International Trade with Increasing Returns in the Transportation Sector

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13 October 2017

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Abstract

In this general equilibrium framework, the transportation sector is modeled as a distinct sector with increasing returns. A more advanced technology has a higher fixed cost but a lower marginal cost of production. Even with both manufacturing firms and transportation firms engage in oligopolistic competition and choose technologies optimally, the model is tractable and results are derived analytically. Technology adoptions in the manufacturing sector and in the transportation sector are reinforcing and multiple equilibria may exist. Firms choose more advanced technologies and the prices decrease when the size of the population is larger.

Keywords: Transportation costs, international trade, the choice of technology, increasing returns, strategic complementarity

JEL Classification Numbers: F10, O14, R40

1. Introduction

As discussed in Rostow (1960) and Chandler (1990), decreases in the levels of transportation costs have significant implications on the performance of an economy. With the important role played by the transportation sector, it is interesting to understand some important features of the transportation sector. First, adoptions of new technologies led to decreases in the levels of transportation costs. There are various examples. For seaborne transport, Harley (1988) shows that the adoption of steam boats decreased seaborne transportation costs of international trade significantly in the process of industrialization. Levinson (2006) shows that the adoption of containers led to significant decreases in the levels of transportation costs. Stopford (2009, chap. 1) provides a detailed discussion of the evolution of technologies for seaborne transportation. For land transport, Summerhill (1997, p. 93) argues that it is unlikely that any single technological or organization innovation was more important in the transition to economic growth in Mexico and Brazil than railroads. By 1913, social saving resulting from using railroads can be as high as 38.5 percent of GDP in Mexico and 22 percent of GDP in Brazil.

Second, new transportation technologies are associated with high levels of fixed costs and thus increasing returns to scale. Levinson (2006) discusses the significance of fixed costs in the transportation sector. For the adoption of containers, ports need to build special terminals to handle containers and transportation companies need to purchase dedicated containerships. By 1986, ports, transportation companies, and shippers around the world had invested 76 billion dollars to carry freight in containers (p. 244). As discussed in Stopford (2009), the movement of some products requires specialized vessels such as oil tanks and increased volume of trade makes the adoption of specialized vessels profitable. The importance of increasing returns in the transportation sector is also discussed in Neary (2001).

Third, there is positive interaction between the manufacturing sector and the transportation sector. Engerman and Sokoloff (1997) discuss the interaction between the manufacturing sector and the transportation sector in the process of economic growth. On the one hand, the construction of railways lowered transportation costs among regions. Engerman and Sokoloff (p. 284) show that farms with easy access to major markets became more specialized and more apt to adopt new crops and products and manufacturing firms close to large markets maintained higher average productivities and were generally operating at larger scales and had higher levels of division of labor. On the other hand, increased degrees of specialization of manufacturing firms led to a higher demand for transportation services. Williamson (2006, chap. 2) discusses evidence on the interaction between the manufacturing sector and the transportation sector in international trade.

In the literature, going back at least to Samuelson (1954), the iceberg transportation cost assumption is commonly used. One appealing feature of this assumption is its tractability. If the transportation sector is not essential to the question to be addressed, this assumption is convenient. However, this assumption could not capture the above significant features in the transportation sector. First, with its exogenous nature, this assumption could not be used to explain the evolution of transportation costs over time. In reality, transportation costs are affected by the volume of trade and the adoption of new transportation technologies. Second, the iceberg technology assumption stipulates constant returns to scale in the transportation sector. Third, with its exogenous nature, it could not be used to address the interaction between the manufacturing sector and the transportation sector. The assumption of iceberg transportation technology is not a good approximation to reality. As shown in Hummels and Skiba (2004a), the iceberg cost assumption is not supported by empirical evidence. In reality, shipping costs are charged on a per unit rather than ad valorem basis. Hummels and Skiba (2004a) show that "the iceberg assumption is neither correct nor innocuous" (p. 1400). Empirical implausibility of the iceberg transport technology is also discussed in McCann (2005). If the transportation sector is essential to the analysis, it is rewarding to depart from the iceberg transportation cost assumption.

This paper presents a general equilibrium model in which transportation costs are endogenously determined by the volume of transportation. This paper contributes to the literature by demonstrating that it is tractable to incorporate increasing returns to scale in the transportation sector into a general equilibrium model in which manufacturing firms and transportation firms engage in oligopolistic competition and choose technologies optimally and by analyzing the interaction between the transportation sector and the manufacturing sector.

First, we study the case that countries are in autarky. We assume that there is no transportation costs for trade within a country. Firms producing manufactured goods are assumed to engage in oligopolistic competition. Manufacturing firms choose their production technologies. A more advanced technology has a higher fixed but a lower marginal cost of production. To determine the pattern of trade, we assume that countries differ in their effective supplies of labor with respect to different goods. We show that the price of a good in a country decreases with the effective supply of labor of individuals in this country. As a result, the prices of goods are different in different countries.

Second, transportation services are needed to make international trade feasible. When population grows, the volume of trade will be large enough to cover the fixed costs of transportation and countries will engage in international trade. Firms providing transportation services between countries choose their technologies to maximize their profits.

The adoption of containers can be used as an example to illustrate the choice of technology in the transportation sector. The adoption of containers is commonly believed to be one of the most important innovations in the transportation sector in the twentieth century. Levinson (2006) provides an interesting study of the history of the adoption of containers. Before the introduction of containers, the loading and unloading of cargos were handled by longshoremen and were labor intensive. With high wage rates, the marginal cost was high. Compared with loading and unloading by longshoremen, containerization is a technology with a higher fixed cost but a lower marginal cost of production. The usage of containers led to sharp rises in the fixed costs of production in the transportation sector. Containerships and container ports are costly. Also, costly specially designed cranes are needed since a container can be as heavy as tens of thousands of pounds. Between 1967 and 1972, the total costs of containerization around the world was close to

$40 billion dollars (in 2005 dollars, see Levinson, p. 214). With containerization, the marginal cost of loading and unloading is low. The cost of building a container port is ten times of that of a traditional port, but a container port can handle twenty times of good of a traditional port. If the volume of transportation is high, it pays to adopt costly containerships and container ports because the fixed costs of containerization can be spread to a high level of output. The adoption of containers also decreased the possibilities of damages of goods transported and possibilities of thefts and led to decreases in the levels of insurance premiums. With sharp decreases in overall costs of transportation, international trade increased dramatically.

We show that there is complementarity of technology adoption between the manufacturing sector and the transportation sector. On the one hand, we show that if the level of transportation technology is exogenously given, a manufacturing firm's level of technology increases with the level of technology in the transportation sector. On the other hand, if the level of manufacturing technology is exogenously given, a transportation firm's level of technology increases with the level of technology in the manufacturing sector. That is, technological improvements in the two sectors are reinforcing. As a result, multiple equilibria may exist and an economy may be trapped in a "poverty trap" with a low level of social welfare.

Our result that more specialized technologies are associated with higher volumes of transportation is consistent with empirical evidence. For example, Stopford (2009, p. 40) shows that ship sizes increased over time.[1] In 1959 the largest tanker afloat has a deadweight tonnage of 122, 867, in 1966 the first very large crude carrier has a deadweight tonnage of 209, 413, and in 1980 it reached 555, 843 deadweight tonnage.

With technologies endogenously chosen in manufacturing and transportation sectors, what determine the levels of technologies? We show that manufacturing firms and transportation firms adopt more advanced technologies and the prices of manufactured goods and transportation services decrease when there is an increase in the size of the population. The reason is that an increase in the size of the market measured by the size of the population leads to a higher level of demand and thus a higher level of output. A higher level of output makes the adoption of more advanced technologies more profitable.

In the literature on increasing returns and industrialization, Murphy et al. (1989) present a stimulating formal model of "big push" based on demand spillovers. In their model, infrastructure

[1] Stapford (2009, p. 538) contains a figure of the increase in the size of container ships over time.

requires a fixed amount of investment. Multiple equilibria may exist. In one equilibrium, there is low level of investment in the manufacturing sector and no investment in infrastructure. In the other equilibrium, high level of investment in the manufacturing sector is accompanied by positive investment in infrastructure. In their model, manufacturing firms engage in monopolistic competition. Because the transportation sector is not modeled explicitly, the impact of the manufacturing sector on the transportation sector is not addressed in their model. In Ciccone (2002), there are two sectors of production. He shows that multiple equilibria may exist if the sector with increasing returns uses intermediate inputs more heavily than the sector with constant returns. In Murphy et al. (1989) and Ciccone (2002), firms face a binary choice in their choices of technologies: either a constant returns technology or an increasing returns technology. In this model, firms face a continuum of technologies. Multiple equilibria result from the complementarities of technology adoptions in the manufacturing sector and the transportation sector.

In the literature on transportation and communication costs, Cassing (1978) models the transportation sector as a distinct sector in a Heckscher-Ohlin framework. There are some significant differences between his model and this one. In his model, the transportation sector exhibits constant returns to scale. As a result, market structure is perfect competition. In this model, the transportation sector has increasing returns to scale. Harris (1995) studies a model in which the communication sector requires a fixed cost but no marginal cost of production. The monopoly firm providing communication service is assumed to charge a price equaling the average cost of production. Manufacturing firms engage in monopolistic competition. The impact of the manufacturing sector on the transportation sector is not addressed in Cassing (1978) and Harris (1995). Bougheas et al. (1999) study a model in which spending on infrastructure decreases transportation costs. One difference between their paper and this one is that in this model the transportation sector is a distinct sector in which firms engage in oligopolistic competition. To study the interaction between industrial location and the transportation sector, Mori and Nishikimi (2002) study a model with three regions. Two competing regions may export the same type of product to the third region. There is no fixed costs in the transportation sector. The transportation cost function is piecewise continuous: when the volume of transportation reaches a critical level, transportation costs decrease. Mori and Nishikimi (2002) show that under this type of cost function, production and trade can be concentrated in one of the two competing regions, rather than evenly distributed between them. However, they do not study the choice of technology in the transportation sector.

The choice of technologies has been studied in Zhou (2007a, 2007b), Hummels and Skiba (2004b), and Gong and Zhou (2014). In Zhou (2007a), though countries only differ in factor endowment *ex ante*, countries may also differ in their chosen technologies *ex post*. The choice of technology is then used to explain the phenomenon of "missing trade" in the sense that the volume of trade observed in reality is smaller than that predicted by traditional trade models. Zhou (2007b) shows that the production functions generated from internal increasing returns and the choice of technologies are similar to those based on external increasing returns. Trade always increases a country's welfare in a two-sector model in which the agricultural sector has constant returns and average cost in the manufacturing sector may decrease without being bounded asymptotically by a given level of marginal cost. Hummels and Skiba study a model in which a monopoly firm chooses between two transportation technologies: the first transportation technology requires no fixed costs, but has a positive marginal cost; the second transportation technology requires a fixed cost, but has no marginal cost. If the volume of trade reaches a critical level, the monopoly transportation firm switches from the first technology to the second one. In Gong and Zhou (2014), manufacturing firms located in a country with a more efficient financial sector choose more advanced technologies and this country has a comparative advantage in the production of manufactured goods. The positive interaction between the transportation sector and the manufacturing sector is not addressed in the above models.

The plan of this paper is as follows. Section 2 studies the equilibrium in which countries are in autarky. Section 3 examines the equilibrium with international trade. Section 4 addresses the interaction between the manufacturing sector and the transportation sector. Section 5 discusses the possibility of the existence of multiple equilibria. Section 6 focuses on the implications of population growth on the choices of technologies and the equilibrium prices. Section 7 identifies some possible generalizations and extensions of the model and concludes.

2. Countries in Autarky

There are two countries: home and foreign. Population increases exogenously and the two countries have the same level of population L at each moment. We assume that individuals do not move between countries. If a good is produced in a country, for consumption within this country, no transportation service is needed. If a good is exported to the other country, transportation service is needed. Specifically, the country exporting a good provides the transportation service for this good. In this section, we study the case that there is no international trade. We focus on the presentation of the home country.

There is a continuum of goods indexed by a number $\varpi \in [0,1]$.[2] Goods enter into a consumer's utility function in the same way. A representative consumer's consumption of good ϖ is $c(\varpi)$ and the consumer's utility function is specified as $\int_0^1 \ln c(\varpi) d\varpi$. Labor is the only factor of production. A representative individual is assumed to have no preference for leisure. Since firms earn zero profits in equilibrium, the wage income w is the only source of income for an individual. The price of good ϖ is $p(\varpi)$. A consumer's budget constraint states that her total spending on all goods equals her wage income: $\int_0^1 p(\varpi)c(\varpi)d\varpi = w$.

This consumer takes the wage rate and the prices of goods as given and chooses her quantities of consumption to maximize her utility. Her utility maximization leads to a fixed percentage of income spent on each good. This consumer's quantity of consumption of a domestically produced good is c. For a domestically produced good, utility maximization requires that

$$pc = w. \tag{1}$$

It is well known that for countries with the same size, patterns of trade under increasing returns to scale are undetermined if countries do not differ in terms of comparative advantage.[3] To determine which country exports which goods, we introduce the following specification (This specification is not necessary because what we need is that each country produces half of the goods under international trade). An individual's productivity in the production of a good is measured by a parameter γ, which may be either γ^1 or γ^2, and $\gamma^1 > \gamma^2 > 0$. Individuals in the two countries differ in their productivities in the production of different goods. Specifically, each individual in the home country is able to supply γ^1 units of effective labor in the production of goods

[2] As discussed in Neary (2003), the purpose of the assumption of a continuum of goods is to eliminate a firm's market power in the labor market.

[3] With positive transportation costs, the trade pattern may be determined. Yu (2005) provides a recent study on this issue.

$\varpi \in [0, 1/2)$, and γ^2 units of effective labor in the production of goods $\varpi \in [1/2, 1]$. Each individual in the foreign country is able to supply γ^2 units of effective labor in the production of goods $\varpi \in [1/2, 1]$, and γ^1 units of effective labor in the production of goods $\varpi \in [0, 1/2)$.

To produce each final good, we assume that there is a continuum of technologies indexed by a positive number n. A higher value of n indicates a more advanced technology. The fixed cost in terms of labor units associated with technology n is $f(n)$ and the corresponding marginal cost in terms of labor units is $\beta(n)$. A more advanced manufacturing technology has a higher fixed but a lower marginal cost of production: $f'(n) > 0$ and $\beta'(n) < 0$. For all goods in the range $[0, 1]$, the specifications of fixed and marginal costs are the same.

Each manufactured good is produced by m identical firms. A manufacturing firm with an output level of x has a total revenue of px. This firm's total cost of hiring labor is $(f + \beta x)w/\gamma$, thus its profit is $px - (f + \beta x)w/\gamma$. Similar to Chao and Yu (1997), Neary (2003), Wang and Zhao (2007), and Zhou (2010), firms producing the same manufactured good are assumed to engage in Cournot competition. Since there is a continuum of goods, a manufacturing firm does not have market power in the labor market. A manufacturing firm takes as given the economy-wide wage rate as well as the output and technology choices of the other firms in its sector. Output and technology are chosen simultaneously, so there are no strategic considerations in the choice of technology. A manufacturing firm's optimal choice of output requires that

$$p + x\frac{\partial p}{\partial x} - \beta\frac{w}{\gamma} = 0. \tag{2}$$

A manufacturing firm's optimal choice of technology leads to the following equation which implies that a firm adopts a more advanced technology when its level of output is higher:

$$-f'(n) - \beta'(n)x = 0.^4 \tag{3}$$

Ignoring the constraint that the number of firms should be an integer number, free entry and exit in the manufacturing sector means a manufacturing firm earns zero profits:[5]

[4] The second order condition requires that $f'' + \beta'' x > 0$. A sufficient condition for this to be satisfied is that $f'' \geq 0$ and $\beta'' > 0$. This second order condition is assumed to be satisfied and it is used later on to sign comparative statics results.

[5] For examples of oligopolistic competition with free entry, see Sections 3.7 and 4.5 of Brander (1995), Chao and Yu (1997), Zhang (2007), and Chen and Shieh (2011).

$$p\,x-(f+\beta\,x)\frac{w}{\gamma}=0\,. \tag{4}$$

For the market for a manufactured good, the total demand is Lc. Each of the m firms supplies x units of output and the total supply is $m\,x$. The clearance of the market for a manufactured good in the home country requires that the quantity demanded equals the quantity supplied:

$$L\,c=m\,x\,. \tag{5}$$

Under autarky, each country produces all goods in the range $[0,\ 1]$. In each period, the demand for labor in the production of one manufactured good is $m(f+\beta\,x)/\gamma$. The total demand for labor is the sum of demand in the production of all goods. The total supply of labor in a country is L. Labor market equilibrium in a country requires that the quantity demanded equals the quantity supplied:

$$\int_0^{1/2}\frac{m(\varpi)[f(\varpi)+\beta(\varpi)x(\varpi)]}{\gamma^1}d\varpi+\int_{1/2}^{1}\frac{m(\varpi)[f(\varpi)+\beta(\varpi)x(\varpi)]}{\gamma^2}d\varpi=L \tag{6}$$

In a Cournot equilibrium, when a firm chooses its level of output, it treats the output of other firms in its sector as given. With this in mind, partial differentiation of (5) yields $\frac{\partial x}{\partial p}=-\frac{wL}{p^2}$. Plugging the value of $\partial x/\partial p$ into (2) leads to the following equation stating that marginal revenue $p\left(1-\frac{1}{m}\right)$ equals marginal cost $\beta\frac{w}{\gamma}$:

$$p\left(1-\frac{1}{m}\right)=\beta\frac{w}{\gamma}. \tag{7}$$

In each period, equations (1) and (3)-(7) form a system of six equations defining a set of six variables p, c, w, m, n, and x. An autarky equilibrium is a tuple (p, c, w, m, n, x) satisfying this set of six equations. The wage rate is used as the numeraire: $w\equiv 1$.

With the specification of the utility function, equal amount of workers will be allocated in the production of each manufactured good. A rearrangement of the first-order output condition (7) yields $p=\frac{m\beta}{(m-1)\gamma}$. Substituting this result into the free entry condition (4) leads to $m=(f+\beta x)/f$. Next, combination of equation (1), product-market clearing condition (5), and the free entry condition (4) yields $\gamma L = m(f + \beta x)$. Plugging the value of $m = (f + \beta x)/f$ into $\gamma L = m(f + \beta x)$ leads to

$$\gamma f L - (f + \beta x)^2 = 0. \tag{8}$$

Equations (3) and (8) form a system of two equations defining two endogenous variables x and n as functions of exogenous parameters. From (3) and (8), it can be shown that $dx/d\gamma > 0$ and $dn/d\lambda > 0$. By using (3), it can be shown that $\frac{d((f + \beta x)/x)}{d\gamma} = -\frac{f}{x^2}\frac{dx}{d\gamma} < 0$. From this inequality and (4), $dp/d\gamma < 0$. Thus, for a good that individuals have a higher effective supply of labor, the output of this good is higher, and a more advanced technology is adopted in the production of this good. Also, the price of this good is lower. The intuition is as follows. Since the effective supply of labor for a good is higher, more output will be produced. This makes the adoption of more advanced technologies more profitable because the higher fixed cost can be spread to a higher level of output. From the condition for a manufacturing firm's optimal choice of technology, a more advanced technology is associated with a lower average cost. When the average cost is lower, the price is also lower because the price equals the average cost when a firm makes zero profits.

Since individuals in the two countries differ in their abilities in the production of the two groups of goods, the prices of the two groups of goods will be different in the two countries. The price for a good $\varpi \in [0, 1/2)$ is lower in the home country. The price for a good $\varpi \in [1/2, 1]$ is lower in the foreign country. This price difference leads to the possibility of trade between the two countries. In the equilibrium with international trade, the home country specializes in the production of goods $\varpi \in [0, 1/2)$ and the foreign country specializes in the production of goods $\varpi \in [1/2, 1]$. To simplify notation, for the rest of the paper, γ^1 is normalized to one.

3. Equilibrium with international trade

Transportation services are needed so that trade between the two countries is possible. Different from the iceberg transportation technology, in this model labor rather than goods themselves is used in the production of transportation service. Variables in the transportation sector are denoted by a subscript s, s for service provided by the transportation sector. For example, the price of transportation service is p_s.

There is a continuum of transportation technologies indexed by a positive number n_s. The fixed cost in terms of labor units associated with technology n_s is $f_s(n_s)$ and the corresponding marginal cost in terms of labor units is $\beta_s(n_s)$. A more advanced transportation technology has a higher fixed but a lower marginal cost of production: $f_s'(n_s) > 0$ and $\beta_s'(n_s) < 0$. Once a transportation firm in a country incurs a fixed cost, it can transport final goods from this country to the other one at a corresponding constant marginal cost.[6]

Since there are fixed costs in the transportation sector, when the size of the population is sufficiently small, the volume of export will not be enough to cover the fixed costs of transportation. Though prices of different groups of goods are different in the two countries, there is no international trade when the size of the population is sufficiently small. When the size of the population grows to a sufficient large level, firms providing transportation service will emerge in each country. A transportation firm's profit is $\pi_s = p_s x_s - (f_s + \beta_s x_s)w$. For the entry of a transportation firm to be profitable, we need $\pi_s \geq 0$. If this condition valid, international trade starts. At the beginning of international trade, the size of the market may be large enough for only one transportation firm. As population keeps on growing, the size of the market is larger and additional firms providing transportation service will emerge in each country.

In a symmetric equilibrium of international trade, since the two countries are the mirror images of each other (they have the same amount of labor and have access to the same set of technologies), the wage rates in the two countries will be the same. In a symmetric equilibrium, the prices of final goods produced in a given country will be the same. Also, prices of all imported final goods will be the same. Variables associated with the foreign country carry an asterisk mark.

The markets for a manufactured good in the two countries are integrated. That is, a manufacturing firm could not engage in price discrimination in different countries. The price of a good produced in the home country is still denoted by p. For a good imported, its price is denoted

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[6] In this model, a transportation firm provides services only to manufacturing firms in the same sector. It can be shown that the intuition and main results of the model are still valid if a transportation firm provides services to manufacturing firms in all sectors. The reason is as follows. Suppose a transportation firm can provide services to all manufacturing sectors. For the market for transportation service, now we add the demand from all sectors and add the supply of all sectors. Then we set quantity demanded for transportation service equals quantity supplied of transportation service. Since all the sectors are symmetric, intuitively, we multiply both the demand and the supply of transportation service by the number of manufactured goods produced by a country. In equilibrium the condition for the clearance of the market for transportation will be the same as the case that a transportation firm provides service to only one manufacturing sector.

by p_i, i for imported. Since one unit of final good is combined with one unit of transportation service to produce one unit of exported final good, the price paid by a foreign consumer for an imported final good is

$$p_i{}^* = p + p_s\,. \tag{9}$$

A domestic consumer's consumption of an imported final good is c_i. Similar to equation (1), for an imported final good, a domestic consumer's utility maximization requires that

$$p_i c_i = w\,. \tag{10}$$

A manufacturing firm takes the price of transportation service as given and a firm providing transportation service takes the price of a manufactured good as given.[7] When there are multiple transportation firms providing transportation service for the same final good, they engage in Cournot competition. A firm providing transportation service takes the wage rate as given and chooses its levels of output and technology to maximize its profit. The optimal output choice for a firm providing transportation service leads to the familiar condition that the marginal revenue equals the marginal cost:

$$p_s + x_s \frac{\partial p_s}{\partial x_s} = \beta_s\, w\,. \tag{11}$$

A transportation firm's optimal choice of technology requires that

$$f_s{}'(n_s) + \beta_s{}'(n_s) x_s = 0\,. \tag{12}$$

For each final good, if the number of transportation firms is not restricted to be an integer number, free entry and exit in the transportation sector means that a transportation firm earns profits of zero:

$$p_s\, x_s - (f_s + \beta_s x_s) w = 0\,. \tag{13}$$

For each final good, each of the m_s firms transports x_s units of this good abroad and the total amount of export is $m_s x_s$. Each of the L consumers in the foreign country demands $c_i{}^*$ units of this imported final good and the total demand of this final good by foreign consumers is $L c_i{}^*$. The quantity supplied and quantity demanded for a transported good should be equal:

[7] Salinger (1986) studies implications of vertical integration on social welfare. In his model, similar to many models in the literature on vertical integration, it is assumed that an upstream firm takes the price of a downstream firm as given. Also, a downstream firm takes the price of an upstream firm as given.

$$m_s x_s = L c_i^* . \tag{14}$$

For the market for a final good, the total demand for it is the sum of the demand from the home country and that from the foreign country. The demand from the home country is Lc. The demand from the foreign country is Lc_i^*. Thus the total demand for a final good is $L\,c + L\,c_i^*$. Each of the m manufacturing firms supplies x units of output and the total supply for a final good is $m\,x$. The clearance of the market for a final good requires that the quantity demanded equals the quantity supplied:[8]

$$L\,c(\varpi) + L\,c_i^*(\varpi) = m(\varpi)x(\varpi) . \tag{15}$$

For the labor market in the home country, the demand for labor is the sum of the demand from the manufacturing sector and that from the transportation sector. For the manufacturing sector, each final good requires $m(f + \beta x)$ units of labor for production. For the transportation sector, the demand for labor for a good is $m_s(f_s + \beta_s x_s)$. The total demand for labor of a final good is $[m(f + \beta x) + m_s(f_s + \beta_s x_s)]/2$. The home country produces goods in the range $[0, 1/2)$ and the total demand for labor in the home country is $\int_0^{1/2} [m(f + \beta x) + m_s(f_s + \beta_s x_s)]d\varpi$. The total supply of labor in the home country is L. Labor market equilibrium in the home country requires that the quantity demanded equals the quantity supplied:[9]

$$\int_0^{1/2} [m(f + \beta x) + m_s(f_s + \beta_s x_s)]d\varpi = L . \tag{16}$$

Since firms engage in Cournot competition, when a transportation firm chooses its level of output, it treats the output of other transportation firms as given. With this in mind, partial differentiation of (14) yields

$$\frac{\partial x_s}{\partial p_s} = -\frac{w^* L}{(p_i^*)^2} . \tag{17}$$

Plugging the value of $\partial x_s / \partial p_s$ from equation (17) into equation (11) yields

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[8] In this model, the quantity of the goods transported should not exceed the quantity of the goods produced. Equation (15) can be used to show that this constraint is satisfied. In this equation, $L\,c_i^*(\varpi)$ is the quantity of the goods transported and $m(\varpi)x(\varpi)$ is the quantity of the goods produced. With $L\,c(\varpi)$ larger than zero, $L\,c_i^*(\varpi)$ will be smaller than $m(\varpi)x(\varpi)$.

[9] Labor market equilibrium in the foreign country is similar to that in the home country and is not presented here. With Walras's law in mind, labor market clears when all other markets clear.

$$\beta_s w - \left(p - x_s \frac{(p_i*)^2}{w*L} \right) = 0 . \tag{18}$$

Similar to the derivation of equation (17), partial differentiation of equation (15) yields

$$\frac{\partial x}{\partial p} = L\frac{\partial c}{\partial p} + L\frac{\partial c_i*}{\partial p_i*}\frac{\partial p_i*}{\partial p}$$

$$= -\frac{L}{p^2} - \frac{w*L}{(p_i*)^2} . \tag{19}$$

Plugging the value of $\partial x/\partial p$ from equation (19) and the value of x from equation (4) into equation (2) yields

$$\beta w - \left(p - \frac{f\,w}{(p-\beta w)}\frac{p^2(p_i*)^2}{[L(p_i*)^2 + w*Lp^2]} \right) = 0 . \tag{20}$$

In a symmetric equilibrium, foreign variables are equal to their domestic counterparts: $w = w*$, $p_i = p_i*$, and $c_i = c_i*$. Equations (1), (3), (4), (9), (10), (12), (13), (14), (15), (16), (18), and (20) form a system of twelve equations defining twelve variables p, p_i, p_s, c, c_i, w, m, m_s, n, n_s, x, and x_s as functions of exogenous parameters. An equilibrium with international trade is a tuple (p, p_i, p_s, c, c_i, w, m, m_s, n, n_s, x, x_s) satisfying this set of twelve equations.

4. Complementarities between Manufacturing and Transport Sectors

Casual observation shows that regions with better transportation infrastructure are more likely to attract investments in the manufacturing sector and regions with higher levels of manufacturing activities are more likely to be connected by railways, highways, and airports. In this section, we establish complementarities of technology adoptions between the manufacturing sector and the transportation sector.

First, we study the impact of a change in the level of technology in the transportation sector on the level of technology in the manufacturing sector. If the level of transportation technology is exogenously given, we can establish the following system of three equations defining three variables n, p_i, and p as functions of exogenous parameters:[10]

[10] The derivation of equations (21a)-(21c) is as follows. First, plugging the value of x from equation (4) into equation (3) yields (21a). Second, plugging the value of p_i (the same as p_i*) from equation (9) into equation (20) yields

$$\Omega_1 \equiv -\beta' \frac{f}{p-\beta} - f' = 0, \tag{21a}$$

$$\Omega_2 \equiv \beta - \left(p - \frac{f\, p^2 (p+p_s)^2}{L(p-\beta)^2 [p^2 + (p+p_s)^2]} \right) = 0, \tag{21b}$$

$$\Omega_3 \equiv \beta_s - \left(p_s - \frac{f_s (p+p_s)^2}{L(p_s - \beta_s)} \right) = 0. \tag{21c}$$

The following proposition studies the impact of a change in the level of technology in the transportation sector on the level of technology in the manufacturing sector.

Proposition 1: If the level of technology in the transportation sector is exogenously given, a more advanced technology in the transportation sector leads firms in the manufacturing sector to choose a more advanced technology.

Proof: Partial differentiation of the system of equations (21a)-(21c) with respect to n, p_i, p, and n_s yields

$$\begin{pmatrix} \frac{\partial \Omega_1}{\partial n} & \frac{\partial \Omega_1}{\partial p} & 0 \\ \frac{\partial \Omega_2}{\partial n} & \frac{\partial \Omega_2}{\partial p} & \frac{\partial \Omega_2}{\partial p_s} \\ 0 & \frac{\partial \Omega_3}{\partial p} & \frac{\partial \Omega_3}{\partial p_s} \end{pmatrix} \begin{pmatrix} dn \\ dp \\ dp_s \end{pmatrix} = - \begin{pmatrix} 0 \\ 0 \\ \frac{\partial \Omega_3}{\partial n_s} \end{pmatrix} dn_s. \tag{22}$$

Let Δ denote the determinant of the coefficient matrix of endogenous variables of (22). An application of Cramer's rule on the system (22) leads to

$$\frac{dn}{dn_s} = - \frac{\partial \Omega_1}{\partial p} \frac{\partial \Omega_2}{\partial p_s} \frac{\partial \Omega_3}{\partial n_s} / \Delta. \tag{23}$$

To determine the sign of dn/dn_s, we need to determine the sign of Δ. To determine the sign of Δ, we conduct the following stability analysis. Suppose that a manufacturing firm chooses a more advanced technology if the marginal benefit of a more advanced technology is higher than the marginal cost. The marginal benefit of a more advanced technology is the amount of marginal

(21b). Third, plugging the value of x_s from equation (13) and the value of p_i from equation (9) into equation (18) yields (21c).

cost saved ($-\beta' x$) and the marginal cost is the amount of additional fixed cost (f'). Since $x = f/(p-\beta)$ from equation (4), the difference between the marginal benefit and the marginal cost of a more advanced manufacturing technology is $-\beta' f/(p-\beta) - f'$. Thus the middle part of equation (21a) shows the evolution of n:

$$\dot{n} = -\beta' \frac{f}{p-\beta} - f'.$$

For a manufacturing firm, when its marginal cost is higher than its marginal revenue, it will reduce its output. When a firm has market power in the goods market, a decrease in the level of output will lead to an increase in the level of price it receives. This motivates our assumption that the price of a manufacturing firm increases if the difference between its marginal cost and marginal revenue increases. A manufacturing firm's marginal cost is β and its marginal revenue is $p + x\partial p/\partial x$. By plugging the value of x from equation (4) and the value of $\partial p/\partial x$ from equation (19) into $p + x\partial p/\partial x$, the difference between a manufacturing firm's marginal cost and marginal revenue is $\beta - p + \frac{f}{p-\beta}\left(\frac{p^2 (p_i)^2}{L[p^2 + (p_i)^2]}\right)$. Thus the middle part of equation (21b) shows the evolution of p. Similarly, suppose that the price of a transportation firm increases if the difference between its marginal cost and marginal revenue increases. The difference between a transportation firm's marginal cost and marginal revenue is $\beta_s - \left(p_s - \frac{f_s (p+p_s)^2}{L(p_s - \beta_s)}\right)$, thus the middle part of equation (21c) shows the evolution of p_s. As discussed in Metzler (1945) and Takayama (1985, p. 316), for the system (21a)-(21c) to be stable, it is necessary that the leading principal minors of Δ will alternative in sign. That is, stability requires that $\partial\Omega_1/\partial n < 0$, $\begin{pmatrix} \frac{\partial\Omega_1}{\partial n} & \frac{\partial\Omega_1}{\partial p} \\ \frac{\partial\Omega_2}{\partial n} & \frac{\partial\Omega_2}{\partial p} \end{pmatrix} > 0$, and $\Delta < 0$.

Partial differentiation of equation (21c) leads to

$$\frac{\partial\Omega_3}{\partial n_s} = \frac{(p+p_s)^2}{L(p_s-\beta_s)}\left(f_s' - \frac{f_s \beta_s'}{p_s - \beta_s}\right) + \beta_s' = \beta_s' < 0.$$

From equation (21a), $\partial\Omega_1 / \partial p < 0$. From equation (21b), $\partial\Omega_2 / \partial p_s > 0$. With $\Delta < 0$, from (23), $dn / dn_s > 0$.

To understand Proposition 1, a more advanced technology in the transportation sector leads to a decrease in the price of transportation service and thus an increase in the quantity of export. This increases the total demand for a final good and makes the adoption of a more advanced technology in the manufacturing sector more profitable because the higher level of fixed cost associated with a more advanced technology can be spread to a higher level of output.[11]

Second, we study the impact of a change in the level of technology in the manufacturing sector on the level of technology in the transportation sector. If the level of manufacturing technology is exogenously given, we can derive the following system of three equations defining n_s, p_i, and p_s as functions of exogenous parameters:[12]

$$\Phi_1 \equiv \beta - \left(p - \frac{f\, p^2 (p + p_s)^2}{L(p-\beta)^2 [p^2 + (p + p_s)^2]} \right) = 0, \tag{24a}$$

$$\Phi_2 \equiv -\beta_s' \frac{f_s}{p_s - \beta_s} - f_s' = 0, \tag{24b}$$

$$\Phi_3 \equiv \beta_s - \left(p_s - \frac{f_s (p + p_s)^2}{L(p_s - \beta_s)} \right) = 0. \tag{24c}$$

The following proposition studies the impact of a change in the level of technology in the manufacturing sector on the level of technology in the transportation sector.

Proposition 2: If the level of technology in the manufacturing sector is exogenously given, a more advanced technology in the manufacturing sector leads firms in the transportation sector to choose a more advanced technology.

[11] In a model with monopolistic competition and a constant elasticity of demand, a firm's scale of production does not change with a decrease in the level of transportation costs. With oligopolistic competition in this model, a firm's scale of production increases when transportation costs decrease. It is this increase in the scale of production leads firms in the manufacturing sector to choose more advanced technologies.

[12] The derivation of equations (24a)-(24c) is as follows. First, plugging the value of p_i (the same as p_i*) from equation (9) into equation (20) yields (24a). Second, plugging the value of x_s from equation (13) into equation (12) yields (24b). Third, plugging the value of x_s from equation (13) into equation (18) yields (24c).

Proof: Partial differentiation of equations (24a)-(24c) with respect to n_s, p_i, p, and n yields

$$\begin{pmatrix} 0 & \frac{\partial \Phi_1}{\partial p} & \frac{\partial \Phi_1}{\partial p_s} \\ \frac{\partial \Phi_2}{\partial n_s} & 0 & \frac{\partial \Phi_2}{\partial p_s} \\ \frac{\partial \Phi_3}{\partial n_s} & \frac{\partial \Phi_3}{\partial p_s} & \frac{\partial \Phi_3}{\partial p_s} \end{pmatrix} \begin{pmatrix} dn_s \\ dp \\ dp_s \end{pmatrix} = - \begin{pmatrix} \frac{\partial \Phi_1}{\partial n} \\ 0 \\ 0 \end{pmatrix} dn . \tag{25}$$

Let Δ_Φ denote the determinant of the coefficient matrix of endogenous variables of (25). An application of Cramer's rule on the system (25) leads to

$$\frac{dn_s}{dn} = \frac{\partial \Phi_1}{\partial n} \frac{\partial \Phi_2}{\partial p_s} \frac{\partial \Phi_3}{\partial p} / \Delta_\Phi . \tag{26}$$

To determine the sign of dn_s / dn, we need to determine the sign of Δ_Φ. To determine the sign of Δ_Φ, we conduct the following stability analysis. Similar to the argument in the proof of Proposition 1, suppose that the price of a manufacturing firm increases if the difference between its marginal cost and its marginal revenue increases. Then the middle part of equation (24a) shows the evolution of p. Suppose that a transportation firm chooses a more advanced technology if its marginal benefit is larger than its marginal cost. The marginal benefit of a more advanced transportation technology is $-\beta_s' x_s$ and the marginal cost is f_s'. Since $x_s = f_s /(p_s - \beta_s)$ from equation (13), the difference between the marginal benefit and the marginal cost of a more advanced transportation technology is $-\beta_s' f_s /(p_s - \beta_s) - f_s'$. Thus the middle part of equation (24b) shows the evolution of n_s. Suppose the price of a transportation firm increases if the difference between its marginal cost and marginal revenue increases, then the middle part of equation (24c) shows the evolution of p_s. For the system (24a)-(24c) to be stable, it is necessary that the leading principal minors of Δ_Φ will alternative in sign. That is, stability requires that

$$\frac{\partial \Phi_1}{\partial n_s} \le 0, \begin{pmatrix} 0 & \frac{\partial \Phi_1}{\partial p} \\ \frac{\partial \Phi_2}{\partial n_s} & 0 \end{pmatrix} > 0, \text{ and } \Delta_\Phi < 0 .$$

Partial differentiation of equation (24a) leads to

$$\frac{\partial \Phi_1}{\partial n} = \frac{p^2(p+p_s)^2}{L(p-\beta)[p^2+(p+p_s)^2]}\left(f' + \frac{f\beta'}{p-\beta}\right) + \beta' = \beta' < 0 .$$

From equation (24b), $\partial \Phi_2 / \partial p_s < 0$. From equation (24c), $\partial \Phi_3 / \partial p > 0$. With $\Delta_\Phi < 0$, from (26), $dn_s / dn > 0$.

To understand Proposition 2, the price of an exported final good is the sum of the domestic price and the price of the transportation service. A more advanced technology in the manufacturing sector leads to a decrease in the domestic price of a final good and thus decreases the price of an exported good. As a result, the quantity demanded for export is higher. The adoption of more advanced technologies in the transportation sector becomes more profitable because the higher fixed cost associated with a more advanced technology can be spread to a higher level of output.

One implication from Propositions 1 and 2 is that technological improvements in the manufacturing and transportation sectors can be reinforcing. Lower transportation costs increase the volume of trade and greater trade volumes increase productivity in the transportation sector and lower prices.

5. The number of equilibria

With the positive interaction between the manufacturing and transportation sectors, multiple equilibria may exist. In this section, we study the number of equilibrium. From equations (21a) and (24a)-(24c), we can derive the following two equations defining the levels of technologies in the two sectors as functions of exogenous parameters:

$$f_s'\left(\beta - \frac{\beta' f}{f'} + \beta_s\right) + \beta_s'\left(\sqrt{f_s L} - f_s\right) = 0 , \tag{27a}$$

$$\frac{1}{(\beta')^2 f} - \frac{L}{(\beta f' - \beta' f)^2} - \frac{(f_s')^2}{(\beta_s')^2 f_s (f')^2} = 0 . \tag{27b}$$

The existence of multiple equilibria is affected by the specifications of the marginal and fixed costs of production in the two sectors. Unfortunately we are not able to provide illuminating conditions for the existence of a unique equilibrium. In the following, we provide an example in which the number of equilibrium is unique and another example in which there are multiple equibria.

Unique equilibrium: Suppose that $f(n)=n$, $\beta(n)=1/n$, $f(n_s)=n_s$, $\beta(n_s)=1/n_s$, and $L=100$. With the above specification, solving the system of equations (27a) and (27b) numerically by *Matlab* leads to the unique set of technologies in the two sectors: $n_s=27.3376$ and $n_s=12.0458$.

Multiple equilibria: Suppose that $f(n)=n$, $\beta(n)=1/n^2$, $f(n_s)=n_s$, $\beta(n_s)=1/(n_s)^2$, and $L=9$. With the above specification, equations (27a) and (27b) becomes

$$(n_s)^{2.5}+(n_s)^{0.5}n^2-2n^2=0,$$

$$n^5-4n^4-(n_s)^5=0.$$

Solving the above system of equations numerically by *Matlab* leads to two sets of solutions: one set of solution is $n=0.0067$ and $n_s=0.0235$; the other set of solution is $n=4.2211$ and $n_s=2.3402$.

When there are multiple equilibria, the following proposition shows that they can be Pareto ranked.

Proposition 3: An equilibrium with lower levels of technologies in the two sectors is dominated by an equilibrium with higher levels of technologies in the two sectors.

Proof: With $w\equiv 1$, a consumer's utility increases when p and p_s decrease. First, we show that p decreases with n. From equation (4), the price of a final good can be expressed as $p=\beta+f/x$. By employing equation (3), the relationship between the price of a final good and the level of technology in the manufacturing sector is given by $\frac{dp}{dn}=-\frac{f}{x^2}\frac{dx}{dn}$. From equation (3), $dx/dn>0$. Thus $dp/dn<0$.

Second, we show that p_s decreases with n_s. From equation (13), the price of transportation service can be expressed as $p_s=\beta_s+f_s/x_s$. By employing equation (12), the relationship between the price of transportation service and the level of technology in the transportation sector is given by $\frac{dp_s}{dn_s} = -\frac{f_s}{x_s^2}\frac{dx_s}{dn_s}$. From equation (12), $dx_s / dn_s > 0$. Thus $dp_s / dn_s < 0$.

The intuition behind Proposition 3 is as follows. Since the wage rate is normalized to one, a consumer's utility increases when the prices of final goods decrease. A more advanced technology leads to a lower average cost. This leads to a lower price of a final good because the price is equal to average cost when firms earn a profit of zero. As a result, a consumer's welfare is higher when more advanced technologies are adopted.

The existence of multiple equilibria has been used to explain the phenomenon of "poverty trap" in developing countries (Murphy et al., 1989). This is related to the complementarity issue which has received much attention in the study of economic development. When multiple equilibria exist, an economy may be trapped in the equilibrium with a lower level of social welfare. More specifically, a firm considering investment in the manufacturing sector may hesitate to invest if transportation infrastructure is poor. A firm considering investment in the transportation sector may hesitate to invest if this firm expects that the low level of activities in the manufacturing sector leads to a low demand for transportation services. If the transportation sector is the main binding constraint of economic development, this model suggests that government intervention such as investments in the transportation sector will increase social welfare. However, in reality, other factors such as civil conflicts might play more significant roles in discouraging investments than a poor transportation infrastructure and an improvement in the transportation sector may not necessarily lead to a better economic performance.

6. Implications of population growth

With technologies determined endogenously in manufacturing and transportation sectors, the remaining exogenous parameter in this model is the size of the population.[13] The following

[13] In this model, the size of the population measures the size of the market. In reality, countries with large size of population such as China and India may not necessarily have a large market for a given good because the level of income is low or consumers in different regions of a country are not integrated.

proposition studies the impact of an increase in the size of the population on the levels of technologies in the two sectors and the prices charged by the two sectors.[14]

Proposition 4: Manufacturing firms and transportation firms adopt more advanced technologies and the prices of final goods and transportation services decrease when the size of the population is larger.

Proof: Equations (21a) and (24a)-(24c) lead to the following system of four equations defining four variables p, p_s, n, and n_s as functions of exogenous parameters.[15]

$$V_1 \equiv -\beta' \frac{f}{p-\beta} - f' = 0, \tag{28a}$$

$$V_2 \equiv \beta - \left(p - \frac{f\, p^2 (p_s - \beta_s)^2}{f_s (p-\beta)[p^2 + (p+p_s)^2]} \right) = 0, \tag{28b}$$

$$V_3 \equiv -\beta_s' \frac{f_s}{p_s - \beta_s} - f_s' = 0, \tag{28c}$$

$$V_4 \equiv \beta_s - \left(p_s - \frac{f_s (p+p_s)^2}{L(p_s - \beta_s)} \right) = 0. \tag{28d}$$

Partial differentiation of equations (28a)-(28d) with respect to n, p_i, n_s, p_s, and L leads to

$$\begin{pmatrix} \frac{\partial V_1}{\partial n} & \frac{\partial V_1}{\partial p} & 0 & 0 \\ \frac{\partial V_2}{\partial n} & \frac{\partial V_2}{\partial p} & \frac{\partial V_2}{\partial n_s} & \frac{\partial V_2}{\partial p_s} \\ 0 & 0 & \frac{\partial V_3}{\partial n_s} & \frac{\partial V_3}{\partial p_s} \\ 0 & \frac{\partial V_4}{\partial p} & \frac{\partial V_4}{\partial n_s} & \frac{\partial V_4}{\partial p_s} \end{pmatrix} \begin{pmatrix} dn \\ dp \\ dn_s \\ dp_s \end{pmatrix} = -\begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{\partial V_4}{\partial L} \end{pmatrix} dL .$$

[14] This type of inquiry is legitimate when the equilibrium is unique. When there are multiple equilibria, it is understood that we limit the analysis to a locally stable neighborhood of an equilibrium. When multiple equilibria exist, comparative statics can be based on the comparison of highest equilibrium or the lowest equilibrium (Milgrom and Roberts, 1994).

[15] Equation (28b) is a combination of equation (24a) and equation (24c).

Let Δ_V denote the determinant of the above coefficient matrix of endogenous variables. An application of Cramer's rule leads to

$$\frac{dn}{dL} = \frac{\partial V_1}{\partial p}\frac{\partial V_4}{\partial L}\left(\frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s} - \frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s}\right) / \Delta_V , \tag{29a}$$

$$\frac{dp}{dL} = \frac{\partial V_1}{\partial n}\frac{\partial V_4}{\partial L}\left(\frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s} - \frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s}\right) / \Delta_V , \tag{29b}$$

$$\frac{dn_s}{dL} = \frac{\partial V_3}{\partial p_s}\frac{\partial V_4}{\partial L}\left(\frac{\partial V_1}{\partial n}\frac{\partial V_2}{\partial p} - \frac{\partial V_1}{\partial p}\frac{\partial V_2}{\partial n}\right) / \Delta_V , \tag{29c}$$

$$\frac{dp_s}{dL} = \frac{\partial V_3}{\partial n_s}\frac{\partial V_4}{\partial L}\left(\frac{\partial V_1}{\partial p}\frac{\partial V_2}{\partial n} - \frac{\partial V_1}{\partial n}\frac{\partial V_2}{\partial p}\right) / \Delta_V . \tag{29d}$$

To determine the signs of dn/dL, dp/dL, dn_s/dL, and dp_s/dL, we need to determine the signs of $\frac{\partial V_1}{\partial n}\frac{\partial V_2}{\partial p} - \frac{\partial V_1}{\partial p}\frac{\partial V_2}{\partial n}$, $\frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s} - \frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s}$, and Δ_V. To determine the signs of $\frac{\partial V_1}{\partial n}\frac{\partial V_2}{\partial p} - \frac{\partial V_1}{\partial p}\frac{\partial V_2}{\partial n}$, $\frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s} - \frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s}$, and Δ_V, we conduct the following stability analysis. Similar to the arguments used in the proofs of Propositions 1 and 2, the middle parts of equation (28a) shows the evolution of n, the middle part of equation (28b) shows the evolution of p, the middle part of equation (28c) shows the evolution of n_s, and the middle part of equation (28d) shows the evolution of p_s. Thus we have the following equations showing the evolution of n, p, n_s, and p_s:

$$\dot{n} = -\beta'\frac{f}{p-\beta} - f' , \tag{30a}$$

$$\dot{p} = \beta - \left(p - \frac{f\, p^2 (p_s - \beta_s)^2}{f_s (p-\beta)[p^2 + (p+p_s)^2]}\right), \tag{30b}$$

$$\dot{n}_s = -\beta_s'\frac{f_s}{p_s - \beta_s} - f_s' , \tag{30c}$$

$$\dot{p}_s = \beta_s - \left(p_s - \frac{f_s (p+p_s)^2}{L(p_s - \beta_s)}\right). \tag{30d}$$

For the system (30a)-(30d) to be stable, it is necessary that the leading principal minors of Δ_v will alternative in sign. That is, stability requires that $\partial V_1 / \partial n < 0$, $\begin{pmatrix} \frac{\partial V_1}{\partial n} & \frac{\partial V_1}{\partial p} \\ \frac{\partial V_2}{\partial n} & \frac{\partial V_2}{\partial p} \end{pmatrix} > 0$,

$\begin{pmatrix} \frac{\partial V_1}{\partial n} & \frac{\partial V_1}{\partial p} & 0 \\ \frac{\partial V_2}{\partial n} & \frac{\partial V_2}{\partial p} & \frac{\partial V_2}{\partial n_s} \\ 0 & 0 & \frac{\partial V_3}{\partial n_s} \end{pmatrix} < 0$, and $\Delta_V > 0$.

Since $\begin{pmatrix} \frac{\partial V_1}{\partial n} & \frac{\partial V_1}{\partial p} \\ \frac{\partial V_2}{\partial n} & \frac{\partial V_2}{\partial p} \end{pmatrix} > 0$, it is clear that $\frac{\partial V_1}{\partial n}\frac{\partial V_2}{\partial p} - \frac{\partial V_1}{\partial p}\frac{\partial V_2}{\partial n} > 0$.

To determine the sign of $(\partial V_2 / \partial p_s)(\partial V_3 / \partial n_s) - (\partial V_2 / \partial n_s)(\partial V_3 / \partial p_s)$, following Samuelson (1983, chap. 8), for the subsystem V_2 and V_3, if V_2 holds and the evolution of n_s is given by (30c), then the evolution of this subsystem is as follows:

$$V_2 \equiv \beta - \left(p - \frac{f\, p^2 (p_s - \beta_s)^2}{f_s (p - \beta)[p^2 + (p + p_s)^2]} \right) = 0,$$

$$\dot{n}_s = -\beta_s' \frac{f_s}{p_s - \beta_s} - f_s'.$$

For this subsystem V_2 and V_3, a characteristic root λ is defined by

$$\begin{pmatrix} \frac{\partial V_2}{\partial n_s} & \frac{\partial V_2}{\partial p_s} \\ \frac{\partial V_3}{\partial n_s} - \lambda & \frac{\partial V_3}{\partial p_s} \end{pmatrix} = 0.$$

The above expression leads to

$$\begin{pmatrix} \dfrac{\partial V_2}{\partial n_s} & \dfrac{\partial V_2}{\partial p_s} \\ \dfrac{\partial V_3}{\partial n_s} & \dfrac{\partial V_3}{\partial p_s} \end{pmatrix} + \lambda \frac{\partial V_2}{\partial p_s} = 0 . \tag{31}$$

Stability of the subsystem V_2 and V_3 requires that $\lambda < 0$. Partial differentiation of V_2 reveals that $\partial V_2 / \partial p_s > 0$. From (31), $\frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s} - \frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s} > 0$, or $\frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s} - \frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s} < 0$.

With $\Delta_V > 0$, $\frac{\partial V_1}{\partial n}\frac{\partial V_2}{\partial p} - \frac{\partial V_1}{\partial p}\frac{\partial V_2}{\partial n} > 0$, and $\frac{\partial V_2}{\partial p_s}\frac{\partial V_3}{\partial n_s} - \frac{\partial V_2}{\partial n_s}\frac{\partial V_3}{\partial p_s} < 0$, from equations (29a)-(29d), it is clear that $dn / dL > 0$, $dn_s / dL > 0$, $dp / dL < 0$, and $dp_s / dL < 0$.

An increase in the size of the population increases the demand for each final good and thus leads to the adoption of more advanced technologies in the two sectors. If more countries are integrated into the world trade system, this can also encourage the adoption of more advanced technologies.

7. Conclusion

For a modern economy, an important feature of the transportation sector is the existence of significant degrees of increasing returns. The volume of transportation thus affects a transportation firm's choices of technologies and the levels of transportation costs are endogenously determined by the volume of transportation. In this paper, we have shown that it is tractable to incorporate increasing returns in the transportation sector into a general equilibrium model in which manufacturing firms and transportation firms engage in oligopolistic competition and choose technologies optimally. The model is tractable and the results are derived analytically. We show that technological improvements in the manufacturing sector and in the transportation sector are reinforcing and multiple equilibria with different levels of social welfare may exist. When the size of the population increases, firms adopt more advanced technologies and the prices of final goods decrease.

The framework may be generalized and extended in various directions. First, in this model, there is only type of goods: manufactured goods. An agricultural good with constant returns to scale production function can be incorporated into the model. If consumers have a homothetic preference, it can be shown that for countries with access to the same production technologies, a country with a higher population has a comparative advantage in the production of the manufactured goods. Second, in this model, labor is the only factor of production. To address the role of capital accumulation in the process of development, capital can be incorporated into the model. Third, in the process of industrialization, different stages of growth might be driven by different factors. In the first stage of industrialization, growth was mainly driven by market expansion. In the second stage of industrialization, growth was mainly driven by research and development effort. Market expansion made research and development spending more profitable. The model may be extended to incorporate endogenous development of new technologies. Finally, transportation costs can be viewed as a special kind of transaction costs. The interaction between transaction costs and the division of labor can be an interesting avenue for future research.

Acknowledgements: The author thanks Antonio Ciccone, Peter J. Neary, Zhiqi Chen, and two anonymous referees for their very insightful suggestions. I am solely responsible for all the remaining errors.

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