Economic Geography and Endogenous Determination of Transportation Technology

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Abstract

This paper studies the interdependence of economic geography and transportation technology. A two-region model is used to obtain the conditions for the modern transportation technology to be adopted in an economy. In particular, the impact of economic geography upon the adoption of the modern technology is examined. Furthermore, I discuss what combination of economic geography (symmetric or core-periphery pattern) and transportation technology (traditional or modern technology) is to be realized in an economy.

Keywords: core-periphery pattern; lock-in effect; modern transportation technology; symmetric pattern; traditional transportation technology; transportation cost

JEL Classification Numbers: F11 (Neoclassical Models of Trade), R13 (General Equilibrium and Welfare Economic Analysis of Regional Economies)

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1 Introduction

Since the seminal work by Krugman (1991), a number of theoretical and empirical studies have been conducted to strengthen our understanding of location of economic activities. One of the basic messages of the "new economic geography" is that transportation cost matters: it affects the decision making of each producer and consumer and, as a result, determines the emerging geographical patterns.[1] Krugman (1991), for instance, constructs a simple two-region model to show that low transportation cost tends to cause an agglomeration of economic activities while high cost a dispersion. This result recurs in various contexts in most chapters of Fujita, Krugman and Venables (1999) and Fujita and Thisse (2002), which examine such diverse topics as regional development, urban systems and international trade.[2]

Surprisingly, however, few researchers have discussed the opposite causality, that is, the causality from the economic geography to the transportation cost. Casual observations suggest that the transportation technology adopted in an economy depends on the location of economic activities within it. A good example may be provided by cities. In cities like Los Angeles where the economic activities are highly dispersed over a broad range of space, a considerable portion of transportation is made by automobiles. In contrast, cities like Paris where the activities are historically concentrated in a narrow district usually see the development of mass transportation systems such as subways and trams, probably because the concentration generates enough demand for their services to cover the cost of their construction. Thus, the economic geography affects the adopted technology and, as a result, the transportation cost.

Studying such a relationship between economic geography and transportation technology is a matter of great importance for several reasons.

First, we often observe that some countries succeed in adopting a "modern" technology like a railroad whereas the others, although similar in most aspects, especially in their levels of economic development, fail to do so, sticking to a "traditional" technology like a motorcycle. This puzzling observation may be well explained by the difference in the economic geography of each country.

Second, the adopted technology determines not only the current level of welfare but also the future path of economic development and consequently its future level. In this regard, studying the adoption of technology is the more important.

Third, the topic is closely related to the problem of coordination in economic development

[1]For recent overviews of the field, see Ottaviano and Puga (1998), Fujita and Thisse (2000) and Neary (2001), among others.

[2]While most research including Fujita, Krugman and Venables (1999) deal with a *general level* of the transportation cost, Behrens (2004) pays attention to its *scheme* with respect to the distance of shipping. He explores the effects of the difference in the scheme upon the economic geography.

and may have some important policy implications. Suppose that, for example, the agglomeration of economic activities yields a sufficient amount of demand for the transportation service based on a superior modern technology, whereas dispersion does not. Then, that technology will be adopted in the economy characterized by the agglomeration but not in that characterized by the dispersion. In other words, the coordination among producers to locate themselves in the same region is necessary for the adoption of the modern technology. In this case, consequently, economic policies should aim at promoting such a coordination. Thus, this study offers another version of the famous 'Big Push' story by Murphy, Shleifer and Vishny (1989).

Fourth, combining both directions of the causality between the economic geography and the transportation technology, we can complete the picture of a circular causation or positive feedback mechanism. Suppose, as in the earlier discussion, that agglomeration rather than dispersion is associated with the superior transportation technology. Then, if a sufficient fraction of economic activities happens to be concentrated in one region, the superior technology is adopted. As a result of its adoption, the transportation cost will decline, which will, in turn, strengthen the tendency toward the agglomeration according to the mechanism described in the standard literature of new economic geography.

Fifth and finally, in order to study the adoption of transportation technology, it is inevitable to explicitly incorporate into the analysis a transportation sector, which has been usually abstracted away in the literature.[3] Nonetheless, it is likely that the sector is characterized by some form of increasing returns, e.g., the increasing returns to scale as Neary (2001) points out and the increasing returns to density as Mori and Nishikimi (2000) discuss. Since the increasing returns is another corner stone of the new economic geography, the omission of the transportation sector is not too innocuous.

This paper is one of the first attempts at studying the interdependence of emerging economic geography and adopted transportation technology. For that purpose, I construct a two-region model with two goods, an intermediate and a final good, in spirit of the new economic geography. It takes some cost to ship the final good from one region to the other although no cost is necessary to ship the intermediate. There are mobile entrepreneurs producing the final good and immobile workers producing the intermediate. For the geography, I focus on two special distribution patterns of entrepreneurs, namely, a symmetric pattern, at which they are distributed equally in the two regions, and a core-periphery pattern, at which they are concentrated in one region. Furthermore, I extend the conventional framework so as to incorporate two sorts of inter-regional transportation technologies into the analysis, "traditional" and "modern" technologies. The former, which is used by consumers

[3] In the literature, they often assume that the transportation cost takes an 'iceberg' form, which enables us to discuss the cost without explicitly modeling the transportation sector.

when they themselves carry the final good on foot, is characterized by constant returns. The latter is applied by the transportation sector that constructs a transportation system and charges a fee for its use. Since the construction of the system involves a fixed cost, it is subject to increasing returns. For the sake of simplicity, I concentrate on the situation in which the level of the user fee is determined so that the revenue from it exactly covers the fixed cost. The modern technology is adopted in an economy when the level of its user fee is sufficiently low and, as a result, the associated transportation cost becomes low enough to beat the traditional technology.

The first question to ask is as follows: in which distribution pattern is the modern transportation technology more likely to be adopted? Given the transportation cost for the traditional technology, the lower the transportation cost for the modern technology is, the more likely the latter technology is to be adopted. To answer the question, therefore, it suffices to find out the distribution pattern at which the transportation cost is lower.@Now, the level of the transportation cost is determined by that of the user fee: the higher the user fee is, the higher the transportation cost is. Furthermore, the user fee that exactly covers the fixed cost declines with the demand for transportation service, which is positively related to the volume of inter-regional trade. Hence, the transportation cost becomes lower at the distribution pattern with a larger volume of inter-regional trade. Thus, we cay say that *the modern technology is more likely to be adopted at the distribution pattern with a larger volume of inter-regional trade*. Here, it is important to note that the volume of trade itself depends on the transportation cost: the transportation cost for the modern technology and the volume of trade are inter-related and must be solved simultaneously. Paying attention to this inter-dependence, I give the answer to the question of which pattern yields a larger volume of trade. The answer turns out to depend on the values of parameters, i.e., the elasticity of substitution in consumers' preference, the cost to construct a modern transportation system and the efficiency of the modern technology.

Next, I ask what combination of economic geography (symmetric or core-periphery pattern) and transportation technology (traditional or modern technology) is to be realized in an economy. Here, in addition to the question of which technology is adopted for a given geography, one needs to answer the question of which geography emerges for a given technology. As an answer to the latter question, I consider a stable long-run equilibrium distribution pattern. It turns out that the realized combination depends on the values of parameters in a highly complicated way. Thus, I would rather pay attention to a couple of interesting cases than enumerate all the cases in more or less great detail.

Some of them are the cases exhibiting a *poverty trap*, in which the economy fails to adopt the modern technology despite the fact that it could do so if the economic geography were different. More specifically, I show that there exists a set of parameter values for which the following holds: When the economy is characterized by the symmetric pattern, on the one hand, the modern technology, being prohibitive, cannot be introduced into it and the traditional technology is adopted. Given the traditional technology, furthermore, the symmetric pattern is a stable long-run equilibrium pattern. On the other hand, when it is characterized by the core-periphery pattern, the modern technology is affordable enough to be adopted in the economy. Given the modern technology, the core-periphery pattern is a stable long-run equilibrium pattern. For such a set of parameter values, the economy with the symmetric pattern is *locked in* to the inferior state, namely, that with the traditional technology, that is to say, it is stuck into the poverty trap. Studying this lock-in effect is important because of not only its theoretical significance but also its far-reaching implications. For one thing, it gives us a justification for policy intervention. What is more, it provides us with an explanation of the fact which I have mentioned earlier, i.e., the fact that some countries succeed in adopting the modern technology while the others cannot even if their levels of economic development are not much different.

Finally, I discuss how the adopted transportation technology and the realized economic geography change in response to a gradual change in economic environment. This would be helpful to understand some aspects of economic development.

The paper is organized as follows. In the next section, I present a basic model. Section 3 gives the transportation costs for the modern technology when the economy is characterized by the symmetric pattern and by the core-periphery pattern, respectively. In the subsequent section, I compare these costs to see which pattern the modern technology is more likely to be adopted at. In Section 5, I define the stable long-run equilibrium pattern. Then, in the next section, I ask what combination of transportation technology and economic geography is realized in an economy. The possibility of the lock-in effect and the change in the combination brought about by a gradual change in an exogenous factor associated with economic development are discussed. Finally, Section 7 concludes.

2 Model

As a basic framework, I use a model presented by Mori and Turrini (2000), extending it so as to allow the possibility that there exist different types of transportation technologies and a transportation sector.

2.1 Basic Framework

There are two regions, denoted by 1 and 2; and two goods, an intermediate and a final good. Total labor force consists of workers and entrepreneurs. The workers are not endowed with the skill necessary to produce the final good and thus engage in the production of the intermediate. There are 2 units of workers in the economy, who cannot migrate between the regions. They are distributed equally in the two regions: 1 unit live in each region. The entrepreneurs are, on the other hand, endowed with the skill so that they can engage in the production of the final good. They can freely move between the two regions. Their number is fixed at n, of which λn live in region 1 and $(1-\lambda)n$ live in region 2 ($\lambda \in [0,1]$).

The intermediate is a homogeneous product and produced in a competitive sector. Each worker produces 1 unit of the intermediate, whose price, therefore, equals his wage rate in each region. The cost to ship the intermediate from one region to the other is assumed to be 0 so that the prices of the intermediate and, consequently, the wage rates of workers are equalized in the two regions. I consider the wage rate a numeraire.

On the contrary, the final good is a differentiated product and produced in a monopolistically competitive sector. Each entrepreneur owns a firm which produces 1 variant in the region of her residence. Thus, there are n variants in the economy of which λn are produced in region 1 while $(1-\lambda)n$ are produced in region 2. Taking a unit appropriately, I suppose that each firm produces 1 unit of a variant from 1 unit of the intermediate using the skill of the respective entrepreneur. All the revenue left after the payment for intermediate is taken by the entrepreneur. In other words, the profit of a firm is equal to 0:

$$pq - 1 \cdot q - w = 0, \tag{1}$$

where p and q denote a price and an amount of a variant produced, and w a wage rate received by an entrepreneur. This setting must be familiar in the analytically solvable core-periphery model (Forslid and Ottaviano (2003)).

The workers and entrepreneurs have the same preference represented by a utility function, $U = [\int_0^n x(k)^\rho \, \mathrm{d}k]^{1/\rho}$, where $\rho \in (0,1)$, and $x(k)$ denotes the amount of the kth variant. Let us denote the amount of money that a consumer must pay to consume 1 unit of the kth variant by $p(k)$. Then, the standard analysis tells us that a consumer, whose income is equal to y, consumes the following amount of the kth variant:

$$x(k) = yp(k)^{-\sigma} P^{\sigma-1} \tag{2}$$

where $\sigma \equiv 1/(1-\rho) > 1$ is the elasticity of substitution and

$$P = \left[\int_0^n p(l)^{1-\sigma} \, \mathrm{d}l \right]^{1/(1-\sigma)} \tag{3}$$

is the price index.

The entrepreneurs sell their variants at the price that maximizes their own wages. Since not only they are subject to the same technological condition but also all the variants enter the utility function in a symmetric manner, they charge the same price as long as they are located in the same region. Thus, I denote the prices of a variant produced in respective regions by p_1 and p_2.

Next, I introduce a transportation cost. In order to consume 1 unit of any variant in region j, it is necessary for consumers to buy $t_{ij} \geq 1$ units of that variant if it is produced in region i. If $i = j$ that is, the regions of production and consumption are the same, $t_{ij} = 1$: no transportation cost is necessary. However, if $i \neq j$, $t_{ij} > 1$: they must pay some transportation cost. I assume that the cost does not depend on the direction of shipment, that is, $t_{12} = t_{21} = t > 1$. To sum up, we have

$$t_{ij} = \begin{cases} 1 & \text{if } i = j \text{, and} \\ t & \text{otherwise.} \end{cases}$$

The transportation cost, $t_{ij} - 1$ may be interpreted either as the amount of the good that melts away during the shipment, as in the standard literature, or as the amount that is received by a transportation sector. In either case, a consumer in region j who consumes 1 unit of the kth variant produced in region i must pay $p(k) = t_{ij}p_i$.

Let X_{jj} and X_{ij} be the total demands, inclusive of transportation cost, in region j for a variant produced in that region and in the other region, respectively. By definition, it follows from (2) and (3) that

$$X_{jj} = Y_j p_j^{-\sigma} P_j^{\sigma-1} \qquad (\ j = 1, 2\ ) \tag{4}$$

and that

$$X_{ij} = Y_j t^{1-\sigma} p_i^{-\sigma} P_j^{\sigma-1} \qquad (\ j = 1, 2\ ) \tag{5}$$

with $i \neq j$, where Y_j is an aggregate income and

$$P_j = \left[n \left\{ \lambda (t_{1j} p_1)^{1-\sigma} + (1-\lambda)(t_{2j} p_2)^{1-\sigma} \right\} \right]^{1/(1-\sigma)} \qquad (\ j = 1, 2\ ) \tag{6}$$

is a price index in region j. Since the amount of each variant produced in region i, q_i, must be equal to its demand, we have

$$q_i = X_{ii} + X_{ij} \qquad (\ i = 1, 2\ ) \tag{7}$$

with $j \neq i$.

An entrepreneur in region i maximizes her wage given by $w_i = p_i q_i - 1 \cdot q_i$ ($i = 1, 2$) (see (1)), setting the price at

$$p_1 = p_2 = \frac{\sigma}{\sigma - 1}. \tag{8}$$

The wage received by an entrepreneur is reduced to

$$w_i = \frac{1}{\sigma - 1} q_i. \qquad (\ i = 1, 2 \ ) \tag{9}$$

Moreover, the aggregate income consists of workers' and entrepreneurs' earnings. It is, therefore, given by

$$\begin{aligned} Y_1 &= 1 + \lambda n w_1 \\ Y_2 &= 1 + (1 - \lambda) n w_2. \end{aligned} \tag{10}$$

This completes a description of a basic framework: a system of equations (4) to (10) determines a short-run equilibrium, in which entrepreneurs' distribution, λ, is given.

I pay my attention to two special distribution patterns of entrepreneurs; a symmetric pattern, in which they are distributed equally in the two regions, namely, $\lambda = 1/2$, and a core-periphery pattern, in which all of them are concentrated in one region, namely, $\lambda = 0$ or $\lambda = 1$. Those two patterns are denoted by S and C, respectively.

2.2 Transportation Technology and Transportation Sector

In the economy, there are two types of transportation technology. The first is a traditional technology, denoted by T. For this technology, a fixed portion of the final good melts away in course of inter-regional shipment. Specifically, 1 unit of the good arrives at a destination when $t_T > 1$ units are dispatched, that is to say, $t = t_T$. For this technology, consumers carry the good by themselves "on foot".

Then, there is a modern technology, denoted by M. Using it, consumers can receive 1 unit of the final good by dispatching merely γ units instead of t_T units ($\gamma \in (1, t_T)$) at the opposite region. Here, γ is inversely related to "efficiency" of the modern technology.

The transportation service based on the modern technology is provided by a transportation sector, which may be private or public. It uses F units of the final good in order to construct, maintain and operate a system of transportation such as a highway network and a high-speed train system. For the sake of simplicity, I assume that the sector provides the service with 0 marginal cost. Furthermore, the sector takes from users of its system $u > 0$ units of the final good per every unit that is shipped out from the origin of the shipment.[4] Thus, u represents a "user fee" in real terms per unit shipment. The point is that, in order to receive 1 unit of the final good at one region, one must dispatch $\gamma/(1-u)$ units at the other region: out of $\gamma/(1-u)$ units, the transportation sector takes portion u, leaving portion $1-u$ or γ units, which melts away but 1 unit. Thus, when the modern technology is used, we have $t = \gamma/(1-u)$.

[4] In order to keep the analysis tractable, I exclude the possibility that the transportation sector gives a subsidy for the use of its system.

The profit of the transportation sector (in real terms) is given by $\pi \equiv uD - F$. Here, D is the total amount of cross-border demand for the final good or the volume of inter-regional trade, measured at the origin of the shipment. It is equal to the sum of $n\lambda X_{12}$ (the amount of the good produced in region 1 for the consumption in region 2) and $n(1-\lambda)X_{21}$ (the amount of the good produced in region 2 for the consumption in region 1):

$$D = n\left[\lambda X_{12} + (1-\lambda)X_{21}\right].^{5} \tag{11}$$

In this paper, I focus on the special case where the profit is equal to 0, that is, the case where the user fee is determined by

$$uD - F = 0, \tag{12}$$

whenever it is in operation. The purpose is to keep the analysis tractable: taking into account the possibility that the sector earns positive profits makes the analysis much more complicated. Since the 0-profit case, as will be shown, becomes an important benchmark for the more general cases with positive profits, this simplification is not too harmful as a first step. Furthermore, it should be noted that the 0-profit case can be interpreted in several ways. First, a government provides the modern transportation service with average cost pricing to balance its budget. Second, a government regulates a privately-owned transportation sector so that no profit is raised. Third and finally, as a result of (potential) free entry, a privately-owned transportation sector is forced to charge the 0-profit user fee.

Now, what conditions are necessary for the adoption of a particular type of transportation technology? First, the technology must be *available* to the consumers. The modern technology is available if there exists a 0-profit user fee. If it does not exist, the transportation sector cannot earn a non-negative profit, as will be shown later, and, as a result, stays out of business. The traditional technology is always available. Second, the technology must be *feasible*. As has been mentioned, the transportation sector takes away some portion of the final goods from those that a consumer has passed to it. However, it is not feasible to take away more than s/he has passed. Therefore, the modern technology is feasible if $u \leq 1$, or

$$\frac{\gamma}{1-u} \geq 0. \tag{13}$$

We can consider the traditional technology to be always feasible because no user fee is taken (u is regarded as 0). Third and finally, when both the technologies are available and feasible, the adopted technology must be actually used by consumers who choose the less expensive

[5] Using (4), (5), (7)-(9), we can rewrite (10) in terms of Y_1, Y_2, P_1 and P_2. Then, solving for Y_1 and Y_2 yields $Y_i P_i^{\sigma-1} = Z_i/(A_1A_2 - B_1B_2)$ where $Z_1 \equiv A_2 + B_1$, $Z_2 \equiv A_1 + B_2$, $A_i \equiv P_i^{1-\sigma} - \rho^{\sigma-1}n\lambda_i/\sigma$, and $B_i \equiv \rho^{\sigma-1}t^{1-\sigma}n\lambda_i/\sigma$ ($\lambda_1 \equiv \lambda$ and $\lambda_2 \equiv 1-\lambda$) ($i = 1, 2$). Furthermore, this gives us $D = \rho^{\sigma}t^{1-\sigma}n\left[(1-\lambda)Z_1 + \lambda Z_2\right]/(A_1A_2 - B_1B_2)$.

mode of transportation. In other words, the transportation cost for the adopted technology must be no higher than that for the other technology: the adopted technology must *undercut* the other technology. Here, in order to avoid an unnecessary complication, I assume that it is the modern technology that is used when the tie occurs.[6] Then, if

$$\frac{\gamma}{1-u} \leq t_T, \tag{14}$$

the modern technology undercuts the traditional technology; and otherwise, the opposite holds.

Now, using these concepts, we can formally discuss the conditions for the adoption of a transportation technology.

Definition 1. (adoption of a transportation technology) *Given a distribution pattern, a transportation technology $i \in \{T, M\}$ is said to be* ***adopted*** *in the economy if one of the following two sets of conditions, i) and ii), is met for $j \in \{T, M\}$ with $j \neq i$:*
i) technology i is available and feasible, while technology j is unavailable and/or infeasible,
ii) technology i is available and feasible, and undercuts technology j, while technology j is available and feasible.

The following lemma, whose proof is relegated to Appendix, immediately follows.

Lemma 1. *Given a distribution pattern, the modern transportation technology is adopted in the economy and $t = \gamma/(1-u)$, if it is available and feasible, and undercuts the traditional technology. Otherwise, the traditional technology is adopted and $t = t_T$.*

Here, we can see that the 0-profit case becomes a benchmark for more general cases with positive profits. Suppose that the modern technology is adopted and that the transportation sector earns a positive profit. Then, the technology is available and feasible, and undercuts the traditional technology. Now, it will be shown later that the 0-profit user fee is lower than any fee associated with positive profits. Therefore, the modern technology is still available and feasible, and undercuts the traditional one when the sector charges the 0-profit fee. That is, whenever the modern technology is adopted for a user fee associated with a positive profit, it can be adopted, too, for the 0-profit fee. Taking contraposition, if the modern technology is not adopted for the 0-profit fee, consequently, it is not adopted, either, for any fee associated with positive profits.

Closing this section, I add one qualification about the values of parameters. In the following analysis, it will be shown that if $F > \rho$, the modern transportation technology, failing to be feasible, is not adopted when the economy is characterized by the core-periphery

[6] This assumption is made only for the sake of simplicity and clarity. It is possible to assume otherwise and obtain similar results.

pattern. In order to focus on interesting cases, therefore, I preclude such a case, assuming that the fixed cost is sufficiently small.

Assumption 1. $F \leq \rho$.

3 Transportation Costs Associated with the Modern Transportation Technology

In this section, supposing that the modern technology is adopted in the economy, I derive the transportation costs associated with it, given the distribution pattern of entrepreneurs. In doing so, I also explore the three conditions for its adoption.

3.1 Transportation Cost at the Symmetric Pattern

In the first place, let us assume the symmetric distribution of entrepreneurs. When the modern technology is adopted, the measure of inter-regional transportation cost, t, becomes equal to $t_S \equiv \gamma/(1-u_S)$, where u_S is a user fee at the symmetric pattern.

According to (11), the amount of the cross-border demand is reduced to

$$D_S = \frac{2}{1+t_S^{\sigma-1}}. \tag{15}$$

It depends on σ and t_S. First, $\partial D_S/\partial\sigma < 0$: the cross-border demand decreases with σ, other things being equal. This is explained as follows. At the symmetric pattern, the cross-border demand originates from not only the workers but also the entrepreneurs. As the elasticity of substitution rises, monopoly power of the entrepreneurs is abated. As a result, the price of the final good declines, which lowers their nominal income (a nominal income effect), on the one hand, and the price index (a price index effect), on the other hand. Since the former effect, it turns out, dominates the latter, their demand for the final good shrinks. Although the decline in the price expands the demand from the workers at the same time, it is more than offset by the shrinkage in the entrepreneurs' demand. This results in the reduction of the cross-border demand. Second, $\partial D_S/\partial t_S < 0$: the cross-border demand decreases with t_S, ceteris paribus. This is because the rise in the transportation cost induces the substitution of the variants produced in the home region for those produced in the foreign region.

Substituting D_S into the profit function yields

$$\pi = \frac{\Omega(t_S)}{t_S(1+t_S^{\sigma-1})} \tag{16}$$

where $\Omega(t_S) \equiv t_S(2-F) - Ft_S^{\sigma} - 2\gamma$. Therefore, the transportation sector earns 0 profit if t_S solves

$$\Omega(t_S) = 0. \tag{17}$$

By definition, the modern technology is available when (17) has a solution. Furthermore, note that $\Omega(t_S)$ approaches the negative infinity as t_S goes to the positive infinity. By continuity, therefore, when there exists no solution to (17), $\Omega(t_S) < 0$ for any t_S, that is, the transportation sector ends up with a negative profit.

Whether (17) has a solution or not depends on the values of parameters. Note that the solution exists if and only if

$$\max_{t_S} \Omega(t_S) \geq 0. \tag{18}$$

Since $\Omega(t_S)$ is concave, it has a unique maximum, reached at $t_S^0 \equiv [(2-F)/\sigma F]^{1/(\sigma-1)} > 0$, where the inequality is assured by Assumption 1. Two observations follow. First, because

$$\frac{\mathrm{d}\left[\max_{t_S} \Omega(t_S)\right]}{\mathrm{d}\sigma} = -\frac{t_S^0(2-F)}{\sigma(\sigma-1)} \ln \frac{2-F}{\sigma F},$$

$\max_{t_S} \Omega(t_S)$ decreases with σ if $1 < \sigma < (2-F)/F$, and increases if $\sigma > (2-F)/F$. Second, $\max_{t_S} \Omega(t_S)$ approaches the positive infinity as σ goes to 1 from above, and -2γ as it goes to the positive infinity. These observations imply that there exists $\bar{\sigma} \in (1, (2-F)/F)$ such that

$$\begin{cases} \max_{t_S} \Omega(t_S) > 0 & \text{for} \quad \sigma < \bar{\sigma}, \\ \max_{t_S} \Omega(t_S) = 0 & \text{for} \quad \sigma = \bar{\sigma}, \text{ and} \\ \max_{t_S} \Omega(t_S) < 0 & \text{for} \quad \sigma > \bar{\sigma}. \end{cases}$$

Because $\max_{t_S} \Omega(t_S) = \Omega(t_S^0)$, $\bar{\sigma}$ is a solution to

$$\Omega\left([(2-F)/\bar{\sigma}F]^{1/(\bar{\sigma}-1)}\right) = 0. \tag{19}$$

Hence, (18) is satisfied and (17) has a solution if and only if $\sigma \leq \bar{\sigma}$, which is the condition for the modern technology to be available.

A figure might be helpful to understand this finding. In Fig. 1, the horizontal axis measures σ while the vertical axis measures t_S. The $t_S(\sigma)$ curve represents the solution to (17) as a function of σ for given values of γ and F ($\gamma = 1.1$ and $F = 0.1$). It has a turning point at $\sigma = \bar{\sigma}$, where the height is equal to $t_S^0|_{\sigma=\bar{\sigma}}$ (see (19)).

____________@Insert Fig. 1 around here ____________

It may be worth noting that this availability condition can be rewritten in terms of the other parameters. Let us begin with parameter F. Notice that $\max_{t_S} \Omega(t_S)$ decreases with F, approaches the positive infinity as F goes to 0, and approaches a negative number as it goes to 1. Therefore, (18) is satisfied and a solution to (17) exists, if and only if F is no greater than a critical value, $\bar{F} \in (0,1)$, which is a solution to $\max_{t_S} \Omega(t_S) = 0$. We can obtain a similar result for γ: a solution to (17) exists if and only if γ is no greater than a critical value, $\bar{\gamma} > 0$, which is a solution to $\max_{t_S} \Omega(t_S) = 0$.[7] It turns out that $\bar{\gamma} = \rho \left[(2-F)^{\sigma}/\sigma F\right]^{\frac{1}{\sigma-1}}/2$.

Having said that (17) has a solution if $\sigma \leq \bar{\sigma}$, I now derive several properties of the solution. First of all, (17) has at most two solutions since $\Omega(\cdot)$ is strictly concave. I denote the solutions as $\underline{t}_S$ and $\bar{t}_S$ with $\underline{t}_S \leq \bar{t}_S$. By construction, we have

$$\underline{t}_S \leq t_S^0 \leq \bar{t}_S. \tag{20}$$

The two solutions, $\underline{t}_S$ and $\bar{t}_S$, are represented by the heights of the increasing part and decreasing part of the $t_S(\sigma)$ curve in Fig. 1, respectively. It is worth noting that $\underline{t}_S$, a low price, is associated with high volume of inter-regional trade while $\bar{t}_S$, a high price, is with low volume of inter-regional trade. Second, note that $\Omega(t_S) > 0$ for any $t_S \in (\underline{t}_S, \bar{t}_S)$, and that $\Omega(t_S) < 0$ for any $t_S < \underline{t}_S$ and for any $t_S > \bar{t}_S$. This immediately follows from the concavity of $\Omega(\cdot)$. Third, all the solutions are greater than γ, that is, $\underline{t}_S > \gamma$. To see this, notice that $\Omega(t_S^0) > 0$ implies that $t_S^0 > 2\gamma/\left[\rho(2-F)\right] > \gamma$. However, $\Omega(\gamma) = -\gamma F\left(1+\gamma^{\sigma-1}\right) < 0$, which implies $\gamma < \underline{t}_S$ or $\gamma > \bar{t}_S$. Consequently, $\underline{t}_S > \gamma$. Fourth and finally, the elasticity of the cross-border demand with respect to the user fee is not greater than 1 at $\underline{t}_S$. This is because

$$-\frac{\mathrm{d}\ln D_S}{\mathrm{d}\ln u_S} = \frac{(\sigma-1)t_S^{\sigma-1}}{1+t_S^{\sigma-1}} \cdot \frac{t_S-\gamma}{\gamma} = \frac{(\sigma-1)F t_S^{\sigma-1}}{2-F(1+t_S^{\sigma-1})},$$

where (15) and (17) are used: applying (17) and (20), we can easily verify that $\mathrm{d}\ln D_S/\mathrm{d}\ln u_S \in (0,1]$ at $\underline{t}_S$.

Of the two solutions, I will limit my attention to $\underline{t}_S$ in the subsequent analyses. There are two reasons. First, $\underline{t}_S$ is associated with a higher level of social welfare than $\bar{t}_S$ is. This is because the former is closer to the marginal cost in the provision of the transportation service, which is 0, than the latter. Viewing it from a different angle, moreover, one can recall that $\underline{t}_S$ involves a low price and a high volume of inter-regional trade while $\bar{t}_S$ a high price and a low volume of inter-regional trade. Since the profit is 0 for both situations, it is obvious that the former is associated with a higher welfare. Therefore, a government will, if any, regulate t_S at $\underline{t}_S$ rather than $\bar{t}_S$. Second, it is not likely that $\bar{t}_S$ is implemented in the real world. As long as $\bar{t}_S > t_S^0$, $\Omega(t_S)$ is decreasing around $\bar{t}_S$. Then, from (16), it is clear that the profit decreases with t_S: the elasticity of the cross-border demand is so high that the sector could earn a higher profit by cutting its user fee. This is not the situation that we usually observe.[8]

[7] Note that $\max_{t_S} \Omega(t_S)$ decreases with γ, approaches a positive number as γ goes to 0, and approaches the negative infinity as it goes to the positive infinity.

[8] In almost all cases, governments set an upper limit but not a lower limit of the user fee when they

It is important to note that $\underline{t}_S > 0$ since $\underline{t}_S > \gamma$. Therefore, (13) is always satisfied: the modern technology is always feasible for the symmetric distribution. Furthermore, the undercutting condition is written as $\underline{t}_S \leq t_T$.

Lastly, some comparative statics analyses would be helpful to understand the structure of the model. Let us define $K_S \equiv \left\{\sigma F \left[\left(t_S^0\right)^{\sigma-1} - \underline{t}_S^{\sigma-1}\right]\right\}^{-1} > 0$.

First, we have $\partial \underline{t}_S / \partial \sigma = K_S F \underline{t}_S^{\sigma} \ln \underline{t}_S > 0$: the transportation cost increases with the elasticity of substitution. This is explained as follows. Suppose that the elasticity rises. As is discussed earlier, this reduces the cross-border demand through the decline in the price of the final good ($\partial D_S / \partial \sigma < 0$). If the user fee were kept constant, therefore, the fixed cost would exceed the revenue of the transportation sector. In order to restore the equality between them, consequently, it is necessary to raise the fee because the elasticity of the cross-border demand is not greater than 1, which has been shown earlier. Thus, the break-even user fee and, therefore, the associated transportation cost must rise.

Second, $\partial \underline{t}_S / \partial F = 2K_S(\underline{t}_S - \gamma)F^{-1} > 0$: the transportation cost increases with the fixed cost. In order to keep the revenue equal to the fixed cost, the rise in the fixed cost must be offset by the rise in the revenue, which is attained through the rise in the user fee and, therefore, that in the transportation cost.

Finally, $\partial \underline{t}_S / \partial \gamma = 2K_S > 0$: the transportation cost is higher for a less efficient modern technology (corresponding to higher γ). The reason is twofold. First, a less efficient technology would be associated with a higher transportation cost by definition even if the transportation sector charged the same fee. Second, the transportation sector indeed charges a higher fee for a less efficient technology. This is explained as follows. Other things being equal, a less efficient technology, which is associated with a higher transportation cost, results in a smaller cross-border demand ($\partial D_S / \partial t_S < 0$) and, therefore, a lower revenue. To make the revenue even with the fixed cost, the sector needs to charge a higher user fee.

To sum up, given the symmetric distribution pattern, the level of t associated with the modern technology is given by $\underline{t}_S$. The technology is available if $\sigma \leq \bar{\sigma}$; it is always feasible; and it undercuts the traditional technology if $\underline{t}_S \leq t_T$. The following proposition immediately follows from Lemma 1.

Proposition 1. *When the economy is characterized by the symmetric pattern, the modern transportation technology is adopted and* $t = \underline{t}_S$*, if and only if both* $\sigma \leq \bar{\sigma}$ *and* $\underline{t}_S \leq t_T$ *are satisfied.*

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regulate transportation sectors. This fact would indicate that the profit of the transportation sector rather increases with the transportation cost it charges.

3.2 Transportation Cost at the Core-Periphery Pattern

Next, let us turn our attention to the economy characterized by the core-periphery pattern. The user fee is now denoted by u_C, for which the measure of transportation cost, t, becomes $t_C \equiv \gamma/(1-u_C)$.

According to (11), the cross-border demand is given as

$$D_C = \rho. \tag{21}$$

Note that $\partial D_C/\partial\sigma > 0$: the cross-border demand increases with σ, which makes a sharp contrast to the previous case. This is because, at the core-periphery pattern, the entire cross-border demand comes from the workers, which implies that any change in the nominal income of entrepreneurs has no effect on it. Hence, as the elasticity of substitution rises and the price of the final good declines as a result, the cross-border demand increases through the price index effect for the workers. Furthermore, $\partial D_C/\partial t_C = 0$: the level of the transportation cost does not affect the cross-border demand. Since the workers in the periphery have no alternative but to buy the final good from the core, the change in the transportation cost induces no substitution of the variants produced in the home region for those produced in the foreign region.[9]

Now, (12) and (21) imply that the break-even level of t_C is given by

$$t_C = K_C\gamma(\sigma-1), \tag{22}$$

where $K_C \equiv (\sigma-1-\sigma F)^{-1}$. Thus, there always exists a user fee that yields 0 profit: the modern technology is always available. Furthermore, (22) explains why we need Assumption 1 for the technology to be feasible. Finally, the modern technology undercuts the traditional one if $K_C\gamma(\sigma-1) \leq t_T$.

Three additional comments are in order. First, the elasticity of the cross-border demand with respect to the user fee is 0. Second, t_C is represented by the $t_C(\sigma)$ curve in Fig. 1. Finally, $\partial t_C/\partial\sigma = K_C t_C F(\sigma-1)^{-1} < 0$, $\partial t_C/\partial F = K_C\sigma t_C > 0$, and $\partial t_C/\partial\gamma = t_C\gamma^{-1} > 0$. We can explain these results by the same logic as in the case of the symmetric pattern, except for two respects. First, as has been discussed earlier, the rise in the elasticity of substitution does not reduce but does expand the cross-border demand ($\partial D_C/\partial\sigma > 0$). Therefore, the sign of $\partial t_C/\partial\sigma$ becomes opposite to that of $\partial \underline{t}_S/\partial\sigma$. Second, although t_C is higher when γ is higher, the break-even user fee is independent of γ. To see this, suppose that the economy is now provided with a less efficient technology. Even if the break-even user fee is kept constant, t_C will rise. However, because the amount of the cross-border demand does not

[9]Recall that the cross-border demand has been measured by the amount dispatched at the origin of the shipment but not the amount that reaches the destination.

depend on the transportation cost ($\partial D_C/\partial t_C = 0$), the break-even user fee does not need to change. At the symmetric pattern, on the contrary, the amount of the cross-border demand decreases with the transportation cost, and, consequently, the break-even user fee needs to rise.

To sum up, for the core-periphery pattern, the modern technology is always available and feasible (as long as Assumption 1 holds); and undercuts the traditional technology if $K_C\gamma(\sigma-1) \leq t_T$. Using Lemma 1, we have established the following proposition.

Proposition 2. *When the economy is characterized by the core-periphery pattern, the modern technology is adopted and* $t = t_C = K_C\gamma(\sigma-1)$, *if and only if* $K_C\gamma(\sigma-1) \leq t_T$.

4 Which Distribution Pattern Favors the Modern Transportation Technology? A Comparison

Having established the conditions for the adoption of the modern technology, we can now compare them to ask a question: is the modern technology more likely to be adopted at the symmetric pattern or at the core-periphery pattern? First of all, recall that the modern technology is always available at the core-periphery pattern but is not necessarily so at the symmetric pattern. When it is not available at the latter pattern, the answer is obvious: the technology is more likely to be adopted at the core-periphery pattern.

When it is available at the symmetric pattern, on the other hand, we need to compare the conditions on the undercutting, $\underline{t}_S \leq t_T$ for the symmetric pattern and $t_C \leq t_T$ for the core-periphery pattern. We can consider that the modern technology is more likely to be adopted at the pattern where the associated transportation cost is lower. There are three justifications. First, the range of t_T for which the modern technology undercuts the traditional one is wider at the pattern with the lower transportation cost, say pattern $k \in \{S, C\}$. It means that the transportation sector faces a less stringent undercutting condition at that pattern. Second, if the sector cannot provide the transportation service profitably at pattern k, then nor can it do so at the other pattern. Conversely, if it can provide the service profitably at the latter pattern, it can do so also at pattern k. Third and finally, there is a possibility that the modern technology is adopted only at pattern k. Yet there is no possibility that it is adopted only at the other pattern.

Unfortunately, however, it turns out that which of $\underline{t}_S$ and t_C is smaller is ambiguous. It is true that they are negatively related to D_S and D_C, respectively (see (12)), and, therefore, that *the transportation cost is lower at the distribution pattern with a larger volume of interregional trade*. But the volume of trade at the symmetric pattern depends in turn on the transportation cost (see (15)). In this sense, the level of transportation cost and the volume of inter-regional trade are inter-related. Thus, the answer to the question of which of $\underline{t}_S$ and t_C is smaller is not obvious. In this section, I explore how the answer depends on the values of parameters.

4.1 Effect of σ

I begin the analysis by examining the effect of σ. Let us return to Fig. 1, where the upward-sloping part of the $t_S(\sigma)$ curve, denoted by $\underline{t}_S(\sigma)$ curve hereafter, and the whole $t_C(\sigma)$ curve represent $\underline{t}_S$ and t_C, respectively. Depending on how they intersect each other, we can distinguish three cases. First, suppose that the $t_C(\sigma)$ curve lies above the $t_S(\sigma)$ curve at $\sigma = \bar{\sigma}$. This occurs if $\Theta(F, \gamma) > 0$, where

$$\Theta(F, \gamma) \equiv \frac{\gamma(\bar{\sigma} - 1)}{\bar{\sigma} - 1 - \bar{\sigma}F} - \left[\frac{2 - F}{\bar{\sigma}F}\right]^{1/(\bar{\sigma}-1)}.$$

Since the $t_C(\sigma)$ curve is downward-sloping, the $\underline{t}_S(\sigma)$ curve lies below the $t_C(\sigma)$ curve in the interval $\sigma \in [1/(1 - F), \bar{\sigma}]$, where $1/(1-F)$ is a minimal value of σ permitted by Assumption 1. Therefore, there is no intersection. Second, suppose that the $t_C(\sigma)$ curve intersects the $t_S(\sigma)$ curve at $\sigma = \bar{\sigma}$. This occurs if $\Theta(F, \gamma) = 0$. In this case, that intersection becomes a unique intersection of the $\underline{t}_S(\sigma)$ curve and the $t_C(\sigma)$ curve. Finally, suppose that the $t_C(\sigma)$ curve lies below the $t_S(\sigma)$ curve at $\sigma = \bar{\sigma}$ as in Fig. 1. This occurs if $\Theta(F, \gamma) < 0$. Since the $t_C(\sigma)$ curve approaches the positive infinity as σ goes to $1/(1 - F)$ from above, the $\underline{t}_S(\sigma)$ curve and the $t_C(\sigma)$ curve necessarily intersect each other. Furthermore, the intersection is unique because the $t_C(\sigma)$ curve is downward-sloping. I refer to σ corresponding to such an intersection as σ^* with $\sigma^* \in [1/(1 - F), \bar{\sigma})$. It is evident that the $\underline{t}_S(\sigma)$ curve lies above the $t_C(\sigma)$ curve for σ greater than σ^* whereas the opposite is true for σ smaller than σ^*. Thus, we have established the following proposition.

Proposition 3. *If $\Theta(F, \gamma) > 0$, then $\underline{t}_S < t_C$ for any $\sigma \in [1/(1 - F), \bar{\sigma}]$. Otherwise, there exists $\sigma^* \in [1/(1 - F), \bar{\sigma}]$ such that $\underline{t}_S \lesseqqgtr t_C$ if $\sigma \lesseqqgtr \sigma^*$ for $\sigma \in [1/(1 - F), \bar{\sigma}]$.*

As σ declines, it becomes more likely that $\sigma < \sigma^*$ and, consequently, that $\underline{t}_S < t_C$. That is, the lower the elasticity of substitution is, the more likely it is that the modern transportation technology is adopted at the symmetric pattern but not at the core-periphery pattern. This is explained as follows. As the elasticity declines, the user fee declines at the symmetric pattern but rises at the core-periphery pattern, which we have seen earlier by the comparative statics analysis. Consequently, it becomes more likely that the transportation cost at the former pattern falls short of the counterpart at the latter pattern.

4.2 Effect of F

Next, I examine the effect of F. In Fig. 2, the $t_S(F)$ curve shows the measure of transportation cost at the symmetric pattern (t_S) as a function of F, given σ and γ. At its turning point, namely, at $F = \bar{F}$, $\max_{t_S} \Omega(t_S) = 0$ and therefore (17) has a unique solution, t_S^0. By construction, the increasing part of the curve gives $\underline{t}_S$, which is a convex function of F. On the other hand, the $t_C(F)$ curve shows the measure of transportation cost at the core-periphery pattern (t_C). It is increasing and a convex function of F. Both the $t_S(F)$ and $t_C(F)$ curves cut the vertical axis at γ. Furthermore, vertical line $F = \rho$, which does not appear in the figure, has a double significance. First, only the region at its left is relevant since ρ is the upper bound of F that satisfies Assumption 1. Second, (22) implies that the line is an asymptote of the $t_C(F)$ curve.

____________@Insert Fig. 2 around here ____________

As an illustration, consider the case where $\sigma = 2$ ($\rho = 0.5$). The first panel in Fig. 2 describes the case with $\gamma = 5$, for which $\bar{F} = 0.0911$. Here, over the interval with $F \in \left(0, \min[\bar{F}, \rho]\right]$, the $t_S(F)$ curve lies above the $t_C(F)$ curve, that is, $\underline{t}_S > t_C$. Now, suppose that γ gradually declines from 5 with σ being kept at 2. Then, both the $t_S(F)$ and $t_C(F)$ curves shift downward (recall that $\partial \underline{t}_S/\partial\gamma > 0$ and that $\partial t_C/\partial\gamma > 0$). As soon as γ drops to 3.258, the increasing part of the $t_S(F)$ curve begins to intersect the $t_C(F)$ curve at positive F. Thus we have entered the second phase, which is represented by the case with $\gamma = 2$ (see Fig. 2 (b)). Let us denote the value of F at the intersection by $F^* \in (0, \bar{F}]$. That is, $\underline{t}_S \lesseqqgtr t_C$, if $F \lesseqqgtr F^*$, respectively, provided that $F \in \left(0, \min[\bar{F}, \rho]\right]$. As γ falls further, F^* rises, and eventually the two curves come to intersect each other at $F = \bar{F}$ when $\gamma = 1.286$. Thereafter, the $t_S(F)$ curve intersects the $t_C(F)$ curve not at its increasing part but at its decreasing part: $\underline{t}_S < t_C$ for $F \in \left(0, \min[\bar{F}, \rho]\right]$. This is the third phase, represented by the case where $\gamma = 1.1$ (see Fig. 2 (c)). Let us define $\Psi(\sigma,\gamma)$ and $\Phi(\sigma,\gamma)$ as $\Psi(\sigma,\gamma) \equiv \left(1+\gamma^{\sigma-1}\right)\left(1+\sigma\gamma^{\sigma-1}\right)(\sigma-1)^2 - 8\sigma^2$ and $\Phi(\sigma,\gamma) \equiv \bar{F}\left[2\sigma^2 - (\sigma-1)^2\right] - 2(\sigma-1)$, respectively. The next proposition, whose proof is relegated to Appendix, states the above findings in a more rigorous manner.

Proposition 4. *i) If $\Psi(\sigma,\gamma) > 0$, then $\underline{t}_S > t_C$ for any $F \in \left(0, \min[\bar{F}, \rho]\right]$.*
ii) If $\Psi(\sigma,\gamma) < 0$ and $\Phi(\sigma,\gamma) \le 0$, then there exists $F^* \in \left(0, \min[\bar{F}, \rho]\right]$ such that

$$\underline{t}_S \lesseqqgtr t_C \text{ if } F \lesseqqgtr F^* \text{ for any } F \in \left(0, \min[\bar{F}, \rho]\right]. \tag{23}$$

iii) If $\Psi(\sigma,\gamma) < 0$ and $\Phi(\sigma,\gamma) > 0$, then $\underline{t}_S < t_C$ for any $F \in \left(0, \min[\bar{F}, \rho]\right]$.

Suppose that $\Psi(\sigma,\gamma) < 0$ and $\Phi(\sigma,\gamma) \le 0$. Then, as F declines, it becomes more likely that $F < F^*$ and that $\underline{t}_S < t_C$. In other words, it becomes more likely that the modern transportation technology is adopted at the symmetric pattern rather than at the core-periphery pattern. This is explained as follows. Suppose that the fixed cost declines. If the user fee were kept constant, the profit of the transportation sector would increase. To break even, the fee and, therefore, the transportation cost need to decline since the elasticity of the cross-border demand is smaller than 1 (recall that $\partial \underline{t}_S/\partial F > 0$ and that $\partial t_C/\partial F > 0$). Now, we know that the elasticity is positive at the symmetric pattern while it is 0 at the core-periphery pattern, that is to say, it is greater at the former pattern. Consequently, the transportation cost needs to decline more sharply at the former pattern.

4.3 Effect of γ

By defining $\Xi(\sigma, F) \equiv \rho(\sigma-1)(2-F)K_C - 2$, we obtain the following result for the effect of γ, whose proof is relegated to Appendix.

Proposition 5. *i) If $\Xi(\sigma, F) < 0$ and $\Omega\left(K_C(\sigma-1)\right) \leq 0$, then $\underline{t}_S > t_C$ for any $\gamma \in (1, \bar{\gamma}]$.*
ii) If $\Xi(\sigma, F) < 0$ and $\Omega\left(K_C(\sigma-1)\right) > 0$, or if $\Xi(\sigma, F) = 0$, then there exists $\gamma^* \in (1, \bar{\gamma}]$ such that

$$\underline{t}_S \lesseqqgtr t_C \text{ if } \gamma \lesseqqgtr \gamma^* \text{ for any } \gamma \in (1, \bar{\gamma}]. \tag{24}$$

iii) If $\Xi(\sigma, F) > 0$, then $\underline{t}_S < t_C$ for any $\gamma \in (1, \bar{\gamma}]$.

Consider case ii). When γ is lower, it is more likely that $\underline{t}_S < t_C$. In other words, the more efficient the technology is, the more likely it is to be adopted at the symmetric pattern but not at the core-periphery pattern. This is explained as follows. Suppose that we are now provided with a more efficient modern technology. *If the user fee were kept constant*, a 1 % decrease in γ would result in a 1% decrease in the measure of transportation cost (t_S or t_C) no matter which distribution pattern prevails in the economy. At the symmetric pattern, however, the lower transportation cost, being associated with a larger cross-border demand, implies a higher revenue of the transportation sector. Consequently, the user fee needs to decline to break even. Hence, a 1% decrease in γ actually brings about more than 1% decrease in t_S. At the core-periphery pattern, to the contrary, the amount of the cross-border demand does not depend on the transportation cost. Therefore, the revenue does not change and the user fee remains constant. Thus, a 1% decrease in γ brings about merely 1% decrease in t_C.

5 Stable Long-Run Equilibrium Pattern

In this section, I study the distribution pattern of entrepreneurs that emerges for a given transportation technology. First of all, it must be a long-run equilibrium pattern at which no entrepreneur has an incentive to migrate. Let V_1 and V_2 be the levels of indirect utility for an entrepreneur in respective regions, and $\hat{V} \equiv V_1/V_2$.[10] Then, a distribution pattern is a long-run equilibrium pattern when the following condition is satisfied:

$$\begin{cases} \hat{V} = 1 & \text{if} \quad \lambda \in (0,1) \\ \hat{V} \geq 1 & \text{if} \quad \lambda = 1 \\ \hat{V} \leq 1 & \text{if} \quad \lambda = 0. \end{cases} \tag{25}$$

In other words, at the equilibrium pattern, the levels of the indirect utility must be equal in the two regions when there are entrepreneurs in both regions. When they are concentrated in one region, instead, they could not enjoy a higher level of utility even if they migrated to the other region unilaterally.

Among the long-run equilibrium patterns, furthermore, I focus on stable ones. Suppose that the economy is initially characterized by the long-run equilibrium pattern, and then a small mass of entrepreneurs migrates from one region to the other. I say that the equilibrium pattern is stable if the indirect utility in the region they arrive at becomes lower than that in the region they has left. Thus, when $\hat{V} \neq 1$, the equilibrium pattern is necessarily stable. When $\hat{V} = 1$, on the other hand, it is stable if $\mathrm{d}\hat{V}/\mathrm{d}\lambda < 0$ and unstable if $\mathrm{d}\hat{V}/\mathrm{d}\lambda \geq 0$.[11] To sum up, we have the following definition.

Definition 2. (SLE pattern) *For a given transportation technology $i \in \{T, M\}$, a distribution pattern $k \in \{S, C\}$ is said to be a stable long-run equilibrium pattern or an* ***SLE pattern*** *if*
i) (25) is satisfied; and, in addition,
ii) either or both of $\hat{V} \neq 1$ and $\mathrm{d}\hat{V}/\mathrm{d}\lambda < 0$ holds.

The set of these conditions is referred to as an SLE condition.

5.1 SLE condition for the Symmetric Pattern

First, let us concentrate on the symmetric pattern. Since $\hat{V} = 1$, it is always a long-run equilibrium pattern. Furthermore, note that

$$\frac{\mathrm{d}\hat{V}}{\mathrm{d}\lambda} = 4 \cdot \frac{t^{\sigma-1} - 1}{t^{\sigma-1} + 1} \cdot \frac{(\sigma-1)(2-\sigma)t^{\sigma-1} + \sigma(\sigma+1)}{(\sigma-1)\left[(\sigma-1)t^{\sigma-1} + \sigma + 1\right]}.$$

[10] A tedious computation yields $\hat{V} = \left(t^{1-\sigma} + \hat{Z}\right) / \left[\hat{P}\left(1 + t^{1-\sigma}\hat{Z}\right)\right]$ where $\hat{P} \equiv P_1/P_2$ and

$$\hat{Z} \equiv \frac{Z_1}{Z_2} = \frac{(1-\lambda)(\sigma-1)t^{\sigma-1} + \lambda(\sigma+1)}{\lambda(\sigma-1)t^{\sigma-1} + (1-\lambda)(\sigma+1)}.$$

[11] I consider that the distribution pattern is unstable when $\mathrm{d}\hat{V}/\mathrm{d}\lambda = 0$. One could obtain the similar results considering otherwise.

If $\sigma \leq 2$, then $\mathrm{d}\hat{V}/\mathrm{d}\lambda > 0$ and the pattern is unstable. To focus on an interesting case, let us preclude this possibility, assuming that $\sigma > 2$, which is known as a no-black-hole condition in the literature.

Assumption 2. (no-black-hole condition) $\sigma > 2$.

If the no-black-hole condition is satisfied, we have $\mathrm{d}\hat{V}/\mathrm{d}\lambda \lesseqqgtr 0$ if $t \gtreqqless \tau_S$ where $\tau_S \equiv [\sigma(\sigma+1)/(\sigma-1)(\sigma-2)]^{1/(\sigma-1)}$. By construction, the symmetric pattern is stable if and only if $t > \tau_S$. Here, one would notice that τ_S corresponds to the "break point" in Fujita, Krugman and Venables (1999): as the transportation cost gradually declines from a sufficiently high level, the symmetric pattern becomes unstable, that is, the symmetry breaks, at a certain point, namely, the break point.

Proposition 6. *Suppose that a transportation technology $i \in \{T, M\}$ is adopted. Then, the symmetric pattern is an SLE pattern if and only if $t > \tau_S$ is satisfied, where $t = t_T$ if $i = T$, and $t = \underline{t}_S$ if $i = M$.*

Now, it is useful to derive several properties of τ_S. First, it depends only on σ. Second, it is a decreasing function of σ due to the no-black-hole condition. Finally, it approaches 1 as σ goes to the positive infinity, and approaches the positive infinity as σ goes to 2 from above. For the case where $\gamma = 1.1$ and $F = 0.1$, τ_S is depicted in Fig. 1 as a $\tau_S(\sigma)$ curve. Proposition 6 states that the symmetric pattern is an SLE pattern if parameters lie above the $\tau_S(\sigma)$ curve.

5.2 SLE condition for the Core-Periphery Pattern

Next, let us turn to the core-periphery pattern. Without loss of generality, I analyze the case where all the entrepreneurs are concentrated in region 1, that is, $\lambda = 1$.

Since $\hat{V} = 2\sigma t^{\sigma} / \left[(\sigma-1)t^{2(\sigma-1)} + \sigma + 1\right]$, we have $\hat{V} \gtreqqless 1$, as $\Gamma(\sigma, t) \gtreqqless 0$, where

$$\Gamma(\sigma, t) \equiv 2\sigma t^{\sigma} - (\sigma-1)t^{2(\sigma-1)} - (\sigma+1).$$

Several observations follow with respect to $\Gamma(\sigma, t)$. First, $\Gamma(\sigma, 1) = 0$ for any σ. Second, since $\partial\Gamma(\sigma,t)/\partial t = 2t^{\sigma-1}\left[\sigma^2 - (\sigma-1)^2 t^{\sigma-2}\right]$, we have $\partial\Gamma(\sigma,t)/\partial t \gtreqqless 0$, if $t \lesseqqgtr \tilde{t}$ for any $\sigma > 2$, where $\tilde{t} \equiv [\sigma/(\sigma-1)]^{2/(\sigma-2)}$. Finally, $\lim_{t\to\infty} \Gamma(\sigma, t) < 0$ for any $\sigma > 2$. From those observations, we can figure out how $\Gamma(\sigma, t)$ changes with t for a given value of σ. As t rises from 1, $\Gamma(\sigma, t)$ at first grows from 0 until t reaches $\tilde{t}$, then declines, becomes equal to 0 when t hits a certain value, $\tau_C > \tilde{t}$, and finally becomes negative. Therefore, we have

$$\Gamma(\sigma, t) \gtreqqless 0 \text{ if } t \lesseqqgtr \tau_C \tag{26}$$

for a given $\sigma > 2$ (remember that $t > 1$). Thus, if $t < \tau_C$, we have $\hat{V} > 1$: the core-periphery pattern is an SLE pattern. If $t = \tau_C$, it is a long-run equilibrium pattern since $\hat{V} = 1$; but is unstable because $\mathrm{d}\hat{V}/\mathrm{d}\lambda = 0$. Finally, if $t > \tau_C$, it is not a long-run equilibrium pattern. One may notice that τ_C corresponds to the "sustain point" in Fujita, Krugman and Venables (1999): as the transportation cost gradually decline from a sufficiently high level, the core-periphery pattern becomes an SLE pattern, that is, it becomes sustainable at a certain point, namely, at the sustain point.

I have established the following proposition.

Proposition 7. *Suppose that a transportation technology $i \in \{T, M\}$ is adopted. Then, the core-periphery pattern is an SLE pattern if and only if $t < \tau_C$ is satisfied, where $t = t_T$ if $i = T$, and $t = \underline{t}_S$ if $i = M$.*

Now, it is useful to derive several properties of τ_C. First, it depends only on σ. This is because $\Gamma(\sigma, t)$ does not depend on the parameters other than σ and t. Second, it is a decreasing function of σ.[12] Third and finally, it approaches 1 as σ goes to the positive infinity, and approaches the positive infinity as σ goes to 2 from above.[13] Notice that all of these properties are similar to the counterparts of τ_S, though their derivation is much more complicated for τ_C. For the case where $\gamma = 1.1$ and $F = 0.1$, τ_C is depicted in Fig. 1 as a $\tau_C(\sigma)$ curve. The core-periphery pattern is an SLE pattern if parameters lie below the $\tau_C(\sigma)$ curve.

5.3 SLE conditions and Distribution Patterns: A Comparison

One important result concerns the relative sizes of τ_S to τ_C. By a tedious computation, I derive the following proposition, whose proof is relegated to Appendix.

Proposition 8. *$\tau_C > \tau_S$ for a given value of $\sigma > 2$.*

This indicates that the $\tau_C(\sigma)$ curve lies above the $\tau_S(\sigma)$ curve in Fig. 1. As should be clear from the preceding discussion, furthermore, the proposition means that the "sustain point" exceeds the "break point". This result is the same as the one shown through a numerical simulation by Fujita, Krugman and Venables (1999) and shown analytically by Forslid and Ottaviano (2003).

The following corollary, whose proof is relegated to Appendix, immediately follows:

[12] Differentiating $\Gamma(\sigma, \tau_C) = 0$ yields

$$\frac{\mathrm{d}\tau_C}{\mathrm{d}\sigma} = -\frac{E + 2\tau_C^\sigma G \ln \tau_C}{2(\sigma-1)^2 \tau_C^{\sigma-1} H}.$$

Here, $E \equiv 1 - 2\tau_C^\sigma + \tau_C^{2(\sigma-1)} = \left[\tau_C^{2(\sigma-1)} - 1\right]/\sigma > 0$ where (26) is used. Furthermore, $\tau_C > \tilde{t}$ implies that $G \equiv (\sigma-1)\tau_C^{\sigma-2} - \sigma > 0$ and that $H \equiv \tau_C^{\sigma-2} - [\sigma/(\sigma-1)]^2 > 0$. Therefore, the differential is negative.

[13] Since $\lim_{\sigma \to 2} \tilde{t} = \infty$ and $\tau_C > \tilde{t}$, we must have $\lim_{\sigma \to 2} \tau_C = \infty$.

Corollary 1. *Suppose that the traditional technology is adopted. If $k \in \{S, C\}$ is not an SLE pattern, then $l \neq k$ ($l \in \{S, C\}$) is an SLE pattern.*

6 Interdependence of Transportation Technology and Economic Geography

So far, we have discussed the adoption of transportation technology given the economic geography in Sections 3 and 4, and, subsequently, the SLE distribution pattern given the transportation technology in Section 5. The remaining task is *the simultaneous determination of the transportation technology and the economic geography*: what combination of the technology and the geography is realized in the economy?

6.1 Maintainability

Yet, first of all, when should we consider a particular combination to be "realized"? There would be a variety of answers with different levels of strictness in the criteria; but, in this paper, I adopt a simple one. For one thing, the transportation technology must be indeed adopted in the economy in the light of Definition 1. Otherwise, either the transportation sector, if any, would suffer a loss (the modern technology would not be available to consumers) or consumers would attempt to use the other technology (the relevant undercutting condition would not be satisfied). Next, the distribution pattern must be an SLE pattern. Otherwise, the pattern would be going to change. That is, if it were not a long-run equilibrium pattern, further adjustment would occur in the migration process of entrepreneurs. If it were not stable, on the other hand, a small perturbation would provoke an influx of migration. A set of these two criteria gives the following definition of maintainability.

Definition 3. (maintainability) *A pair (i, k) is said to be* ***maintainable*** *if the transportation technology $i \in \{T, M\}$ is adopted in the economy given the distribution pattern $k \in \{S, C\}$ and, at the same time, the distribution pattern $k \in \{S, C\}$ is an SLE pattern given the transportation technology $i \in \{T, M\}$.*

Using the results obtained so far, we can find the range of parameters for which each of the four possible pairs, (T, S), (M, S), (T, C) and (M, C), is maintainable. Fig. 3 depicts the same situation as Fig. 1 ($\gamma = 1.1$ and $F = 0.1$) does. The sets of (σ, t_T)'s that make pairs (T, S), (M, S), (T, C) and (M, C) maintainable, respectively, are represented by the shaded areas in Figs. 3. (a)-(d).

____________@Insert Fig. 3 around here ____________

It is worth noting that the concept of maintainability is *exclusive* in terms of the transportation technology. That is to say, if pair (i, k) is maintainable, then pair (j, k) with $j \neq i$ is not maintainable: whenever a particular technology constitutes a maintainable pair, the other technology does not do so as long as the distribution pattern is the same. This result follows directly from the definition of the adoption of technology. On the contrary, *the concept of maintainability is not necessarily exclusive in terms of the distribution pattern*: that pair (i, k) is maintainable does not preclude the possibility that pair (i, l) with $l \neq k$ is also maintainable. This can be easily verified from the fact that the shaded areas in (a) and (b) (and also those in (c) and (d)) of Fig. 3 have a non-empty intersection. Thus, the same technology can constitute a maintainable pair with each of the two distribution patterns.

6.2 Lock-in Effect

Paying attention to the interdependence of transportation technology and economic geography enables us to discuss the possibility of a *lock-in effect*. It concerns the situation in which a transportation technology fails to be adopted given a particular distribution pattern despite the fact that it could be adopted if the distribution pattern were different. More specifically, this is a situation in which both pair (T, k) and pair (M, l) with $l \neq k$ are maintainable. Here, if the realized pattern happens to be k, the economy is locked in to the inferior state where the traditional technology is adopted: if the realized pattern is not k but l, it succeeds in adopting the modern technology and is locked in to the superior state. The following statement gives a formal definition:

Definition 4. (lock-in effect) *The economy is* ***locked in*** *if both pair (i, k) and pair (j, l) are maintainable for $i \in \{T, M\}$, $k \in \{S, C\}$, $j \in \{T, M\}$ with $j \neq i$, and $l \in \{S, C\}$ with $l \neq k$.*

It is worth while studying the lock-in effect not only because it is theoretically significant but also because it has some important implications and applications.

First, the lock-in effect justifies a policy intervention. If the inferior state with the traditional technology is realized once, the economy cannot attain the superior state with the modern technology by a decentralized mechanism when the lock-in effect is present. To escape from this poverty trap, consequently, some sort of policy intervention is necessary. The government may, for example, take a certain measure stimulating entrepreneurs to change their locations so that the pair associated with the inferior state becomes not maintainable.

Second, the lock-in effect provides us with one explanation for a puzzling fact that some countries succeed in adopting the modern technology while the others cannot, even if their economic environments are not much different. Our explanation is that there is no intrinsic divergence between the two groups of countries: some are luckier than the others. Here, usual argument concerning the multiple equilibria applies. That is, we are attempting to reveal what combination of the transportation technology and the economic geography *can be* realized in the economy but not what combination *is* actually realized. The latter question would be answered in terms of the factors which are out of consideration in this paper, such as historical accidents.

An immediate question is which distribution pattern is associated with the traditional technology. It may be a symmetric pattern when pair (T, S) and pair (M, C) are maintainable. Or, it may be a core-periphery pattern when pair (T, C) and pair (M, S) are maintainable. Mobilizing the requirements for the maintainability, we can easily establish the following proposition, which is thus presented without a proof.

Proposition 9. *i) The economy is locked in if all of the following conditions, a)-d), are satisfied:*
a) either $\sigma > \bar{\sigma}$ *or* $t_T < \underline{t}_S$*,*
b) $t_T > \tau_S$*,*
c) $t_T \geq t_C$*, and*
d) $t_C < \tau_C$*.*
In this case, the symmetric pattern is associated with the traditional technology while the core-periphery pattern is associated with the modern technology.
ii) The economy is locked in if all of the following conditions, a)-d), are satisfied:
a) $\sigma \leq \bar{\sigma}$*,*
b) $\underline{t}_S \leq t_T < t_C$*,*
c) $\underline{t}_S > \tau_S$*, and*
d) $t_T < \tau_C$*.*
In this case, the core-periphery pattern is associated with the traditional technology while the symmetric pattern is associated with the modern technology.

In Fig. 4, which is drawn for the same values of parameters as Fig. 1 ($\gamma = 1.1$ and $F = 0.1$), the shaded area represents the set of (σ, t_T)'s for which the five conditions in i) are simultaneously satisfied. Obviously, it is the intersection of the set for which pair (T, S) is maintainable and that for which pair (M, C) is maintainable.

____________@Insert Fig. 4 around here ____________

The other case, described in ii) of Proposition 9, is not plausible to occur. When $\gamma = 1.1$ and $F = 0.1$, there is no (σ, t_T)'s for which the four conditions in ii) are satisfied at the same time. Then, one might guess that the same applies for any γ and F. Since the conditions are highly nonlinear and some of them take an implicit form, however, it is not possible to prove it analytically. By numerical simulation, we can show that the case described in ii) is unlikely to occur.[14]

To sum up, there is a possibility that the economy is locked in to the inferior state with the traditional technology when it is characterized by the symmetric pattern. When it is characterized by the core-periphery pattern, instead, it is unlikely that the economy is locked in to the inferior state.

6.3 An Application: Economic Development and the Endogenous Change of Transportation Technology

Applying the concept of maintainable pair, we can examine how the adopted transportation technology and the emerging economic geography change as a result of an exogenous shock in an economic environment. In this subsection, I examine the change brought by a gradual decline in F, the fixed cost measured by the final good, as an illustration. The decline can be regarded as one of the consequences of economic development when one takes a sufficiently long time horizon.[15] It would be also possible to analyze the decline in γ, the inverse measure of the efficiency of the modern transportation technology, which might be another consequence of economic development. It is, however, omitted due to the limitation of space.

I assume that all the adjustments, not only the short-run adjustment in prices, consumption and production but also the long-run adjustment in entrepreneurs' location take place rapidly compared to the speed of the decline in F. That is to say, we consider the following world of artifact. At the beginning of each time period, F declines by a small amount. Then, F remains constant up until the end of that period. All the while, the adjustments are made and a maintainable pair is realized. Then, at the beginning of the next period, F declines again. It remains constant for a while and the adjustments follow; and the process continues. Of course, for a more rigorous and throughout treatment, it would be necessary to formulate the dynamic process explicitly. However, it would demand sizable length of

[14] In order for the four conditions to be satisfied, it is necessary that the value of σ at which the increasing part of the $t_S(\sigma)$ curve ($\underline{t}_S(\sigma)$ curve) intersects the $\tau_S(\sigma)$ curve is lower than $\bar{\sigma}$ (see Fig. 4). If this is not met, $\sigma \leq \bar{\sigma}$ and $\underline{\sigma} > \tau_S$ cannot be satisfied at the same time, since the $\tau_S(\sigma)$ curve is downward-sloping. Another necessary condition is that the $\underline{t}_S(\sigma)$ curve intersects the $t_C(\sigma)$ curve at a greater value of σ than the former intersects the $\tau_S(\sigma)$ curve. If this is violated as in Fig. 4, $\underline{t}_S \leq t_T < t_C$ and $\underline{t}_S > \tau_S$ cannot hold simultaneously, because both the $t_C(\sigma)$ curve and the $\tau_S(\sigma)$ curve are downward-sloping. A simulation analysis suggests that no relevant combination of parameters satisfies these two necessary conditions at the same time.

[15] In the literature of economic geography, it is not rare that economic development is expressed, explicitly or implicitly, by the gradual change in an exogenous parameter, noticeably, the expansion of population or the decline in transportation cost. The examples abound in Fujita, Krugman and Venables (1999).

analysis without yielding much additional insight. Therefore, I rather take a more or less intuitive approach, sacrificing formality.

In Fig. 5, $\underline{t}_S(F)$ and $t_C(F)$ curves describe $\underline{t}_S$ and t_C, respectively, as functions of F as in Fig. 2, for $\sigma = 4.5$ and $\gamma = 1.1$. In addition, τ_S and τ_C, which are now constant, are shown by horizontal lines.[16] Now, I pick up three representative cases and, with a help of the figure, describe the trajectory along which the economy evolves over time.

In the first case, the transportation cost associated with the traditional technology is relatively high. In Fig. 5, the initial values of F and t_T are represented by point A. Because (T, S) is a unique maintainable pair for those parameter values, it is natural for us to predict that (T, S) is realized in the economy.

____________@Insert Fig. 5 around here ____________

As the economy develops and F declines, we move along the horizontal line passing through point A. As soon as the economy reaches point B where $t_C = \tau_C$, the core-periphery pattern becomes an SLE pattern given the modern technology. Then, both (T, S) and (M, C) become a maintainable pair. Here, we encounter the problem of the multiplicity of maintainable pair. To avoid an unnecessary complication, I take a rather ad hoc approach of law of inertia, which says that the economy moves toward the state with the smallest friction. If the economy shifts from the state with (T, S) to the state with (M, C), both the transportation technology and the distribution pattern need to change. However, it can remain at the state with (T, S) involving no change in the technology nor in the pattern. In this sense, the "friction" incurred in the latter scenario is smaller than that in the former. Therefore, I consider that the economy sticks to (T, S).

The economy enters a different state when F hits $\bar{F}$ at point C. For this value of F, the modern technology becomes available and undercuts the traditional technology given the symmetric distribution. Therefore, (M, S) becomes a maintainable pair whereas (T, S) ceases to be so. Now, we have two maintainable pairs, (M, S) and (M, C). Applying the law of inertia, one can conclude that (M, S) will be realized in the economy.[17] Here, the economy jumps to point D; and the transportation cost decreases by a discrete amount, that is, the change is discontinuous. Afterward, the transportation cost decreases continuously as t_S moves along the $\underline{t}_S(F)$ curve.

The next turning point comes at point E. As soon as the economy reaches it, the symmetric pattern becomes unstable and ceases to be an SLE pattern or "breaks", because $\underline{t}_S$

[16]The parameter values give $\bar{F} = 0.104$, $t_S^0|_{F=\bar{F}} = 1.491$, $\tau_S = 1.346$ and $\tau_C = 1.368$.

[17]The shift from the state with (T, S) to that with (M, S) involves a change only in the technology while the shift to the state with (M, C) involves changes in both the technology and distribution pattern. Thus, the former shift incurs smaller friction than the latter.

is no longer higher than τ_S. Therefore, (M, S) ceases to be a maintainable pair. Notice that (M, C) has already been a maintainable pair. It now becomes a unique maintainable pair. Thus, we can predict that the state changes from that with (M, S) to that with (M, C). Recall that the adjustment in the entrepreneurs' location is assumed to be sufficiently rapid compared to the change in F. As a limiting case, we might consider that the adjustment is made immediately. Then, the economy jumps from point E to point F with a discrete decrease in the transportation cost. After this change, it evolves along with the $t_C(F)$ curve. Here, the transportation cost gradually declines.

Next, let us turn to the second case where the transportation cost associated with the traditional technology is of moderate size. The initial values of F and t_T are represented by point G in Fig. 5. For those values, we have two maintainable pairs, (T, S) and (T, C). Our framework cannot prescribe from which pair the economy starts.

On the one hand, suppose that (T, S) is initially chosen. As F declines, it moves along the horizontal line passing through point G. Suppose that the economy reaches at point H. *If it were characterized by the core-periphery pattern*, the modern technology, which would have been available, now could undercut the traditional technology: (M, C) becomes a maintainable pair and (T, C) ceases to be so. Nonetheless, the modern technology is still not available *given the symmetric pattern*. Therefore, (T, S) continues to be a maintainable pair. Here, we end up with the two maintainable pairs, (M, C) and (T, S). This is the situation with the lock-in effect. By the law of inertia, the latter remains to be realized in the economy. After it comes to point I where $t_T = t_S$, the traditional technology is undercut by the modern technology, which has been available, given the symmetric pattern. Therefore, the state will switch to (M, S). Then, the economy traces the same path as in the previous case.

On the other hand, suppose that (T, C) is initially realized. As has been discussed, the traditional technology is undercut by the modern technology, given the core-periphery pattern, after point H. Therefore, the economy shifts to the state with (M, C) and enjoys the superior modern technology, whereas, in the previous scenario, it sticks to the state with (T, S). This is an example of how history matters when the lock-in effect is present. Finally, after point H, there is no change in the state; and the transportation cost continuously declines along with the $t_C(F)$ curve.

The third and the final case, in which the economy starts from point J, is not too interesting: there is always a unique maintainable pair; and the modern technology replaces the traditional one as soon as the former comes to undercut the latter.

Several observations follow. First, our framework can provide a complete explanation for why and how the adopted transportation technology and the emerging economic geography change as a result of the decline in F. In the explanation, their interdependence plays a critical role. Second, a small difference in the initial values of parameters may result in a big difference in the paths of the transportation cost. This is because it can provoke the divergence in the adopted technology and the realized geography. Third, even with the same parameter values, an economy may experience different paths depending on the initial geography, as is described by the second case. This occurs when there exist multiple maintainable pairs. Finally, our framework gives a story often uttered in the standard literature, the story that the symmetric distribution breaks and then the core-periphery pattern emerges as a result of economic development.

7 Concluding Remarks

In this paper, I have studied the interdependence of economic geography and transportation technology. Constructing a simple two-region model, I have examined the conditions for the modern transportation technology to be adopted in an economy. In particular, the impact of economic geography upon the adoption of the modern technology has been explored. Furthermore, I have discussed which combination of the economic geography (symmetric or core-periphery pattern) and the transportation technology (traditional or modern technology) is to be realized in an economy. Among others, the possibility that it is locked in to an inferior state has been shown. When it occurs, the economy fails to adopt the modern technology at a given economic geography, although it could successfully adopt the technology if the economic geography were different. Finally, I have examined the changes in the adopted transportation technology and the realized economic geography due to a gradual change in an exogenous factor, which is associated with economic development.

It should be noted nevertheless that this study is only a first step toward the throughout understanding of the endogenous determination of transportation technology. Among the limitations of this paper, the followings seem to be especially important. First, I have relied on a two-region model, which allows us to take into account only the symmetric and the core-periphery patterns as a distribution of economic activities. In the reality, however, there are more than two regions, or it may be even better to consider that economic activities are distributed over a continuous space. It would be necessary for us to recognize a richer variety of economic geography. Second, we have considered only one class of the modern transportation technology. By admitting more than one class, one would be able to discuss some interesting problems such as the selection between a "heavy" transportation technology with higher fixed cost plus lower operation cost, and a "light" technology with lower fixed cost plus higher operation cost. Third and finally, we have focused upon the special situation in which the transportation sector earns no profit. In recent years, however, it has been becoming more and more common in many developed countries that the transportation sector, in particular, railways, is run by private companies. It is plausible that its profit-seeking behavior alters our results drastically.

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Appendix

In some of the subsequent proofs, common notations are used: $D^0 \equiv \underline{t}_S - t_C$, $D^1_x \equiv \partial\underline{t}_S/\partial x - \partial t_C/\partial x$ and $D^2_x \equiv \partial^2\underline{t}_S/\partial x^2 - \partial^2 t_C/\partial x^2$ for $x \in \{\sigma, F, \gamma\}$.

Proof of Lemma 1.

If the modern technology is available and feasible, and undercuts the traditional technology, ii) of Definition 1 indicates that the modern technology is adopted. (Note that the traditional technology is always available and feasible.) Next, if the modern technology is unavailable and/or infeasible, it follows from i) of Definition 1 that the traditional technology is adopted. Finally, if the modern technology is available and feasible but does not undercut the traditional technology, ii) of Definition 1 implies that the traditional technology is adopted. QED

Proof of Proposition 4.

At $F = \bar{F}$, on the one hand, the $t_S(F)$ curve becomes a vertical line while the $t_C(F)$ curve has a positive slope provided that $\bar{F} < \rho$. For $F < \bar{F}$, on the other hand, $\underline{t}_S < t^0_S$ by construction. It implies that $\underline{t}_S < 2\sigma\gamma/(\sigma-1)(2-F)$ since (17) prescribes that $\underline{t}_S^{\sigma-1} = \left[(2-F)\underline{t}_S - 2\gamma\right]/(F\underline{t}_S)$. Therefore, we have

$$D^1_F|_{\underline{t}_S = t_C} = \frac{(K_C)^2\sigma(\sigma-1)(\sigma+1)F\gamma t_C}{2\sigma\gamma - (\sigma-1)(2-F)\underline{t}_S} > 0$$

for any $F > 0$: the increasing part of the $t_S(F)$ curve ($\underline{t}_S(F)$ curve) is steeper than the $t_C(F)$ curve whenever they pass through the same point. Hence, it is not possible for the two curves to be tangent to each other at any $F \in \left(0, \min[\bar{F}, \rho]\right]$; and, furthermore, whenever they intersect within that interval, the $\underline{t}_S(F)$ curve cuts the $t_C(F)$ curve from below. I refer to this as a *relative steepness property* of the two curves. Now, pay our attention to the neighborhood of $F = 0$. We have $D^0|_{F=0} = 0$ and $D^1_F|_{F=0} = 0$. Moreover, a tedious computation yields $D^2_F|_{F=0} = \gamma\Phi(\sigma,\gamma)/2(\sigma-1)^2$ since $\underline{t}_S = t_C = \gamma$ at $F = 0$ and (17) implies that $(\underline{t}_S - \gamma)/F = (\underline{t}_S + \underline{t}_S^\sigma)/2$. I consider two cases. First, suppose that $\Phi(\sigma,\gamma) > 0$. Then, we have $D^2_F|_{F=0} > 0$. Therefore, $\underline{t}_S > t_C$ in the neighborhood of $F = 0$ with $F > 0$. Because of the relative steepness property, however, the two curves cannot intersect nor cannot be tangent to each other. Consequently, the $t_S(F)$ curve lies above the $t_C(F)$ curve for any $F \in \left(0, \min[\bar{F}, \rho]\right]$. This establishes i). Second, suppose that $\Phi(\sigma,\gamma) < 0$. In this case, $\underline{t}_S < t_C$ in the neighborhood of $F = 0$ with $F > 0$. Furthermore, using (19) and the fact that $\underline{t}_S|_{F=\bar{F}} = \left[(2-\bar{F})/\sigma\bar{F}\right]^{1/(\sigma-1)}$, we have

$$D^0|_{F=\bar{F}} = \frac{2\gamma}{\rho(2-\bar{F})} - \frac{(\sigma-1)\gamma}{\sigma - 1 - \sigma\bar{F}} = -\frac{\gamma}{\sigma}\Psi(\sigma,\gamma).$$

If $\Psi(\sigma,\gamma) \leq 0$, on the one hand, $\underline{t}_S \geq t_C$ at $F = \bar{F}$. By the relative steepness property, therefore, the $t_S(F)$ curve intersects the $t_C(F)$ curve at its increasing part, and only once. Hence, there exists $F^* \in \left(0, \bar{F}\right]$ that satisfies (23). Since $\Psi(\sigma,\gamma) \leq 0$ implies that $\bar{F} < \rho$, such F^* lies in the interval $\left(0, \min[\bar{F}, \rho]\right]$. Thus we have proved ii). If $\Psi(\sigma,\gamma) > 0$, on the other hand, $\underline{t}_S < t_C$ at $F = \bar{F}$. Because of the relative steepness property, it must be true that $\underline{t}_S < t_C$ for any $F \in \left(0, \bar{F}\right]$ and consequently, for $F \in \left(0, \min[\bar{F}, \rho]\right]$. This establishes iii). QED

Proof of Proposition 5.

In parallel with the $t_S(F)$ and $t_C(F)$ curves, we can depict $t_S(\gamma)$ and $t_C(\gamma)$ curves that give t_S and t_C, respectively, as a function of γ given σ and F. The $t_S(\gamma)$ curve turns around at $\gamma = \bar{\gamma}$, where $\max_{t_S} \Omega(t_S) = 0$ and, therefore, $t_S = t_S^0$. Furthermore, its increasing part ($\underline{t}_S(\gamma)$ curve) gives $\underline{t}_S$. Because

$$D_\gamma^1|_{\underline{t}_S = t_C} = \frac{(\sigma-1)t_C\left[(2-F)t_C^2\gamma\right]}{\gamma\left[2\sigma\gamma-(\sigma-1)(2-F)t_C\right]} > 0$$

for any $\gamma < \bar{\gamma}$, moreover, the $\underline{t}_S(\gamma)$ and $t_C(\gamma)$ curves exhibit the relative steepness property that is similar to the counterpart the $\underline{t}_S(F)$ and $t_C(F)$ curves exhibit (see Proof of Proposition 4). First, suppose that $\Theta(\sigma, F) < 0$, which implies that $t_C < \underline{t}_S$ at $\gamma = \bar{\gamma}$, that is, $t_C|_{\gamma=\bar{\gamma}} < t_S^0$. Since the $t_C(\gamma)$ curve is upward sloping, we have $t_C|_{\gamma=1} = K_C(\sigma-1) < t_C|_{\gamma=\bar{\gamma}} < t_S^0$. Two cases are distinguished. On the one hand, suppose that $\Omega\left(K_C(\sigma-1)\right) = \Omega\left(t_C|_{\gamma=1}\right) \leq 0$. In Section 3.1, I have argued that $\Omega(t_S) > 0$ for any $t_S \in (\underline{t}_S, \bar{t}_S)$. Therefore, it must be true that either $t_C \leq \underline{t}_S$ or $t_C \geq \bar{t}_S$ at $\gamma = 1$. Because $\bar{t}_S \geq t_S^0$, the latter contradicts the fact that $t_C|_{\gamma=1} < t_S^0$ and, consequently, we have $t_C \leq \underline{t}_S$ at $\gamma = 1$. The fact that $t_C < \underline{t}_S$ at $\gamma = \bar{\gamma}$ and $t_C \leq \underline{t}_S$ at $\gamma = 1$, together with the continuity and the relative steepness property, implies that the $t_S(\gamma)$ curve lies above the $t_C(\gamma)$ curve for any $\gamma \in (1, \bar{\gamma}]$. Thus we have established i). On the other hand, suppose that $\Omega\left(K_C(\sigma-1)\right) = \Omega\left(t_C|_{\gamma=1}\right) > 0$, which implies that $t_C > \underline{t}_S$ at $\gamma = 1$. Since $t_C < \underline{t}_S$ at $\gamma = \bar{\gamma}$, the two curves intersect with each other, and only once, at some $\gamma \in (1, \bar{\gamma}]$. Therefore, there exists $\gamma^* \in (1, \bar{\gamma}]$ that satisfies (24). Second, suppose that $\Theta(\sigma, F) = 0$, that is, $t_C < \underline{t}_S$ at $\gamma = \bar{\gamma}$. The relative steepness property implies that $t_C < \underline{t}_S$ for any $\gamma \in (1, \bar{\gamma})$. Consequently, (24) still holds if we set $\gamma^* = \bar{\gamma}$. This completes the proof of ii). Third and finally, suppose that $\Theta(\sigma, F) > 0$, that is, $t_C > \underline{t}_S$ at $\gamma = \bar{\gamma}$. Due to the relative steepness property, the $t_S(\gamma)$ curve cannot intersect the $t_C(\gamma)$ curve at its increasing part. Thus, we have iii). QED

Proof of Proposition 8.[18]

According to (26), it is sufficient to show that $\Gamma(\sigma, \tau_S) > 0$ for $\sigma > 2$. Note that $\Gamma(\sigma, \tau_S) = 2\sigma^2(\sigma+1)(\tau_S - K)/(\sigma-1)(\sigma-2)$, where $K \equiv (\sigma^3 - 2\sigma^2 + 4\sigma^2)/\sigma^2(\sigma-2)$. Taking a logarithm, we can obtain $\ln\tau_S - \ln K = \Delta(\sigma)/(\sigma-1)$, where

$$\Delta(\sigma) \equiv (2\sigma-1)\ln\sigma - \ln(\sigma-1) + (\sigma-2)\ln(\sigma-2) + \ln(\sigma+1) - (\sigma-1)\ln(\sigma^3 - 2\sigma^2 + 4\sigma - 2).$$

Three properties of function $\Delta(\sigma)$ are important. First, $\lim_{\sigma\to\infty} \Delta(\sigma) = 0$. Second, $\lim_{\sigma\to\infty} \mathrm{d}\Delta(\sigma)/\mathrm{d}\sigma = 0$. Third and finally, $\mathrm{d}^2\Delta(\sigma)/\mathrm{d}\sigma^2 > 0$ for $\sigma > 2$. The last two properties imply that $\Delta(\sigma)$ is a decreasing function. Together with the first property, consequently, we can say that $\Delta(\sigma) > 0$, which implies that $\Gamma(\sigma, \tau_S) > 0$ by definition. QED

Proof of Corollary 1.

First, suppose that the symmetric pattern is an SLE pattern. According to Proposition 6, $t_T \leq \tau_S$. Since $\tau_S < \tau_C$ by Proposition 8, it must be true that $t_T < \tau_C$, which implies that the core-periphery pattern is an SLE pattern (see Proposition 7). Next, suppose that the core-periphery pattern is not an SLE pattern. Proposition 7 implies that $t_T \geq \tau_C$. However, by Proposition 8, it implies that $t_T > \tau_S$. Hence, the symmetric pattern is an SLE pattern by Proposition 6. QED

[18]The idea of this proof is based on a comment made by Takatoshi Tabuchi, which is greatly appreciated.