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Bilateral Trade and Productivity Differences in a Ricardo-Cournot Model*

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Abstract

Purpose – Using a model that highlights Ricardian comparative advantage and Cournot competition, I derive theoretical predictions on how bilateral measures of trade intensity, specialization, and intra-industry are interrelated, and how Ricardian productivity differences affect these measures. We test the predictions using trade and production data, and confirm them.

Design/methodology – A simple two-country general equilibrium model is constructed to derive theory-based bilateral indexes. We then test the relationships among them using panel data for 35 countries and 14 industries between 1996 and 2008.

Findings – Bilateral trade intensity is increasing in specialization, as in the classical trade theory, and in intra-industry trade, as in the new trade theory. However, productivity differences positively affect specialization, and negatively affect intra-industry trade. These effects cancel each other; thus productivity differences have little impact on trade intensity.

Originality/value – This paper provides a comprehensive conceptual framework for understanding the relationship among trade intensity, specialization, intra-industry trade, and productivity differences. We derive theory-consistent measures of specialization, intra-industry trade, and productivity differences. Moreover, we reevaluate the empirical relevance of these variables for the study of gravity equations. This paper is also an effort to capture oligopolistic competition in a general equilibrium framework, interests in which recently resurged.

Keywords: Comparative advantage, Cournot competition, Intra-industry trade, Labor productivity, Specialization

JEL Classifications: F10, F12, F14

1. Introduction

This study explores, both theoretically and empirically, the influence of bilateral productivity differences on trade intensity, specialization, and intra-industry trade. We construct a Ricardian trade model featuring Cournot competition to show that trade intensity is increasing in specialization, as in the classical trade theory, and in intra-industry trade, as in the new trade theory. However, the model predicts that productivity differences between trading partners do not affect trade intensity because they increase specialization and decrease intra-industry trade simultaneously, the two effects canceling each other.

We test the theoretical predictions using trade and production data for 35 countries and 14 industries between 1996 and 2008. Our estimation results largely support our model, although the quantitative effects of our indexes are smaller than their theoretical values. We find that our bilateral indexes of specialization and intra-industry trade are positively correlated with bilateral trade intensity as implied by our model. We also find that our index

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of productivity differences positively affects specialization, but negatively affects intra-industry. However, productivity differences have no additional explanatory power on trade intensity after the effects of trade costs are controlled for, confirming our theory.

The effect of productivity differences on trade volume is a long-studied topic in Ricardian trade theory. The influence of specialization and intra-industry trade on trade volume has also been intensively studied in the classical and the new trade theory. However, a study investigating the relationship among trade volume, specialization, intra-industry trade, and productivity differences in a single comprehensive framework is rare. This paper does so based on a minimalist general equilibrium model where Cournot competition between a domestic firm and a foreign firm prevails in every industry.

The lack of theoretical generality would look limiting given the remarkable progress of general equilibrium trade theory in the last two decades. Eaton and Kortum (2002) elevated the empirical applicability of the Ricardian model by successfully introducing multiple countries and transportation costs. Anderson and van Wincoop (2003) did so for the mono-polistic competition model of Krugman (1997), and Melitz (2003) and Chaney (2008) further amplified the model by incorporating heterogeneous firms. Now researchers can apply their estimation equation from a theory directly to data without apology. However, with the advancement of trade theories mirroring real- world complexity, the literature moved away from trade pattern theory in the classical sense. Bilateral differences or similarities between trading partners in terms of productivities, endowments, or production structure had been a dominant concept for explaining the volume and pattern of bilateral trade. Bilateral indexes measuring differences between trading partners are also frequently used to study business cycle synchronization or optimum currency areas (*e.g.* Clark and Van Wincoop, 2001; Imbs, 2004; Baxter and Kouparitsas, 2005; Duval, Saraf, and Seneviratne, 2016). Now, they are seldom used in the frontier studies of gravity equations because their presence in the estimation equation is hard to justify in a rigorous multi-country model.

The bilateral indexes examined in this study have long and frequently been used in the international trade literature. We measure trade intensity as the ratio of trade volume to the product of partner incomes. The gravity equation theories, from the simple version of Leamer and Stern (1970) to the full-fledged versions of Eaton and Kortum (2002), Anderson and van Wincoop (2003), and Chaney (2008), all focus on expressing this ratio as a function of trade costs. Our index of specialization, which measures the difference between two countries in the industry distribution of value-added shares, has been used by several authors (Krugman, 1991; Clark and van Wincoop, 2001; and Imbs, 2004) because it makes an intuitive sense. However, to our knowledge, it had never been derived from a theory. Our measure of intra-industry trade is a simple transformation of the well-known index by Grubel-Lloyd (1975), which became the standard for measuring the intensity of intra-industry trade. Finally, we measure productivity differences as the difference in the industry distribution of labor productivity relative to the country-wide average. This index captures the classic concept of the Ricardian comparative advantage simply and intuitively. However, as far as we know, it has never been theoretically derived or empirically tested.

We derive all these measures theoretically and show that these measures have clear-cut theoretical relationships. Moreover, we demonstrate their empirical significance in the prediction of trade volume and pattern. We believe that our findings suggest the necessity to expand our model further rather than drop them from the empirical application because a current forefront model cannot justify them.

The work of Costinot, Donaldson, and Komunjer (2012) is an important exception in the recent literature that investigates the empirical significance of bilateral productivity differences in explaining trade pattern. They tested a Ricardian prediction on trade pattern derived from the Eaton and Kortum (2002) model: the ratio between the relative export of a pair of exporters to a third country in one industry and that in another is increasing in the ratio between the relative labor productivities of the pair in the two industries. This proposition is perhaps the strongest Ricardian prediction derivable from a general Ricardian model. However, it is distanced from the conventional notion on the relationship between comparative advantage and trade pattern.

Costinot, Donaldson, and Komunjer (2012) also anticipated some of our results. In a numerical simulation, they found that the complete removal of the Ricardian comparative advantage across all countries would reduce world trade flows only slightly. They attributed the small reduction to an increase in intra-industry trade following the disappearance of comparative advantages. This is consistent with our finding that a reduction in productivity differences has little effect on trade intensity because it decreases specialization and simultaneously increases intra-industry trade. However, the authors neither algebraically derived nor econometrically tested the prediction as we do here.

It seems a great irony that general equilibrium trade theory is being drawn more and more into the atomistic models of perfect and monopolistic competition when a small number of multinational giants increasingly dominate international trade. Recently, interest in incorporating oligopolistic competition in general equilibrium trade theory resurged (Atkeson and Burstein, 2008; Neary, 2010/2016; Head and Spencer, 2017). This paper is an effort to capture oligopolistic competition in a general equilibrium framework. Our model is similar to Neary (2016) in some respects, but we derive different propositions and empirically test them. This study is an extension of Song and Sohn (2012), who used a similar model, but narrowly focused on the determinants of intra-industry trade. Here, we deal with trade volume and pattern in general, and use more reliable data to calculate labor productivity, which determines our key index.

This paper is naturally related to the classic literature testing the influence of Ricardian comparative advantage on bilateral trade (Macdougall, 1951; Stern, 1962; Balassa, 1963; Gohub and Hsieh, 2000). Our study tests different Ricardian predictions that embody the new trade theory, and is more theory-based. Related are the multi-industry versions of the Eaton and Kortum (2002) model (*e.g.* Costinot, Donaldson, and Komunjer, 2012; Levchenko and Zhang, 2012; Caliendo and Parro, 2015; Burstein and Vogel, 2017). These models are based on perfect competition, but they generate intra-industry trade by introducing intra-industry technological heterogeneity across firms. These models have a potential to generate propositions similar to ours.

The remainder of this paper is organized as follows. Section 2 constructs a simple Cournot-Ricardo model. Section 3 presents the empirical results. Section 4 concludes the paper.

2. A Simple Ricardian Model of International Rivalry

The world is composed of two countries, “home” and “foreign”, that produce a continuum of goods indexed over the unit interval $[0,1]$. The countries share an industry classification system in which goods are classified into N industries such that each industry is represented by a subinterval I_n $(n = 1, 2, \dots, N)$, and $\cup_{n=1}^{N} I_n = [0,1]$.

The two countries are populated by consumers with identical Cobb-Douglas tastes. Denoting the expenditure share of good z by $\gamma(z)$, we write the problem of the home consumers as maximizing the following utility function:

$$U = \int_0^1 \gamma(z) \log d(z) \; dz,$$

where $d(z)$ denotes the home consumption of good z and $\int_0^1 \gamma(z)\ dz = 1$. With the industry classification system, the objective function can be rewritten as:

$$U = \sum_{n=1}^{N} \beta_n \log c_n,$$

where $\beta_n = \int_{z \in I_n} \gamma(z)\ dz$ and $\log c_n = \int_{z \in I_n} \frac{\gamma(z)}{\beta_n} \log d(z)\ dz$. Likewise, denoting foreign variables by asterisks, we can express the utility function of the foreign consumers as:

$$\begin{aligned} U^* &= \int_0^1 \gamma(z) \log d^*(z)\ dz \\ &= \sum_{n=1}^{N} \beta_n \log c_n^*, \end{aligned}$$

where $\log c_n^* = \int_{z \in I_n} \frac{\gamma(z)}{\beta_n} \log d^*(z)\ dz$.

We assume that each good is produced by one home firm and one foreign firm. They engage in separate Cournot competition in the home and foreign markets, as in the reciprocal dumping model of Brander (1981) and Brander and Krugman (1983). Firms must incur iceberg-type transportation costs to move goods across the countries, and a firm located in one country has to to produce τ (>1) units of a good to deliver one unit of the good to the other country. Labor is the only factor of production, and it is mobile across industries, but not between countries.

Let $\alpha(z)$ and $\alpha^*(z)$ be the labor productivities of the home and foreign firm producing good z, and $p(z)$ and $p^*(z)$ the home and foreign price of the good. We use Y and Y^* to denote the gross domestic products of the home and foreign country, and w and w^* their wages, respectively. Overall trade is balanced, and in each country, total consumption expenditure is equal to gross domestic product, which we also call income. We can easily derive the following results:

$$d(z) = \frac{\gamma(z)\, Y}{p(z)}, \tag{1}$$

$$d^*(z) = \frac{\gamma(z)\ Y^*}{p^*(z)}, \tag{2}$$

$$p(z) = \frac{w}{\alpha(z)} + \frac{\tau\, w^*}{\alpha^*(z)}, \tag{3}$$

$$p^*(z) = \frac{\tau\, w}{\alpha(z)} + \frac{w^*}{\alpha^*(z)}. \tag{4}$$

Let $s(z)$ denote the home firm's share in the home market for good z, and $s^*(z)$ denote the home (not foreign) firm's share in the foreign market for good z. L and L^* denote home and foreign labor endowments. Then, we can show that

$$s(z) = \frac{\frac{\alpha(z)}{\alpha^*(z)} \frac{L}{L^*}}{\frac{\alpha(z)}{\alpha^*(z)} \frac{L}{L^*} + \frac{1}{\tau}}, \tag{5}$$

$$s^*(z) = \frac{\frac{\alpha(z)}{\alpha^*(z)} \frac{L}{L^*}}{\frac{\alpha(z)}{\alpha^*(z)} \frac{L}{L^*} + \tau}. \tag{6}$$

The proofs for the equations above are in the appendix. (5) and (6) state that the home firm's share, in both the home and foreign market, increases with the home firm's relative productivity $\alpha(z)/\alpha^*(z)$. It also increases with L/L^* because an increase in L/L^* reduces the relative wage w/w^*. Because $\tau > 1$, $s(z)$ is always greater than $s^*(z)$. In addition, an increase in τ raises $s(z)$ and lowers $s^*(z)$, intensifying home bias in sales.

We introduce the following notations to express the link between production pattern and trade pattern in terms of variables observed in industry-level data.

$$s_n = \int_{z \in I_n} \frac{\gamma(z)}{\beta_n} s(z)\, dz, \quad (7)$$

$$\overline{s} = \sum_{n=1}^{N} \beta_n\, s_n, \quad (8)$$

$$s_n^* = \int_{z \in I_n} \frac{\gamma(z)}{\beta_n} s^*(z)\, dz, \quad (9)$$

$$\overline{s^*} = \sum_{n=1}^{N} \beta_n\, s_n^*\,. \quad (10)$$

In other words, s_n is the home firms' average share in the home markets of industry n, and $\overline{s}$ is the home firms' average share in the home markets of all industries. The weights in each case are given by the markets' relative sizes, which in turn are determined by the expenditure shares. Similarly, s_n^* and $\overline{s^*}$ are the home firms' average shares in the foreign markets. Let Y_n and Y_n^* be home and foreign valued added produced in industry n. Then, $Y = \sum_{n=1}^{N} Y_n$ and $Y^* = \sum_{n=1}^{N} Y_n^*$. The total expenditures of home and foreign consumers on goods of industry n are equal to $\beta_n\, Y$ and $\beta_n\, Y^*$, and the home firms' shares in the home and foreign market are equal to s_n and s_n^*, respectively. Therefore, the following equations must hold.

$$Y_n = s_n\, \beta_n\, Y + s_n^*\, \beta_n\, Y^*, \quad (11)$$

$$Y_n^* = (1 - s_n)\, \beta_n\, Y + (1 - s_n^*)\, \beta_n\, Y^*. \quad (12)$$

Adding both sides of (11) over n, we obtain $Y = \overline{s}\, Y + \overline{s^*}\, Y^*$. Therefore, the share of home GDP in world GDP is given by:

$$\frac{Y}{Y_W} = \frac{\overline{s^*}}{1 - \overline{s} + \overline{s^*}}. \quad (13)$$

where Y_W is equal to $Y + Y^*$. Let X_n and X_n^* be the home and foreign country's exports in industry n. Then, using (13), we obtain

$$X_n = s_n^*\, \beta_n\, Y^* = \frac{s_n^*}{\overline{s^*}}\, \beta_n\, (1 - \overline{s} + \overline{s^*})\, \frac{Y\, Y^*}{Y_W}, \quad (14)$$

$$X_n^* = (1 - s_n)\, \beta_n\, Y = \frac{1 - s_n}{1 - \overline{s}}\, \beta_n\, (1 - \overline{s} + \overline{s^*})\, \frac{Y\, Y^*}{Y_W}. \quad (15)$$

The current study investigates the influence of Ricardian comparative advantage on trade intensity, production specialization, and intra-industry trade. Trade intensity is normalized trade volume. It is frequently measured as the ratio of bilateral trade volume to the sum of partner incomes or as the ratio of bilateral trade volume to the product of partner incomes. The latter method has a more theoretical basis because most gravity equation theories express the latter ratio as a function of trade costs and other variables. The most influential gravity models—those of Eaton and Kortum (2002), Anderson and van Wincoop (2003), and Chaney (2008)—all derive from a multi-country model the gravity equation in the following form.

$$\frac{X_{ij}}{\frac{Y_i Y_j}{Y_W}} = \left(\frac{\tau_{ij}}{\Pi_i P_j}\right)^{1-\theta}. \tag{16}$$

X_{ij} denotes the value of exports from county *i* to country *j*, Y_i country *i*'s income, Y_W world income, and τ_{ij} transportation costs from county *i* to country *j*. θ represents different parameters in different models. θ is equal to a parameter measuring inter-firm technological heterogeneity in the Ricardian model of Eaton and Kortum (2002) or in the monopolistic competition model of Chaney (2008).[1] It is given by the elasticity of substitution in the demand for differentiated products in the monopolistic competition model of Anderson and Van Wincoop (2003). Π_i and P_j are the complex functions of trade costs, price levels, and incomes involving all trading partners of countries *i* and *j*. Their exact form varies between models. The literature calls them "multilateral resistance" terms, following Anderson and Van Wincoop (2003). The right-hand side of (16) becomes equal to 1 in the absence of trade costs in all models.

As in the above literature, we measure trade intensity as the ratio of trade volume to the product of partner incomes (relative to world income). We first show that in our two-country model, trade intensity is determined as

$$TRADE \equiv \frac{X}{Y\,Y^*/Y_W} = \frac{X^*}{Y\,Y^*/Y_W} = 1 - \bar{s} + \bar{s}^*. \tag{17}$$

$X = \sum_{n=1}^{N} X_n$ and $X^* = \sum_{n=1}^{N} X_n^*$. (17) directly follows from (8) and (14). It is strikingly simple compared to (16). Trade intensity depends only on the difference between the average share of home firms in the home market and that in the foreign market, which in turn is increasing in trade costs as we show later. Of course, this is a special result coming from a two-country model with restrictive assumptions.

We measure the degree of bilateral production specialization by the difference in industrial structure:

$$SPEC \equiv \frac{1}{2}\sum_{n=1}^{N}\left|\frac{Y_n}{Y} - \frac{Y_n^*}{Y^*}\right| = \frac{1}{2}\sum_{n=1}^{N}\left|\frac{s_n^*}{\bar{s}^*} - \frac{1-s_n}{1-\bar{s}}\right| \beta_n\,(1 - \bar{s} + \bar{s}^*). \tag{18}$$

The proof for (18) is in the appendix. When the two countries have an identical industry structure, that is, $Y_n/Y = Y_n^*/Y^*$ for every n, *SPEC* takes the minimum value of 0. If complete specialization occurs in the sense that whenever one country produces in an industry, the other country does not produce in the same industry, *SPEC* takes the maximum value of 1. A few authors have used the index to measure the degree of bilateral specialization between two regions. (Krugman, 1991; Clark and van Wincoop, 2001; and Imbs, 2004). Note that $s_n^*/\bar{s}^*$ is the home country's foreign market share in industry n relative to its overall foreign market share. Meanwhile, $(1 - s_n)/(1 - \bar{s})$ is the foreign country's home market share in industry n relative to its overall home market share. (18) states that the specialization index is increasing in the difference between the two countries in the distribution of overseas market shares.

To measure the intensity of intra-industry trade, we use a transformation of the Grubel-Lloyd (1975) index:

$$IIT \equiv \left(\frac{\sum_{n=1}^{N}|X_n - X_n^*|}{\sum_{n=1}^{N}(X_n + X_n^*)}\right)^{-1} = \left(\frac{1}{2}\sum_{n=1}^{N}\left|\frac{s_n^*}{\bar{s}^*} - \frac{1-s_n}{1-\bar{s}}\right|\beta_n\right)^{-1} \tag{19}$$

[1] Chaney (2008) has an additional term for capturing the fixed costs of exporting.

Note that *IIT* is equal to $1/(1-\text{the Grubel Lloyd index})$. IIT takes the minimum value of 1 when all trade is inter-industry trade, and it goes to infinity when all trade is intra-industry trade ($X_n = X_n^*$ for every n). (19) is proved in the appendix.

Comparing (17), (18) and (19), we can see that

$$TRADE = SPEC \times IIT. \tag{20}$$

Trade intensity is equal to the product of the degree of production specialization and the intensity of intra-industry trade. This is not a special property of our model. Song (2011) shows that (20) always hold in a world of two countries running balanced trade if transportation costs of iceberg type are the only barrier to trade and consumers have identical Cobb-Douglas preferences. In traditional trade models such as the Ricardian or the Heckscher-Ohlin model where intra-industry trade does not exist, *IIT* is equal to 1. Without intra-industry trade, trade is nothing but the difference between the production and the consumption vector at the industry level, and when trading partners share a common consumption structure, trade intensity is equal to the difference in production structure. By contrast, in the new trade theory, trade intensity can be high or low for a given difference in industrial structure depending on how much two-way trade occurs in identical industries.

To link the three indexes above to the industry distribution of productivities, we define the following variables.

$$\alpha_n = \int_{z \in I_n} \alpha(z) \frac{\gamma(z)}{\beta_n} dz, \tag{21}$$

$$\overline{\alpha} = \sum_{n=1}^{N} \alpha_n \beta_n, \tag{22}$$

$$\alpha_n^* = \int_{z \in I_n} \alpha^*(z) \frac{\gamma(z)}{\beta_n} dz, \tag{23}$$

$$\overline{\alpha^*} = \sum_{n=1}^{N} \alpha_n^* \beta_n. \tag{24}$$

α_n is the average productivity of the home firms in industry n, and $\overline{\alpha}$ is the average productivity of all home firms. Again, the weights are given by the relative sizes of the markets. Similarly, α_n^* and $\overline{\alpha^*}$ are the foreign firms' average productivity in industry n and and that in all industries.

The market shares in (5) and (6) are nonlinear functions of commodity-level productivities. Thus, to express them as functions of industry averages, we linearize (5) and (6) in terms of $\alpha(z)$, $\alpha^*(z)$, and τ at $\alpha(z) = \overline{\alpha}$, $\alpha^*(z) = \overline{\alpha^*}$, and $\tau = 1$. We obtain

$$s(z) \cong \sigma + \sigma(1-\sigma)\left(\frac{\alpha(z)}{\overline{\alpha}} - \frac{\alpha^*(z)}{\overline{\alpha^*}}\right) + \sigma(1-\sigma)(\tau - 1), \tag{25}$$

$$s^*(z) \cong \sigma + \sigma(1-\sigma)\left(\frac{\alpha(z)}{\overline{\alpha}} - \frac{\alpha^*(z)}{\overline{\alpha^*}}\right) - \sigma(1-\sigma)(\tau - 1). \tag{26}$$

The proof is in the appendix. σ is a constant, which can be interpreted as the home firm's market share when $\alpha(z) = \overline{\alpha}$, $\alpha^*(z) = \overline{\alpha^*}$, and $\tau = 1$.

$$\sigma = \frac{\frac{\overline{\alpha}}{\overline{\alpha^*}}\frac{L}{L^*}}{\frac{\overline{\alpha}}{\overline{\alpha^*}}\frac{L}{L^*}+1} \tag{27}$$

Plugging (25) and (26) into (7) through (10), we obtain

$$s_n \cong \sigma + \sigma(1-\sigma)\left(\frac{\alpha_n}{\overline{\alpha}} - \frac{\alpha_n^*}{\overline{\alpha^*}}\right) + \sigma(1-\sigma)(\tau-1), \tag{28}$$

$$\bar{s} \cong \sigma + \sigma(1-\sigma)(\tau-1), \tag{29}$$

$$s_n^* \cong \sigma + \sigma(1-\sigma)\left(\frac{\alpha_n}{\overline{\alpha}} - \frac{\alpha_n^*}{\overline{\alpha^*}}\right) - \sigma(1-\sigma)(\tau-1), \tag{30}$$

$$\overline{s^*} \cong \sigma - \sigma(1-\sigma)(\tau-1). \tag{31}$$

Finally, we plug these approximations into (17), (18) and (19) to obtain the following equations.

$$TRADE \equiv \frac{X}{Y\,Y^*/Y_W} = 1 - 2\sigma(1-\sigma)(\tau-1), \tag{32}$$

$$SPEC = \frac{1}{2}\sum_{n=1}^{N}\left|\frac{Y_n}{Y} - \frac{Y_n^*}{Y^*}\right| = \big(1 - 2\sigma(1-\sigma)(\tau-1)\big)\,\rho(\tau)\,PRODDIF, \tag{33}$$

$$IIT = \left(\frac{\sum_{n=1}^{N}|X_n - M_n|}{\sum_{n=1}^{N}(X_n + M_n)}\right)^{-1} = (\rho(\tau)\,PRODDIF)^{-1}, \tag{34}$$

where

$$PRODDIF = \frac{1}{2}\sum_{n=1}^{N}\left|\frac{\alpha_n}{\overline{\alpha}} - \frac{\alpha_n^*}{\overline{\alpha^*}}\right|\beta_n, \tag{35}$$

$$\rho(\tau) = \frac{\sigma}{1-\sigma(\tau-1)} + \frac{1-\sigma}{1-(1-\sigma)(\tau-1)}. \tag{36}$$

$PRODDIF$ is our key variable. The essence of the Ricardian trade theory is that productivity differences, or more precisely the difference in the industry distribution of productivities between trading partners, are the driver of trade. *PRODDIF* offers a theory-based measure of this difference. When the mean-differenced productivities of the two countries are similarly distributed across industries, or when the pattern of comparative advantages is weak, *PRODDIF* will be close to zero. As the pattern of comparative advantage becomes stronger, it will increase toward 1. (33) states that the extent of specialization is proportional to this Ricardian measure of productivity differences. Meanwhile, (34) states that the degree of intra-industry trade is inversely proportional to the measure of productivity differences.

However, our result on trade intensity in (32) is non-Ricardian. Trade intensity is not affected by the difference in productivity distribution. Only transportation cost τ affects trade intensity by driving in the wedge between firms' market shares in the two countries. Productivity differences increase specialization, enlarging trade flows, but they decrease intra-industry trade, reducing trade flows. The two effects exactly offset each other because trade intensity is equal to the product of specialization and intra-industry trade.

Finally, we note that $\rho(\tau)$ is increasing in τ. Therefore, IIT is decreasing in τ, as can be seen from (34). However, the effect of τ on *SPEC* is ambiguous. $\big(1 - 2\sigma(1-\sigma)(\tau-1)\big)\,\rho(\tau)$ can increase or decrease with τ in (33).

3. Empirical Results

3.1. Data and Measurements

Our data on bilateral trade and value-added at the industry level are obtained from the World Input-Output Database (WIOD, Release 2013); see Timmer et al. (2015) for details.

The database provides annual data from 1995 to 2011 for 40 countries, including most major industrial countries and some emerging economies. Some data are estimated rather than observed, but the database suits our purpose in that it presents trade and production data in a mutually consistent way. We will restrict our investigation to manufacturing, which the WIOD classifies into 14 industries according to the International Standard Industrial Classification (ISIC) Revision 3. Table 1 presents the description for these industries.

The 14 industry classification of manufacturing may not be fine enough to catch all the major trade and industry structure variations. Our choice was dictated by the availability of consistent data on labor productivity. To obtain internationally comparable data on labor productivity, which is crucial to calculate our key index *PRODDIF*, we have to deflate nominal labor productivities calculated from national sources by international relative prices based on purchasing power parity. The most reliable source for relative producer price indexes at the industry level that we can find is the GGDC Productivity Level Database (2005 Benchmark); see Inklaar and Timmer (2014) for details.[2] The database was constructed as a complement to the WIOD, and thus uses the same industry classification as the WIOD. Following Mano and Castillo (2015), we stretch them to other years using inflation rates in local currencies because only the price indexes for a single year (2005) were provided.

Table 1. Industry Classification

Industry description	**ISIC Rev. 3 Code**
Food , beverages and tobacco	15 to 16
Textiles and textile products	17 to 18
Leather, leather products and footwear	19
Wood, wood products and cork	20
Paper, paper products, printing and publishing	21 to 22
Coke, refined petroleum and nuclear fuel	23
Chemicals and chemical products	24
Rubber and plastics products	25
Other nonmetallic mineral products	26
Basic metals and fabricated metal products	27 to 28
Machinery and equipment n.e.c.	29
Electrical and optical equipment	30 to 33
Transport equipment	34 to 35
Manufacturing n.e.c. and recycling	36 to 37

Source: Timmer et al. (2015).

The labor productivity of industry n in country i in year t is calculated by the following formula.

$$\alpha_{nit} = \frac{Y_{nit}}{L_{nit}} \frac{1}{P_{nit} \;\; EX_{i2005} \;\; PPP_{ni2005}}. \tag{37}$$

[2] The database matches numerous products in different countries meticulously to control for quality differences. Costinot et al. (2012) also use this database to test the Ricardian prediction from the Eaton and Kortum (2002) model.

For industry n in country i in year t, Y_{nit} is gross value added in current local currency units, L_{nit} is the number of engaged people, P_{nit} is the local price index of gross value added using 2005 as the base year ($P_{ni2005} = 1$). These data come from the Socio Economic Accounts of the WIOD. EX_{i2005} is the nominal exchange rate of local currency units per USD in 2005. PPP_{ni2005} is the relative price level of gross output in year 2005 using US GDP as the numeraire (its price level is equal to 1). It comes from the GGDC Productivity Level Database.[3] The idea is that labor productivity in current local currency units (Y_{nit}/L_{nit}) is converted into constant 2005 local currency units via P_{nit}, then into 2005 USD via EX_{i2005}, and then into 2005 international price units via PPP_{ni2005}.

Our theory comes from a two-country world with balanced trade, but, somewhat uncomfortably, we apply it to data from the multi-country world with unbalanced bilateral trade. To do that, we slightly modify the definition of our indexes.

$$TRADE_{ijt} \equiv \frac{\sqrt{X_{ijt}}\sqrt{X_{jit}}}{Y_{it}\,Y_{jt}/(Y_{it}+Y_{jt})}. \tag{38}$$

Y_{it} is total manufacturing valued added of country i in year t. Bilateral trade is not balanced in the data; hence, we use the geometric average of exports from i to j (X_{ijt}) and exports from j to i (X_{jit}). The other indexes are calculated as:

$$SPEC_{ijt} = \frac{1}{2}\sum_{n=1}^{N}\left|\frac{Y_{nit}}{Y_{it}} - \frac{Y_{njt}}{Y_{jt}}\right|, \tag{39}$$

$$IIT_{ijt} = \left(\frac{\sum_{n=1}^{N}|X_{nijt}-X_{njit}|}{\sum_{n=1}^{N}(X_{nijt}+X_{njit})}\right)^{-1}, \tag{40}$$

$$PRODDIF_{ijt} = \frac{1}{2}\sum_{n=1}^{N}\left|\frac{\alpha_{nit}}{\overline{\alpha_{it}}} - \frac{\alpha_{njt}}{\overline{\alpha_{jt}}}\right|\beta(n). \tag{41}$$

$\beta(n)$ in (41), the expenditure share of industry n, is calculated using the share of industry n in the world output of manufactured goods.

Finally, we capture bilateral transportation cost τ by geographical variables used in the standard gravity equations. Data for distance and dummies for contiguity, common language, colonial ties, and RTAs come from the CEPII gravity dataset (Head, Mayer, and Ries, 2010; Head and Mayer, 2014).

Because structural changes would be slow, we use observations made in the quadrennial years of 1996, 2000, 2004, and 2008 out of the entire sample years from 1995 to 2011.[4] All four indexes above can be obtained for country pairs composed of 34 countries. Most of them are OECD countries, but some non-OECD countries (Bulgaria, Brazil, China, Indonesia, India, Lithuania, and Russia) are also included. Countries covered are listed in the footnote of Table 2. Every index above is identical for country pairs (i, j) and (j, i); thus, we use only one of them. Our panel is almost balanced. We make on average 3.9 observations per country pair for 561 country pairs, totaling 2,209 observations.

Table 2 reports the summary statistics for our indexes. Because trade is almost zero for many country pairs (but it is never exactly zero), the mean of *TRADE* is small. *SPEC* and *PRODDIF* have the mean of 0.25 and 0.24, respectively, out of the possible maximum of 1.

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[3] Ideally, we should use the price level of gross value added, but it is not available at the level of disaggregation.

[4] We cannot use most of the data for 2010 and 2011 because we cannot observe labor productivities for many countries.

The mean of *IIT* is approximately 2, which corresponds to the Grubel-Lloyd index equal to 0.5.

Table 2. Summary Statistics for Key Indexes

Variable	Mean	Std. Dev.	Min	Max	Obs.
TRADE	0.07	0.12	0.00	1.34	2,209
SPEC	0.25	0.08	0.06	0.55	2,209
IIT	2.05	1.03	1.00	10.99	2,209
PRODDIF	0.24	0.11	0.04	0.62	2,209

Notes: The indexes are calculated from data on 34 countries (Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Japan, Korea, Latvia, Mexico, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Turkey, UK, USA, Bulgaria, Brazil, China, Indonesia, India, Lithuania, and Russia) observed for the four years 1996, 2000, 2004, and 2008. The industries covered are the 14 manufacturing industries of Table 1.

Sources: WIOD (2013 Release); GGDC Productivity Level Database (2005 Benchmark).

Table 3 presents the correlations among the four indexes. All correlation coefficients are highly significant. *TRADE* is strongly positively correlated with *IIT*. *SPEC* is positively correlated, and *IIT* is negatively correlated with *PRODDIF*, in accordance with our model. The negative correlation between *TRADE* and *SPEC* does not accord well with our model, and neither does the negative correlation between *TRADE* and *PRODDIF*. However, what matters is partial correlations, conditional upon other variables, which we now investigate.

Table 3. Correlations among Key Indexes

	TRADE	***SPEC***	***IIT***	***PRODDIF***
TRADE	1.00			
SPEC	-0.17 ***	1.00		
IIT	0.60 ***	-0.41 ***	1.00	
PRODDIF	-0.13 ***	0.18 ***	-0.26 ***	1.00

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Sources: WIOD (2013 Release); GGDC Productivity Level Database (2005 Benchmark).

3.2. Estimation Results

We start by examining the determinants of trade intensity in Table 4. Taking natural logarithm of (20),

$$\ln TRADE_{ijt} = \ln SPEC_{ijt} + \ln IIT_{ijt}. \tag{42}$$

(42) would not fit the data perfectly because the world is distant from our two-country Ricardo-Cournot model. This study asks how much trace of our simple model we can detect in the data. In regression (1), we regress $\ln TRADE$ on $\ln SPEC$ and $\ln IIT$ without controlling for any other variable. We do not intend to test (42) by running this regression. *TRADE, SPEC* and *IIT* are jointly determined by the influence of many variables, and by relative productivity differences and trade costs even in the narrow context of our model, generating endogeneity problems. We just inspect the partial correlations of *TRADE* with

Table 4. Trade, Specialization, Intra-industry trade, and Productivity Differences

Dependent variable	(1) ln $TRADE$	(2) ln $TRADE$	(3) ln $TRADE$	(4) ln $TRADE$
ln $SPEC$	0.29**	0.28**		0.29**
	(0.13)	(0.12)		(0.12)
ln IIT	2.35***	0.80***		0.80***
	(0.11)	(0.11)		(0.11)
ln $PRODDIFF$			-0.10	-0.06
			(0.07)	(0.07)
ln Distance		-0.81***	-0.91***	-0.80***
		(0.06)	(0.06)	(0.06)
Contiguity		0.58***	0.72***	0.58***
		(0.13)	(0.14)	(0.13)
Common language		0.38***	0.44***	0.37***
		(0.15)	(0.15)	(0.15)
Colony		0.16	0.20	0.16
		(0.17)	(0.18)	(0.17)
RTA		-0.06	-0.00	-0.07
		(0.12)	(0.12)	(0.12)
Fixed Effects		country×year	country×year	country×year
R^2	0.37	0.71	0.69	0.71
Obs.	2,209	2,209	2,209	2,209

Notes: Numbers in parentheses are robust standard errors clustered by country pairs.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

$SPEC$ and IIT to check the usefulness of the latter variables in the least squares sense. In regression (1), we observe significant positive partial correlations, which agree with our model, but the coefficients are quite different from the theoretical values of 1.[5] For example, the coefficient of 0.29 on ln $TRADE$ implies that a 10% increase in the specialization index (say from the sample mean of 0.25 in Table 2 to 0.275) would raise trade intensity by 2.9% (say from the sample mean of 0.07 in Table 2 to 0.072). However, according to equation (42), a 10% increase in the specialization index should raise trade intensity by a full 10%. The coefficient of 2.35 on ln IIT implies that a 10% increase in the intra-industry index (say from the sample mean of 2.05 in Table 2 to 2.255) would raise trade intensity by 23.5% (say from the sample mean of 0.07 in Table 2 to 0.086), not by a 10% as dictated by equation (42). However, we note that the R-squared of 0.37 seems high with just two variables.

In regression (2), we inspect the explanatory powers of bilateral production and trade structure differently. We plug the indexes in the gravity equation to see if they have any additional explanatory power over the standard gravity variables. The log of distance and binary dummies for contiguity, common language, colonial ties, RTAs are geographical variables frequently used to capture the effect of trade costs in gravity equations. Additionally, as has now become standard in the estimation of gravity equations (see Head, Mayer, and Ries, 2014), we also include country dummies to control for the third countries effects or the

[5] Standard errors reported in Table 4 are clustered by country pairs to correct for possible serial correlations among error terms. Without clustering, all the coefficients on ln $SPEC$ in Table 1 are significant at 1%.

"multilateral resistance" of Anderson and van Wincoop (2014). These country dummies can also be regarded as representing the scales of countries (population, land etc.) or country-specific trade barriers. These variables change over time; thus, we introduce country dummies that vary over years (country × year fixed effects).[6] In regression (2), we see that the coefficients for $\ln SPEC$ and $\ln IIT$ are significantly positive, although they are significantly smaller than the theoretical value of 1. Bilateral production and trade structure have extra explanatory power over the theory-based variables that are commonly employed to predict bilateral trade volume.

In regression (3), we test the first prediction of our model. According to equation (32), $\ln TRADE$ should not be systemically influenced by productivity differences after we control for the effects of trade costs because its effects on specialization and intra-industry trade cancel each other. However, it should be negatively affected by trade costs. We capture the effect of trade costs using the same geographical variables as used in regression (2). The estimation result supports our model. The coefficient for $\ln PRODDIF$ is not significantly different from zero, whereas most trade cost variables negatively affect trade intensity. In regression (4), we add $\ln SPEC$ and $\ln IIT$ in the equation. These two variables are endogenous variables, while $\ln PRODDIF$ is an exogenous variable that determines these variables. Thus, potential econometric problems exist. However, by running this regression, we might be able to check if productivity differences influence trade intensity only through specialization and intra-industry trade, but not independently from them, as our theory argues. We find that the coefficients for $\ln SPEC$ and $\ln IIT$ change little from those in regression (2), and the coefficient for $\ln PRODDIF$ is still insignificant. This agrees with our theory.

Table 5. Specialization, Intra-industry trade, and Productivity Differences

Dependent variable	**(5)** **ln $SPEC$**	**(6)** **ln $SPEC$**	**(7)** **ln IIT**	**(8)** **ln IIT**
ln $PRODDIFF$	0.17***	0.12***	-0.16***	-0.09***
	(0.02)	(0.02)	(0.02)	(0.02)
ln Distance	0.02	0.04*	-0.11***	-0.14***
	(0.02)	(0.02)	(0.02)	(0.02)
Contiguity	-0.18***	-0.19***	0.25***	0.25***
	(0.06)	(0.06)	(0.08)	(0.06)
Common language	-0.11**	-0.06	0.23***	0.10*
	(0.05)	(0.05)	(0.06)	(0.05)
Colony	-0.07	-0.08	0.06	0.07
	(0.09)	(0.07)	(0.09)	(0.06)
RTA	0.07**	0.10***	0.11***	0.05
	(0.03)	(0.04)	(0.03)	(0.03)
Fixed Effects	year	country × year	year	country × year
R^2	0.10	0.38	0.35	0.55
Obs.	2,209	2,209	2,209	2,209

Notes: Numbers in parentheses are robust standard errors clustered by country pairs.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

[6] We do not distinguish between export from country i to j and export from country j to i. Therefore, we restrict a dummy for country i to have the same coefficient when it is an exporter and it is an importer.

We test the other predictions of our model in Table 5. Taking the logarithm of both sides, equation (33) predicts that ln $SPEC$ increases one-to-one with ln $PRODDIF$, but it is ambiguously affected by trade costs. Regression (5) is largely consistent with this prediction. The coefficient for ln $PRODDIF$ is 0.17 and highly significant. In regression (6), we add time-varying country fixed effects. Unlike the case of gravity equations, theoretical justification for including these variables is not straightforward, but they can be thought as representing country-specific trade barriers. ln $PRODDIF$ is still significantly positive, although its coefficient shrinks. The influence of variables representing trade costs is not clear-cut. The negative estimated coefficients on *Contiguity* in regressions (5) and (6) suggest a positive influence of trade costs on specialization. In contrast, the positive coefficient on RTA implies a negative influence, and distance seems to have little effect.

In regressions (7) and (8), we confirm the negative influence of productivity differences on intra-industry trade, supporting equation (33). The estimated coefficients on ln $PRODDIF$ are negative and highly significant. The estimated coefficients on geographical variables are also largely consistent with our theory. The coefficients on *Distance*, *Contiguity*, *Common language* and RTA in regression (7) all imply the negative effects of trade costs on intra-industry trade, supporting equation (34). However, the significance of *Common language* and RTA almost vanishes in regression (8) where we incorporate time-varying country fixed effects.

The estimated coefficients on ln $PRODDIFF$ are all significant at the 1% level. However, their absolute values are much smaller than 1, the value predicted by our theory. The reason is unclear to us. It could be measurement errors that frequently show up in labor productivity statistics. Or, as we mentioned before, our industry classification composed of only 14 industries may be too coarse to catch the variations of productivity distribution across countries and years. However, the main reason is probably the presence of third country effects. The production and trade pattern of two countries trading with each other must be heavily influenced by those of the other countries that two countries trade with. Our two-country model does not capture this influence, and hence its prediction would only be partly reflected in the data.

Table 6. Regressions with Pair Fixed Effects

Dependent variable	**(9)** **ln $TRADE$**	**(10)** **ln $TRADE$**	**(11)** **ln $SPEC$**	**(12)** **ln IIT**
ln $SPEC$	0.75***			
	(0.12)			
ln IIT	0.35***			
	(0.08)			
ln $PRODDIF$		0.00	0.04***	-0.05***
		(0.03)	(0.01)	(0.02)
RTA		0.33***	0.05***	0.03
		(0.06)	(0.02)	(0.03)
Fixed Effects	country pair	year country pair	year country pair	year country pair
R^2	0.06	0.29	0.10	0.04
Obs.	2,209	2,209	2,209	2,209

Notes: Numbers in parentheses are robust standard errors clustered by country pairs. All variables in Table 5 that are constant over time are dropped because country pair dummies subsume them. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Finally, in Table 6, we focus on the time series variations of our indexes within country pairs. In all regressions, we introduce country-pair fixed effects. They can be regarded as capturing all time-invariant bilateral trade costs.[7] Regression (9) is the counter part of regression (1). We examine the partial correlations of trade intensity, in this case across time, with specialization and intra-industry trade. They are all highly significant and positive, and their sizes are also large. Over time, trade intensity, specialization and intra-industry trade tend to move together. In regressions (10), (11) and (12), we test equations (31), (32) and (33), respectively. Productivity differences have no effect on trade intensity, a positive effect on specialization and a negative effect on intra-industry trade, all confirming the predictions of our model. However, the estimated effect of $\ln PRODDIF$ becomes even smaller with pair fixed effects.

4. Conclusion

This paper tests propositions regarding how bilateral trade intensity is related to differences between trading partners in production structure and in productivity distribution. These variables had been central in the analysis of bilateral trade flows, but are seldom used in recent studies. We find that bilateral trade intensity is increasing in both specialization and intra-industry trade, but it is not affected by productivity differences. The reason is that productivity differences intensify specialization, but reduce intra-industry trade, the two effects offsetting each other. However, the estimated effects of productivity differences on specialization and intra-industry are much smaller than the values predicted by our model. This is mostly likely due to the presence of third-country effects that our model ignores. We should improve our model to incorporate them.

We believe that our empirical finding is interesting by itself. However, we also believe that this study contributes toward enlarging the applicability of oligopolistic trade models by deriving tractable and testable propositions using a general equilibrium Cournot model. Oligopolistic trade models once occupied a central stage in trade theory when oligopoly played a starring role in the formation of strategic trade policy theory in the 1980s. After that, they faded out and the literature has been dominated by new theories based on perfect and monopolistic competition that assume the world composed of atomistic firms. This transition is ironic because it occurred when a small number of giant multinationals were increasingly dominating international trade.

The relative decline of oligopolistic models may be due to two major reasons: tractability and utility. For tractability, incorporating oligopolistic models into a general equilibrium model and producing testable propositions are very difficult. For utility, oligopolistic models may be superior in terms of descriptive realism, but why should we use messy models when we have alternative models that look unrealistic, but handle most questions more elegantly? This paper bypasses the first hurdle by imposing quite restrictive assumptions. They are difficult to justify at the high level of rigor, but we extract the central features of Cournot oligopoly with maximum tractability, and let them interact with the Ricardian forces of comparative advantage. In our model, trade occurs not because of cost differences or product differentiation. Trade occurs as Cournot competitors try capturing foreign monopoly rents. The mutual penetration of the foreign rival's market in a single industry generates intra-industry trade, and it drives all trade.

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[7] We tried regressions that incorporate both pair fixed effects and country-year fixed effects, but we do not report them here because a multi-collinearity problem occurred in our Stata program in this case.

In this setting, the distribution of market shares between international rivals becomes a dominant force for determining trade volume and pattern. Trade volume, relative to the product of trading partners' GDPs, is decreasing in the difference between firms' market shares in the home and foreign market. An increase in trade costs enlarges this difference, and thus decreases trade volume. In other words, our model produces a gravity equation based on international market share rivalry, which is distinct from other gravity theories. Simultaneously, relative productivity between international rivals determines their relative market shares, and this is where Ricardian comparative advantage kicks in. When the pattern of comparative advantage is strong, or when productivity differences between international rivals are on average large, the asymmetry between their market shares is on average high, implying a low level of pure cross-hauling or intra-industry trade. However, net trade is large across industries because in each country, resources move toward industries where domestic firms have larger market shares. This leads to a high level of specialization and inter-industry trade. The two forces exactly offset each other in our model, and comparative advantage does not affect overall trade volume. However, it strongly affects the intensity of intra-industry trade and the degree of production specialization. The exact cancelation may not hold in a more general setting. However, the main mechanism through which the interplay between Cournot competition and Ricardian comparative advantage determines trade volume and pattern would survive many extensions. We also believe that the mechanism newly identified in this study is working in the real world because it is supported by our empirical findings.

Regarding the second reason for the decline of oligopolistic models, this study contributes little, but may serve as a basis for future studies that enhance the usefulness of oligopolistic models. To prove utility, we must demonstrate the usefulness of Cournot models in tacking questions that models based on perfect or monopolistic competition are ill-equipped to handle. Such questions include the effects of trade policies on income distribution because oligopolistic models generate excess profits, the welfare effect of trade policies because they can improve national welfare by profit-shifting, and the effect of competition policies because they constrain oligopolists' behavior. Partial equilibrium models have analyzed these issues, but exploring their interactions with comparative advantage in a general equilibrium setting has a potential to generate interesting results. Although we do not pursue these difficult challenges here, our model may serve as a basis for further extensions to address these issues.

Another aspect of Cournot competition that can be explored in this paper is the effect of trade costs on trade volume in oligopolistic models. Cournot firms consider the effect of their own decision on the market price, and this leads to the behavior called "pricing to the market." This may imply the relationship between trade costs and trade volume quite distinct from those found in models based on perfect or monopolistic competition. Our model implies that the negative effect of trade costs on trade volume intensifies as international rivals become more symmetric in size. Pursuing and testing its general-equilibrium implication should be deferred to a future study.

Finally, this paper treats productivity differences among countries as exogenous variables, as most Ricardian models implicitly assume. However, in the presence of scale economies or endogenous technological change, they may be determined simultaneously with trade flows. Overcoming this problem econometrically or endogenizing productivity differences as in the new literature on the role of institutions in the formation of comparative advantage (*e.g.* Levchenko, 2007; Nunn, 2007; Chor, 2010) should also be left as a future task.

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Appendix

A.1 Proof for equations (3), (4), and (5)

Let w and w^* be the home and foreign wage, respectively. In the home market, the profit maximization of the duopolists implies that

$$p(z)\big(1 - s(z)\big) = \frac{w}{\alpha(z)}, \tag{A1}$$

$$p(z)s(z) = \frac{\tau w^*}{\alpha^*(z)}. \tag{A2}$$

From these equations, we obtain (3). (4) is similarly derived. By plugging (3) into (A2), we can calculate that

$$s(z) = \frac{\frac{\tau w^*}{\alpha^*(z)}}{\frac{w}{\alpha(z)} + \frac{\tau w^*}{\alpha^*(z)}}. \tag{A3}$$

$$s^*(z) = \frac{\frac{w^*}{\alpha^*(z)}}{\frac{\tau w}{\alpha(z)} + \frac{w^*}{\alpha^*(z)}}. \tag{A4}$$

The total income of home workers must be equal to the total employment of the home firms times w. Therefore,

$$\begin{aligned} w\,L &= \int_0^1 \Big[s(z)\frac{w}{\alpha(z)}\, d(z) + s^*(z)\frac{\tau w}{\alpha(z)}\, d^*(z)\Big]\, dz\,, \\ &= \int_0^1 \Big[s(z)\frac{\frac{w}{\alpha(z)}}{\frac{w}{\alpha(z)} + \frac{\tau w^*}{\alpha^*(z)}}\,\gamma(z)\,Y + s^*(z)\frac{\frac{\tau w}{\alpha(z)}}{\frac{\tau w}{\alpha(z)} + \frac{w^*}{\alpha^*(z)}}\,\gamma(z)\,Y^*\Big]\, dz. \\ &= \int_0^1 [\,s(z)(1 - s(z))\,\gamma(z)\,Y + s^*(z)(1 - s^*(z))\,\gamma(z)\,Y^*]\, dz. \end{aligned} \tag{A5}$$

Likewise,

$$\begin{aligned} w^*\,L^* &= \int_0^1 \Big[(1 - s(z))\frac{\tau w^*}{\alpha^*(z)}\, d(z) + (1 - s^*(z))\frac{w^*}{\alpha^*(z)}\, d^*(z)\Big]\, dz\,, \\ &= \int_0^1 [\,(1 - s(z))s(z)\,\gamma(z)\,Y + (1 - s^*(z))s^*(z)\,\gamma(z)\;Y^*]\, dz. \end{aligned} \tag{A6}$$

Therefore, $w\,L = w^*L^*$. Plugging this relationship into (A3) and (A4) and reshuffling terms, we obtain (5) and (6).

A.2 Proofs for equations (18) and (19)

(18) follows from (11), (12), (13), and (16).

$$\sum_{n=1}^{N}\left|\frac{Y_n}{Y} - \frac{Y_n^*}{Y^*}\right| = \sum_{n=1}^{N}\left|\Big(s_n\beta_n + s_n^*\beta_n\frac{1-\bar{s}}{\overline{s^*}}\Big) - \Big((1 - s_n)\beta_n\frac{\overline{s^*}}{1-\bar{s}} + (1 - s_n^*)\beta_n\Big)\right|$$

$$= \sum_{n=1}^{N}\left|\Big(s_n + s_n^*\frac{1-\bar{s}}{\overline{s^*}}\Big) - \Big((1 - s_n)\frac{\overline{s^*}}{1-\bar{s}} + (1 - s_n^*)\Big)\right|\,\beta_n$$

$$= \sum_{n=1}^{N} \left| \frac{s_n^*}{\overline{s^*}} - \frac{1-s_n}{1-\overline{s}} \right| \beta_n \left(1 - \overline{s} + \overline{s^*}\right). \tag{A7}$$

(19) can be similarly proved using (14), (15), and (16).

$$\frac{\sum_{n=1}^{N} |X_n - X_n^*|}{\sum_{n=1}^{N} (X_n + X_n^*)} = \frac{\sum_{n=1}^{N} \left| \frac{s_n^*}{\overline{s^*}} - \frac{1-s_n}{1-\overline{s}} \right| \beta_n \left(1-\overline{s}+\overline{s^*}\right) \frac{Y\,Y^*}{Y_W}}{2\left(1-\overline{s}+\overline{s^*}\right) \frac{Y\,Y^*}{Y_W}} = \frac{1}{2} \sum_{n=1}^{N} \left| \frac{s_n^*}{\overline{s^*}} - \frac{1-s_n}{1-\overline{s}} \right| \beta_n \,. \tag{A8}$$

A.3 Proofs for equations (25) and (26)

(5) can be rewritten as:

$$s = \frac{\alpha\, L}{\alpha\, L + \frac{1}{\tau} \alpha^* \, L^*} = f(\alpha, \alpha^*, \tau)$$
$$\cong f(\overline{\alpha}, \overline{\alpha^*}, 1) + f_\alpha(\overline{\alpha}, \overline{\alpha^*}, 1)(\alpha - \overline{\alpha}) + f_{\alpha^*}(\overline{\alpha}, \overline{\alpha^*}, 1)(\alpha^* - \overline{\alpha^*}) + f_\tau(\overline{\alpha}, \overline{\alpha^*}, 1)(\tau - 1)$$
$$= \sigma + \sigma(1-\sigma)\left(\frac{\alpha}{\overline{\alpha}} - 1\right) - \sigma(1-\sigma)\left(\frac{\alpha^*}{\overline{\alpha^*}} - 1\right) + \sigma(1-\sigma)(\tau - 1). \tag{A9}$$

Similarly, (6) can be approximated by

$$s^* = \frac{\alpha\, L}{\alpha\, L + \tau\, \alpha^* \, L^*} \cong \sigma + \sigma(1-\sigma)\left(\frac{\alpha}{\overline{\alpha}} - 1\right) - \sigma(1-\sigma)\left(\frac{\alpha^*}{\overline{\alpha^*}} - 1\right) - \sigma(1-\sigma)(\tau - 1).$$