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Agglomeration and directional imbalance of freight rates: The role of density economies in the transport sector

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February 2015

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Keywords: agglomeration, asymmetric transport costs, directional imbalance of freight rates, density economies

JEL classification: L91, R12, R41,

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This paper examines the conventional assumption that bilateral transport costs are symmetric. We develop an economic geography model with transport sector in which asymmetric freight rates can occur as a result of density economies. Comparing this to models without density economies, we show that agglomeration of economic activities is more likely to emerge and that multiple equilibria can emerge for some parameters. Then we show the change in its bifurcation and stability of equilibrium and conclude that economies of density in transport flows can act as an agglomeration force.

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1 Introduction

Recent decades have witnessed the emergence of a growing literature that analyzes the relationship between transport costs and the spatial structure of economic activities (Fujita, Krugman and Venables (1999)). The remarkable progress in this field was made possible in part by adopting the simple assumption that transport costs are symmetric. The purpose of this paper is to relax this assumption of *symmetric transport costs*. Hereafter, we call freight rates as the price for transport services and transport costs as its costs. We call the typical assumption of symmetric transport costs as symmetric freight rates to distinguish the difference between them.[1] Freight rates are often asymmetric, even along the same route. Some simple results of the Survey of Net National Freight Circulation of Japan (SNNFCJ) in truck transportation indicates that the degree of asymmetry in freight rates (resp., transport flow) is 1.45 (resp. 1.85) at the 50th percentile and 3.98 (resp. 11.6) at the 95the percentile.[2] Such directional imbalance in freight rates simultaneously result from and in the cause of agglomeration.

In the studies on truck transport, *economies of density* are one of the characteristics of this sector. With microdata of SNNFCJ, Konishi, Mun, Nishiyama and Sung (2012) focused on shipment delivery by chartered trucks, which a transport firm used a single truck to transport only for a single customer. By analyzing such a data, they found that significant scale economies were present at the individual-shipment level. At the firm level, Keeler (1989) found evidence of increasing returns from survival analysis during the period that followed deregulation in the United States. Allen and Liu (1995) confirmed scale economies in truck transport sector by controlling the service quality such as transit time, delivery reliability, and shipper convenience. At the route level, Tanaka and Tsubota (2014) used SNNFCJ data to show the occurrence of asymmetry in freight rates as a result of the presence of density economies and found that unit freight rates appeared to be lower for the direction of a route with the greater flow of truck shipments. All of these studies indicate the presence of density economies in the transport sector.[3] In this paper, we elucidate the role that density economies plays in

[1] Throughout this paper, we assume that transport costs are identical for both direction. However, our analysis shows that freight rates can be asymmetric.

[2] SNNFCJ is a commodity flow survey conducted once five years. For details empirical study, see Tanaka and Tsubota (2014).

[3] Apart from truck transport, Jonkeren, Demirel, van Ommeren and Rietveld (2011) investigated the effect of directional imbalance of shipment flows on one-way marine freight rates. In their study, the imbalance of transport flows was identified as a backhaul problem for a maritime transport firm, implying that for a given pair of points, a larger quantity of shipments in one direction led to higher freight rates for this direction. Their analysis of inland marine shipments in Northern Europe showed that imbalance of transport flows increased the unit shipping prices. Additionally, Clark, Dollar and

accounting for a directional imbalance of freight rates within a competitive market for transport services.[4] The simplest assumption on freight rates is that freight rates are symmetric and independent of transport flow. This assumption can be interpreted as modeling the case in which the technology of the transport sector has constant returns to scale and thus cost depends on only the distance. With a few exceptions, this assumption is typically adopted in the construction of the models in New Economic Geography and international trade. Instead of assuming symmetry or constant returns to scale, we assume that transportation technology is characterized by density economies and that freight rates are lower price for larger volume. In this case, density economies tends to reduce freight rates in the direction associated with greater transport flows. In addition, the higher demand for transport services encourages the entry of transport firms into the region of greater outflow to meet the transport demand. As a result, this competitive effect will further lower freight rates in the direction with greater transport flows. Meanwhile, because chartered trucks are being used, transport firms in region A will have an incentive to charge lower prices than those in region B, which has smaller transport flows. Such behavior of transport firms affects the location choice of (for example manufacturing) firms which can choose either of the two regions. The relocation of some manufacturing firms from B to A would affect interregional demand in the following two ways. First, this relocation directly reverses the direction of the shipment of the goods. Second, migration of skilled workers is associated with the relocation of firms, which results in a change in the relative market size since these workers are consumers of the goods produced in the other region. The first effect increases interregional demand from A to B, the second effect decreases it. These two forces affect interregional demand and make the manufactured goods market and transport market dependent on one another. Because of this interlinkage among two sectors in two regions, technological improvement in the transport sector is expected to affect all of the markets. Our analysis shows that endogenous determination of freight rates yields important implications for the spatial location of economic activities.

Micco (2004) and Blonigen and Wilson (2008) provided similar evidence of the impact of a trade imbalance on freight rates in international trade involving marine shipping.

[4] Note that in the transport literature, as scale economies capture increasing returns with proportional increase of serving points, density economies capture increasing returns with given serving points. For example, see the definition in Caves, Christensen and Tretheway (1984). In the two-region model without space in each region, we cannot model scale economies in transport sector including serving points. In this paper, we employ density economies as a notion to capture the decline in price as demand increases for a route in one direction. However, we partly capture scale economies in regard to the presence of fixed inputs except serving points. Possible extensions including scale economies in transport sector are discussed in the last section.

Intuitively, the concentration of production in a core region implies large transport flows from the core to the peripheral region. When transport flows from the core to the periphery increase, freight rates decline further in this direction because of the operation of economies of density in transport flows, leading to a relative increase in the transport cost for the opposite direction. Consequently, endogenous determination of freight rates magnifies the directional imbalance of transport flows. A directional imbalance of freight rates can thus act as an additional agglomeration force. To examine the impact of density economies on the location of economic activities, we constructed an economic geography model and examine how it shapes the distribution of firms. Specifically, we embedded endogenous determination of freight rates in the model of Ottaviano, Tabuchi and Thisse (2002). The resulting model showed that there were mutual interactions between density economies and the spatial distribution of economic activities. A comparison of our model with a model in which density economies were absent in transport sector showed that agglomeration of economic activities is more likely to emerge under any range of cost parameters. Thus, our results suggest that endogenous freight rates magnify agglomeration forces but not dispersing forces.

The rest of the paper is organized as follows. In Section 2, we develop an economic geography model to analyze spatial agglomeration and introduce the transport sector. In Section 3, we demonstrate location equilibria and analyze the impacts of technical improvements in the transport sector. Section 4 offers policy implications stemming from a comparison with previous results described in the literature, and some concluding comments.

2 Theoretical Analysis

Before going into the details of our analysis, we first contrast our model with those described in previous studies. Our theoretical analysis is closely related to that in some of these studies, but it differs in the specifics of the transport sector. Mori and Nishikimi (2002) introduced density economies into a three-region model and showed the emergence of a hub as an agglomeration of economic activities. However, there were no directional imbalance in the transport flow and costs in that model. Behrens, Gaigne and Thisse (2009) examined the presence of density economies in an economic geography model in which total transport flows in both directions determined freight rates. However, because of this specification, endogenous directional imbalance of freight rates cannot arise. In contrast, on the basis of observation of the backhaul problem in maritime transport, Behrens and Picard (2011) and Takahashi (2011) considered directional imbalance of both the transport flow and freight rates. They assumed that freight rates depend on the directional imbalance of transport flow and that, for a given route, freight rates are higher in the direction for which volumes were larger. They find that shrinkage of core–periphery patterns occur due to the weakened agglomeration force. In contrast to the assumptions of Behrens and Picard (2011) and Takahashi (2011), we incorporate the role of density economies and directional imbalance of transport flow and freight rates.

Our model is built upon the one in Ottaviano et al. (2002). Their model can be regarded as a model, for comparison, without density economies nor directional imbalance. We introduce density economies in the form employed by Behrens et al. (2009) where density economies exist at route level. To provide a simple model with transport sector, we focus exclusively on chartered transport.[5] Relaxing the assumption of symmetric freight rates within a simple two-region model and allowing for the presence of density economies in transport routes, we offer an explanation for the directional imbalance of freight rates and examine stable location equilibria.

2.1 The model

The economy in this study is composed of two regions, labeled r and s. There are two production factors: H, the units of skilled workers, and L, the units of unskilled workers. Whereas unskilled workers are viewed as immobile and are equally dispersed between the two regions, skilled workers can move freely between the two regions and their distribution is expressed as $\lambda_r + \lambda_s = 1 = H$. We include three sectors in the model: the traditional sector produces a homogeneous good (q_0) under a technology with constant returns to scale; the manufacturing sector produces a continuum of differentiated goods, indexed by $v \in [0, 1]$; and the transport sector produces cross-regional shipment services. We assume preferences are identical among all workers and are described by

$$U_r = q_0 + \alpha \int_0^1 q_r(v)\, dv - \frac{\beta - \gamma}{2} \int_0^1 (q_r(v))^2\, dv - \frac{\gamma}{2} \left(\int_0^1 q_r(v)\, dv \right)^2, \qquad (1)$$

[5]Tanaka and Tsubota (2014) showed an empirical specification to identify net effects between backhaul problem and density economies and found the dominance of density economies in Japanese truck transport. Our assumption is consistent with their findings.

where $\alpha > 0$ and $\beta > \gamma > 0$ are parameters, and $q_r(v)$ is the consumption of good i in region r. [6] Consumers maximize a utility function subject to a budget constraint, given as $\int_0^1 p_r(v)\, q_r(v)\, dv + q_0 = w_r + \overline{q_0}$, where w_r is the wage rate in region r. The demand for a good v is expressed as

$$q_{sr}(v) = a - (b + c)\, p_{sr}(v) + cP_r, \tag{2}$$

where $a = \alpha\beta^{-1}$, $b = \beta^{-1}$, $c = \gamma(\beta - \gamma)^{-1}\beta^{-1}$ and P_r indicates the price index of region r. For the sake of simplicity, we assume manufacturing firms are symmetric and drop the index of good. The price index can then be written as $P_r = \int_0^1 p_r(v)\, di = n_r p_{rr} + n_s p_{sr}$, where all the subscripts expressed by the two characters, r and s, indicate origin and destination regions, and n_r and n_s are the number of manufacturing firms in regions r and s, respectively.

The production of one unit of a homogeneous good is assumed to require one unit of unskilled labor, and the shipment of this homogeneous good is assumed to be costless. Thus, the wages of unskilled workers are equal between regions and set as the numéraire ($p_r^0 = p_s^0 = w_r = w_s = 1$). In contrast to homogeneous goods, cross-regional shipments of manufacturing goods incur freight rates. The freight rates from region r to region s are expressed by t_{rs}, which is set by the transport sector. Production of differentiated manufactured goods requires unskilled workers as a variable input and skilled workers as a fixed input. As in Ottaviano et al. (2002) and without loss of generality, we set the marginal requirement of unskilled workers equal to zero. The profit function of a manufacturing firm in region r is then expressed as

$$\pi_r = p_{rr} q_{rr} + (p_{rs} - t_{rs})\, q_{rs} - W_r, \tag{3}$$

where W_r represents the nominal wage for skilled workers. We assume that each region is segmented and that firms set their price in a spatially discriminated manner. Accordingly, firms in region r maximize their profit with respect to the sum of p_{rr} and p_{rs}. As shown in Ottaviano et al. (2002),we obtain the equilibrium prices as follows:

$$p_{rr} = \frac{2a + cn_s t_{sr}}{2(2b + c)},\ p_{rs} = p_{rr} + \frac{t_{rs}}{2},\ \text{for } r \neq s, \tag{4}$$

$$q_{rr} = (b + c)\, p_{rr},\ q_{rs} = (b + c)(p_{rs} - t_{rs}),\ \text{for } r \neq s. \tag{5}$$

[6] For a given value of β, γ expresses the substitutability between goods, and so long as $\beta > \gamma$, the utility function exhibits love of variety.

It is evident from the cross-regional demand for manufactured goods that when freight rates are high, the demand becomes zero. When freight rates are too high to have positive demand, the condition can be written as,

$$\overline{t_{rs}} < \frac{2a}{2b + c - cn_r}, \text{ for } r \neq s, \tag{6}$$

which is obtained from the cross-regional demand in (5). This trade feasibility condition is directional. As we discuss in the following sections, and in contrast to the previous literature and original model of Ottaviano et al. (2002), for some of our cases, only unidirectional trade occurs. In such cases, freight rates for one direction exceed the trade feasibility condition and the demand is consequently zero. When freight rates for both directions are above the trade feasibility condition, there is no trade at all between regions, autonomy. To ensure positive trade at least in the case of symmetric distribution, we obtain trade feasibility conditions as

$$\overline{t_{rs}}\Big|_{n_r=\lambda=1/2} < \frac{4a}{4b + c}. \tag{7}$$

At equilibrium, all operating profits of manufacturing firms are assumed to be zero. Applying the zero-profit condition to manufacturing firms, we obtain the wages of skilled workers as follows:

$$W_r = (b + c)\left(\left(\frac{L}{2} + \lambda_r\right) p_{rr}^2 + \left(\frac{L}{2} + \lambda_s\right)\left(p_{ss} - \frac{t_{rs}}{2}\right)^2\right). \tag{8}$$

With the equilibrium prices, the consumer surplus, S_r, in the equilibrium can be written as

$$S_r = \frac{a^2}{2b} - a\left(n_r p_{rr} + n_s p_{sr}\right) - \frac{c}{2}\left(n_r p_{rr} + n_s p_{sr}\right)^2 + \frac{b + c}{2}\left(n_r p_{rr}^2 + n_s p_{sr}^2\right). \tag{9}$$

For the above equations, symmetric expressions hold for region s.

2.2 Transport sector

In this section, we model a transport sector based on the empirical observations on the density economies. We assume that the technology of the transport sector exhibits economies of density and is characterized by the presence of fixed costs. The production of transport services needs unskilled workers as both variable and fixed inputs. In order to keep the model simple, we also assume that transport market is spatially segmented and firms operate only for one direction and determine the freight rates for one direction of a specific route depending on its transport flow a là Cournout. Since there is no restriction on worker mobility between the traditional and transport sectors, the wages of unskilled workers are identical between sectors and equal to one. Then the profit function of a transport firm i is written as

$$\pi_{rs}^{T}\left(d_i^{rs}, \mathbf{d}_{-i}^{rs}\right) = \left(t_{rs}\left(D_{rs}\right) - \tau\right) d_i^{rs} - f, \tag{10}$$

where d_i^{rs} is the quantity of transport services from region r to s, $\mathbf{d}_{-i}^{rs}$ is the quantity of transport service from r to s supplied by the other firms, $t_{rs}\left(D_{rs}\right)$ is an inverse demand for transport services, τ is the marginal requirement of unskilled workers, and f is the fixed requirement.[7]

From (5), the aggregate demand for transport services can be expressed by the transport flow of cross-regional manufactured goods as

$$D_{rs} = n_r\left(\frac{L}{2} + \lambda_s\right) q_{rs} = n_r\left(b + c\right)\left(p_{rs} - t_{rs}\right)\left(\frac{L}{2} + \lambda_s\right), \text{ for } r \neq s. \tag{11}$$

Using the above equation, we obtain an inverse demand for transport services as follows,

$$t_{rs}\left(D_{rs}\right) = \frac{2a}{2b + c - cn_r} - \frac{2\left(2b + c\right)}{\left(2b + c - cn_r\right) n_r\left(L/2 + \lambda_s\right)} D_{rs}. \tag{12}$$

For the market-clearing condition, we have $D_{rs} = \sum_{i=1}^{m_{rs}} d_i^{rs}$, where m_{rs} is the number of transport firms serving a transport route from r to s. Since the inverse demand in (12) is a linear function, there is a Nash equilibrium in the space of pure strategies. The equilibrium freight rate is given by a unique and symmetric solution as

$$t_{rs}\left(n_r, m_{rs}\left(n_r, \lambda_s\right)\right) = \frac{2a}{\left(2b + c - cn_r\right)\left(1 + m_{rs}\right)} - \frac{\tau}{1 + m_{rs}} + \tau. \tag{13}$$

Applying the free entry condition in the transport sector on (10) with (13), we obtain the equilibrium number of transport companies as follows:

$$m_{rs}\left(n_s, \lambda_s\right) = \left(\frac{2a}{2b + c - cn_r} - \tau\right)\left(\frac{2\left(2b + c\right) f}{\left(2b + c - cn_r\right) n_r\left(L/2 + \lambda_s\right)}\right)^{-\frac{1}{2}} - 1. \tag{14}$$

As is clear from the above equation, the comparative statics show $\frac{dm_{rs}}{df} < 0$ and $\frac{dm_{rs}}{d\tau} < 0$. An increase in fixed and marginal costs leads to a reduction in the number of transport companies. Note that the population of region r i expressed in the denominator of the

[7] This fixed requirement is assumed to be non-negative.

second term as $(L/2+\lambda_r)$. The effect of population size in the destination region is $\frac{dm_{rs}}{d(L/2+\lambda_r)} > 0$. Similarly, we also have the effect of manufacturing firms in the origin region as $\frac{dm_{rs}}{dn_r} > 0$.

Substituting the equation (14) into (13) , we can rewrite the unit freight rate function as

$$t_{rs}(n_r, \lambda_s) = \left(\frac{2(2b+c) f}{(2b+c(1-n_r)) n_r (L/2+\lambda_s)} \right)^{\frac{1}{2}} + \tau. \tag{15}$$

Increases in marginal and fixed costs naturally increase freight rate as we have $\frac{dt_{rs}}{d\tau} > 0$ and $\frac{dt_{rs}}{df} > 0$. This shows unambiguous correspondence between freight rates and transport costs. Additional observations of the unit freight rate function shows the following properties: $\frac{dt_{rs}}{dn_r} < 0$, and $\frac{dt_{rs}}{d(L/2+\lambda_s)} < 0$. This means that transport volume and price are a function of the number of shippers (i.e., manufacturing companies), and the size of the consumer population. To observe positive demand for transport services, there must be a company producing a commodity in one region and shipping it to customers in another region. The derivative shows that unit freight rate decreases when there is an increase in either manufacturing firms in the origin region or skilled workers in the destination region. The reason for this is that these two effects increase cross-regional demand, and this greater demand decreases unit freight rate through density economies. Since one unit of skilled workers is employed by a manufacturing firm, there is a one-to-one correspondence between the share of firms, n, and that of skilled workers, λ. Substituting $n_r = \lambda_r = \lambda$ and $\lambda_s = 1 - \lambda$, we can rewrite the unit freight rate function as,

$$t_{rs}(\lambda) = \left(\frac{2(2b+c) f}{(2b+c(1-\lambda)) \lambda (L/2+(1-\lambda))} \right)^{\frac{1}{2}} + \tau. \tag{16}$$

The above equation indicates that distribution of skilled workers and the relative population size of unskilled workers determine the shape of the function. This is because the distribution of skilled workers corresponds to the location of supply of the differentiated goods, while the distribution of both workers determines the demand for the goods. Note that when fixed costs of the transport sector, f, are zero, freight rates depend on constant marginal costs only. Examining the properties of this function, as detailed in Appendix II, we present the following proposition.

Proposition 1 *Unit freight rate function has the following characteristics associated with the relative population size of unskilled workers and the degree of spatial concentration of skilled workers.*

(i) When $f = 0$, it is constant.

(ii) When $f > 0$ and $L < 4b/(2b-c)$, it has its minimum in $\lambda \in [0,1]$.

(iii) When $f > 0$ and $L \geqq 4b/(2b-c)$, it is monotonically decreasing in λ.

This proposition states that fixed requirements in the transport sector are essential to exhibit density economies and that the population size of unskilled workers determines the shape of the function. Since the distribution of both skilled and unskilled workers affects the demand for inter-regional transport, the relative sizes of the populations also matters for the determination of freight rates. In Figure 1, we plot freight rates from the origin r to the destination s for four cases of the population of unskilled workers L.[8] Note that $\overline{t_{rs}}$ is the maximum freight rates to have the cross-regional demand non-negative. From the top, L is 1, 3, 5, and 10, respectively.

=Figure 1 comes around here.=

There are two forces at work, namely, the relocation of producers and consumers. Suppose that some firms relocate from region B to region A. The change of production location must reverse the direction of intra-regional transport flow. This change increases intra-regional transport flow from A to B, while decreasing the flow from B to A. On the other hand, since skilled workers employed at the relocating firms were also consumers in region B, their relocation shift intra-regional demand from A to B. Thus, in the event of some firms relocating from B to A, the sum of these two effects may decrease or increase intra-regional demand from A to B. If the population size of unskilled workers is relatively smaller, the relocation effect of producers is smaller since there are fewer unskilled consumers in the other region, while the relocation effect of consumers becomes larger since the relative consumption expenditure of skilled is larger. Consequently, the relocation effect of producers may be smaller than that of consumers. This means that the intra-regional demand for some varieties that change production location is smaller than the amount consumed by the skilled workers who changed their residence. In other words, the relative population size of skilled and unskilled workers matters because it affects the determination of the dominant force in either of the abovementioned cases. When the population size of unskilled workers is relatively smaller (specifically, when $L < 4b/(2b-c)$), the freight rates function becomes U-shaped. In such cases, the relocation of skilled workers does not always

[8]The parameters are as follows: $b = 1$, $c = 1$, $f = 0.1$,and $\tau = 0$. As is obvious from (16), increasing the marginal costs, τ, simply pushes the function upward. Under the above parameters, the critical value in determining the shape of transport costs function is 4.

decrease freight rates. Such examples, when $L = 1$ or 3, are shown in Figure 1. When the population of unskilled workers holds the condition, $L \geqq 4b/(2b - c)$, the freight rates function is monotonically decreasing.

Unit freight rate function reflects the spatial distribution of economic activities when transport technology is characterized by density economies. This is consistent with the findings of Keeler (1989) and others discussed in the previous section. In the following sections, we further examine interdependencies with manufacturing sector and associated location equilibria.

3 Location equilibria

The preceding section keeps the distribution of skilled workers as exogenous. In this section, we extend our analysis to the long run equilibrium of industrial locations determined by mobile skilled workers. The analysis follows Ottaviano et al. (2002). Without a loss of generality, we drop the subscript of the share of skilled workers by specifying $\lambda_r = \lambda$ and $\lambda_s = 1 - \lambda$. Moreover, for the sake of convenience, we set region r as the *core* region when it emerges. The law of motion of skilled workers is defined by the welfare comparison of workers and is expressed by

$$\Delta V_r (\lambda, m_{rs}, m_{sr}) \equiv V_r (\lambda, m_{rs}, m_{sr}) - V_s (\lambda, m_{rs}, m_{sr}), \tag{17}$$

where $V_r = S_r + W_r + \overline{q_0}$. We define a spatial equilibrium as a distribution of skilled workers that satisfies one of the following three conditions: i) $\lambda^* \in (0, 1)$ when $\Delta V_r (\lambda^*) = 0$, ii) $\lambda^* = 1$ when $\Delta V_r (1) > 0$, or iii) $\lambda^* = 0$ when $\Delta V_r (0) < 0$. An interior equilibrium is stable if and only if any marginal migration of skilled workers recover original distribution by inverse migration. For example, marginal migration decreases the utility at the destination region and induces reverse migration to the original region. This stability condition can be expressed as $d\Delta V (\lambda^*) / d\lambda < 0$ at $\lambda = \lambda^*$.

3.1 Symmetric equilibrium

Inclusion of the directional imbalance of freight rates within the model makes the expression of indirect utility differential more complicated than that of the models with symmetric freight rates (cf. Ottaviano et al. (2002)). However, as shown in Appendix III, we have simpler expressions for the effects of directional freight rates around symmetric distribution:

$$
\begin{aligned}
d\Delta V|_{\lambda=1/2} &= d\Delta W|_{\lambda=1/2} + d\Delta S|_{\lambda=1/2} && (18)\\
&= \rho_1 t^* \left(\rho_2 - t^*\right) && (19)\\
\text{where } t^* &\equiv t_{sr}|_{\lambda=1/2} = t_{rs}|_{\lambda=1/2} = \tau + 4\sqrt{\frac{(2b+c)\, f}{(L+1)\,(4b+c)}}, && (20)\\
\rho_1 &\equiv \frac{(b+c)\left(\left(6bc+6b^2+c^2\right)+c\,(2b+c)\,L\right)}{2\,(2b+c)^2},\\
\rho_2 &\equiv \frac{4a\,(3b+2c)}{\left(\left(6bc+6b^2+c^2\right)+c\,(2b+c)\,L\right)}.
\end{aligned}
$$

We found that there is a critical value of stable symmetric equilibrium that satisfies $d\Delta V\left(\lambda^*\right)/d\lambda = 0$. We call this critical value a *break point*. The break point can be expressed as $\rho_2 = t^*$. Note that t^* is the freight rates evaluated at the symmetric distribution of skilled workers, which is equivalent to the break point in Ottaviano et al. (2002). When $\rho_2 < t^*$, the symmetric distribution is stable; otherwise it is unstable.

Proposition 2 *If $\rho_2 < \tau + 4\sqrt{(2b+c)\, f/\,(L+1)\,(4b+c)}$, then the symmetric distribution is stable for all values of τ and f. Otherwise, it is unstable.*

From the proposition, we can find that endogenous determination of freight rates leads to the decomposition of *break point* and it shows that break point is a function of preference parameters, transport cost parameters and population of unskilled workers. When transport costs are higher or unskilled population is smaller, symmetric distribution is more stable. Figure 2 shows numerical simulation results for the indirect utility differential, $V(\lambda)$, with different cost parameters for the given preference parameters.[9] Specifically, Figure 2 shows how marginal changes in the distribution of skilled workers affect the indirect utility differential. The figure indicates the decrease in fixed (resp., marginal) costs. Location equilibria are obtained at the crossing points of the function and the x-axis. The equilibrium is stable when the slope is negative. When more than one crossing occur, this indicates multiple equilibria. Such instances of partial agglomeration are observed for decreasing fixed costs when $f = 0.9$ or 0.85, and for decreasing marginal costs when $\tau = 0.15$. In these cases, two equilibria with partial agglomeration are stable and the symmetric distribution is unstable. As is evident from Figure 2, symmetric distribution is always an equilibrium point, but its stability depends on the

[9] We set the parameters as $a = 1.5$, $b = c = 1$ and $L = 6$. For the result in Figure 2a, we set $\tau = 0.05$, and for Figure 2b $f = 0.7$.

parameter values. From both the figure and the analytical solution presented in (20), it can be seen that with decreasing marginal and/or fixed costs, there is a change in location equilibria from a symmetric distribution to a core-periphery structure.

=Figure 2 comes around here.=

We can further characterize the break point analytically. Taking equality between freight rates function at symmetric distribution, $t_{rs}|_{\lambda=1/2}$ in (20), and *symmetry break point*, ρ_2 as $t_{rs}|_{\lambda=1/2} = \rho_2$, and arranging this equality for fixed costs, we obtain the symmetry break point as,

$$f = \frac{(1+L)(4b+c)}{16(2b+c)}(\rho_2 - \tau)^2 \text{ for } \tau \in [0, \rho_2]. \tag{21}$$

When $\tau > \rho_2$, we always have symmetric equilibrium. Note that when $f = 0$, our model is identical to that of Ottaviano et al. (2002) and that keeping all parameter values constant, if fixed costs are higher, it induces not only strong economies of density but also higher freight rates. Two other conditions guarantee positive trade between regions under symmetric equilibrium. Both conditions are simply written as $t^* < \overline{t_{12}}|_{\lambda=1/2}$ and $\rho_2 < \overline{t_{12}}|_{\lambda=1/2}$. For $t^* < \overline{t_{12}}|_{\lambda=1/2}$. Then, from (7) and (20), we have the inequality as $t^* < \overline{t_{rs}}$. After rearranging the equation, we have

$$f < \frac{(1+L)((4b+c)\tau - 4a)^2}{16(2b+c)(4b+c)} \text{ for } \tau \in \left[0, \frac{4a}{4b+c}\right]. \tag{22}$$

Whenever the condition in (22) holds, two symmetric regions have positive trade. When $f \geq \frac{(1+L)((4b+c)\tau-4a)^2}{16(2b+c)(4b+c)}$ for $\tau \in \left[0, \frac{4a}{4b+c}\right]$, or $\tau > \frac{4a}{4b+c}$, the two regions are symmetric autarkies.[10] For $\rho_2 < \overline{t_{12}}|_{\lambda=1/2}$, after arranging the equations, we obtain

$$\frac{3b+c}{c} < L. \tag{23}$$

These are the conditions for attaining a stable symmetric equilibrium with positive trade. Under such conditions, the freight rates function is also limited in some ranges. Comparing the threshold in Proposition 1 with (23), we have the following equation:

$$\frac{3b+c}{c} - \frac{4b}{2b-c} = \frac{(b-c)(6b+c)}{c(2b-c)}. \tag{24}$$

[10]Note that the type of utility function is quasi-log linear and it allows the demand to be zero for some of differentiated goods that appear under conditions of symmetric autarky. See, for example, Melitz and Ottaviano (2008) and Comite, Thisse and Vandenbussche (2014).

As long as we assume that the utility function as $b \geq c$, we have $L > \frac{3b+c}{c} \geq \frac{4b}{2b-c}$ and, consequently, the freight rates function is strictly decreasing. Otherwise, when the population size is $\frac{3b+c}{c} < L < \frac{4b}{2b-c}$, the freight rates function is U-shape.

3.2 Core-periphery structure

When all firms are concentrated in a region, the resulting location equilibrium is known as the core-periphery structure. The sustainability of the core-periphery structure can be characterized by the presence of an incentive for any firm to change their location from the core region to the peripheral region. To observe the presence of such incentives, we examine the differences between the indirect utilities of the core and periphery, expressing these as $\Delta V(1) = \Delta W(1) + \Delta S(1)$. Obviously, as long as $\Delta V(1) > 0$,, there is no incentive for firms to relocate from the core to the periphery. Because of the presence of density economies in the transport sector, as skilled workers agglomerate in the core, the freight rates from the core to the periphery decrease and those from the periphery to the core increase. When most of the skilled workers agglomerate in the core region, only the small fraction of manufacturing firms remain in the periphery so that there is little demand for transport services to the core region. Because the transport demand from the periphery is too small for shipments, freight rates increase and may exceed the feasibility condition of trade in (6) as $\overline{t_{sr}} = \lim_{\lambda_r=1} \overline{t_{sr}} = 2a/(2b+c)$. To highlight the incentives that exist in the core-periphery structure, we obtain the indirect utility differential with freight rates from the periphery at their maximum as, $\overline{t_{sr}} = 2a/(2b+c)$. After some straightforward calculations, we have

$$\Delta S|_{\lambda=1} = \frac{(b+c)^2 (2a - bt_{rs}) t_{rs}}{2(2b+c)^2} > 0, \tag{25}$$

$$\Delta W|_{\lambda=1} = \frac{(b+c)}{8(2b+c)} \left[8at_{sr} + L(t_{sr} - t_{rs})(4a - (t_{sr} + t_{rs})(2b-c)) - 2t_{sr}^2(2b+c+Lc)\right], \tag{26}$$

where the inequality shown in (25) comes from $t_{rs}|_{\lambda=1} < \overline{t_{rs}} \leq 2a/(2b+c)$.Because $\partial t_{sr}/\partial \lambda_s < 0$ and $\lambda = 1$, we always have $t_{sr} > t_{rs}$. Observing the above equations with preference parameters constant reveals two main factors that support the sustainability of the core-periphery structure. One is freight rates from the core to the periphery and the other is the population of unskilled workers. It is evident from the equations that $\Delta V|_{\lambda=1}$ may be negative, only when the bracketed part takes negative values in (26). Such cases emerge under two circumstances. First, the second term in the bracketed part may become negative when $4a < (t_{sr} + t_{rs})(2b - c)$. Since we know that for a core-periphery structure, $t_{sr} = \overline{t_{sr}} = 2a/(2b + c)$, by substituting this equation into the inequality, we can obtain the condition $t_{rs} > 2a(2b + 3c)/(2b - c)(2b + c)$. Similarly, the third term in the bracket becomes larger when t_{rs} is higher. Thus, for higher freight rates from the core to the periphery, t_{rs}, the inequality holds and the core-periphery structure becomes unstable. Second, the third term takes large values when the population of unskilled workers is larger. When the population of immobile unskilled is larger, the dispersion force becomes stronger, which is consistent with the findings in Ottaviano et al. (2002). However, since we cannot obtain an analytical solution for the critical value of the stable core-periphery structure, the so-called *sustain point*, we simulate the values for certain parameters. In our setting, the equilibrium price of manufacturing firms contains competition effect where in the same market if there are more competitors price becomes lower and so there are the incentives for the firms at the core to move to periphery where there is less competitive environment even with the high freight rates.

=Figure 3 comes around here.=

Figure 3 shows the effect of decreasing marginal costs and the population size of unskilled workers.[11] The core-periphery structure is sustainable even at relatively high fixed costs when marginal costs are low. Since transport costs are composed of marginal and fixed costs, the decrease in transport costs is captured by at least one of the two costs. When the transport sector is highly regulated, transport firms are required to have higher fixed costs, as characterized by high density economies. In this case, a directional imbalance of freight rates becomes larger. Specifically, freight rates from the periphery to the core become higher, while those in the opposite direction become lower. Consequently, freight rates from the periphery to the core reach the trade feasibility condition shown in (6). This will cease cross-regional shipments from the periphery to the core. In this case, while firms located in the periphery cannot serve a market located in the core, firms in the core can serve the other market and enjoy lower freight rates. This indicates stronger agglomeration forces due to economies of density. Figure 3*b* shows that a decrease in the immobile population of unskilled workers results in less stability of the core-periphery structure. A decrease in the population of unskilled workers leads to a relative expansion in the size of the population of

[11] For both figures, the parameters are set as $a = 1.5$, and $b = c = 1$. We also set $L = 6$ for Figure 3a and $\tau = 0.1$ for Figure 3b.

skilled workers. Since the population of unskilled workers is assumed to be symmetric between regions, and they are consumers of differentiated goods, the dispersed demand of the population of unskilled workers anchors firms in their regions. As the immobile population increases, the proportion of the peripheral population within the economy becomes smaller, reducing the benefits of being located in the periphery.

Proposition 3 *As transport costs are lowered and/or the relative size of the population of unskilled workers is reduced, the core-periphery structure is more likely to emerge as a stable location equilibrium.*

Note that when fixed costs are very high, the core-periphery structure is always unstable. While high fixed costs may be interpreted as large economies of density, it also implies high average transport costs. Because of high transport costs, a symmetric distribution is more stable.

3.3 Stable location equilibria

In the previous section, we examine the stability of symmetric and core-periphery distributions of economic activities. In this section, by combining these results, we provide a comprehensive analysis of stable location equilibria. Proposition 2 states that lower transport costs make symmetric distribution more unstable. Since symmetric distribution becomes more unstable, this can be interpreted as an increase in agglomeration forces. Proposition 3 states that lower transport costs induce more stability in the core-periphery structure. These propositions are mutually consistent and suggest that lower freight rates induce agglomeration of economic activities. For given preference parameters, we simulated the stable location equilibria for various ranges of fixed and marginal costs, f and τ, which describe a change in transport costs. As in (16), there is a clear correspondence between freight rates and transport costs. Any decreases in transport costs by policy changes such as deregulations or technological advancement can result in decrease in freight rates. Figure 4 summarizes all of the stable location equilibria from the numerical simulations of (17) for all combinations of f, τ, and λ. High freight rates and high transport costs can be expressed by high fixed and marginal costs, as depicted in the upper right area of Figure 4.[12] Corresponding low transport costs are shown in the lower left area of the figure. Decreasing transport costs always correspond to decreasing freight rates and are described by the move from the upper right-side to the lower left-side.

[12]The parameters are set as $a = 1.5$, $b = 1$, $c = 1$ and $L = 5$.

The four main areas shown in Figure 4 depict symmetric autarky, symmetric equilibrium, core-periphery structure, and multiple equilibria. As shown in the upper right area of Figure 4, the stable equilibria change from symmetric autarky, symmetric equilibrium, multiple equilibria, to a core-periphery structure as transport costs decrease. These results are consistent with those of previous studies in New Economic Geography. These studies have found that an agglomeration of economic activities occurs as transport costs decrease, and the core-periphery structure becomes stable as a location equilibrium. Symmetric autarky emerges above the transport costs of trade feasibility and results in no trade between regions. The symmetric equilibrium is the location equilibrium with positive trade and is the only stable equilibrium. Multiple equilibria are areas with more than one stable equilibrium. There are three possible combinations: core-periphery + symmetric equilibrium, core-periphery + partial agglomeration equilibrium + symmetric equilibrium, and symmetric equilibrium + partial agglomeration equilibrium. For the area designated as core-periphery, agglomeration of skilled workers emerges and it is the unique equilibrium.

=Figure 4 comes around here.=

There are four thresholds, in the figure. Two of them are analytically obtained. First, the critical value separating symmetric equilibrium from symmetric autarky can be expressed as (22), which comes from the trade feasibility condition. Second, the lowest transport costs for the stable symmetric equilibrium are at the break point of symmetric equilibrium, which separates the area of the core-periphery structure from that of multiple equilibria. This is written as (21).[13] The other two thresholds are obtained numerically. One is the threshold between multiple equilibria and the symmetric equilibrium and was obtained from the sustainability point of the core-periphery structure. Using (25) + (25), the threshold is the values that hold $\Delta V(1) = 0$. The other threshold is for the area of partial agglomeration equilibrium. As discussed with Figure 2, there are stable partial agglomeration equilibria. Unfortunately, we could not obtain implicit expressions of the conditions for this area. Alternatively, we can obtain this area by checking the shape of the function in (17). For each pair of f and τ, we obtained the continuous function (17) and counted the number of sign changes by $\lambda \in [0, 1]$. The occurrence of 3 or 5 sign changes indicates the region of partial agglomeration equilibrium. We constructed a model based on Ottaviano

[13]Substituting $f = 0$ in (16) and ρ_2 in (19) and setting all the parameters as described in footnote 10, we obtained the symmetry break point as $\tau = 0.9677$.

et al. (2002), whose results showed neither partial agglomeration nor multiple equilibria. By contrast, our results exhibited both multiple equilibria and partial agglomeration. Given that our break point in (21) is qualitatively equivalent to the one in Ottaviano et al. (2002), the overlapping area of the core-periphery structure in the symmetric equilibrium indicates higher sustainability of the core-periphery structure and suggests the agglomeration force becomes stronger in the model. The above results show that the introduction of density economies in the transport sector drastically changes the location equilibria, and we observe the emergence of multiple equilibria and partial agglomeration. Summarizing these results, we present the following proposition.

Proposition 4 *The presence of density economies in the transport sector acts as an agglomeration force and results in multiple equilibria.*

Note that when fixed costs are too high, the core-periphery structure is always unstable and symmetric distribution is the only stable equilibrium.

4 Conclusion

This paper relaxes the simple assumption on symmetric transport costs in New Economic Geography. From the empirical observations of a large variation in transport costs for a given pair of regions as in Tanaka and Tsubota (2014) and the presence of density economies shown by Konishi et al. (2012), we constructed an economic geography model with density economies. Applying this model, we found that when the transport demand in one direction of a given route is greater than that in the opposite direction, this reduces relative freight rates for the former in relation to the latter. Consequently, the presence of density economies reduced transport costs from the larger region. Moreover, it strengthened agglomeration forces to the core region by increasing its accessibility. This result implies the existence of an additional market-driven force that acts to strengthen the hierarchical structure among regions.

Critical difference with and without endogenous freight rates enables us to consider a deregulation of transport sector which levies uniform pricing which may be a function of distance only. If regions are different in their sizes, any policy reform which allows non-uniform pricing leads to a greater concentration of regional structure. Our results imply that theoretical discussions that assume symmetric transport costs have overlooked the additional agglomeration force emanating from the transport sector.

To further discuss our findings, it is possible to interpret high fixed costs as strict entry regulations or as less competitive environments. In such a case, symmetric distribution is more likely to be stable. In other words, a more competitive transport sector induces the symmetric distribution to become more stable and the core-periphery structure to become more stable. This suggests that policy reform of regulations governing the transport sector would bring the agglomeration of economic activities.

There are some limitations in our paper. One crucial assumption is that all of the transportations are assumed to be chartered. This assumption implies that all of the return transport is empty. Returning empty or with less-than-full volume is a non-negligible problem in transportation, which is called backhaul problem. Formal introduction of this mechanism would require a combination of searching and matching among suppliers and transporters and customers.[14] To relax this assumption, further consideration is needed on the composition of freight loads and the possible emergence of consolidation services. Furthermore, transport networks are more complicated in terms of its hubs and spoke systems than our simple two-region model. For such network analysis, extension to multi-regional structure is necessary. These limitations suggest directions for future research.

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[14] See for example Demirel, Ommeren and Rietveld (2010).

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Appendix I: Transport costs

The inverse transport service function can be rewritten as: (12) as,

$$\begin{aligned}
t_{rs}\left(D_{rs}\right) &= g_{rs} - g_{rs}h_{rs}D_{rs}, \\
\text{where } D_{rs} &\equiv m_{rs}d_i^{rs} \\
g_{rs} &\equiv \frac{2a}{2b + c - cn_r}, \\
h_{rs} &\equiv \frac{(2b + c)}{an_r\left(L/2 + \lambda_s\right)}.
\end{aligned}$$

Then, the unit freight rate function and volume of transport services are also rewritten as,

$$\begin{aligned}
t_{rs}\left(\lambda_r, m_{rs}\right) &= \frac{g_{rs}}{1 + m_{rs}} - \frac{\tau}{1 + m_{rs}} + \tau, \\
d_i^{rs} &= \frac{g_{rs} - \tau}{\left(1 + m_{rs}\right)g_{rs}h_{rs}}.
\end{aligned}$$

Applying the free entry condition of this sector, $\left(t_{rs} - \tau\right)D_{rs}/m_{rs} - f = 0$, we can obtain the number of transport companies as,

$$m_{rs} = \frac{g_{rs} - \tau}{\sqrt{fg_{rs}h_{rs}}} - 1.$$

Since h_{rs} reflects the market size of the destination and the number of firms in the origin, it is clear that the number of transport companies varies with changes in the demand. Substituting the above results, we can rewrite the unit freight rate function as

$$t_{rs} = \sqrt{fg_{rs}h_{rs}} + \tau.$$

Similarly, the quantity can be derived as

$$d_i^{rs} = \sqrt{\frac{f}{g_{rs}h_{rs}}} = \sqrt{\frac{f\left(2b + c - cn_r\right)n_r\left(L/2 + \lambda_s\right)}{2\left(2b + c\right)}}.$$

Appendix II: Properties of the unit freight rate function

Taking $\lambda_r = \lambda$ and $\lambda_s = 1 - \lambda$ and the derivative of (16), we have

$$\Omega \equiv \frac{d}{d\lambda} t_{rs} = \frac{f\,(2b+c)\left(-6c\lambda^2 + (2\lambda - 1)(4b + 4c + Lc) + 2(c - Lb)\right)}{\lambda^2 (2b + c - c\lambda)^2 (L - 2\lambda + 2)^2 \sqrt{\frac{f(2b+c)}{\lambda(2b+c-c\lambda)(L+2(1-\lambda))}}}.$$

Since the denominator is always positive, the sign depends only on the numerator. Note that if $f = 0$, then $t_{rs} = \tau$. Otherwise, the sign of Ω depends on a part of the numerator, which, for notational convenience, we express as $\Theta(\lambda) \equiv -6c\lambda^2 + (2\lambda - 1)(4b + 4c + Lc) + 2(c - Lb)$. This is a quadratic function of λ. The first-order derivative is obtained as $\frac{d}{d\lambda}\Theta(\lambda) = 2(4b + 4c - 6c\lambda + Lc)$. At $\lambda = 0$, we have $\Theta(0) = -(L+2)(2b+c) < 0$ and $\frac{d}{d\lambda}\Theta(0) = 2(4b + 4c + Lc) > 0$. Thus, Ω is a decreasing function in the neighborhood at $\lambda = 0$. At $\lambda = 1$, we have $\Theta(1) = L(2b - c) - 4b$ and $\frac{d}{d\lambda}\Theta(1) = -2(4b - 2c + Lc)$. Additionally, at $\lambda = 1$, we have $\Theta(1) = 4b - L(2b - c)$ and $\frac{d}{d\lambda}\Theta(1) = 2(4b - 2c + Lc)$. Solving the last expression, when $L > \frac{2c-4b}{c}$, we have $\frac{d}{d\lambda}\Theta < 0$, and $\Theta(\lambda)$ is a monotonically decreasing function for $\lambda \in [0,1]$. Otherwise, $\Theta(\lambda)$ has a minimum in $\lambda \in [0,1]$.

Appendix III: Stability of symmetric distribution

The differentials of wage and consumer surplus are written as

$$\begin{aligned}
\Delta W &= W_r - W_s = (b+c)\left(\left(\frac{L}{2} + \lambda\right) t_{sr}\left(\left(\frac{2a + c(1-\lambda)\,t_{sr}}{2(2b+c)}\right) - \frac{t_{sr}}{4}\right)\right. \\
&\quad \left. - \left(\frac{L}{2} + 1 - \lambda\right) t_{rs}\left(\left(\frac{2a + c\lambda t_{rs}}{2(2b+c)}\right) - \frac{t_{rs}}{4}\right)\right), \\
\Delta S &= S_r - S_s = \frac{(b+c)}{8(2b+c)^2}\left(4(b+c)\left(\left(2a(t_{rs} + t_{sr}) - b\left(t_{rs}^2 + t_{sr}^2\right)\right)\lambda - t_{sr}(2a - bt_{sr})\right)\right. \\
&\quad \left. + c^2\lambda(t_{sr} - t_{rs})(t_{rs} + t_{sr})(1-\lambda)\right).
\end{aligned}$$

As long as freight rates are identical under symmetric distribution and we express freight rates as $t_{rs} = t_{sr} = t^*$, the above differential can be written as

$$\begin{aligned}\Delta W + \Delta S &= \frac{t^*(b+c)\left((2b+c)Lc + (6b^2+6bc+c^2)\right)}{8(2b+c)^2}\left(\frac{1}{2}-\lambda\right) \\ &\quad \left(t^* - \frac{4a(3b+2c)}{(2b+c)Lc + (6b^2+6bc+c^2)}\right) \\ &= \frac{\rho_1\rho_2}{2}\left(\frac{1}{2}-\lambda\right)\left(t^* - \frac{\rho_3}{\rho_2}\right),\end{aligned}$$

where $\rho_1 = (b+c)/(2b+c)^2$, $\rho_2 = (2b+c)Lc + (6b^2+6bc+c^2)$, and $\rho_3 = 4a(3b+2c)$. Note that we have $t_{rs}|_{\lambda=1/2} = t_{sr}|_{\lambda=1/2} = \tau + 4\sqrt{(2b+c)f/(L+1)(4b+c)}$, when the distribution is symmetric. By differentiating the equations and evaluating at the equal distribution of skilled workers, we can examine the stability of the symmetric distribution. The impact of the relocation of workers can be decomposed as

$$[d\Delta V]_{1/2} = [d\Delta W]_{1/2} + [d\Delta S]_{1/2}\,.$$

Each elements can be expressed as

$$[d\Delta W]_{\frac{1}{2}} = \left[\frac{\partial \Delta W}{\partial \lambda}\right]_{\frac{1}{2}} + \left[\frac{\partial \Delta W}{\partial t_{rs}}\right]_{\frac{1}{2}}\left[\frac{\partial t_{rs}}{\partial \lambda}\right]_{\frac{1}{2}} + \left[\frac{\partial \Delta W}{\partial t_{sr}}\right]_{\frac{1}{2}}\left[\frac{\partial t_{sr}}{\partial \lambda}\right]_{\frac{1}{2}},$$

and

$$[d\Delta S]_{\frac{1}{2}} = \left[\frac{\partial \Delta S}{\partial \lambda}\right]_{\frac{1}{2}} + \left[\frac{\partial \Delta S}{\partial t_{rs}}\right]_{\frac{1}{2}}\left[\frac{\partial t_{rs}}{\partial \lambda}\right]_{\frac{1}{2}} + \left[\frac{\partial \Delta S}{\partial t_{sr}}\right]_{\frac{1}{2}}\left[\frac{\partial t_{sr}}{\partial \lambda}\right]_{\frac{1}{2}}.$$

Note that $\left[\frac{\partial t_{sr}}{\partial \lambda}\right]_{1/2} = -\left[\frac{\partial t_{rs}}{\partial \lambda}\right]_{1/2} = \frac{4(4Ab-c)(4b+c)}{(L+1)}\sqrt{\frac{f(2b+c)(L+1)}{(4b+c)}}$. The derivatives of each elements can be expressed as follows: $[\partial \Delta W/\partial t_{rs}]_{1/2} = -[\partial \Delta W/\partial t_{sr}]_{1/2} = -\frac{(L-bt)(L+1)(b+c)}{2(2b+c)}$, $[\partial \Delta W/\partial \lambda]_{1/2} = \frac{(b+c)(L+2(1-\lambda))(4a-t(2b+c+Ac))t}{4(2b+c)}$, $[\partial \Delta S/\partial \lambda]_{1/2} = \frac{(b+c)^2(2a-bt)t}{(2b+c)^2}$ and $[\partial \Delta S/\partial t_{rs}]_{1/2}$ $= -[\partial \Delta S/\partial t_{sr}]_{1/2} = \frac{(b+c)\left(8a(b+c)+c^2t-2t(2b+c)^2\right)}{16(2b+c)^2}$. Applying these results, we have the following equation

$$[d\Delta V]_{1/2} = \left[\frac{\partial \Delta W}{\partial \lambda}\right]_{\frac{1}{2}} + \left[\frac{\partial \Delta S}{\partial \lambda}\right]_{\frac{1}{2}},$$

as in (18).

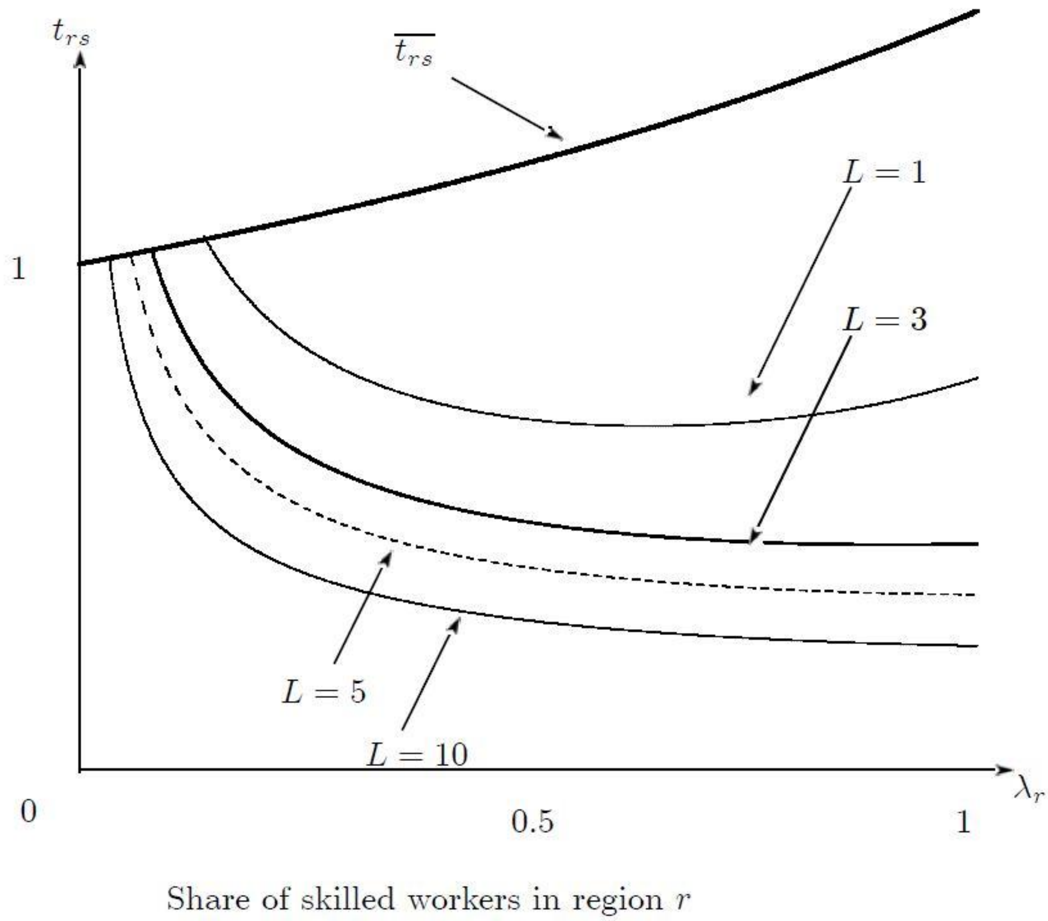
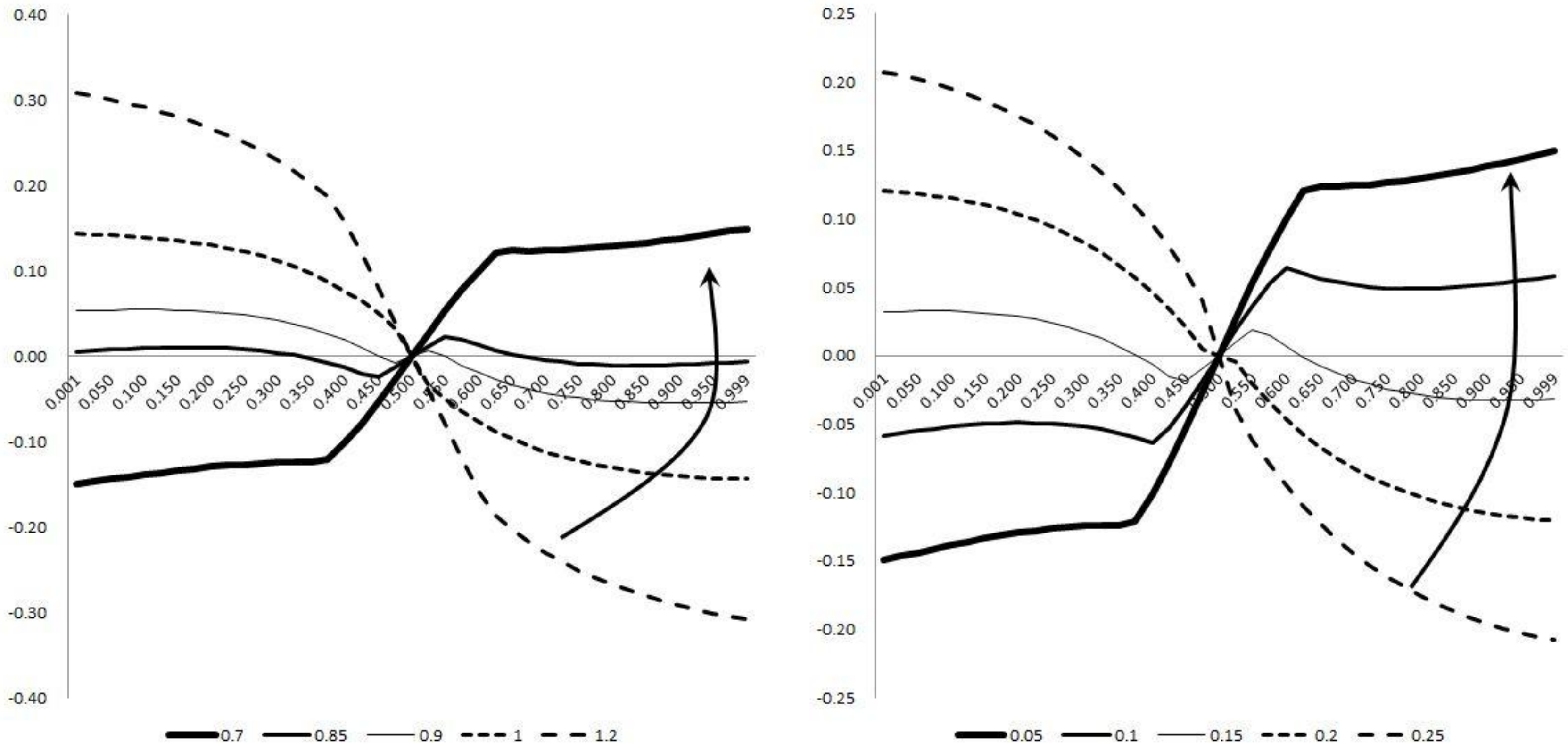


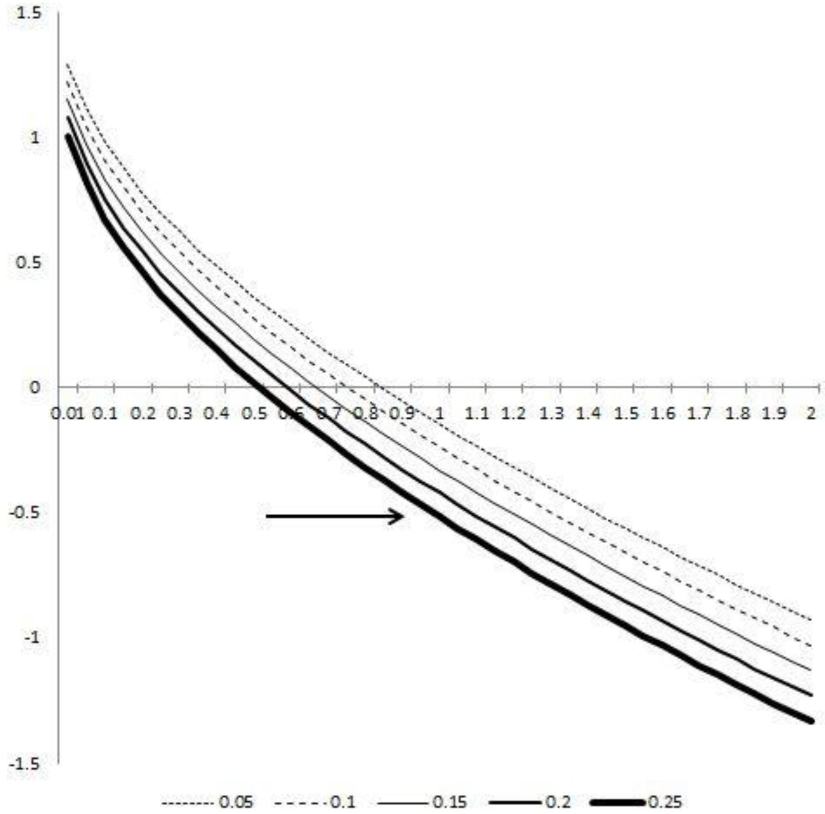
Figure 1: Transport costs from region r to s



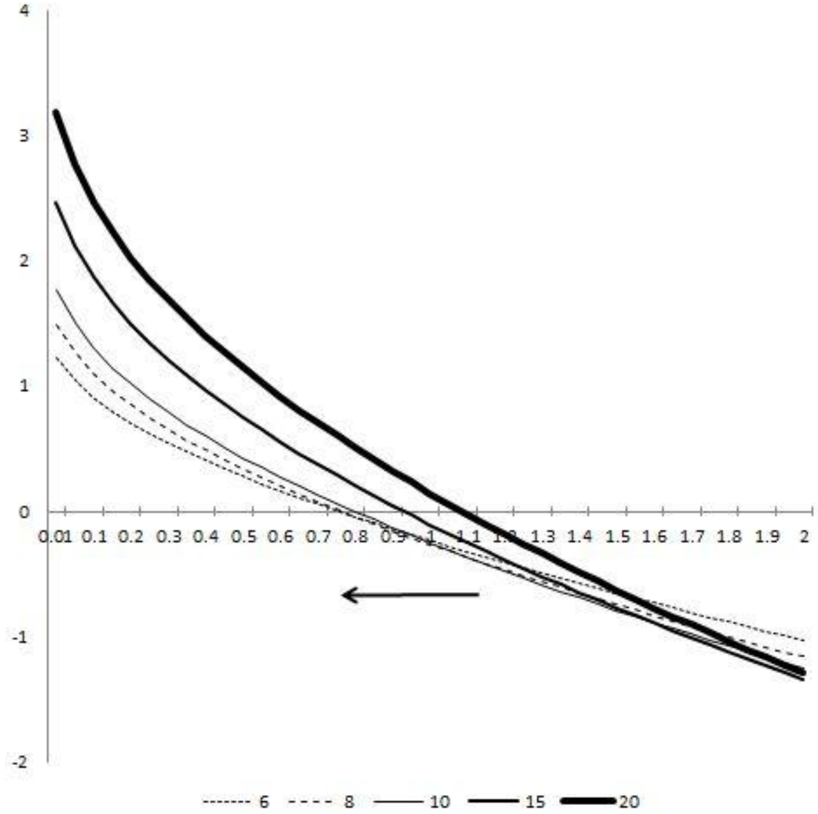
(2a) Decreasing fixed costs (2b) Decreasing marginal costs

Figure 2: Stability of symmetric distribution

Notes: Horizontal axis is the difference of indirect utility at different share of skilled workers. Dotted lines indicate stable symmetric equilibrium and solid lines indicate unstable symmetric equilibrium. In (2a), we set τ=0.05. When f=0.9 or 0.85, partial equilibrium is stable. When f=0.7, Core-periphery structure is stable. In (2b), we set f=0.7. When τ=0.15, partial equilibrium is stable. When τ=0.1 and τ=0.05, Core-periphery structure is stable.



(3a) Decreasing marginal costs



(3b) Decreasing unskilled population

Figure 3: Simulation of sustain point

Notes: Horizontal axis is the difference of indirect utility at Core periphery. When the function is below zero, it shows the incentives of skilled workers and firms to relocate to the peripheral region. Thicker line shows larger value of (a) marginal costs or unskilled population.

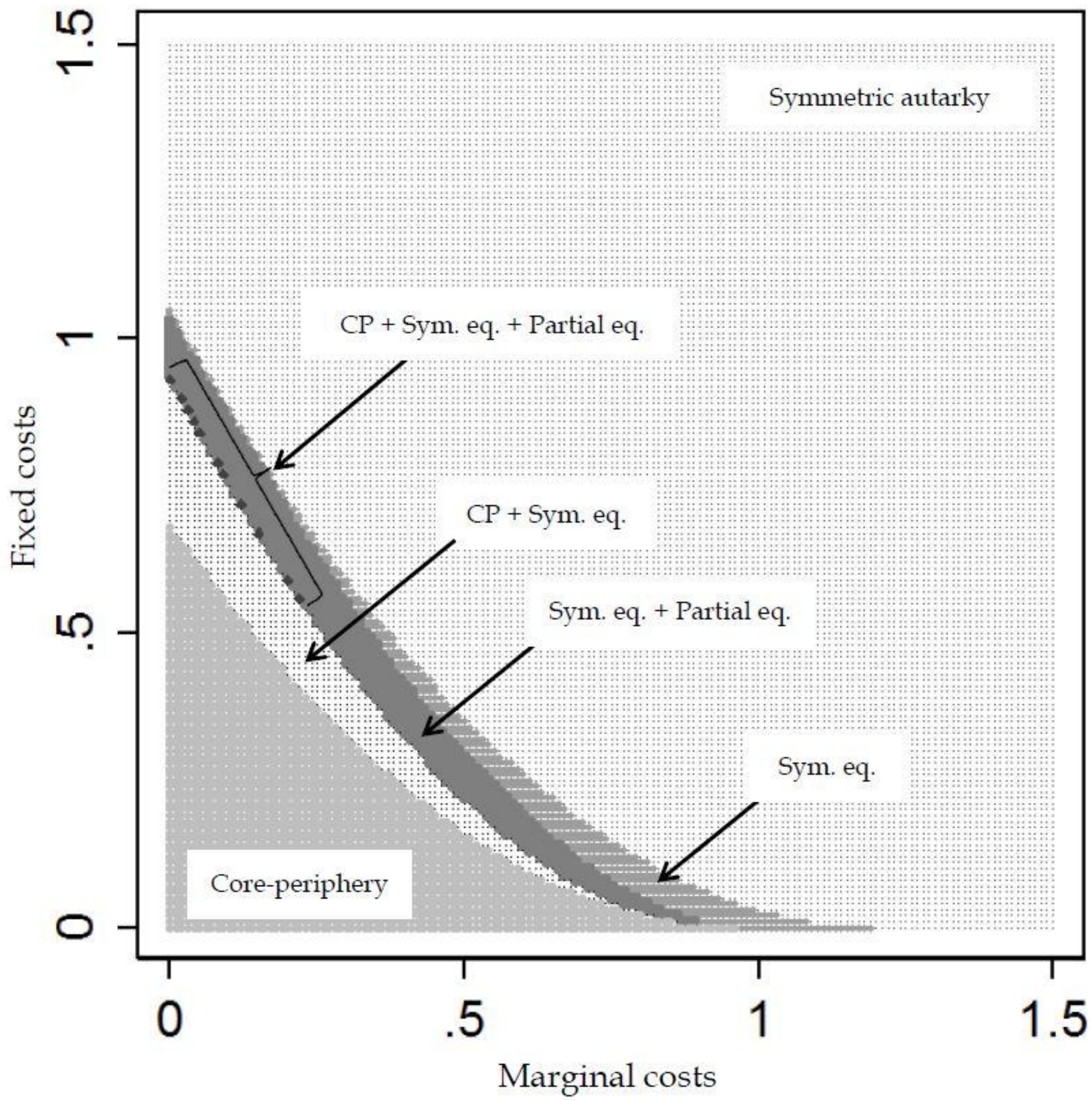


Figure 4: Location equilibria in (f, τ)-space

Notes: This simulation is performed over 151*151 cells. The share of each area is as follows; Symmetric autarky (81.8%), Symmetric equilibrium (2.26%), Core-periphery (10.02%), CP+Sym (3.65%), Symmetric and Partial equilibrium (2.94%), and CP, Symmetric and Partial equilibrium (0.05%). (f, τ)=(0,0) is excluded for the above calculation since any distribution of skilled workers gives identical real wages any distribution can be equilibrium. Figures with different values of unskilled population are available upon request.