effects, the most affected by this price increase are the cities furthest from the central city and far from the highway (northwest agricultural city).

Moreover, as shown in Panel (b), agricultural good prices increase near the central city but decrease near agricultural cities, reaching its minimum in the farthest city to the northwest. This is explained because the price of the industrial good, which is scarcer, increase in these agricultural cities. Therefore, to adjust their consumption of industrial good, they must offer a greater quantity of agricultural good to acquire industrial good. This makes the relative price of the agricultural good lower with respect to the industrial good, so we see a decrease in prices in cities intensive in the agricultural sector.

Figure 6: Effects on Trade Flows, Taxes and Transport Costs

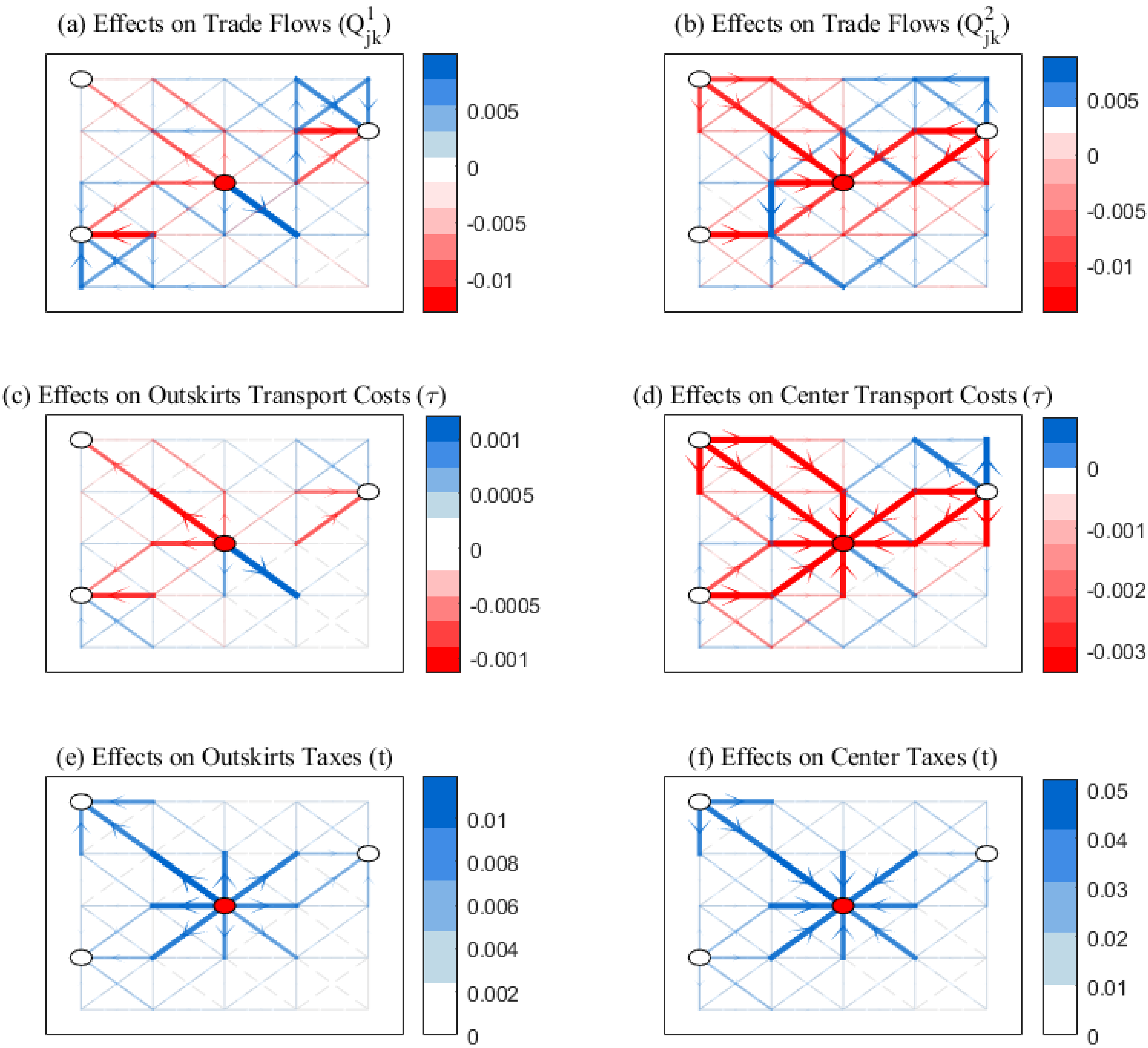
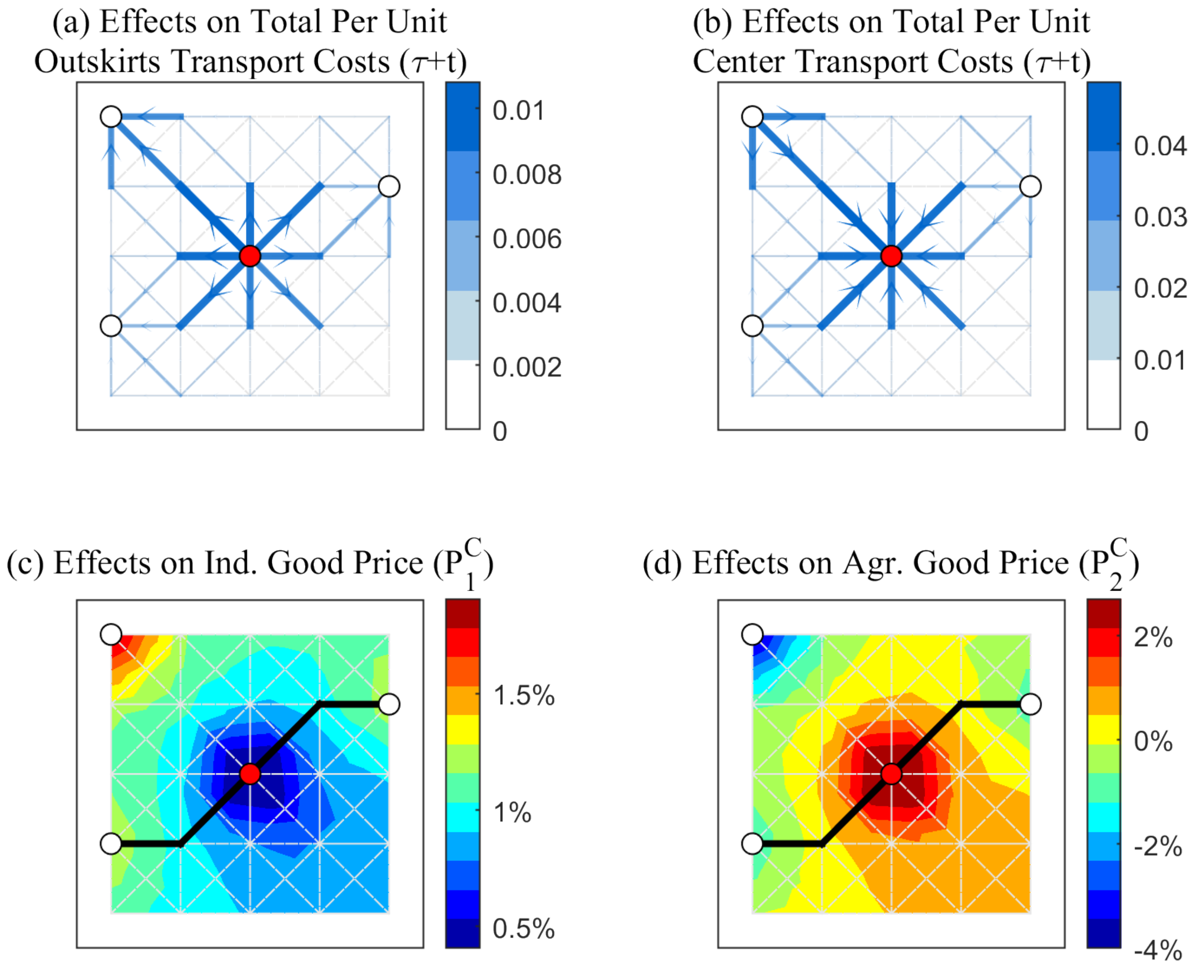


Figure 7: Effects on Total Per Unit Transport Costs and Distribution of Prices



IV.3.2 Case II: Highway Only Corrective Taxes

In this section, we now study the effects of a restricted internalization of the congestion externalities through Pigouvian taxes. This case assumes that there is a taxation technology that only allows the policymaker to impose corrective taxes for the highway ($\lambda^H_{jk} = 1, \lambda^s_{jk} = 0 \;\; \forall j, k$). This provision occurs because it would not be realistic to think that an economy could internalize the effects of congestion in all available routes because there are legal and technological restrictions that would not allow a complete internalization of the externality. So, it is relevant to study the effects of partial internalization in the spatial distribution of the economy. In Figures B.5 and B.6, we show the levels of trade flows, taxes, transport costs, and the prices distribution of the economy under a partial internalization of the externality.

We begin analyzing the effects of the internalization in the trade flows and transport costs shown in Figure 8. As we observe in Panels (e) and (f) of Figure 8, there is only active pricing for goods being transported on the highway and the transport sector faces an increase in the highway transport costs for the main route for two connected agricultural cities. The transport sector will seek to minimize the transport costs by reducing the trade flows through the highway and diversify the flows through other routes with lower relative transportation costs to get to the target destinations. We see this behavior in Panel (a) of Figure 8, where we show the effects on industrial good trade flows after partially internalizing the externality. Note that the transport sector reduced the trade flows through the highway (red links) and increased trade flows on other less direct alternative routes (blue links) that presented lower relative cost levels. This substitution of the highway toward alternative routes increases the transportation costs of the local streets due to higher levels of congestion. The latter can be observed in Panel (c) and (d) of Figure 8 where we show the effects of the partial internalization on transport costs (τ). The transport sector managed to reduce the transport costs along the highway (red links) by reducing the trade flows and by partitioning the trade flows through other alternative routes. This implies an increase in transport costs (blue links) caused by higher levels of congestion in these alternative routes as detailed earlier.

What has been discussed above reflects one of the main problems of internalizing the externality locally. Local streets gain higher levels of congestion with active externalities because the transport sector now uses them more intensively to reduce its transportation costs. This scenario represents a typically accurate representation of the current state of an economy with suboptimal correction policies resulting in inefficient equilibria because of the active externalities that are not possible or not optimal to correct. This problem emphasizes the analysis bias that studying efficient equilibria has, where congestion externalities are internalized by the central planner. From that method of analysis, one assumes that the economy is without any active sources of inefficiencies in terms of externalities, leaving aside all the effects on spatial distribution that have been studied and, reflecting potential bias in analyzing efficient equilibrium.

Finally, in Figure 9 we show the effects on total per unit transport costs and prices distribution. In Panel (c) we can see that, unlike the previous case, the most affected are the agricultural cities connected by the highway because of the increases of transportation costs in their main routes from the central city.

These cities are the most affected since they value the highway relatively more, as it is one of the main routes for them to exchange goods with the central city. This relationship can be seen in Panel (c) where we observe a greater increase of industrial good prices in these cities. Moreover, in Panel (d) we can see that agricultural good prices decrease near the connected agricultural cities because in these cities the industrial good become scarcer than before and gain more value. As a result, the cities are willing to offer more agricultural goods per unit of industrial good due to the increase in transport costs in their main routes.

From this situation, we can also observe that for the northwest agricultural city, this corrective policy did not significantly impact changes in prices since the target routes were not part of the main routes of the carrier for the exchange between the central city and this one; showing the relevance of targeted pricing on the economy. In this particular case, the most distant city with lower levels of welfare increased its welfare, since now the central city relatively increased trade with it because transportation costs with connected agricultural cities increased with the internalization.

Figure 8: Effects on Trade Flows, Taxes and Transport Costs

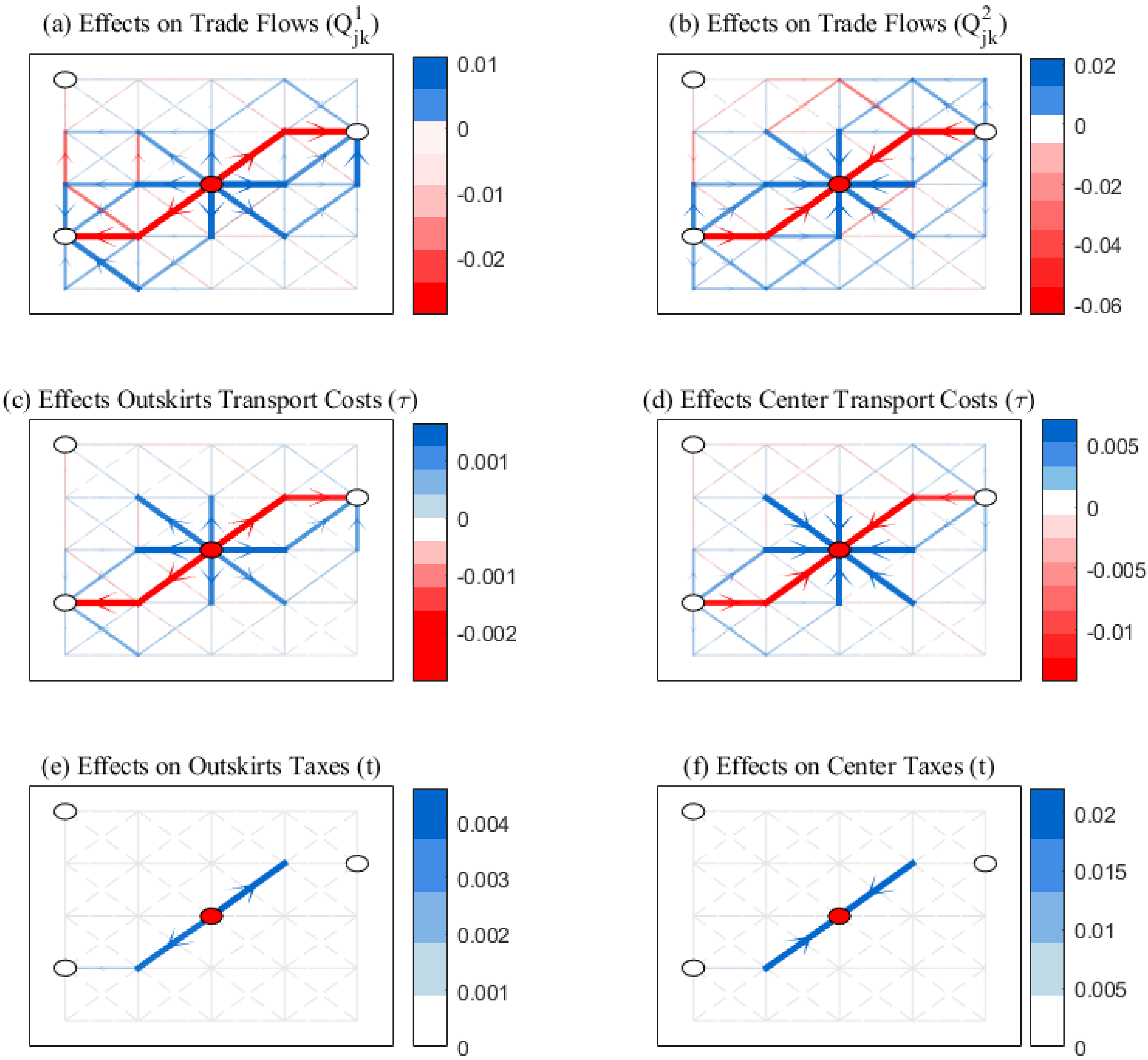
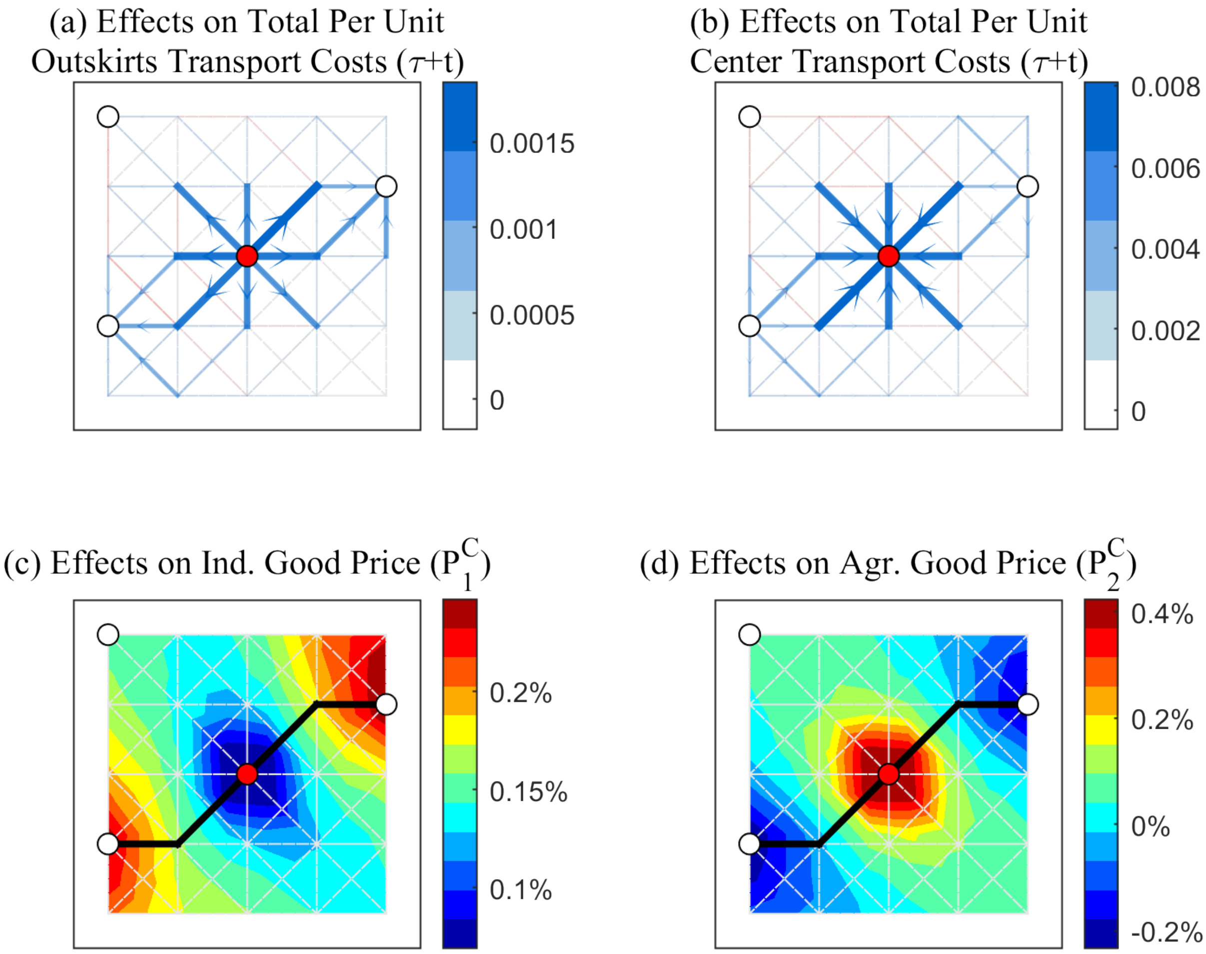


Figure 9: Effects on Total Per Unit Transport Costs and Distribution of Prices

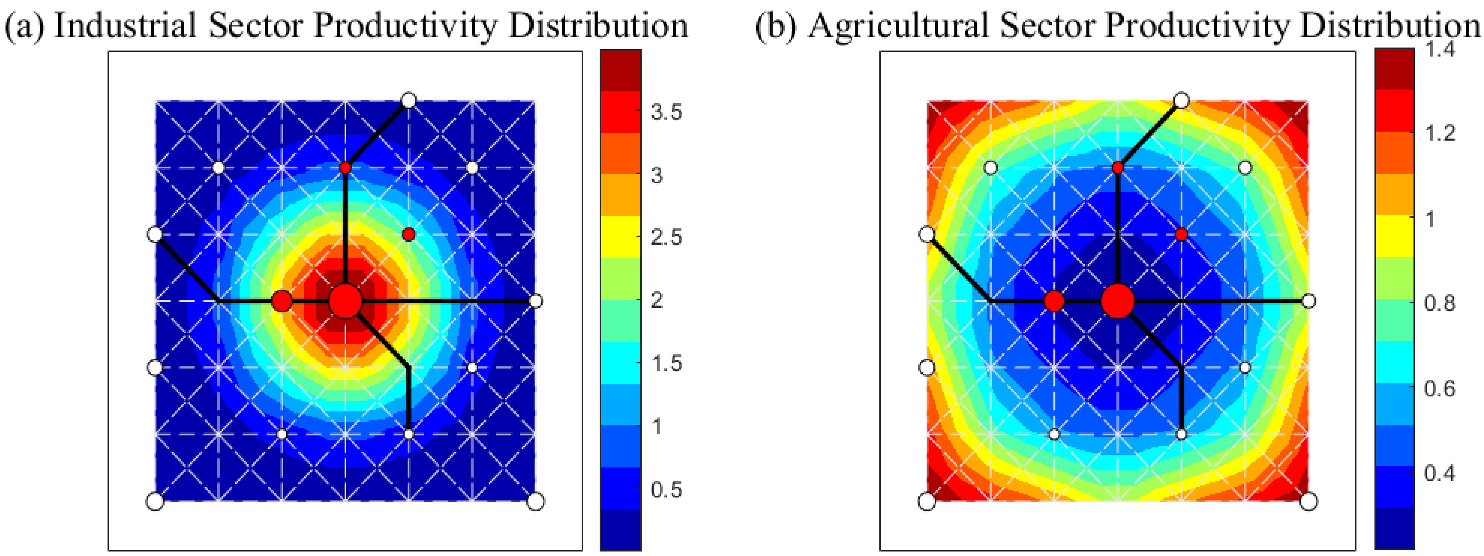


IV.4 Application II: Spatial Distribution

In this section, we analyze the effects of congestion externalities on the spatial distribution of the economy. For this, we set an economy with 15 cities on a 7x7 grid with two types of roads. We also assume different productivity distributions for both tradable sectors in this economy. In Figure 10, we observe this economy and the distribution of productivities.

We assume that productivities are based on the assumption that cities present higher productivity in the industrial sector as they are closer to the center, decreasing toward the extremes of the economy. While for the agricultural sector, the peak of productivity is in the extremes of the economy, decreasing toward the center of the economy. This leads to the existence of two types of cities: cities more intensive in producing industrial goods (red circles) and agricultural cities more intensive in producing the agricultural good (white circles). Furthermore, this distribution implies that cities located between the extremes and the center will have a minor difference between productivities from each sector.

Figure 10: Productivity Distributions in the Economy



In Figure 11 and 12 we show the spatial equilibrium of the economy under null internalization of the externalities. In Panel (a) of Figure 11 we observe that industrial good prices will be lower in the center since it is the location where the most productive cities of this good are concentrated, with greater availability of the good in the central zone and more scarcity in the extremes. As discussed in Application I, the distribution of prices will be determined by the cost of transporting a good from one location to another. Therefore, we can see in Panel (a) that as we move away from the central city, the prices of the tradable good rise, since transport costs become higher with longer routes.

However, as we discussed, prices are determined by traveled distance, road congestion, drivers' wages, taxes, road infrastructure, and spatial competitiveness between cities. This can be seen by comparing prices in the northeast sector with those in the southwest sector of the economy. Northeast cities have greater connectivity with the highway and are closer to industrial cities, so transportation costs will be lower and there will be greater availability of this good relative to southwestern cities. On the other hand, we can see that there are fewer agricultural cities generating less relative aggregated demand for the industrial good in this sector with more available routes and lower flows of goods, so prices in this sector will also be lower for this reason because, if cities are closer to each other, there is a higher local aggregate demand for the tradable good. This aggregated demand increases trade flows on local roads and, therefore, increases transport costs in that sector due to the effects of congestion.

In Figure C.1 in the Appendix, we show the trade flows, taxes, and transport costs for the case of null internalization of the externalities. We see in Panel (a) and (b) respectively, trade flows of the industrial and agricultural goods. We observe trade flows that the industrial cities trade to the outskirts of the economy is supplying the agricultural cities. In contrast, agricultural good is traded from the outskirts to the center, which occurs because cities become intensive where they are more productive and then export this good in order to acquire the tradable good for which they are less productive.

Additionally, if we observe the level of flows and transport costs in C.1, we determine that the highway, enables sustaining higher levels of trade flows while maintaining relatively similar levels of transport costs. This allows the economy to benefit more from the exchange of goods by permitting higher levels of trade flows and, therefore, lower prices, especially for the cities closer to the highway. In the same way, we note that the transport sector uses local streets as secondary roads to divert flows and reduce transport costs. The latter is relevant for our analysis, since we will analyze how different internalization measures would affect decisions of the traders' routes and the congestion effects on local streets.

On the other hand, Panel (c) of Figure 11 shows the land price distribution in the economy. As expected, land price is higher in the central city because it has the highest income and therefore, the highest levels of consumption because this consumer who presents higher levels of consumption and availability of tradable goods values the non-tradable good relatively more. As a result, prices of land in richer cities are higher. We can see that, in general, central cities which are more productive in the industrial sector, present higher land prices, followed by the most productive cities in agricultural goods for the same reasons. Consumers maximize utility by equalizing the marginal utility per price spent in their optimal consumption decision. Thus, if more tradable goods are available, the land will be relatively more valued.

Furthermore, in Panel (d) of Figure 11 we show the distribution of wages in the economy, and observe that naturally, wages will be higher in the central cities and in the cities at the extremes of the economy as the value of the marginal product of labor is higher given their productivity. Also, in Panel (a) and (b) of 12 we observe the distribution of firm profits in the economy, which, for the industrial sector, profits are higher in the central city, resulting from a higher level of exports relative to the other industrial cities. The same happens with the agricultural sector, reflecting higher levels of profits in extreme cities.

Finally, in Panel (d) of Figure 12, we show the distribution of consumer utility in the economy. In the more central and extreme cities, there are higher levels of utility because this cities have greater comparative advantages resulting from their levels of productivity and, therefore, greater purchasing power for goods consumption. Panel (c), shows the distribution of income in the economy, and demonstrates that the cities with the lowest incomes are those that lie between the center and the extremes of the economy.

Next, we analyze the effects of two cases of corrective policy on the spatial distribution of the economy.

Figure 11: Spatial Equilibrium: Null Internalization ($\lambda_{jk} = 0$)

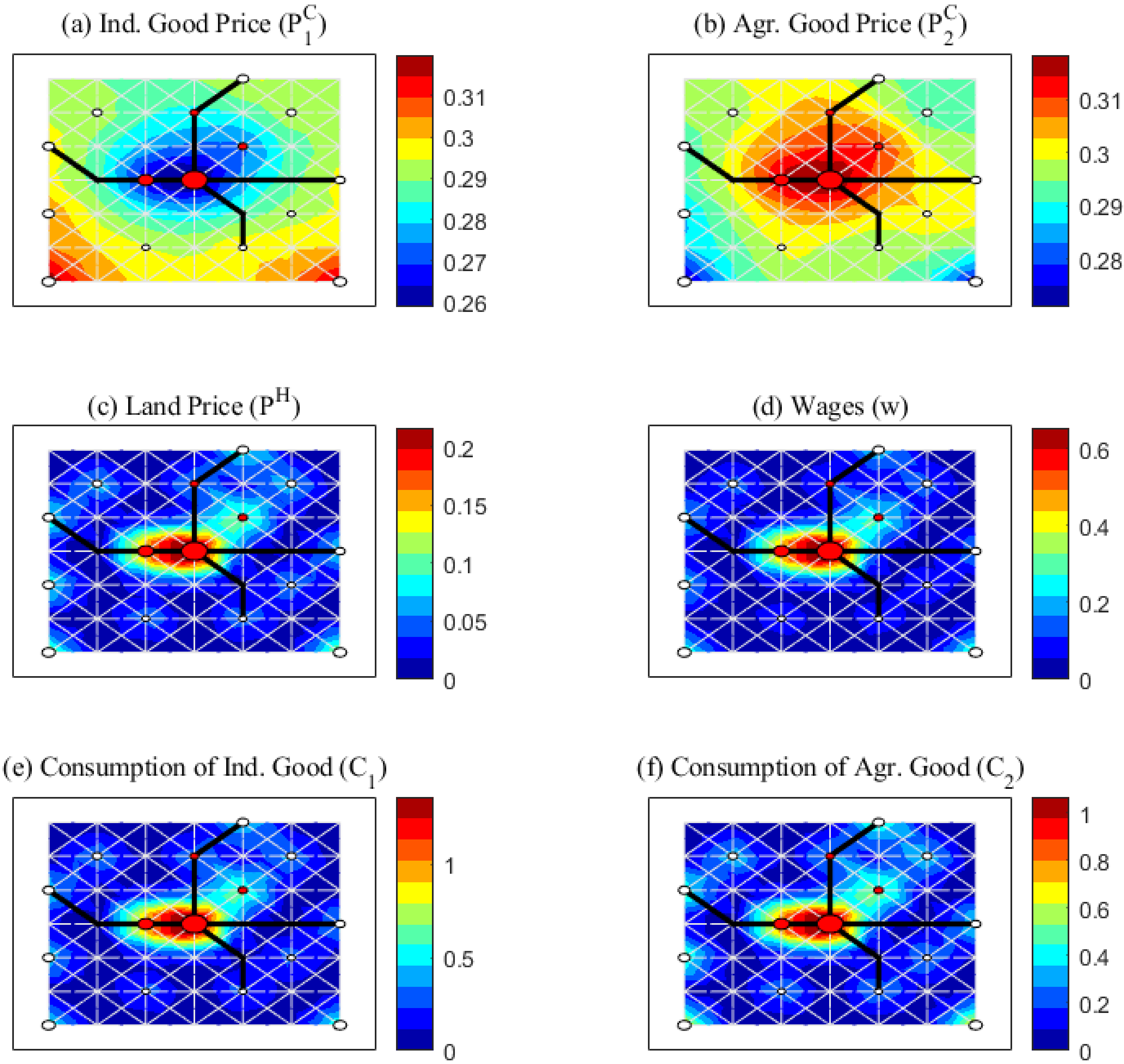
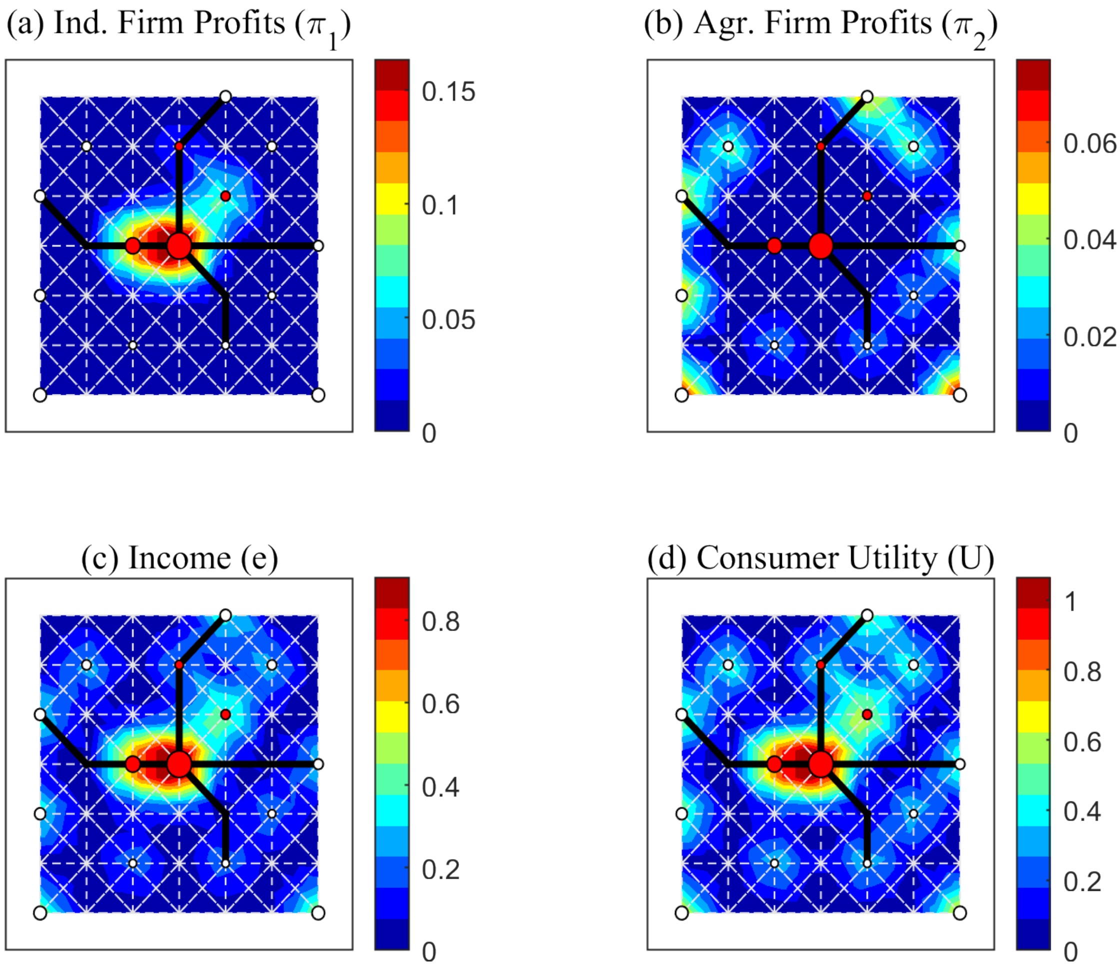


Figure 12: Spatial Equilibrium: Null Internalization II ($\lambda_{jk} = 0$)



IV.4.1 Case I: Global Corrective Taxes

Here we analyze the effects of full internalization in the spatial distribution of the economy. Figures 13 and 14 show the effects of the full internalization of the externality on the spatial distribution of the economy. The effects are expressed in terms of percentage changes with respect to the case with null internalization of the externalities (counterfactual).

If we observe the effects in the distribution of industrial good price in Panel (a) of Figure 13 we determine that there is a global increase in the level of prices reaching increases of 30% in cities with less connectivity and that are farther from the center (southwestern and southeastern cities). Also, in Panel (b), we see an increase in the prices of agricultural goods reaching a peak in the central city with an increase of 25%.

These prices are explained by the increases in transport costs generated by the imposition of corrective taxes. The transport sector is not willing to maintain the same level of trade flows for the same prices, so with the internalization there are fewer trade flows at higher prices as a result of the mechanisms discussed in Application I. Regarding the magnitude of the effects, it is worth noting that the most affected by this price increases are the most sensitive cities to trade. These are the cities in the center and extremes that present greater productivity only in the production of one of the tradable goods.

Therefore, trade restrictions affect their utility levels relatively more than they do to other cities, since these central and extremes cities do not present productivity that allows them to smooth out the lower availability of the good where they are less productive. The consumption level of the tradable good where these cities are not intensive is highly sensitive on the exchange with other cities. These cities become intensive in the sector where they are more productive to produce more efficiently given their comparative advantage, and then to exchange this good for the tradable good of the sector where they are less productive.

This effect of trade restrictions can be seen in Panel (d) of Figure 14 where we note that these cities showed reductions in their utility levels in the range of 2% to 3%. This reduction occurs because as trade flows have been reduced, non-intensive goods in these cities are scarcer and therefore more expensive, which reduces the level of consumption of the good. However, the extreme cities connected to the highway do not present decreases in utility while those that are not connected do. This distinction emphasizes the relevance of connectivity that reduces transportation costs by softening the effect of internalization on these cities with the highway as one of their main trade routes.

We also can see in Panels (a) and (b) of Figure 14 that these more affected cities seek to soften this effect by slightly reducing their intensity in the good where they are more productive to produce more of the scarce good. We see that the central cities increase their profits in the production of agricultural goods by over 100%, while the agricultural cities increase their utility levels in the industrial sector by up to 200%. These increases are due to the adjustment of a greater allocation of workers to the production of the good where they are not intensive due to the increase in their prices, that leads to a higher value of the marginal productivity of labor in that sector.

On the other hand, as seen in Panel (d) of Figure 14, we now see that the cities that are between the center and the extremes increase their levels of utility in 2% to 4% due to the complete internalization of the externality. These cities can now gain competitiveness in trade since transport costs are higher and therefore, they will have more relative trade with the more productive cities at the extremes and center since these cities located in the middle are at a closer distance and therefore present lower relative transportation costs. Another way of looking at this situation is that now the extreme and central cities are willing to give more of the good where they are more intensive for the tradable good where they are less productive, enabling the cities in the middle to benefit from these changes in relative prices.

The above is evidenced by observing Panels (e) and (f) of of Figure 13, that show these middle cities increasing their consumption levels of both industrial and agricultural tradable goods by up to 5%, while the central city reduces its level of agricultural good consumption by 10%. The most extreme cities reach an 11% reduction in their consumption levels of industrial goods.

These increases in the consumption of tradable goods in the middle cities imply that the relative valuation of the non-tradable good increases, which is seen in Panel (c) of Figure 13, land prices in these middle cities increases by approximately 20%.

On the other hand, as we observe Panel (d) of Figure 13, wages increase in the middle cities as the value of the marginal productivity of labor increases with the rise of the prices of the tradable goods in the economy. This increase in the range of 12.5% to 16% in wages is directly explained by the increases in the prices of the tradable good. For example, when observing the cities of the middle that are intensive in the agricultural sector, we see that they present increases in prices of the agricultural good in similar ranges.

The income increases are explained by the rise in wages, firm utilities, land price, and taxes redistribution. But these income increases are not real increases because the analysis demonstrated that individuals from the extremes and central cities, who have increases in income as seen in Panel (c) of Figure 14, lose purchasing power as the internalization policy generated higher prices due to the increases in transport costs.

Finally, this analysis shows that the full internalization of the externality created a winners and losers game. The most negatively affected are, in this case, the most productive cities that are more sensitive to trade restrictions. While the winners of the internalization of the externalities are the middle cities that benefit from increased competitiveness in trade with the most productive cities due to transportation costs increase.

This evidence reflects the relevance of this study of congestion externalities with the comparison of efficient and inefficient cases, where we show that there are significant effects and mechanisms that affect the spatial distribution of the economy and the welfare of individuals.

With these welfare effects of the corrective policy, we find a game of winners and losers with adverse effects on specific individuals. Thus, it is relevant to study global welfare and to analyze and discuss whether the internalization of externalities would be optimal, specially considering the trade-off between economic efficiency and inequality. On the other hand, it is also relevant to analyze the effects of other sets of taxes redistribution policies (ϕ_j^t) and second best pricing policies in terms of the degree of internalization of the externality ($\lambda_{jk} \in (0, 1)$) that could improve the welfare of individuals. Section E of the Appendix presents both intuition and a methodology to analyze these welfare effects.

Figure 13: Effects on Spatial Equilibrium: Global Corrective Taxes

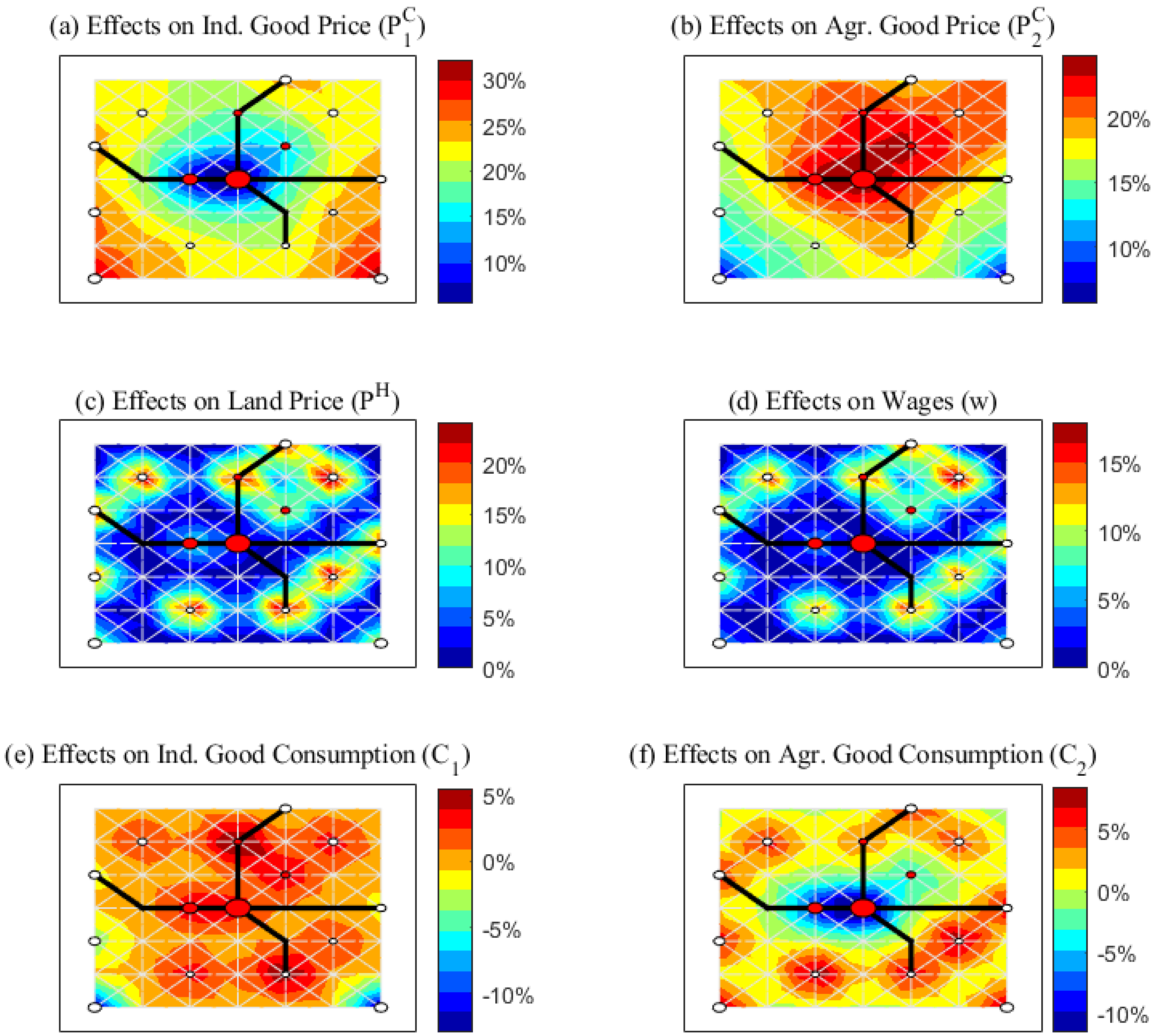
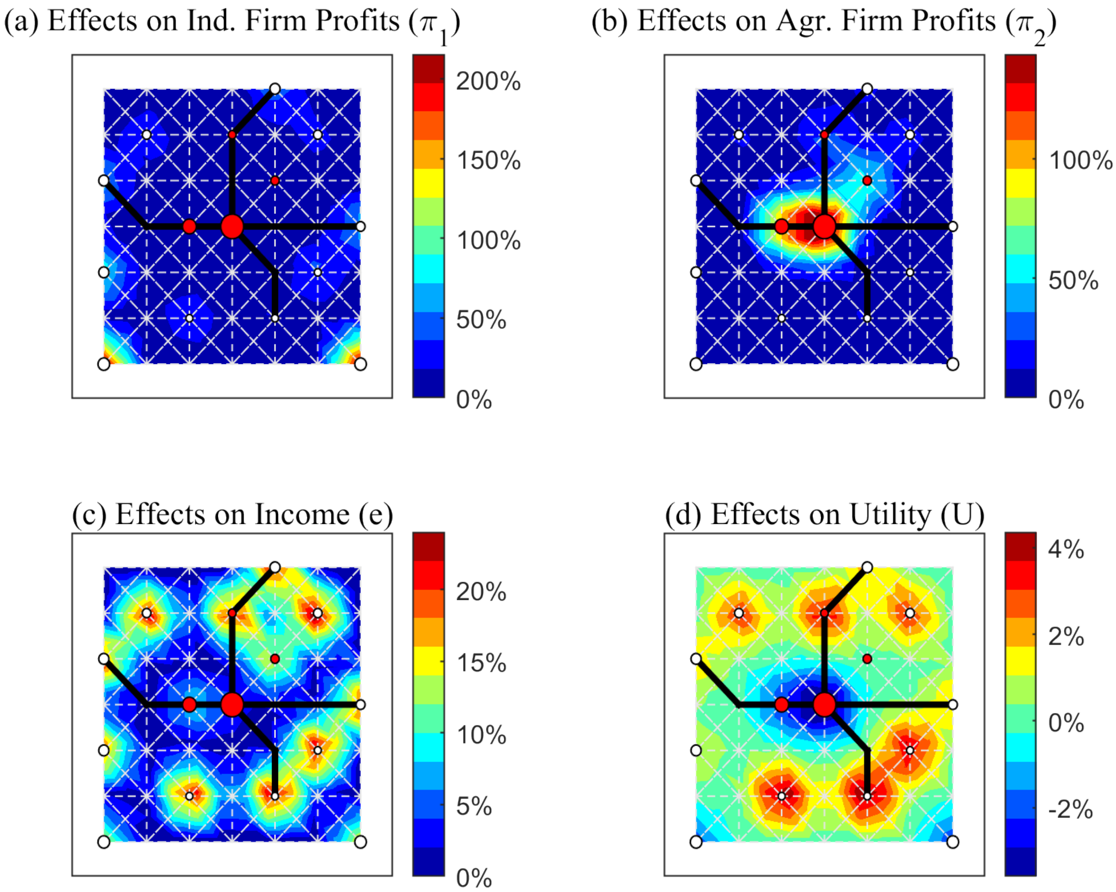


Figure 14: Effects on Spatial Equilibrium: Global Corrective Taxes II



IV.4.2 Case II: Highway Only Corrective Taxes

This section explores the effects on the spatial distribution of the economy under a restricted internalization of the congestion externalities through Pigouvian taxes.

In Figure 15 and 16, we observe the effects of the partial internalization of the externality. This scenario of partial internalization captures the exact mechanisms discussed in Case I, of the effects of the corrective policy on spatial distribution. The finding is that the cities on the highways and close to it are more negatively affected than the others.

This difference results from the increase in transportation costs on the highway, implying that cities that most value and depend on these routes are affected by decreases in trade flow caused by this increase in costs. In Figure C.2 of the Appendix we can see the effects of the internalization on trade flows and transportation costs.

In Panel (a) of Figure 15, we can observe how the agricultural city to the east that is connected by the highway with the central city is the the city reporting the largest increases in the prices of the industrial good, reaching around an 8% increase. This increase is directly due to the pricing of its main route, which leads to reductions in exchange flows and, therefore, lower levels of consumption of the industrial good, as seen in Panel (e) of Figure 15 showing that this city decreases its consumption of industrial good by 3%.

Furthermore, given this reduction in the availability of industrial goods, this eastern city adjusts the increasing labor factor in the industrial sector in order to soften the effects of the internalization on industrial good consumption. Now the city seeks to increase its consumption by increasing the local production of the industrial good. This can be seen in Panel (a) of Figure 16 showing that city increases its firm profits by 25% even though wages in that city increased by 10% (Panel (d) of Figure 15) and prices only by 8%. This adjustment comes from the increase in the price of the industrial good in the city, which increases the value of the marginal productivity of labor in that sector.

Finally, we see in Panel (d) of Figure 16 that the cities more affected in terms of utility are the same as in the previous case, the central and extreme cities. However, we see that among these, the most affected are those that are along the highway and closer to it. This loss of welfare is due to the increase in costs in the main trade route of these cities, which refers to the relevance of targeting taxes to internalize the congestion externality. These factors could be restricting the main routes of certain cities negatively, affecting the welfare of individuals as seen in this particular scenario.

Figure 15: Effects on Spatial Equilibrium: Highway Only Corrective Taxes

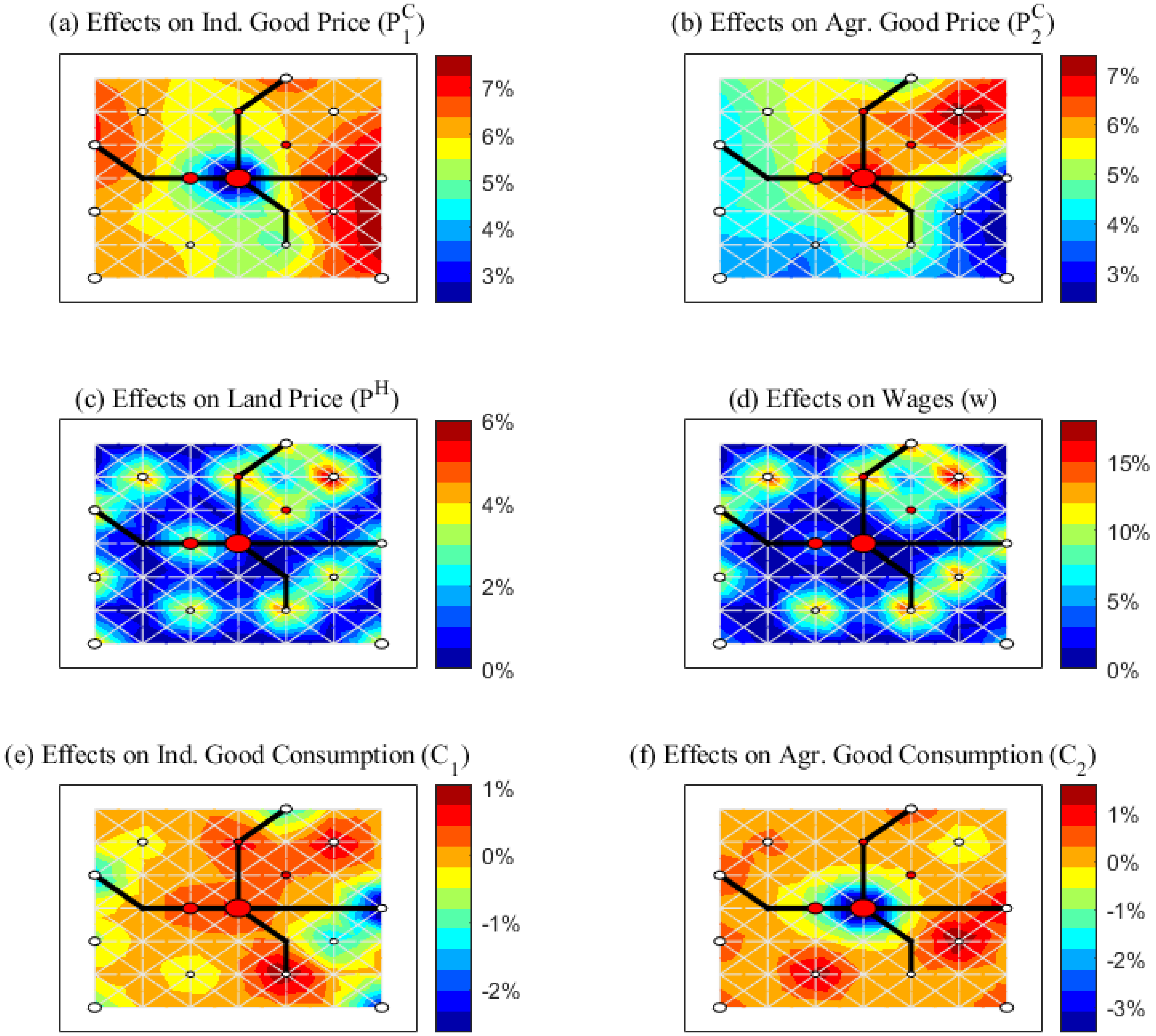
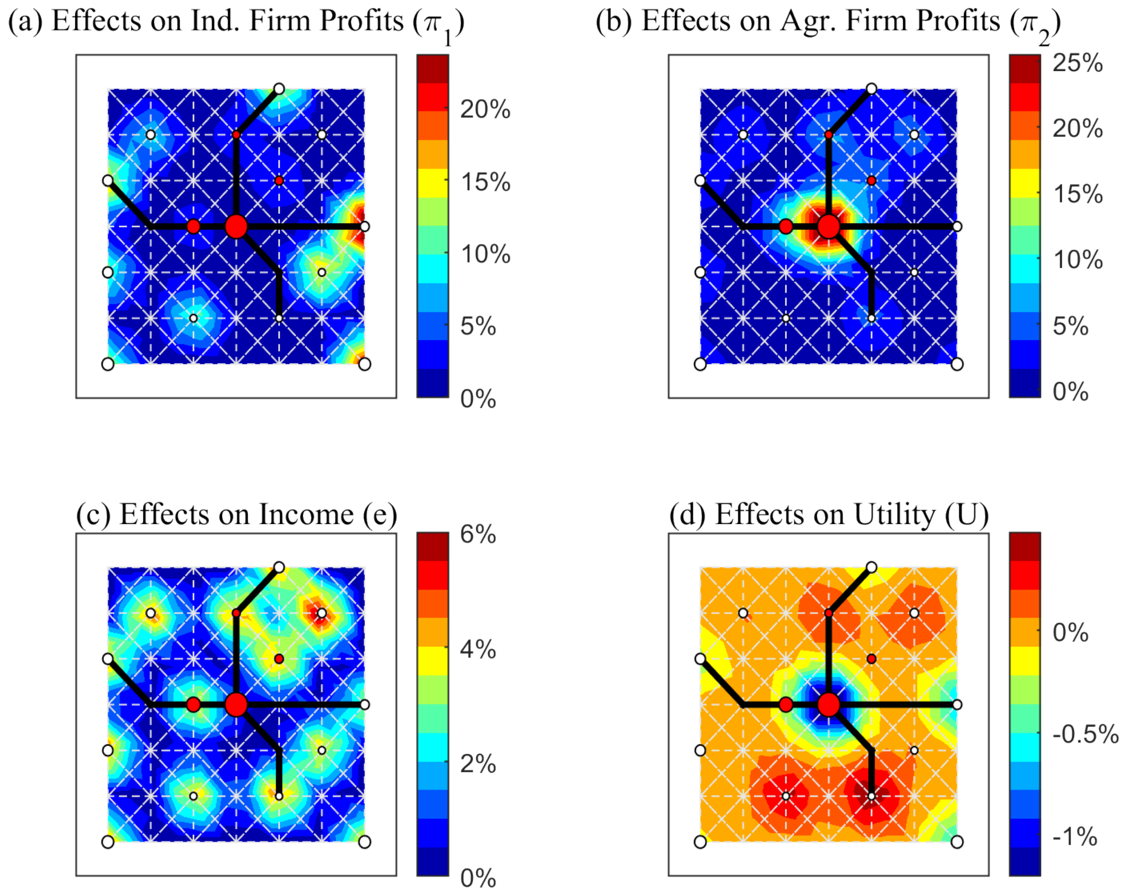


Figure 16: Effects on Spatial Equilibrium: Highway Only Corrective Taxes II



IV.4.3 Magnitude of the Effects: Case I and Case II Comparison

In this section, we quantify the effects discussed earlier to determine more accurately the impact of congestion externalities on the spatial distribution of the economy. We compare the results from the two different studied cases to analyze the differences between a full and partial internalization of the externality. We also quantify and compare the trade flows, transport costs and taxes in the cases of null, full and partial internalization of the externality.

To quantify the effects and be able to compare, we separate the cities into three groups, the central cities, the middle cities and the extreme cities. The quantification of the effects of internalization can be observed in Table C.1 in the Appendix where we show the average effects for each group. We consider the same weight for each city to construct the average and determine the level of utility of the group. These groups of cities enable us to study the heterogeneous effects generated by internalization discussed in the previous sections.

Analyzing the welfare effects of the complete internalization (Case I), we can see that central cities are the most affected by increases in transport costs and their sensitivity to trade restrictions, decreasing their equal-weighted utility by 4.5%. We discussed that these cities, more productive in industrial goods, present greater dependence on the trade of agricultural goods, since these cities have low productivity in that sector. Therefore, with the imposition of taxes, these cities face a 25% average price rise for the agricultural good. These central cities are also the most affected by increases in transport costs and by their sensitivity to trade restrictions. We argue that these cities, being more productive in industrial goods, present greater dependence on trade in agricultural goods, since these cities have low productivity in that sector. Therefore, with the imposition of taxes, these cities face lower availability of agricultural good, reporting a decrease in the consumption of this good of 14.9%. They also decrease their intensity in the production of the industrial good in order to smooth consumption from the local production of the agricultural good. We observe this situation with the 137.8% increase in agricultural sector profits given that this increase is greater than the increases in prices. This increase is explained because there was a transfer of labor to that sector.

On the other hand, when observing the effects of complete internalization for the middle cities, we can see that they increase their utility by 3.8%. This results from their presenting now greater relative competitiveness when trading with the most productive cities that are now willing to give more units of the good in which they are intensive for the good in which they are not. Middle cities benefit from this, as they also have lower relative transportation costs with more productive cities being closer to them. We see that these middle cities increase their consumption of industrial good by 5.1% and of agricultural good by 4.9% with greater increases in income of 26.1% relative to the central and extreme cities that increase their income by 6.7% and 20.2% respectively.

Finally, we see that extreme cities show an increase in utility of 0.4% which represents the average of welfare losses for extreme cities not connected to the highway with extreme cities that were connected to the highway that reported increases in their welfare. In these cities we see similar behavior to that of the central city, due to increases in the price level of the industrial good of 27.6%, a decrease of 5.6% in the consumption levels of the industrial good and a softening in the local production of this good with increases in profits in industrial firms by 77.6%.

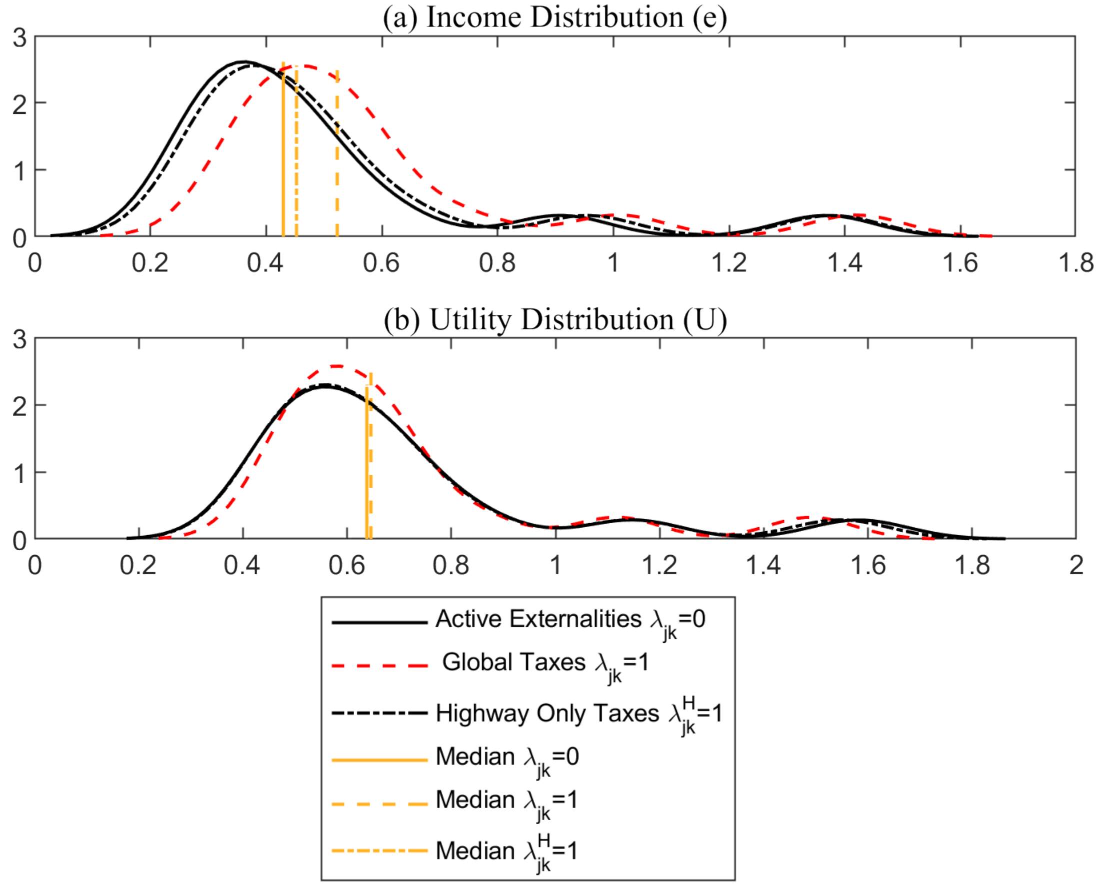
Furthermore, to better analyze the income and welfare effects of the externality we present in Figure 17 the distribution of income and welfare of the economy for the three scenarios. We can see that the internalization of the externality present increases in income in the economy significantly, shifting the distribution to higher income levels in the economy, with an increase of the median income for both cases. However, we discussed earlier, these increases are not in real income. Therefore, although the economy is better in terms of income, these increases might not cover the increase in prices caused by increases in transportation costs, reducing welfare for some individuals due to lower levels of consumption.

To analyze this, in Panel (b) we present the utility distribution of the economy where we can see that the median utility increases slightly for the case of complete internalization, and where is observed an increase in utility levels for poorer cities (middle cities). While the richest cities (central and extremes not connected to the highway) show decreases in utility. This generates greater equality in terms of welfare, which can also be seen by a narrower distribution curve in the case of complete internalization relative to the case of null internalization of the externalities.

These effects on welfare show the relevance of congestion externalities effects, since they can affect cities and individuals differently according to the spatial distribution of cities in the economy. We observe that for this particular case, the internalization of the externality benefits some individuals and not others, affecting them differently in terms of prices, consumption, wages and income; so, it is relevant to be able to incorporate these effects in the spatial analysis.

In Figure C.3 of the Appendix we show the kernel approximations of the spatial distributions for this economy reflecting more clearly the effects of internalization discussed in the previous sections.

Figure 17: Income and Utility Distributions (Kernel Approximation)



In addition to the analysis in Table C.2 from the Appendix we present descriptive statistics of trade flows, transport costs and taxes for the three different scenarios. We can observe that for the case without any internalization of the externalities, the total iceberg costs relative to the total trade flows are relatively lower than for the cases with full and partial internalization for both directions of the flows. We see that for the outskirts direction that represents the flows of the industrial good mainly. Furthermore, we see that the total iceberg costs relative to the total flows are 5.7% in the case of null internalization and 12.03% in the case of full internalization, emphasizing that with internalization the transport sector would be paying more per unit of good transported. This increased cost can be seen by observing the effects on the average total costs per unit, which go from 3.5% in the case without internalization to 6.8% with full internalization for the outskirts direction of trade flows.

We also can see the same situation in the case of partial internalization relative to the null internalization case, where a greater quantity of good transport is lost in absolute terms, explained by the higher level of transportation costs which presents an average of 3.9% for the outskirts direction. We see that in the case of partial internalization, the effects on costs are lower, since the carrier still has available routes that are not chargeable to diverge the exchange flows and be able to compensate for the increase in transportation costs.

The above can be demonstrated, with the measure of highway use that we present, where we determine which percentage of the total flows are transported through the highway and the local streets. The latter helps us to quantify how the imposition of taxes could affect the intensity of use of the different types of roads. We observe that for the null internalization case, the transport sector moved 18.9% of the trade flows in the direction of the outskirts through the highway. While for the case of partial internalization, the use of the road decreases to 14.5%, which implies that the carrier effectively reduced the flows on the highway, making more intensive use of the local streets to reduce its transportation costs.

This reduction of the highway use for the partial internalization case is relevant in the sense that by focusing taxes on the highway, we now generate a lower highway use relative to the case of complete internalization of the externality. We see that the flows through the highway increase with the full internalization to 19.7%, with respect to the case with externalities. These flows increase since, in this case, all routes are priced and the highway allowed to compensate for these increases in relative costs due to its level of infrastructure.

This result implies that the targeting of corrective taxes on transport would affect the intensity of use of unpriced routes, which was previously shown when we observed how the transport sector minimized its costs by substituting main routes for alternatively relatively less expensive routes and partitioning the trade flows in a larger number of routes.

IV.5 Application III: Labor Mobility

In this final section, we focus on analyzing the effects of congestion on the mobility decisions of workers in the economy. For this, we assume an economy with 49 cities in a 7x7 grid with two tradable goods, one non-tradable good, and productivity distributions assumptions for industrial and agricultural goods production equal to those assumed for the previous application seen in Figure 10. We assume free labor mobility between locations with a labor supply of 49, to observe the effects on the spatial distribution of the economy, internalizing the possibility that workers can now adjust to this imposition of corrective taxes through migration to other cities.

In Figures D.1, D.2 and D.3 of the Appendix, we show the spatial distribution of the economy together with the trade flows and transport costs for the case of null internalization of the externalities. We note that, given the assumption of productivities, the industrial cities are located in the center of the economy, the hybrid cities in the middle, and the most productive in agricultural goods to the extremes.Thus, the trade flows of the industrial good are from the center to the outskirts and the opposite for the agricultural good for the reasons discussed in the previous sections.

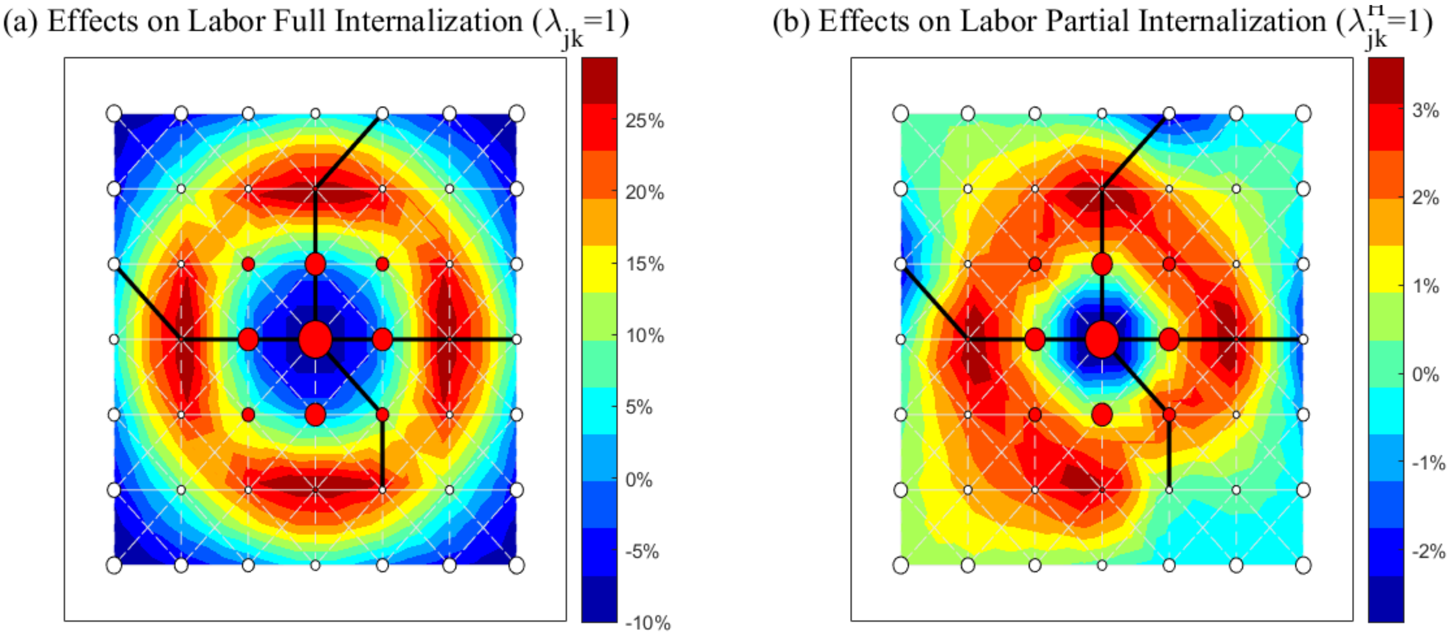
On the other hand, Figure D.7 shows the distribution of workers in the economy, where it can be seen that in equilibrium, there is a larger number of workers located in the central industrial sector. This distribution of labor takes this form because, since in equilibrium the utility of an individual in each location must be the same, there is a larger relative number of workers in the most productive cities, because these cities present higher wages, with lower prices of the industrial good in the economy. However, in equilibrium, the adjustment in utility occurs due to the increase in the local demand for land and agricultural goods that cause the local prices of these goods to rise, which causes the utility of individuals of this city adjust to the equilibrium utility level of the economy.

Another way of looking at this situation is to analyze the three geographical sectors of the economy in Figure D.1. Individuals can decide to live in the central zone with lower prices of the industrial good, and higher wages, but higher prices of land and agricultural good. The second option is to live in the middle cities, with average prices of tradable goods, and lower wages, but lower land prices. And finally, in the agricultural cities of the extremes, with higher prices of the industrial good, but lower prices of agricultural goods, and average land prices and wages.

For this reason, we analyze the effects of the congestion externalities on labor mobility decisions, because these decisions significantly affect the spatial distribution of the economy.

In Figure 18 we show the effects of full and partial internalization of the congestion externalities. We observe in Panel (a) that there is a migration of workers from the central and extreme zones to the middle leading to reductions in the workforce in these sectors of up to 10% in the most productive areas and increasing the workforce in the middle hybrid cities in a range of 20-30%.

Figure 18: Effects on Labor Distribution



This migration of workers from the more productive cities is explained because the more productive cities are sensitive to trade restrictions. As discussed earlier, for the case of the central cities, being more productive in the industrial sector, present greater dependence on the trade of agricultural good since these central cities have low productivity in that sector. Therefore, with the imposition of taxes, these cities experience the largest increases in the prices of the agricultural good, in which they are less productive, since they are the furthest from the extremes. This price increase can be observed in Panel (b) of Figure D.4 where we show a 60% rise for agricultural good prices for central cities.

This price rise leads to a decrease in the availability of agricultural goods in these central cities, reducing their consumption of this good by 20%. And, as studied in the previous section, this last situation leads these more productive cities to adjust their production intensity by transferring workers to the sector where they are less productive in order to increase the local production of that scarcer good and, therefore, to be able to soften the effects of internalization. These effects can be seen in Figure D.5 from the Appendix.

We see that the central cities are now willing to give more quantity of industrial good per unit of agricultural good; so, the cities in the middle benefit due to a higher level of availability of tradable goods. In addition, the cities in the middle become relatively more competitive in trade since now, due to increases in transport costs, the level of trade with the more productive cities increases. These middle cities, are at a shorter distance relative to the most productive cities of the other tradable good; and, thus, we see that the middle cities increase their consumption of agricultural and industrial goods by approximately 20%.

For these reasons, labor migration to the middle cities occurs, because these cities benefit from the internalization policies at the cost of the relative losses of the most productive cities of the center and extremes as seen in Application II.

This migration caused by internalization is relevant, since we see that externalities directly affect workers' mobility decisions, observing that with corrective policies, workers move to benefited cities, reducing the number of individuals in negatively affected cities.

However, this migration increases non-tradable goods given the increase in demand from the more significant number of workers and exchange gains in these cities. As a result, in equilibrium, the level of an individual's utility adjusts, leaving individuals indifferent to living in any of the 49 cities of the economy.

The latter situation becomes more interesting in Panel (b) of Figure 19, showing the effects of the partial internalization of the externality on the distribution of workers in the economy. We see that in the case of highway only pricing, the most significant migration occurs from the cities that value the highway the most for trade. Furthermore, we see that the central city and the extreme agricultural cities connected by the highway to the north, west, and east are the most affected, decreasing their numbers of workers with the internalization in a range of 2-3%. This migration is relevant because internalization policies affect the trade of these cities due to the increase in transportation costs and the level of workers in these cities more dependent on the highway.

Finally, we can see that now in the case of full internalization, the distribution of workers in the economy gains homogeneity, and increases the levels of welfare of the economy, as can be observed in Table 1 showing the levels of workers by geographic sector and the levels of utility for the three case studies. We see that with internalization, workers in the middle cities go from representing a 12.9% of the total number of workers in the economy to 15.88%. As can be seen in Table 1, this increase results from labor migration from extreme and central cities.

Regarding the gains in utility from internalization, we see an increase of 2.8% in utility levels for the case of complete internalization, which is explained by the correction of excess trade, increasing efficiency in the economy.

Table 1: Effects on Labor and Utility

	Null Internalization	Full Internalization	Partial Internalization
Pigouvian Taxes	$\lambda_{jk} = 0$	$\lambda^H_{jk} = 1; \lambda^s_{jk} = 1$	$\lambda^H_{jk} = 1; \lambda^s_{jk} = 0$
Labor Extremes Cities	45.82%	44.21%	45.65%
Labor Middle Cities	12.90%	15.88%	13.17%
Labor Central Cities	41.28%	39.89%	41.18%
Utility	0.67513	0.69408	0.67626

V Conclusion

This thesis studies the welfare effects of congestion externalities in a general equilibrium spatial model. We develop a spatial model capable of characterizing a decentralized equilibrium in the presence of congestion externalities enabling the study of the effects of the externality on trade flows and on the spatial distribution at different levels and targeting of pricing policies.

This study focuses on inefficient equilibria in spatial trade models, which has not been widely studied in the literature since much focuses on efficient study without congestion or centralized equilibrium with a central planner that fully internalizes the externality. We contribute to the quantitative study of spatial models by showing results that support the biases of the planner's optimum analysis. We also contribute to the study of inefficient equilibrium analysis and optimal corrective policies by extending the model proposed by Fajgelbaum & Schaal (2020) and developing a proposal for the study of optimal policies for congestion externalities.

We also contribute by presenting the different effects of congestion externalities in agents' decisions and in the spatial distribution of the economy in three different applications, providing improved understanding of the mechanisms by which this externality affects the welfare of individuals and economic efficiency.

First in Application I, we show how congestion externalities directly affected the trader's optimal route choices, affecting trade flows, prices and consumption heterogeneously in the economy, according to which cities show greater sensitivity and dependence on trade. On the other hand, we also observed how targeted pricing could negatively affect the transportation costs of non-priced routes since the trader compensate for the increase in costs with more intensive use of alternative routes.

Second in Application II, we show that congestion externalities affect the spatial distribution of the economy, implying increases and losses in welfare for different individuals depending on their city's geographic location, connectivity with the highway, proximity to other cities regarding the effects on prices generated by greater local aggregate demand, and degree of dependence on trade concerning productivity and intensity of the tradable good production. We also show heterogeneous effects on individuals, concluding that pricing policies increase income and improve equality in utility distribution. Additionally, we show how the internalization of the externality could affect the production sectors, affecting the intensity of production in an economy, by observing that in the most negatively affected cities, there was a transfer of workers to the sector where the cities were less productive in order to smooth consumption by increasing local production.

Third in Application III, we show how congestion externalities affect labor mobility decisions, as we observed migration of workers from the most productive cities to the less productive cities with the internalization. We also observed that the effects of the externalities of congestion generate more concentration of workers in the most productive cities, as we find that, with internalization, workers migrated to the less populated cities in the middle of the economy. Finally, we showed that target pricing produced migration of workers to cities less dependent on the priced routes and finally, we showed that the pricing policies in the case with labor mobility increased welfare levels due to the correction of excess trade in the economy.

To conclude, this study contributes for future welfare and optimal corrective policies analysis. We find that corrective policies affect income and utility distributions in the economy. Therefore, it is relevant to study optimal pricing policies that can increase welfare of individuals by internalizing the trade-off between economic efficiency and inequality. We provide in section E as a proposal for future welfare analysis, an extension of the model to determine optimal pricing policies with a planner who internalizes this trade-off.

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A Appendix to Decentralized Equilibrium

Exogenous Variables:

$$[\alpha_1, \alpha_2, \alpha_3, a, \phi, \beta, \gamma, \{z_j^n\}^j, \{\delta_{jk}\}^{jk}, \{I_{jk}\}^{jk}, \{H_j^s\}^j, \{L_j^s\}^j, w_{central}].$$

Exogenous/Endogenous (for optimal pricing and redistribution) variables from the Planner's Dilemma:

$$[\{\psi_j^G\}^j, \{\psi_j^t\}^j, \{\psi_j^H\}^j, \{\lambda_{jk}\}^{jk}].$$

Endogenous Variables from the Competitive Market:

$$[\{C_j^n\}^j, \{H_j\}^j, \{L_j^n\}^j, \{Q_{jk}^n\}_{k\in\mathcal{N}(j)}^j, \{p_j^n\}^j, \{p_j^H\}^j, \{w_j\}^{j\neq central}].$$

(i) Consumers Problem:
Marshallian Demands for Tradable (C_j^n) and Non Tradable Goods (H_j) for each location j.

$$C_j^n = \frac{\alpha_n e_j}{p_j^n} \quad ; \quad H_j = \frac{\alpha_h e_j}{p_j^H} \quad \forall j, n.$$

Income:

$$e_j = [\sum_n w_j L_j^n + \sum_n \pi_j^n + \psi_j^H \underbrace{\sum_j p_j^H H_j}_{\text{Land Rents}} + \psi_j^t \underbrace{\sum_n \sum_j \sum_{\kappa\in\mathcal{N}(j)} t_{jk} p_k^n Q_{jk}^n}_{\text{Taxes Collected}}] \frac{1}{\sum_n L_j^n} \quad \forall j, n.$$

(ii) Production Sector:
Labor Demand:

$$L_j^n = \left(\frac{w_j}{a\ p_j^n\ z_j^n}\right)^{\frac{1}{a-1}} \quad \forall j, n.$$

Profits:

$$\pi_j^n = p_j^n z_j^n (L_j^n)^a - w_j L_j^n \quad \forall j, n.$$

(iii) Transport Sector:
Profit Maximization:

$$\pi_{od}^{TS} = \max_{r=(j_0,\ldots,j_\rho)\in\mathcal{R}_{od}} p_d^n - p_o^n - \sum_{k=0}^{\rho-1} p_{jk}^n \tau_{jkjk+1} - \sum_{k=0}^{\rho-1} p_{jk}^n t_{jkjk+1} \leq 0.$$

Transport Costs:

$$\tau_{jk} = \phi\delta_{jk} + \delta_{jk}\frac{(Q_{jk}^T)^\beta}{I_{jk}^\gamma} \ ; \ Q_{jk}^T = \sum_n Q_{jk}^n \quad \forall j, k.$$

Pigouvian Taxes:

$$t_{jk} = \lambda_{jk}\frac{\partial\tau_{jk}}{\partial Q_{jk}^T} Q_{jk}^T \ ; \ \lambda_{jk} \in [0, 1] \quad \forall j, k.$$

No-Arbitrage Condition:

$$\frac{p_k^n}{p_j^n} \leq 1 + \tau_{jk} + t_{jk} \quad \forall j, k.$$

(iv) Conservation of Flows:

$$Y_j^n \geq C_j^n + \sum_{\kappa \in \mathcal{N}(j)} (1 + \tau_{jk}) \, Q_{jk}^n - \sum_{\kappa \in \mathcal{N}(j)} Q_{kj}^n \quad \forall j, n.$$

(v) Labor Market and Land Market Equilibriums:
In the case of immobile labor between locations we will have the following equilibrium conditions for the labor market:

$$L_j^s = \sum_n L_j^n \quad \forall j, n.$$

While in the case of labor mobility between locations we will have the following conditions:

$$\sum_j L_j^s = \sum_j \sum_n L_j^n \quad \forall j, n.$$

$$u = U_j(\{C_j^n\}^n, H_j) \quad \forall j \in \mathcal{J}.$$

Land Market:

$$H_j^s = H_j \quad \forall j \in \mathcal{J}.$$

B Appendix to Application I

Figure B.1: Spatial Equilibrium: Null Internalization ($\lambda_{jk} = 0$)

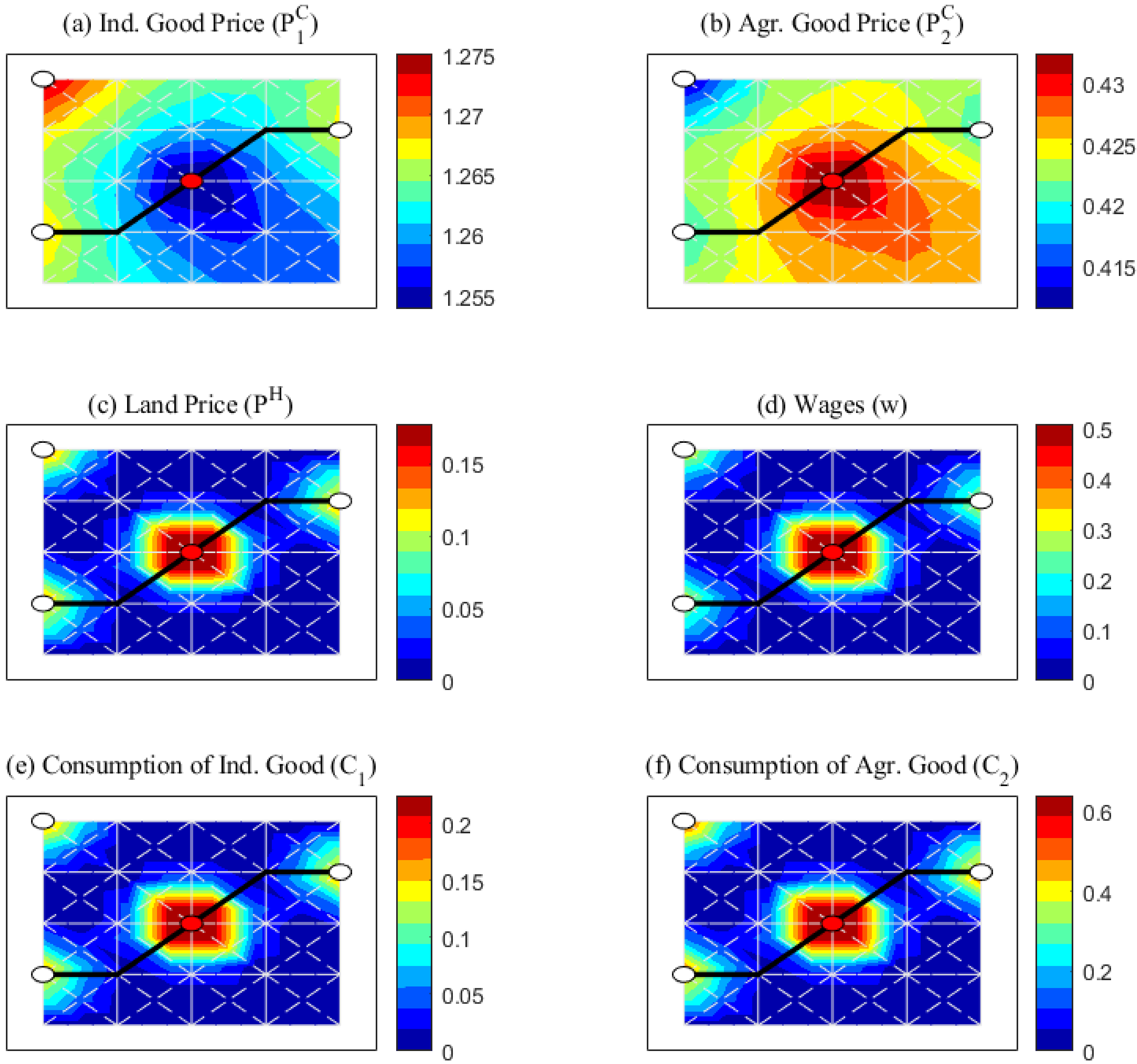


Figure B.2: Spatial Equilibrium: Null Internalization II ($\lambda_{jk} = 0$)

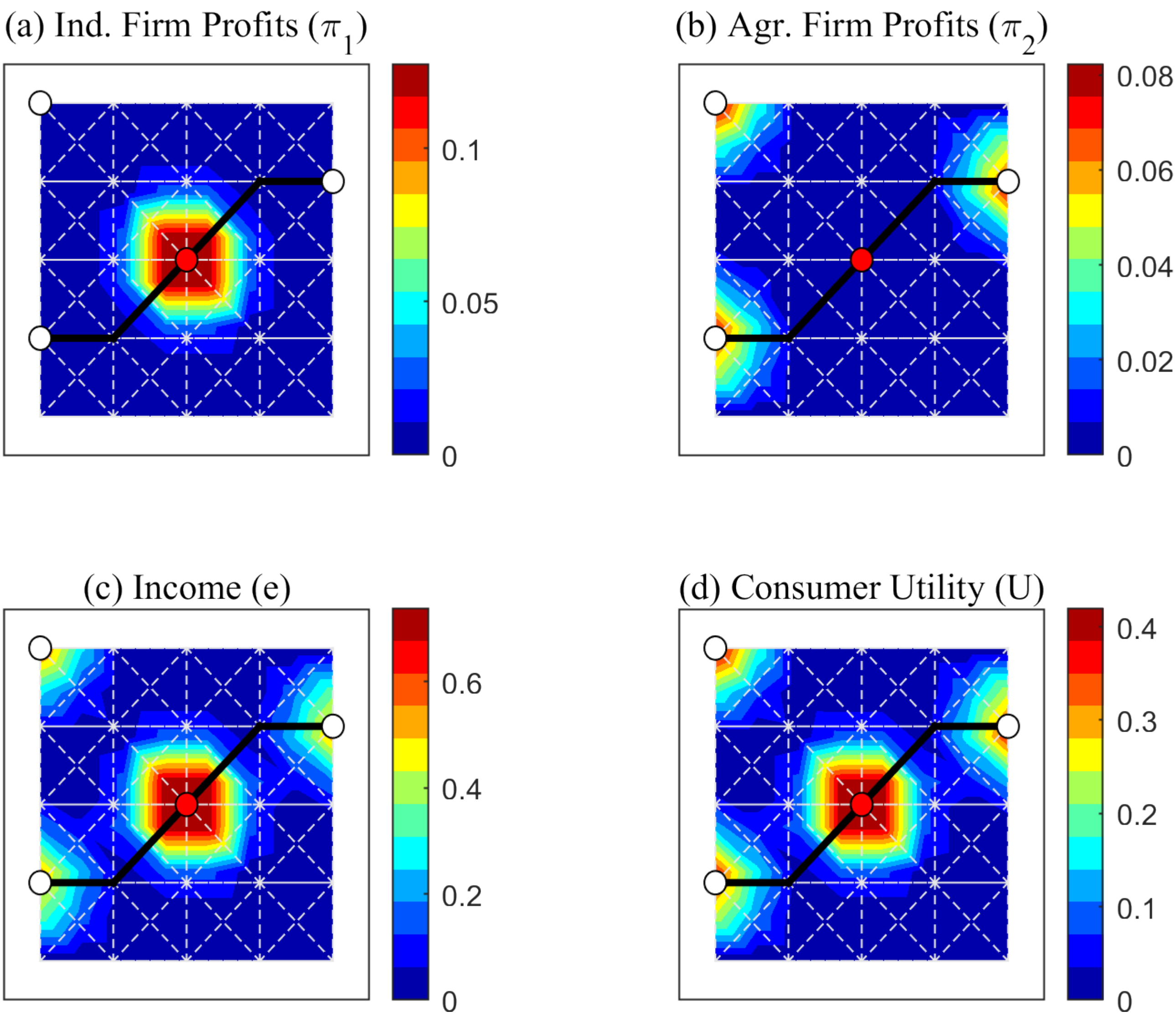


Figure B.3: Trade Flows, Taxes and Transport Costs ($\lambda_{jk} = 1$)

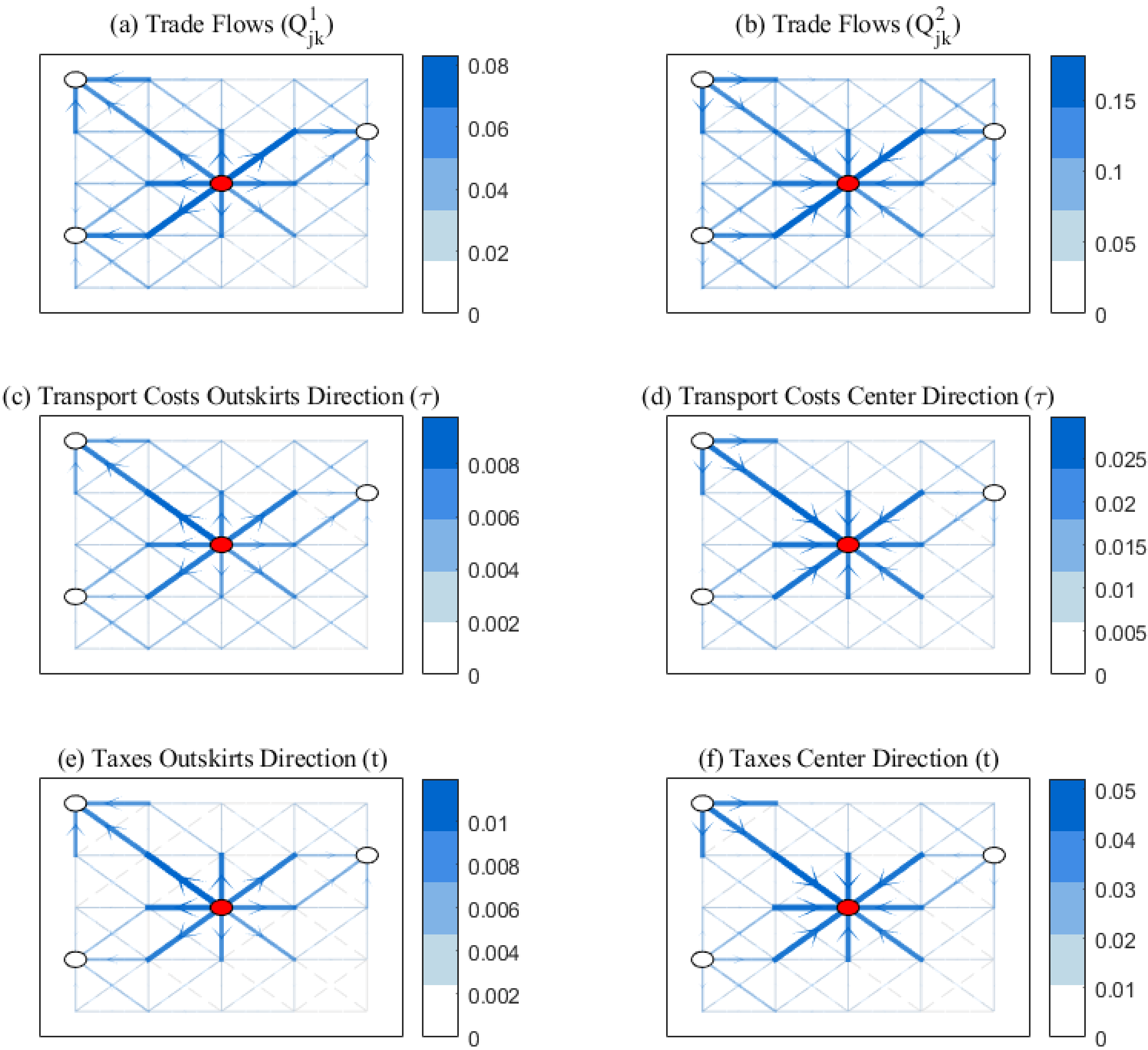


Figure B.4: Total Transport Costs and Distribution of Prices ($\lambda_{jk} = 1$)

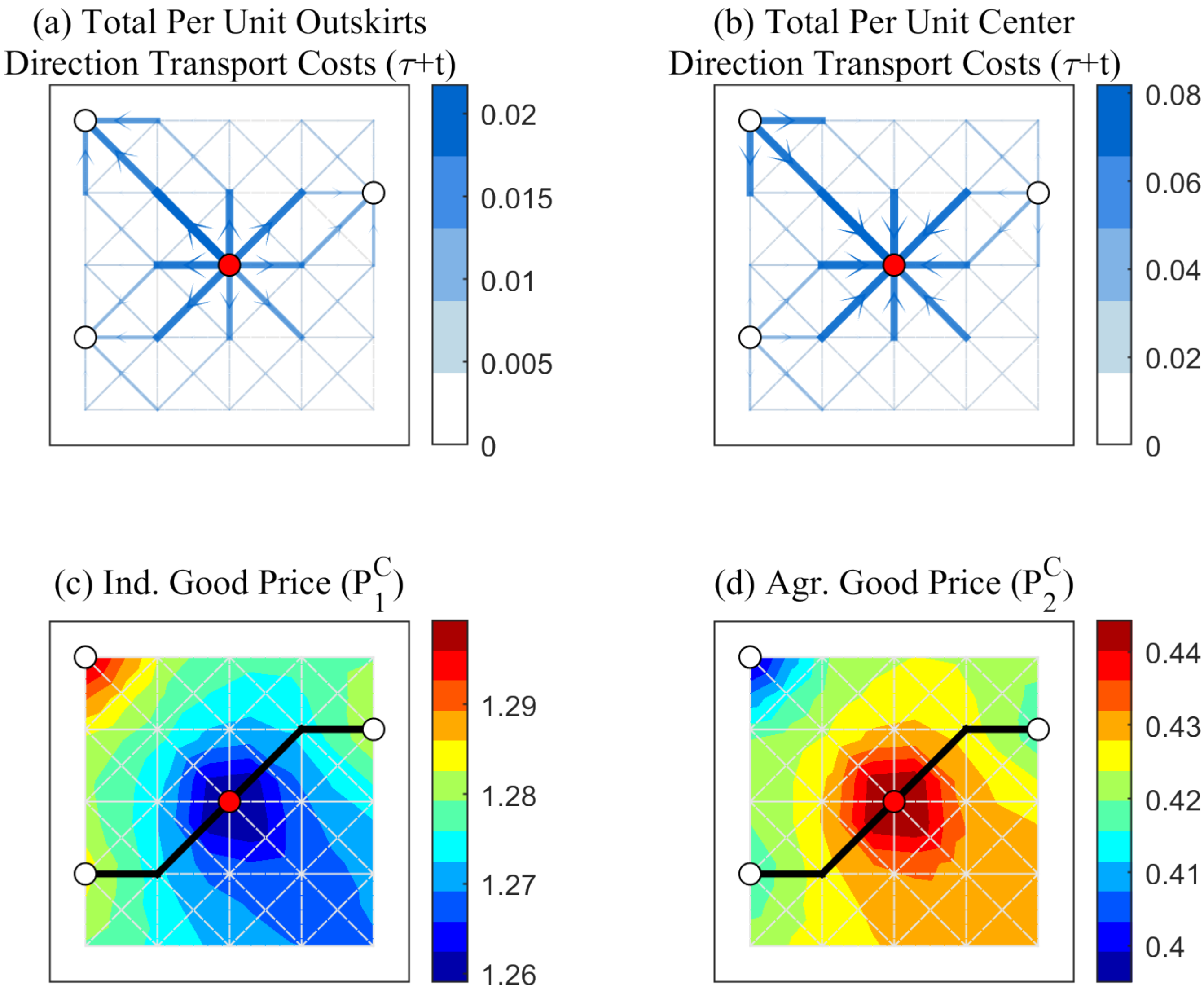


Figure B.5: Trade Flows, Taxes and Transport Costs
Highway Only Taxes ($\lambda^H_{jk} = 1$)

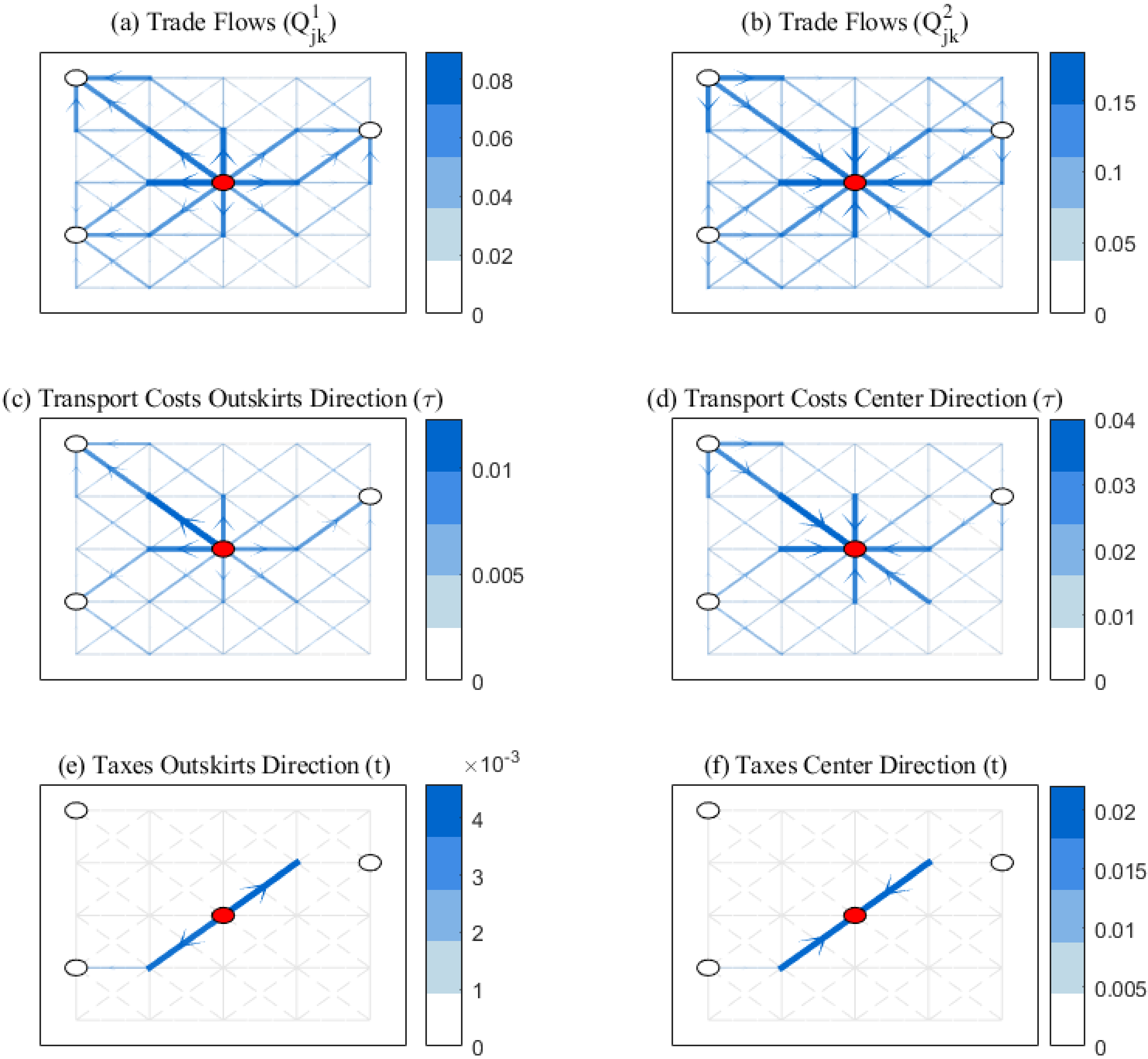
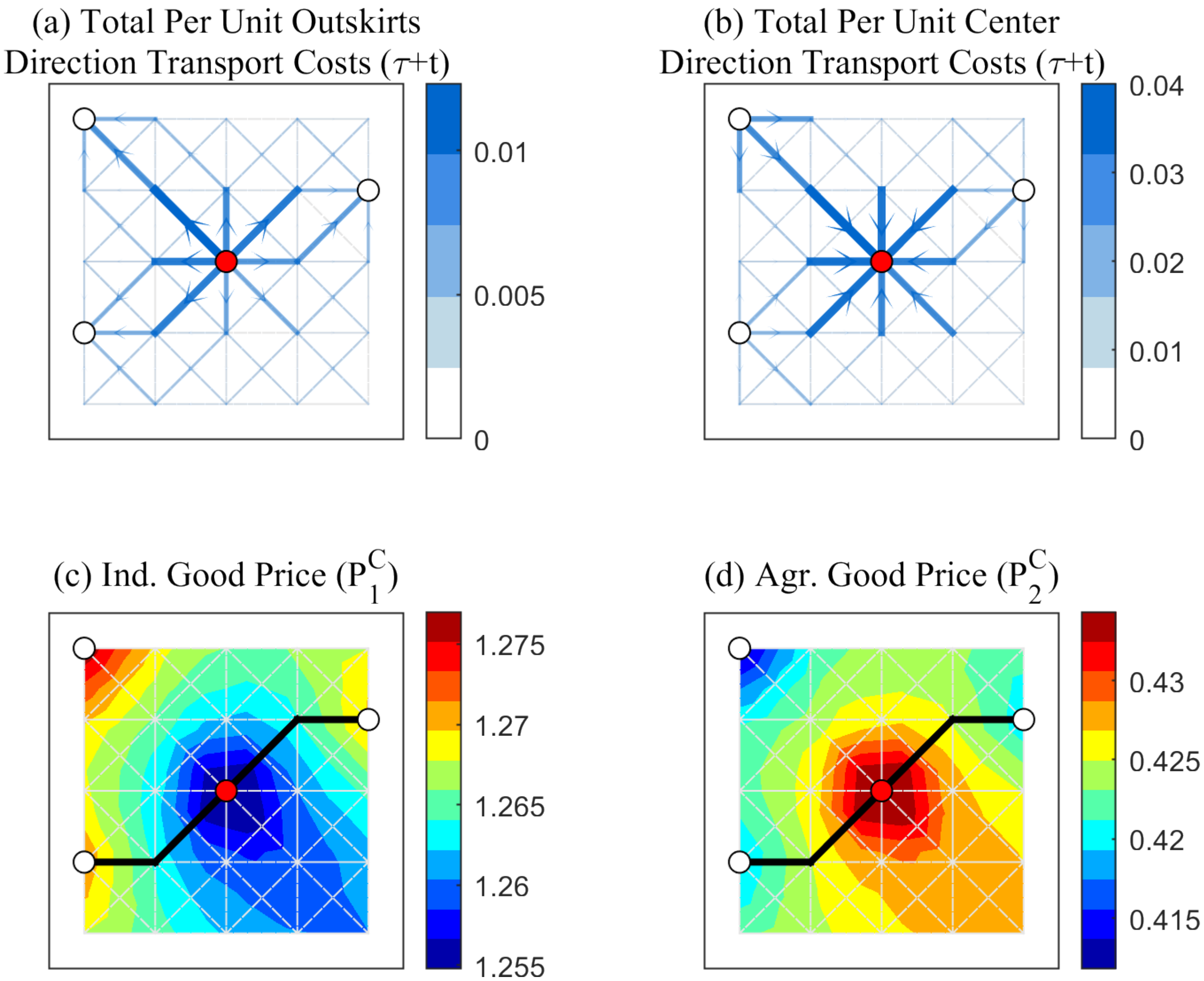


Figure B.6: Total Transport Costs and Distribution of Prices
Highway Only Taxes ($\lambda^H_{jk} = 1$)



C Appendix to Application II

Figure C.1: Trade Flows, Taxes and Transport Costs ($\lambda_{jk} = 0$)

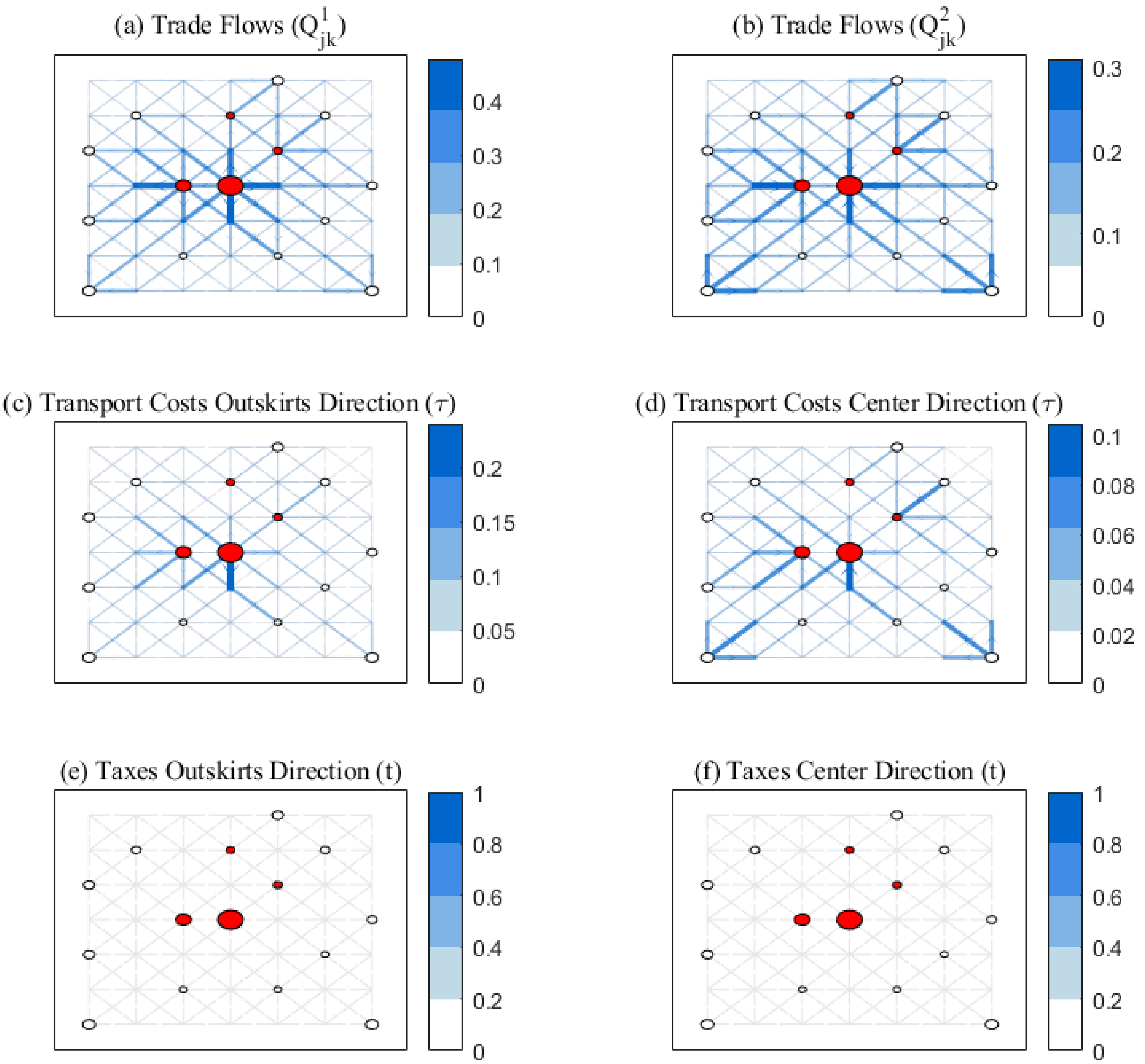


Figure C.2: Effects on Trade Flows, Taxes and Transport Costs
Highway Only Corrective Taxes ($\lambda_{jk}^{H} = 1$)

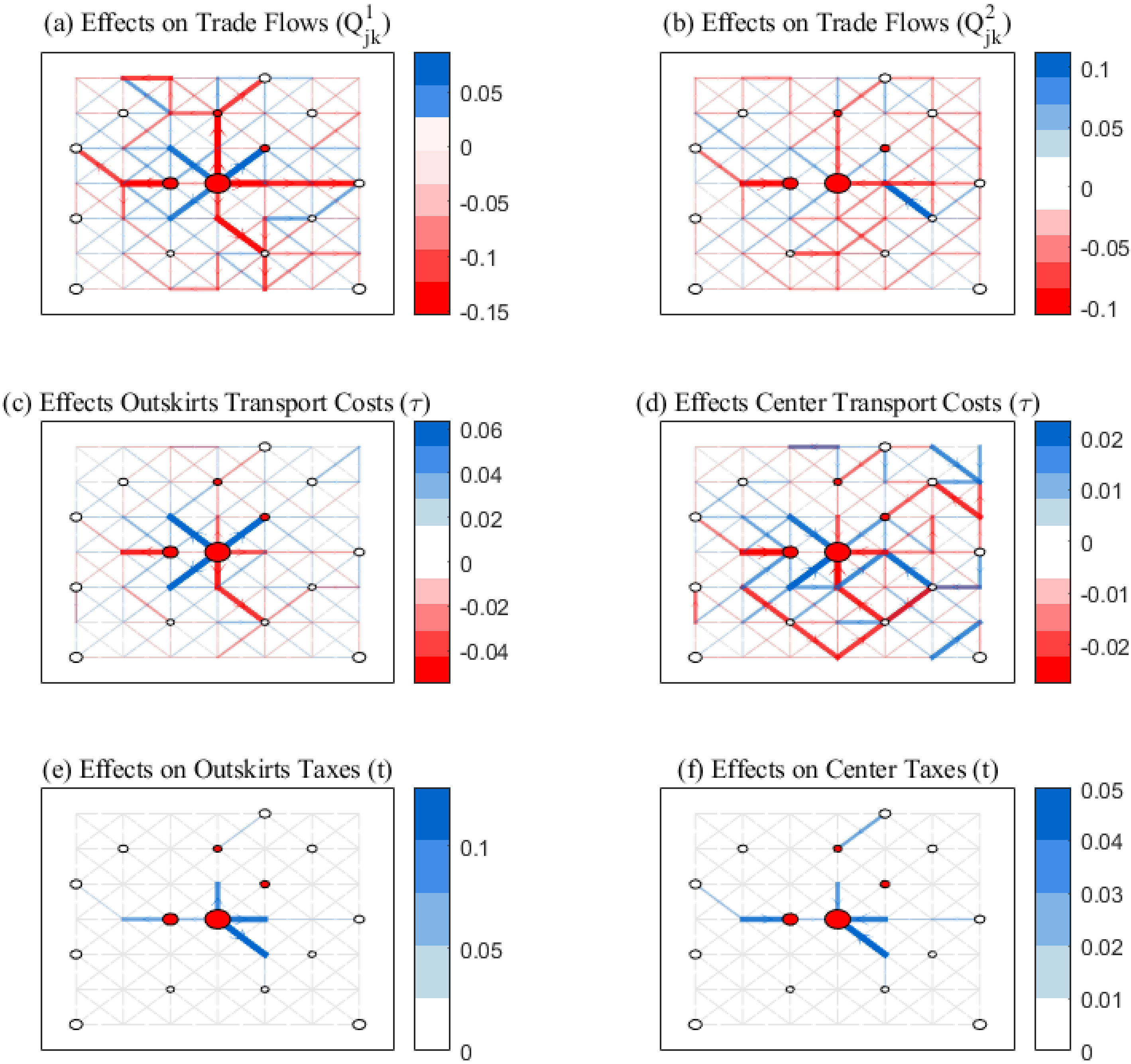


Figure C.3: Spatial Distribution (Kernel Approximation)

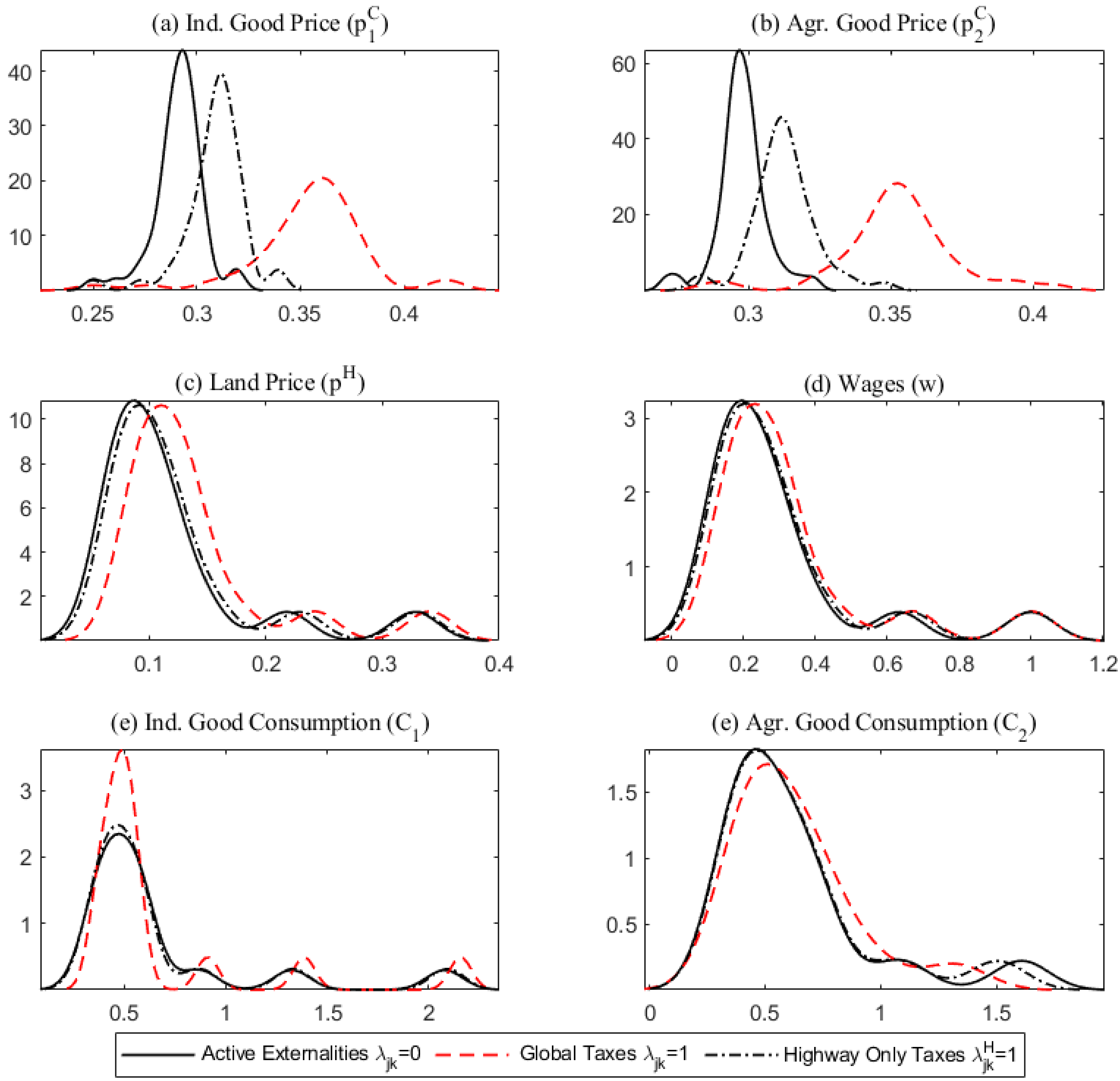


Table C.1: Effects on Spatial Equilibrium

Pigouvian Taxes		Case I $\lambda^H_{jk} = 1; \lambda^s_{jk} = 1$	Case II $\lambda^H_{jk} = 1; \lambda^s_{jk} = 0$
	Ind. Good Prices P_1^C	0.276	0.067
	Agr. Good Prices P_2^C	0.125	0.038
	Land Price P^H	0.202	0.047
	Wages w	0.118	0.038
Extremes	Income e	0.202	0.047
Cities	Ind. Good Consumption C_1	-0.056	-0.018
	Agr. Good Consumption C_2	0.074	0.009
	Ind. Sector Profits π_1	0.776	0.309
	Agr. Sector Profits π_2	0.119	0.039
	Utility U	0.004	-0.003
	Ind. Good Prices P_1^C	0.211	0.058
	Agr. Good Prices P_2^C	0.198	0.053
	Land Price P^H	0.261	0.060
	Wages w	0.174	0.055
Middle	Income e	0.261	0.060
Cities	Ind. Good Consumption C_1	0.051	0.001
	Agr. Good Consumption C_2	0.049	0.005
	Ind. Sector Profits π_1	0.177	0.064
	Agr. Sector Profits π_2	0.169	0.045
	Utility U	0.038	0.002
	Ind. Good Prices P_1^C	0.031	0.024
	Agr. Good Prices P_2^C	0.254	0.068
	Land Price P^H	0.068	0.025
	Wages w	0.024	0.018
Central	Income e	0.067	0.025
Cities	Ind. Good Consumption C_1	0.042	0.006
	Agr. Good Consumption C_2	-0.149	-0.041
	Ind. Sector Profits π_1	0.025	0.019
	Agr. Sector Profits π_2	1.378	0.116
	Utility U	-0.045	-0.014

Table C.2: Transport Costs, Trade Flows and Taxes

	Active Externalities	Full Internalization	Partial Internalization
Pigouvian Taxes	$\lambda_{jk} = 0$	$\lambda_{jk}^{H} = 1; \lambda_{jk}^{s} = 1$	$\lambda_{jk}^{H} = 1; \lambda_{jk}^{s} = 0$
Outskirts Direction			
Total Iceberg Cost / Total Flows $\frac{\sum Q(\tau+t)}{\sum Q}$	0.057	0.123	0.069
Total Iceberg Cost $\sum Q(\tau+t)$	0.904	1.891	1.062
Average Transport Cost $\bar{\tau}$	0.035	0.032	0.035
Average Taxes $\bar{t}$	0.000	0.036	0.053
Average T. Per Unit Transport Costs $\tau + t$	0.035	0.068	0.039
Maximum T. Per Unit Transport Cost $\tau + t$	0.240	0.364	0.210
T. Per Unit Transport Cost STD $\sigma_{\tau+t}$	0.031	0.074	0.039
Highway Use	0.189	0.197	0.145
Center Direction			
Total Iceberg Cost / Total Flows $\frac{\sum Q(\tau+t)}{\sum Q}$	0.037	0.067	0.043
Total Iceberg Cost $\sum Q(\tau+t)$	0.480	0.748	0.499
Average Transport Cost $\bar{\tau}$	0.027	0.024	0.027
Average Taxes $\bar{t}$	0.000	0.019	0.022
Average T. Per Unit Transport Costs $\tau + t$	0.0269	0.0427	0.0283
Maximum T. Per Unit Transport Cost $\tau + t$	0.104	0.168	0.092
T. Per Unit Transport Cost STD $\sigma_{\tau+t}$	0.017	0.035	0.019
Highway Use	0.157	0.160	0.124

D Appendix to Application III

Figure D.1: Spatial Equilibrium: Null Internalization ($\lambda_{jk} = 0$)

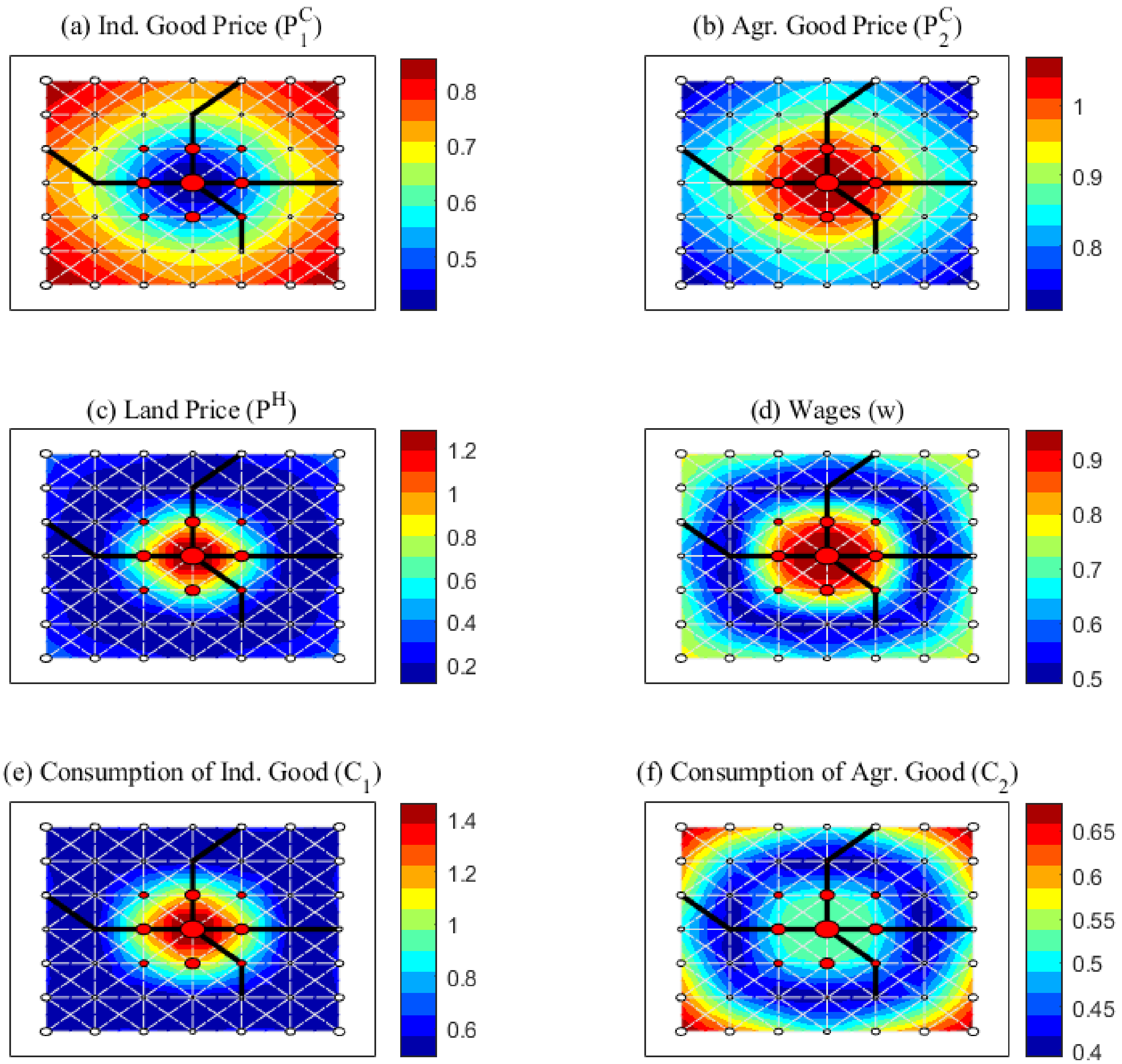


Figure D.2: Spatial Equilibrium: Null Internalization II
($\lambda_{jk} = 0$)

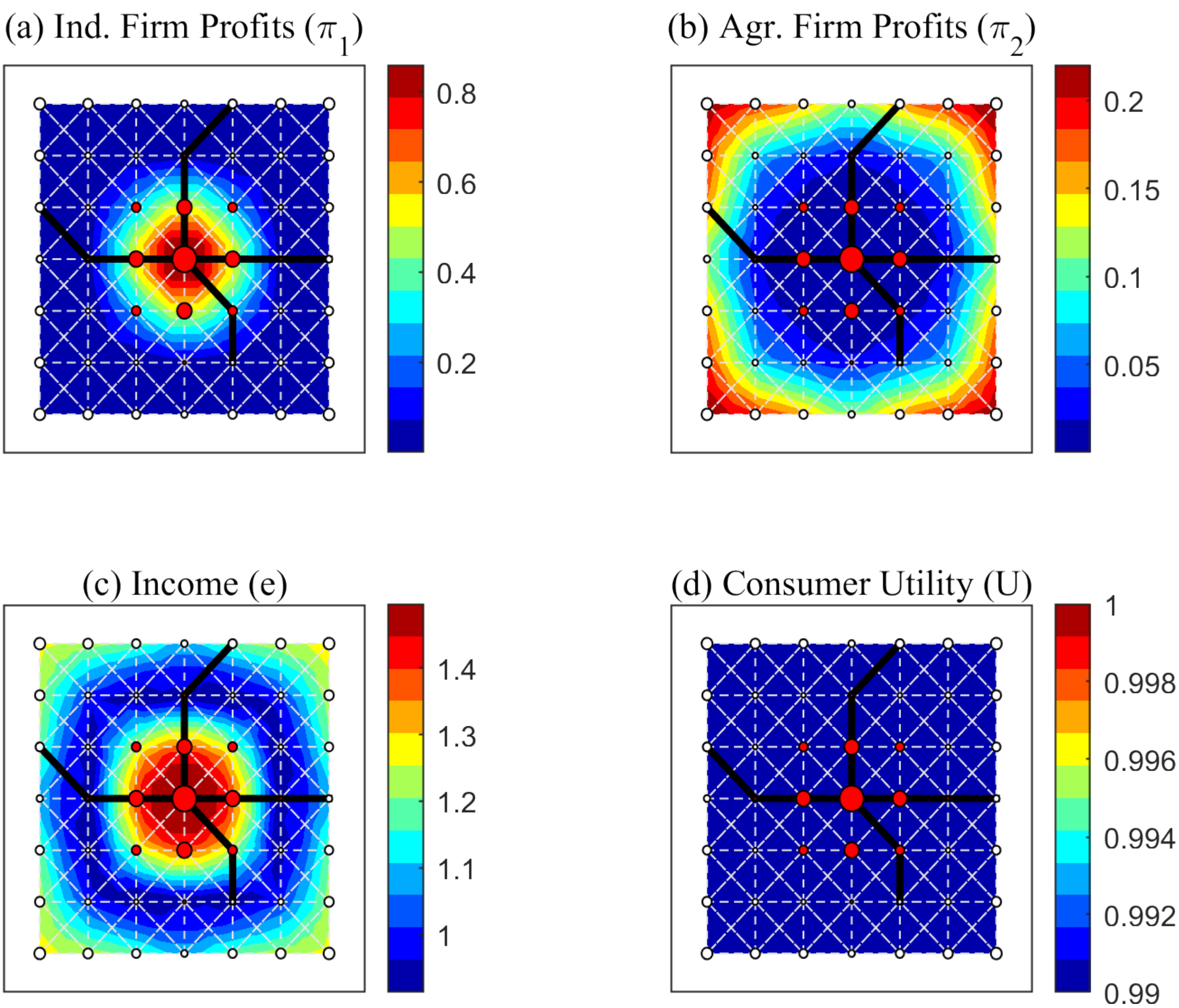


Figure D.3: Trade Flows, Taxes and Transport Costs ($\lambda_{jk} = 0$)

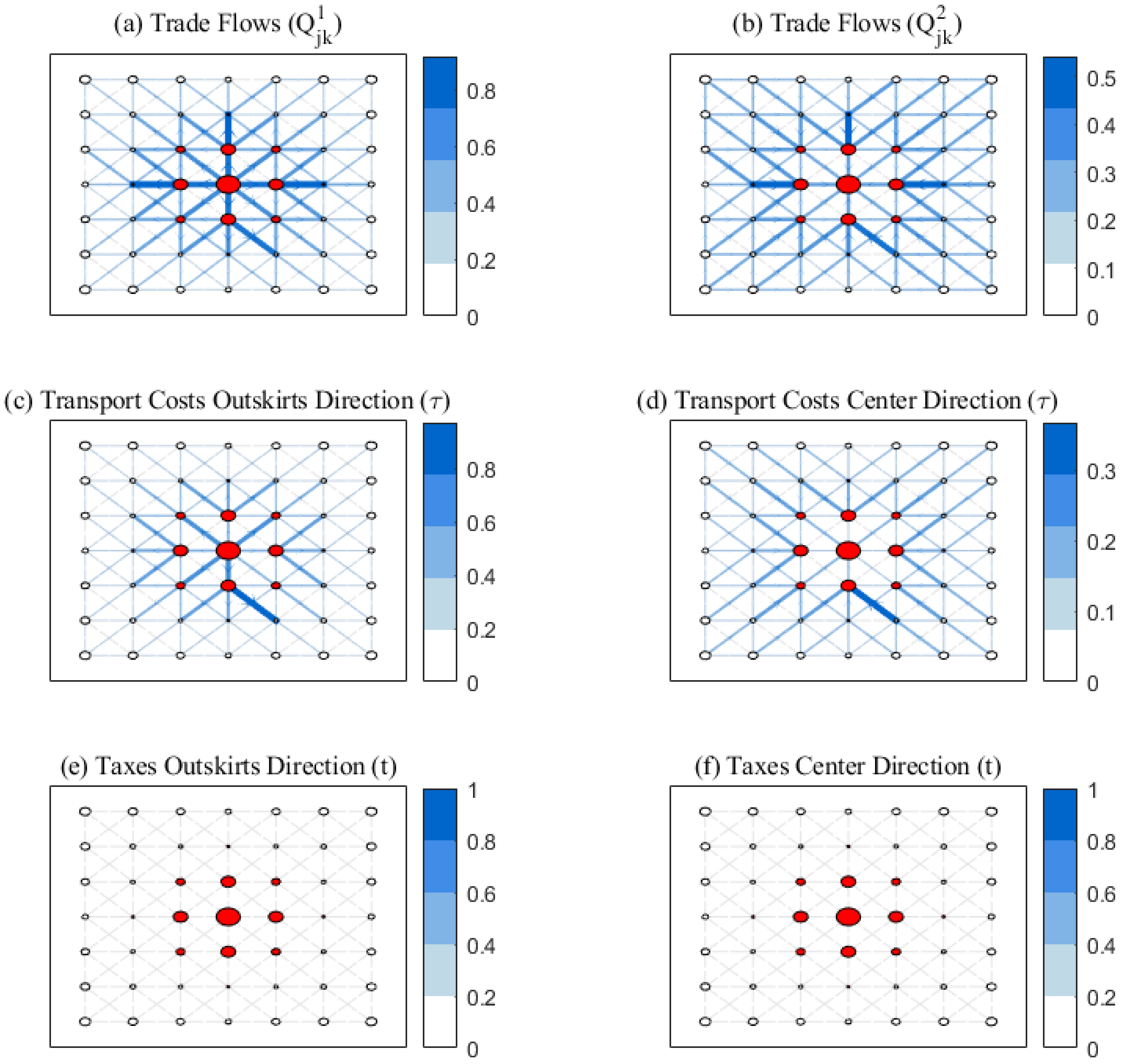


Figure D.4: Effects on Spatial Equilibrium: Global Corrective Taxes ($\lambda_{jk} = 1$)

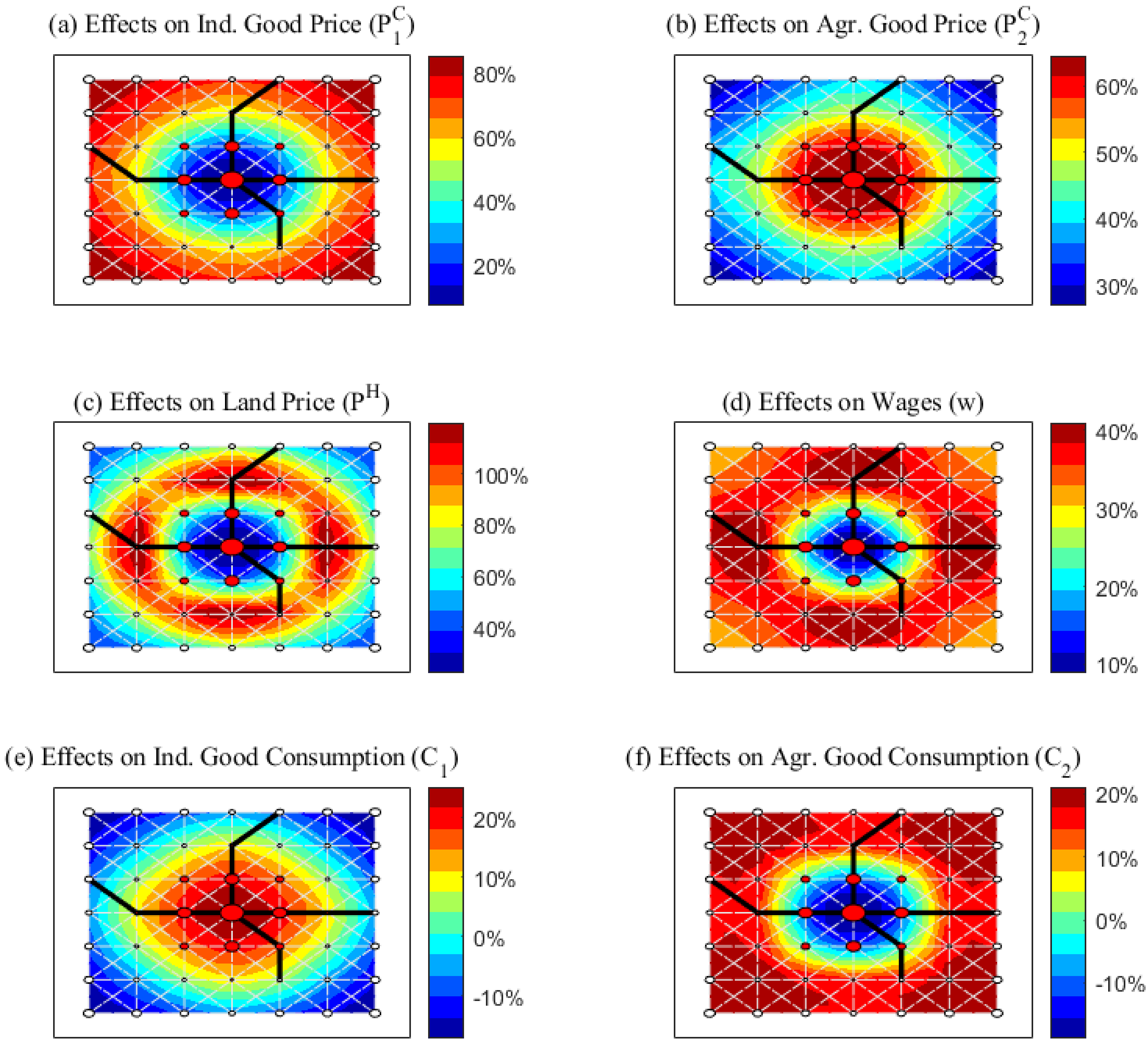
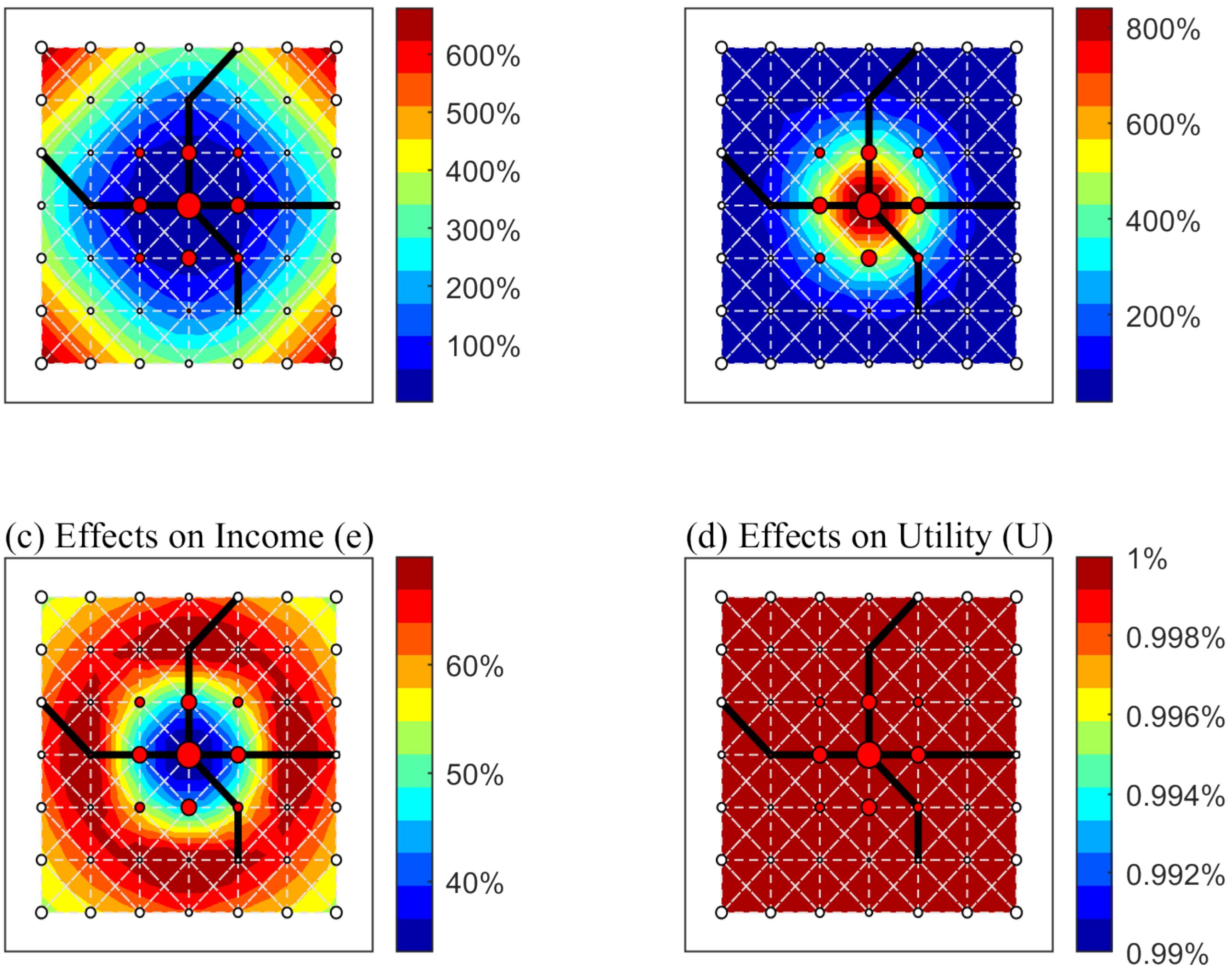


Figure D.5: Effects on Spatial Equilibrium: Global Corrective Taxes II ($\lambda_{jk} = 1$)



(a) Effects on Ind. Firm Profits (π_1)

(b) Effects on Agr. Firm Profits (π_2)

(c) Effects on Income (e)

(d) Effects on Utility (U)

Figure D.6: Effects on Trade Flows, Taxes and Transport Costs Highway Only Corrective Taxes ($\lambda_{jk}^{H} = 1$)

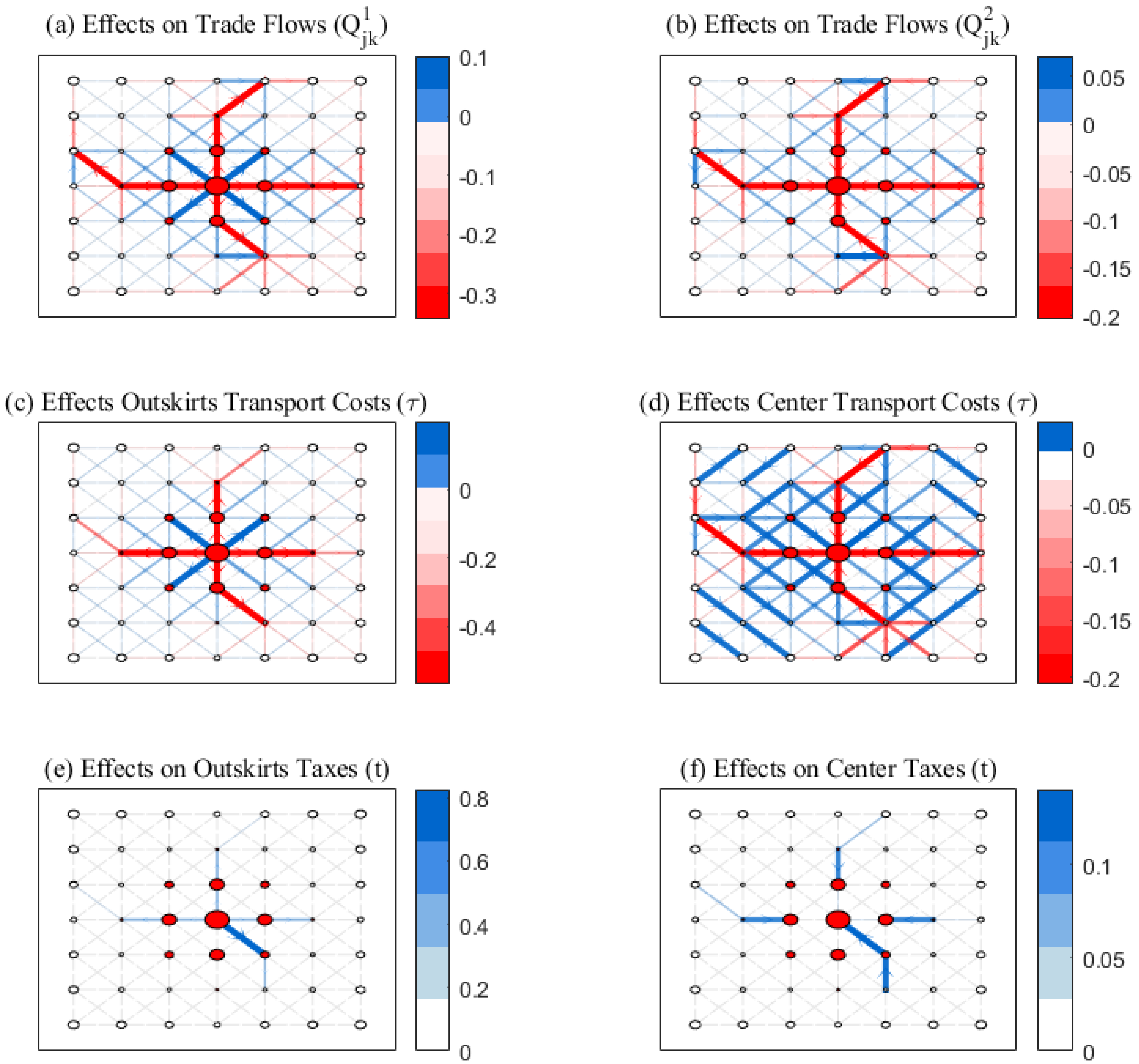
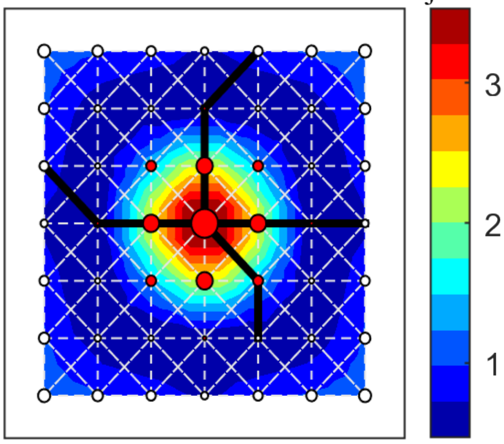
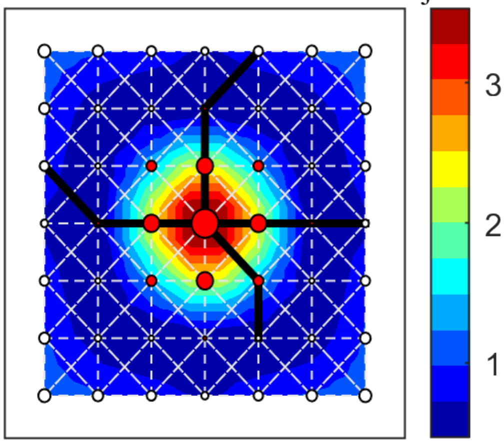


Figure D.7: Labor Distribution

(a) Labor Active Externalities (λ_{jk}=0)



(b) Labor Full Internalization (λ_{jk}=1)



(c) Labor Partial Internalization (λ^{H}_{jk}=1)

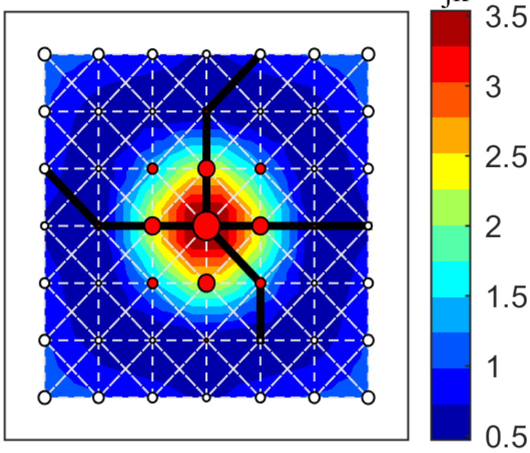


Figure D.8: Spatial Distribution: Kernel Approximation

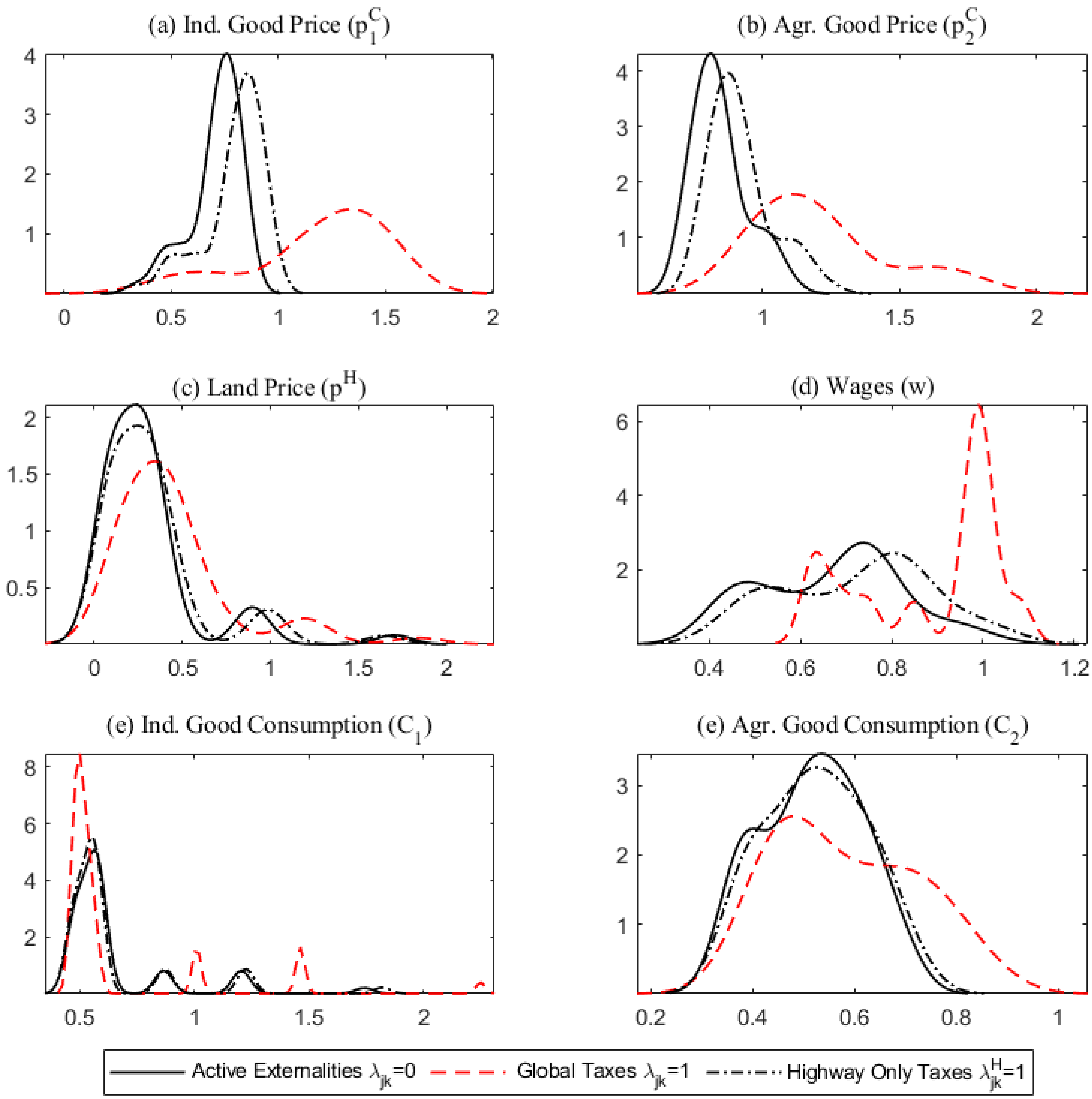
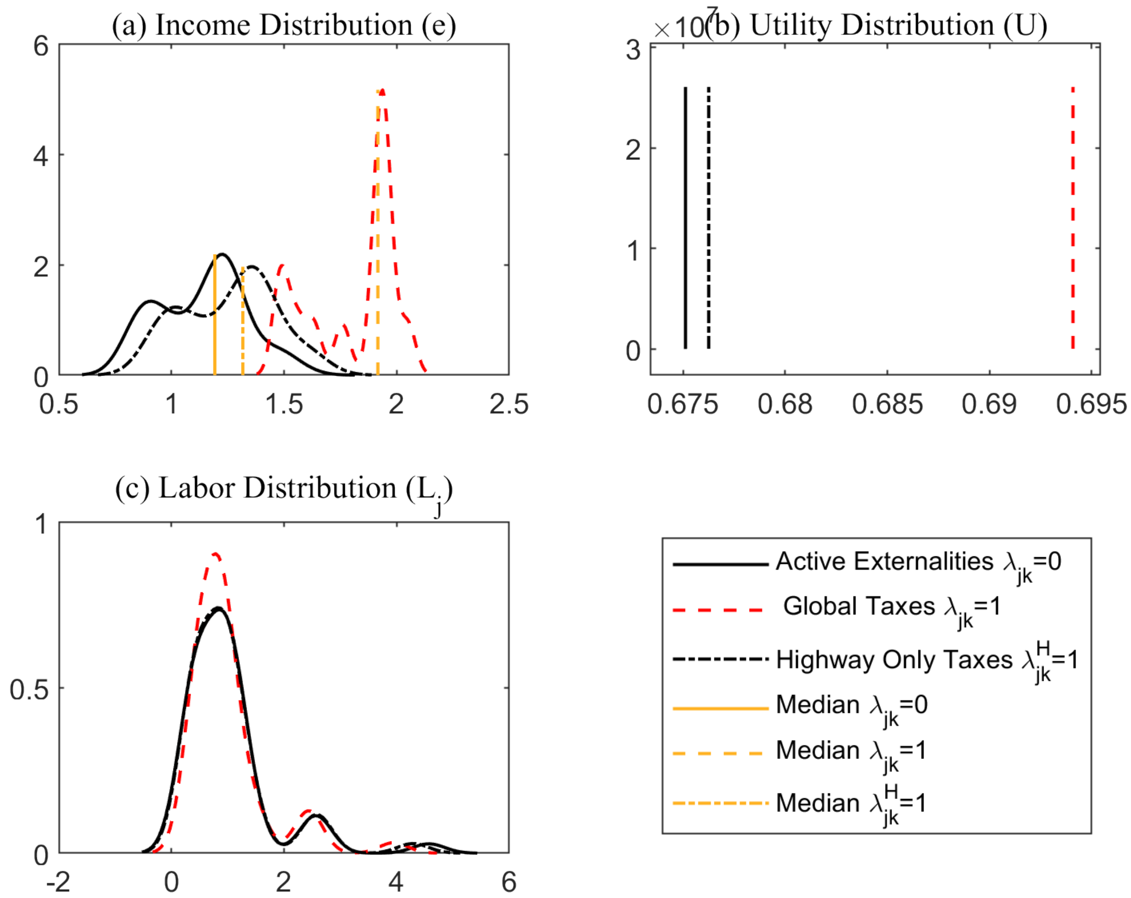


Figure D.9: Income, Utility and Labor Distributions: Kernel Approximation



E Appendix to Welfare Economics

As discussed, this thesis addresses the "Welfare Economics" dilemma studied extensively, arriving at different theories about how to face the relativity of social welfare in an economy. Pigou (1920) addresses the "social welfare function" by emphasizing the relationship between economic welfare and social welfare by aggregating the welfare of individuals, and this aggregation indirectly introduces weights to individuals in the economy. From the above, Hicks (1939) affirms that there is no reason why a specific weighting combination should be the one chosen, as there is no universal acceptance. Moreover, Pigou does not consider the variations in terms of marginal utility of income between the richest and the poorest individuals. The latter is key to our analysis as we seek to make individuals comparable considering their differences in terms of wealth.

The imposition of corrective taxes distort the distribution of wealth as we showed in this study. In this matter, Hicks (1939) points out three ways of dealing with this dilemma in which two are rejected as unsatisfactory. In the first proposal the investigator decides what is best for the economy based on his biased beliefs. Hicks claims that this is "the way of the prophet and the social reformer" and not the way of economists, as the welfare function will be determined by an individual's beliefs. The second approach is Pigou's traditional method of aggregating the welfare of individuals that we discussed earlier, together with its limitations on determining the relative weights between individuals. The third and not rejected method is that described by Kaldor (1939) wherein the decision is made by internalizing that these policies lead to shifts in the distribution of income and welfare of individuals, identifying "winners and losers" as some will benefit from internalizing the externalities of congestion and others will not. Kaldor claims that when the sum of individuals' dispositions to pay for the policy is positive, the winners could compensate the losers by using lump-sum transfers. In our case, this affirmation claims that the individuals from the "winner city" could compensate those from the "loser city" with individual transfers. Another complementary method would be to redistribute a higher percentage of the Pigouvian tax revenues to the losers. On the contrary, however, Hicks (1940) affirms that if the sum of individuals dispositions to pay is negative, then there could be a combination of lump-sum transfers that Pareto dominates the assignation given by the policy, that is to say, that we could improve the economic welfare through other policies rather than internalizing the externality.

Along the same line, Hendren (2019) addresses the problem of measuring economic efficiency and desirability of economic policies by developing an efficient weighting method in the spirit of Kaldor (1939) and Hicks (1940) that internalize the heterogeneous distortionary costs of income taxation using as base the model developed in Saez & Stantcheva (2016) concluding that it would be efficient to give a greater relative weight of the surplus to the poor relative to the rich. Hendren argues that by establishing a social welfare function that resolves the "equity-efficiency trade-off," one abandons the possibility of providing normative guidance since the function would be biased by the researcher's preferences, as discussed earlier.

Similarly, Negishi (1972) develops a social welfare function that is an aggregate of individual utilities under specific weights. Negishi argues that when this social welfare function is maximized, it also maximizes individual utility if and only if the specific weights are the inverse of the marginal utility of income of individuals. In this sense, if we assume diminishing returns of consumption to utility, the Negishi method would give more relative weight to the rich, and give less importance to equality in the distribution of wealth in the economy.

Finally, Stark, Jakubek & Falniowski (2014) address the optimal tax-transfers policies tension between a Rawlsian social planner who measures the welfare of a society based on the individual with the least utility (Rawls, 1999) and a utilitarian social planner who measures utility by the aggregate of individual utilities, showing that under certain conditions a utilitarian could coincide with the Rawlsian in choosing an income distribution in the economy.

E.1 Welfare Economics: The Planner's Moral

In the study above, we did not discuss any system of redistribution and weighting decisions of the planner. This section focuses on analyzing an optimal taxes policy system choosing the optimal taxes levels for each link and taxes redistributions weightings given a social welfare function.

E.1.1 Social Welfare Function

In order to evaluate the impact of the congestion externalities on the welfare of the economy, we must compute a social welfare function that is capable of solving the "interpersonal comparison" problem internalizing the differences between the consumers. As we discussed in previous sections, this is not trivial, as we can end up with a biased function based on the "researcher's moral" (the way of the prophet). Since consumers own the firms, and the transport sector is a free-entry market ($\pi^{T.C.} = 0$), the social welfare function will only consider the consumer's utilities taking the form:

$$W^G = \sum_j \psi_j^G \, U_j$$

Implying that:

$$\sum_j \psi_j^G = 1$$

We specify an indirect method for determining the individual weights of the social function of the economy. This method will be addressed in section E.1.3.

E.1.2 The Planner's Decision

In this section, we characterize the planner's decision of deciding the degree of the corrective taxes λ_{jk} and the redistribution of taxes weights $\{weight_j^t\}^j$ subject to his "morality" in terms of preferences for income equality among consumers. These last preferences will be represented by a maximum tolerable Gini (σ_G^{max}) for the economy that would restrict the policy decision of the planner. We assume that the weights assigned to every individual in the welfare function $\{weight_j^G\}^j$ are exogenous as they reflect the planner's moral. This problem will take the form:

$$\max_{\{\{\lambda_{jk}\}^{jk},\{\psi_j^t\}^j\}} W^G = \sum_j \psi_j^G \; U_j(\lambda_{jk}, \psi_j^t) + \theta_1(\sigma_G^{max} - \sigma_G^I) + \theta_2(1 - \sum_j \psi_j^t).$$

We define the Gini coefficient from the Relative Mean Absolute Difference definition:

$$\sigma_G^I = \frac{\sum\limits_{j,k} |e_j - e_k|}{2n^2\bar{e}},$$

taking n as the number of consumers in the economy, and $\bar{e}$ as the average income. From this problem, we derive the following FOC's:

$$[\lambda_{jk}] : \sum_j \psi_j^G \frac{\partial U_j}{\partial \lambda_{jk}} - \theta_1 \sum_j \frac{\partial \sigma_G^I}{\partial \lambda} = 0,$$

$$[\psi_j^t] : \psi_j^G \frac{\partial U_j}{\partial \psi_j^t} - \theta_1 \frac{\partial \sigma_G^I}{\partial \psi_j^t} - \theta_2 = 0.$$

Solving this FOC's and assuming that there are only two consumers ubicated in $j = \{1, 2\}$ in the economy located in two different locations, we derive the following optimality condition:

$$\psi_1^G \frac{\partial U_1}{\partial \lambda_{jk}} + \psi_2^G \frac{\partial U_2}{\partial \lambda_{jk}} - \left[\frac{\psi_2^G \frac{\partial U_2}{\partial \psi_2^t} - \psi_1^G \frac{\partial U_1}{\partial \psi_1^t}}{\frac{\partial \sigma_G^I}{\partial \psi_2^t} - \frac{\partial \sigma_G^I}{\partial \psi_1^t}} \right] \left[2 \frac{\partial \sigma_G^I}{\partial \lambda_{jk}} \right] = 0 \quad \forall j, k.$$

From this equation, we can determine that for the optimal assignation of corrective taxes and redistribution of weights, the planner considers (i) the marginal impact of taxes on the utility of individuals and their marginal impact on the income inequality proxy of the economy (Gini coefficient). Also, the planner's decision considers (ii) the marginal effects of redistribution taxes weights on the utilities of the individuals and on the Gini coefficient. Given, this we can argue that this planner considers the differences of the individuals in terms of marginal utilities from taxes and weighting, internalizing the trade-off between market efficiency and equality.

For example, let's set up a winners and losers game (two consumers in different locations), assuming that the individual with the higher income is the winner, meaning that the poorer individual is the loser, so the imposition of taxes will be a regressive policy. In this case, the planner will consider that the marginal utility of income of the high-income individual will be lower than that of the poorer one as a result of diminishing returns of consumption. Given this, the planner will have incentives to give more weight to the poorest individual in redistributing taxes for two reasons: (i) the marginal welfare returns of giving a poorer individual one additional monetary unit of taxes redistribution will be higher than giving the same amount to the richer individual, and (ii) redistributing more taxes to the rich would increase income inequality in terms of the Gini coefficient, so the planner will have motives to target the taxes redistribution to the individual with the lowest income. Therefore, the decision will result from a cost-benefit analysis, wherein the planner equalizes the weighted marginal benefit of the winner in terms of economic efficiency with the weighted marginal costs of the policy in terms of inequality, regarding the regressive impact that the taxes have on the poorer individual.

E.1.3 Analysis Assumption

We now assume that the planner decided to fully internalize the externality in every link ($\lambda_{jk} = 1\ \forall j, k$) from a cost-benefit analysis. This assumption enables us to identify the "moral" of the planner in terms of the social welfare function by obtaining the utility weights that the planner gives to each individual (ψ_j^G). Also, we assume that all redistribution of taxes will be equally distributed and that the planner is not restricted by the inequality constraint discussed earlier (maximum tolerated Gini).

Given this, we can derive the following from the problem described in the previous section:

$$[\lambda_{jk}] : \sum_j \psi_j^G \frac{\partial U_j}{\partial \lambda_{jk}} = 0,$$

$$[\psi_j^t] : \psi_j^G \frac{\partial U_j}{\partial \psi_j^t} = 0.$$

As the planner is fully internalizing the externality in every link, we take λ as the level of internalization for each link in the network ($\lambda_{jk} = \lambda$), leaving the following for the first optimality condition:

$$\sum_j \psi_j^G \frac{\partial U_j}{\partial \lambda} = 0.$$

Now, because we can identify every level of utility from each of the individuals given our assumptions on tax redistribution weights and level of taxes (Pigouvian taxes, full internalization of the externality), this last equation, along with the other FOC's enables us to obtain the social function weights of each individual. This equation is interesting as it represents the sum of the weighted marginal benefits (WMB) and weighted marginal costs (WMC) of internalizing externalities for each individual, so the optimum would be where the weighted marginal benefits of the corrective policy are equal to weighted the marginal costs (WMB=WMC). Given our assumptions, this optimum would be where there is a full internalization of the externalities and where the redistribution of taxes is equally redistributed among the consumers. Figure E.1 provides a graphic representation of this discussion. As we see, social welfare is maximized where $\lambda = 1$, which implies the full internalization of the externalities via Pigouvian taxes to the transport sector. W_{nt}^G

represents the inefficient equilibrium ($\lambda = 0$, no corrective taxes). Thus, the impact of congestion externalities on social welfare in this scenario is: $-(W^{G*} - W^G_{nt})$.

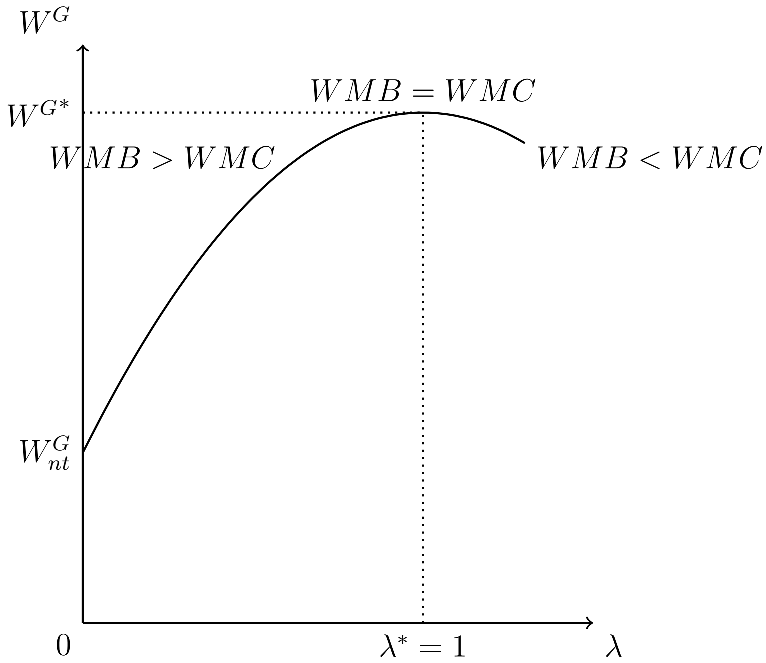


Figure E.1: Social Welfare and Pigouvian Taxes Cost-Benefits