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Carrying Carbon?
Negative and Positive Carbon Leakage with International Transport[*]

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Abstract

This study examines the effects of carbon pricing of greenhouse gas (GHG) emissions from international transport, production, and consumption of traded goods by modeling the international transport sector explicitly. Endogenous international transport explains the novel mechanism of carbon leakage across borders and sectors. The effectiveness of carbon pricing depends on whether the backhaul problem (i.e., the imbalance of shipping volume in outgoing and incoming routes) is present. If the backhaul problem is absent, any carbon pricing is effective because the global GHG emissions are necessarily reduced. With the backhaul problem, carbon pricing in goods consumption remains effective, whereas carbon pricing in goods production results in cross-border carbon leakage. However, endogenous transport costs mitigate this leakage. The opportunity of foreign direct investment also affects carbon pricing effectiveness. In particular, carbon pricing in the transport sector may not affect GHG emissions at all.

Keywords: Transportation; Backhaul problem; International oligopoly; Climate changes; Carbon pricing; Carbon leakage
JEL classification: F12, F18, F23, L13, Q56, R40

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1 Introduction

We witness rising global temperatures that have been accompanied by changes in the climate causing extensive damage all over the world. As various taxes have been designed to deal with environmental issues, it is natural to take carbon pricing, including carbon taxes, as a countermeasure against global warming. Unilateral carbon pricing by a group of countries may cause cross-border carbon leakage, which refers to an increase in foreign carbon emissions that results as a consequence of domestic actions to reduce emissions. The global carbon emissions can even increase as a result of cross-border carbon leakage. Because global warming depends on total carbon emissions in the world, cross-border carbon leakage is a major policy concern. This study identifies a new mechanism of carbon leakage due to endogenous international transport costs.

The literature has identified a few carbon leakage channels. The first is the energy market channel: a carbon policy by a major importer or exporter of carbon intensive goods leads to lower global fossil fuel prices, higher consumption of fossil fuel, and hence more carbon emissions elsewhere (e.g., Bohm 1993; Felder and Rutherford 1993; Eichner and Pethig 2015; Kiyono and Ishikawa 2004, 2013). The second is the competitiveness channel: economic activities associated with carbon-intensive, trade-exposed industries would shift from a country with stringent emission regulations to those with less stringent regulations. This channel consists of (i) the relocation of firms in those industries to countries with laxer regulations (e.g., Markusen et al. 1993, 1995; Kayalica and Lahiri 2005; Zeng and Zhao 2009; Dijkstra et al. 2011; Ishikawa and Okubo 2011, 2016, 2017); and (ii) changes in market shares such that foreign competitors, which have cost advantages in carbon-intensive production, would produce more and hence discharge more carbon emissions (e.g., Copeland and Taylor 2005; Ishikawa and Kiyono 2006; Ishikawa et al. 2012, 2020).[1]

These carbon leakage channels indicate that international trade and foreign direct investment (FDI) contribute to cross-border carbon leakage. In the context of cross-border pollution including global warming, many studies have investigated the effectiveness of emission regulations in the presence of international trade and FDI. However, most of those studies do not consider international transport, which plays a crucial role in international trade and FDI. A few studies that address the interaction between trade, transport, and environment assume that the freight rates are exogenously given without an explicit modeling of the transport sector (Cristea et al. 2013, Vöhringer et al. 2013, Shapiro 2016).[2] Once we incorporate

[1] The discussion draws from Fischer (2015) and Naegele and Zaklan (2019) Many studies have investigated the extent of carbon leakage using various computational general equilibrium modeling (e.g., Böhringer et al. 2017).

[2] An exception is Abe et al. (2014), which considers market power by transport firms in a strategic trade

endogenous international transport costs, we can identify emissions leakage mechanisms that are not addressed in the existing carbon leakage literature. This study demonstrates that these mechanisms are quantitatively important because they can amplify the magnitude of carbon leakage that the conventional mechanisms explain in some cases, whereas they can reduce or even reverse the sign of carbon leakage ("negative carbon leakage") in others.

The international transport sector also poses challenges and opportunities in the context of climate change mitigation. International Maritime Organization (2020) reports that international shipping generated 919 million tonnes of CO_2 in 2018—larger than Germany's emissions in the same year—with an 8% increase since 2012. While all shipping accounts for 2.9% of global anthropogenic CO_2 emissions, international shipping contributes approximately 2.5%. These facts, together with projected increases in carbon emissions from shipping over the next decades (International Maritime Organization, 2020),[3] indicate that efforts to reduce greenhouse gas (GHG) emissions in international transport will make a sizeable contribution to global mitigation strategies.[4]

However, regulating emissions from international transport is not straightforward. A study estimates that $1.4 to $1.9 trillion of investment would be required to fully decarbonize the shipping sector by 2050 (including the costs needed for land-based facilities to produce carbon-free shipping fuels such as hydrogen, Smith et al. 2021). The 2016 Paris Agreement under the United Nations Framework Convention on Climate Change, which requested the member countries to submit their national climate action plans, excluded international aviation and shipping emissions from its scope. While the jurisdiction over emissions associated with each trade route is not clearly defined, effective regulation calls for cooperation by the governments of trading partners.

The International Maritime Organization (IMO) has yet to impose binding regulations on GHG emissions from international shipping, though its Marine Environment Protection Committee may adopt mandatory regulations to cut the carbon intensity of existing ships in the near future. The European Union has proposed extending the European Union emissions trading system (EU ETS) to cover ocean shipping. As the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is debated at the UN International

and environmental policy framework. Their study illustrates that a country's unilateral increase in emissions tax benefits the transport firm in the foreign country at the expense of lower profits on the transport firm in the domestic country. The key to our model (i.e., transport firm's shipping capacity constraints and associated backhaul problems) is not addressed in their model.

[3]The International Maritime Organization (IMO) predicts that the growth of the world maritime trade could increase the CO_2 emissions from international shipping between 50% and 250% by 2050.

[4]Olsthoorn (2001) estimates that CO_2 emissions from international aviation may increase by 200% to 500% between 1995 and 2050. Cristea et al. (2013) report that international transport accounts for 33% of global trade-related emissions and more than 75% of emissions for major manufacturing categories.

Civil Aviation Organization, international cooperation on emissions reduction has been a high-priority policy issue in the international transport sector. In the meantime, more than 150 companies and business associations called for governments to commit to decarbonizing the international shipping sector fully by 2050 (Global Maritime Forum, November 2021). At the 2021 United Nations Climate Change Conference (COP26), more than 20 countries agreed to create zero-emissions shipping trade routes (Clydebank Declaration, November 2021). The International Chamber of Shipping, the global trade association for ship operators, is proposing the introduction of a global carbon levy on carbon emissions from ships. Thus carbon regulation in general, and carbon pricing in particular, is a critical policy issue for the transport sector.

Against this background, this study aims to explore carbon pricing in the presence of the international transport sector theoretically. Our theoretical model is based on the endogenous transport cost literature which has found that the international transport sector (both aviation and shipping) are highly concentrated with transport firms having market power (Hummels et al., 2009), and charging asymmetric freight rates on shipping in different directions on the same trade route, subject to the backhaul problem. The backhaul problem arises when the transport firm's shipping capacity is not utilized at the maximum level on the backhaul because of asymmetry in trade volumes. We demonstrate that incorporating these fundamental features of international transport provides new insights about the effects of various carbon pricing—including carbon pricing in international transport or unilateral carbon pricing by a trading partner—of trade-related emissions.

The effectiveness of carbon pricing depends on whether the volume of trade is imbalanced or balanced, or whether the backhaul problem exists.[5] In particular, we show that both cross-border and cross-sector carbon leakage caused by carbon pricing can be "negative" in the absence of the backhaul problem, implying that carbon pricing can be more effective. If the exports from country A to B (the fronthaul) exceed those from country B to A (the backhaul), the equilibrium freight rate on exports from B to A is independent of the marginal costs of shipping (Ishikawa and Tarui, 2018). Therefore, even though carbon pricing in shipping raises the effective marginal costs of shipping, it affects the freight rates in an asymmetric manner when the backhaul problem is present. Under this situation, carbon pricing in the transport sector reduces the fronthaul but does not affect the backhaul, thereby affecting the associated emissions. By contrast, if the fronthaul equals the backhaul (i.e., the backhaul problem is absent), carbon pricing in shipping increases freight rates of both directions, leading to the decrease in both fronthaul and backhaul. Thus, emissions not

[5] In our discussion, we focus on the balance or imbalance in the volume of trade as opposed to a balance in trade values.

only from the transport firm but also from the manufacturing firms can decrease, implying negative "cross-sector" carbon leakage can occur. This observation identifies a new source of carbon leakage due to endogenous transport costs.

If the backhaul problem is absent, any carbon pricing is effective because the global GHG emissions necessarily decrease. With the backhaul problem, carbon pricing in goods consumption remains effective. However, carbon pricing in goods production results in cross-border carbon leakage: country A's unilateral carbon pricing in production decreases the fronthaul but increases the backhaul and hence generates cross-border carbon leakage. These changes are conventional, but the endogenous transport costs mitigate them, meaning cross-border carbon leakage is weakened.

We also find that carbon pricing in international transport may not reduce overall trade-related emissions once we consider an interplay between endogenous transport costs and manufacturers' decisions on FDI. Facing the opportunity of manufacturers' horizontal FDI, the carrier may deter it strategically because the demand for transport decreases with horizontal FDI. Moreover, even if the carrier accommodates FDI, it prefers FDI with a single foreign plant to FDI with two plants (a domestic and foreign plant) because there is no demand for international transport with two-plant FDI. Thus, the carrier has an incentive to induce single-plant FDI. These strategic moves by the carrier also affect the global emissions.

These findings follow from our theoretical framework, which address the interlinkage between trade, transport, and environment by considering the transport sector explicitly. They indicate another benefit of comprehensive emissions regulation of emissions from both production (or consumption) and transport. Studies such as Felder and Rutherford (1993), Copeland and Taylor (2005), Jakob et al. (2013) and Baylis et al. (2014) indicate negative carbon leakage.[6] However, to our knowledge, no study has related transport to negative carbon leakage.

In what follows, section 2 introduces our basic model where the transport sector is explicitly introduced. Section 3 investigates carbon tax as a typical carbon-pricing policy. Another typical carbon-pricing policy is emissions trading. However, the effects of carbon taxes on GHG emissions are equivalent to those of emissions trading if trade in emission permits is subject to perfect competition. Section 4 extends the analysis by incorporating the opportunity of manufacturers' FDI into the model. Section 5 concludes.

[6]See Baylis et al. (2014) for more literature on negative carbon leakage.

2 Basic model with the international transport sector

The modeling of the transport sector builds on Ishikawa and Tarui (2015, 2018, 2021). In our basic model, to demonstrate our carbon-leakage mechanism clearly, we specifically assume that the product market structure is an international Cournot duopoly, and the transport firm is monopolistic. Our results would be valid with general numbers of firms. In particular, even if the product markets are perfectly competitive, the essence of our results would not change. However, we adopt the international oligopoly framework because perfect-competition models are not suitable for studying FDI. Our results are also valid with Bertrand competition.[7]

There are two countries, A and B. There is a single manufacturing firm in each country (firm α in country A and firm β in country B) and a single transport firm, firm τ. Firms α and β produce a homogeneous good and serve both countries.[8] Serving the foreign country requires transport services. The marginal costs (MCs) of producing the good of firm l ($l = \alpha, \beta$), c_l, are constant. Firm l's fixed costs (FCs) for producing the good are normalized to zero.

The inverse demand for the good in countries A and B are given by[9]

$$P_A = A - aX_A, \quad P_B = B - bX_B, \tag{1}$$

where P_i and X_i are the price of the good and quantity of the good demanded in country i ($i = A, B$), respectively. Parameters A, B, a and b are positive scalars. We assume that the two markets are segmented.

The profits of firm l, Π_l, are

$$\begin{aligned} \Pi_\alpha &= (P_A - c_\alpha)x_{\alpha AA} + (P_B - c_\alpha - T_{AB})x_{\alpha AB}, \\ \Pi_\beta &= (P_B - c_\beta)x_{\beta BB} + (P_A - c_\beta - T_{BA})x_{\beta BA}, \end{aligned}$$

where x_{lij} is firm l's output produced in country i and consumed in country j, and T_{ij} is the freight rate when shipping goods from country i to country j. We assume that the freight rate is linear and additive by following the empirical findings supporting this specification.[10]

[7] For details, see Appendix A.

[8] Our main results are also valid even if the goods are differentiated.

[9] The assumption of linear demands is not crucial for our main results.

[10] Using multi-country bilateral trade data at the 6-digit HS classification, Hummels and Skiba (2004) find that shipping technology for a single homogeneous shipment more closely resembles per unit, rather than ad-valorem, transport costs. Using Norwegian data on quantities and prices for exports at the firm/product/destination level, Irarrazabal et al. (2015) find the presence of additive (as opposed to iceberg) trade costs for a large majority of product-destination pairs.

We also assume $T_{ii} = 0$.

In our setting, firm τ first sets freight rates and makes a take-it-or-leave-it offer to manufacturing firms α and β.[11] Then, firms α and β decide whether to accept the offer. If firm l accepts (rejects) the offer, it enters both markets (only the domestic market). Thus, if both firms accept the offer, then they compete in each country. We solve the model with backward induction.

Given the freight rates, we obtain firm l's sales in countries A and B under Cournot competition as follows:

$$
\begin{aligned}
x_{\alpha AA} &= \frac{A - 2c_\alpha + c_\beta + T_{BA}}{3a}, \quad x_{\beta BA} = \frac{A + c_\alpha - 2(c_\beta + T_{BA})}{3a}, && (2)\\
x_{\beta BB} &= \frac{B - 2c_\beta + c_\alpha + T_{AB}}{3b}, \quad x_{\alpha AB} = \frac{B + c_\beta - 2(c_\alpha + T_{AB})}{3b}, && (3)\\
\Pi_\alpha &= \pi_{\alpha AA} + \pi_{\alpha AB} = a x_{\alpha AA}^2 + b x_{\alpha AB}^2, \\
\Pi_\beta &= \pi_{\beta BB} + \pi_{\beta BA} = b x_{\beta BB}^2 + a x_{\beta BA}^2. && (4)
\end{aligned}
$$

We assume that $x_{\alpha AA}$, $x_{\beta BB}$, $x_{\alpha AB}$, and $x_{\beta BA}$ are positive.

The costs of firm τ, C_τ, are given by

$$C_\tau = f + rk,$$

where f, r, and k are, respectively, the FCs, the MCs of operating a means of transport, and the capacity, that is, $\max\{x_{\alpha AB}, x_{\beta BA}\} = k$. In the following, we assume $f = 0$ for the sake of simplicity. The profits of firm τ are:

$$\Pi_\tau = T_{AB} x_{\alpha AB} + T_{BA} x_{\beta BA} - rk.$$

We consider the following three cases without any carbon tax: I) $x_{\alpha AB} > x_{\beta BA}$, II) $x_{\alpha AB} = x_{\beta BA}$, and III) $x_{\alpha AB} < x_{\beta BA}$. In the first case, firm τ maximizes its profits with $k = x_{\alpha AB}$. We can obtain the equilibrium as follows:

$$
\begin{aligned}
T_{AB}^{I*} &= \frac{B + 2r - 2c_\alpha + c_\beta}{4}, \quad T_{BA}^{I*} = \frac{A + c_\alpha - 2c_\beta}{4}, \\
x_{\alpha AA}^{I*} &= \frac{5A - 7c_\alpha + 2c_\beta}{12a}, \quad x_{\beta BA}^{I*} = \frac{A + c_\alpha - 2c_\beta}{6a}, \\
x_{\beta BB}^{I*} &= \frac{5B + 2c_\alpha - 7c_\beta + 2r}{12b}, \quad x_{\alpha AB}^{I*} = \frac{B - 2c_\alpha + c_\beta - 2r}{6b}.
\end{aligned}
$$

[11] In Behrens et al. (2009) and Behrens and Picard (2011), for example, the manufacturing firms determine their supplies by taking the freight rate as given.

We call this the type-I equilibrium, in which the backhaul problem is present because $x_{\alpha AB} > x_{\beta BA}$. Note that T_{BA} is independent of r. The intuition is that firm τ wants to have $x_{\alpha AB} = x_{\beta BA}$ from an efficiency point of view and hence raises only T_{AB} when r increases. Thus, a change in r does not affect the sales of either firm in country A. This result has an implication about the effect of carbon pricing on transport costs, as we will see later.

In the second case, firm τ's profits are maximized with the carrying capacity binding in both directions, $x_{\alpha AB} = x_{\beta BA}$:

$$\begin{aligned}
T_{AB}^{II*} &= \frac{2ac_\beta - 4ac_\alpha - 3bc_\alpha + 3bc_\beta + 2br - Ab + 2Ba + Bb}{4(a+b)}, \\
T_{BA}^{II*} &= \frac{3ac_\alpha - 3ac_\beta + 2bc_\alpha - 4bc_\beta + 2ar + Aa + 2Ab - Ba}{4(a+b)}, \\
x_{\alpha AA}^{II*} &= \frac{(5a+6b)A - aB - (5a+6b)c_\alpha + ac_\beta + 2ar}{12a(a+b)}, \\
x_{\beta BB}^{II*} &= \frac{-bA + (6a+5b)B + bc_\alpha - (6a+5b)c_\beta + 2br}{12b(a+b)}, \\
x_{\alpha AB}^{II*} &= x_{\beta BA}^{II*} = \frac{A + B - 2r - c_\alpha - c_\beta}{6(a+b)}.
\end{aligned}$$

We call this the type-II equilibrium, in which there is no backhaul problem.

The third case, where $k = x_{\beta BA}$ holds, is analogous to the first case. The equilibrium, which we call the type-III equilibrium, is given by

$$\begin{aligned}
T_{AB}^{III*} &= \frac{B - 2c_\alpha + c_\beta}{4}, \quad T_{BA}^{III*} = \frac{A + 2r + c_\alpha - 2c_\beta}{4}, \\
x_{\alpha AA}^{III*} &= \frac{5A - 7c_\alpha + 2c_\beta + 2r}{12a}, \quad x_{\beta BA}^{III*} = \frac{A + c_\alpha - 2c_\beta - 2r}{6a}, \\
x_{\beta BB}^{III*} &= \frac{5B + 2c_\alpha - 7c_\beta}{12b}, \quad x_{\alpha AB}^{III*} = \frac{B - 2c_\alpha + c_\beta}{6b}.
\end{aligned}$$

As in the type-I equilibrium, there is a backhaul problem. In the type-III equilibrium, T_{AB} is independent of r, and a change in r does not affect the sales of either firm in country B.

In the type-I (type-III) equilibrium, there is a large demand gap between the two countries, implying an excess shipping capacity from country B (A) to A (B). That is, a full load is not realized for shipping from country B (A) to A (B). In the type-II equilibrium, the demand gap is relatively small. Thus, firm τ adjusts its freight rates so that it does not have an excess shipping capacity, that is, it realizes a full load in both directions. Obviously, the type-II equilibrium arises if the two markets and the two manufacturing firms are identical.

3 Carbon taxes

In this section, we explore the effects of specific carbon taxes. Regarding carbon emissions pertaining to goods, we specifically consider two cases separately. GHGs are discharged during production in the first case and during consumption in the second case. A carbon tax on the emissions from production increases the firm's effective MC, which is defined as the sum of the marginal production cost, the freight rate, and the specific tax. By contrast, a carbon tax on the emissions from consumption lowers the demand for the goods. With respect to transport services, production and consumption occur simultaneously, meaning we cannot deal with the two cases separately.

We assume that the emissions per unit of transport (i.e., the emission coefficient of transport), e_τ, is constant. We also assume that firm τ's emissions do not depend on whether there is a backhaul problem.[12] Thus, e_τ is emissions per round trip of each capacity. Total emissions stemming from transport, E_τ, are given by

$$E_\tau = e_\tau(I_A x_{\alpha AB} + I_B x_{\beta BA}).$$

Note that I_A equals 1 in the cases of types I and II, whereas it is 0 in the type-III case. Similarly, I_B equals 1 in the type-III case, whereas it is 0 in the cases of types I and II.

We also let $e_l(l = \alpha, \beta)$ denote the emission coefficient of firm l's production. GHG emissions from firms α and β , E_α and E_β, are given by

$$\begin{aligned} E_\alpha &= e_\alpha(x_{\alpha AA} + x_{\alpha AB}) = e_\alpha X_\alpha, \\ E_\beta &= e_\beta(x_{\beta BA} + x_{\beta BB}) = e_\beta X_\beta, \end{aligned}$$

where X_l $(l = \alpha, \beta,)$ is the total output of firm l. Similarly, we let e_c denote the emission coefficient of goods consumption. Noting that the consumed goods are identical between countries A and B, we assume that the coefficient is also identical between the two countries. GHG emissions from consumption are given by

$$E_c = e_c(x_{\alpha AA} + x_{\beta BA} + x_{\alpha AB} + x_{\beta BB}) = E_A + E_B = e_c(X_A + X_B),$$

where E_i $(i = A, B)$ is the total emissions in country i.

[12] It is likely that emissions are less with the backhaul problem because of less fuel use. This feature could be incorporated into the model. However, this simply complicates the analysis without gaining a deeper insight.

3.1 Carbon taxes on transport

In this subsection, we consider a specific carbon tax, t_T, in the transport sector. The carbon tax increases the effective MC of operating a means of transport r by t_T. We show that carbon tax in the transport sector affects both the production and consumption of the good. We first examine the case where GHGs are emitted from both transport and goods production.

The effects of an increase in t_T on emissions in the type-I equilibrium are readily verified by the following:

$$\begin{aligned} \frac{\partial x^{I*}_{\alpha AA}}{\partial t_T} &= \frac{\partial x^{I*}_{\beta BA}}{\partial t_T} = 0, \quad \frac{\partial x^{I*}_{\alpha AB}}{\partial t_T} = -\frac{1}{3b}, \quad \frac{\partial x^{I*}_{\beta BB}}{\partial t_T} = \frac{1}{6b}, \\ \frac{\partial (x^{I*}_{\alpha AA} + x^{I*}_{\alpha AB})}{\partial t_T} &= -\frac{1}{3b}, \quad \frac{\partial (x^{I*}_{\beta BA} + x^{I*}_{\beta BB})}{\partial t_T} = \frac{1}{6b}. \end{aligned}$$

An increase in t_T decreases GHG emissions from both transport and goods production in country A, but increases those from goods production in country B. An increase in t_T increases T_{AB} but does not affect T_{BA} in the type-I equilibrium, which in turn decreases $x_{\alpha AB}$. Since the outputs are strategic substitutes, a decrease in $x_{\alpha AB}$ increases $x_{\beta BB}$. Thus, a carbon tax in the transport sector leads to negative carbon leakage to firm α but positive carbon leakage to firm β. Noting that the global GHG emissions are given by

$$E \equiv e_\alpha(x_{\alpha AA} + x_{\alpha AB}) + e_\beta(x_{\beta BA} + x_{\beta BB}) + e_\tau x_{\alpha AB},$$

they decrease if and only if

$$e_\beta < 2(e_\alpha + e_\tau).$$

Thus, a carbon tax on transportation lowers the GHG emissions from transport but may increase the global GHG emissions.

We next consider the effects of an increase in t_T on emissions in the type-II equilibrium. Note that an increase in t_T in the type-I equilibrium may result in $x_{\alpha AB} = x_{\beta BA}$, because an increase in t_T decreases $x_{\alpha AB}$ and does not affect $x_{\beta BA}$. We let t^{II}_T denote the tax rate that results in $x_{\alpha AB} = x_{\beta BA}$ (i.e., the equilibrium switches from Type I to Type II at t^{II}_T). The effects of an increase in t_T on outputs in the type-II equilibrium are given by

$$\begin{aligned} \frac{\partial x^{II*}_{\alpha AA}}{\partial t_T} &= \frac{\partial x^{II*}_{\beta BB}}{\partial t_T} = \frac{1}{6(a+b)}, \quad \frac{\partial x^{II*}_{\alpha AB}}{\partial t_T} = \frac{\partial x^{II*}_{\beta BA}}{\partial t_T} = -\frac{1}{3(a+b)} \\ \frac{\partial (x^{II*}_{\alpha AA} + x^{II*}_{\alpha AB})}{\partial t_T} &= \frac{\partial (x^{II*}_{\beta BA} + x^{II*}_{\beta BB})}{\partial t_T} = -\frac{1}{6(a+b)}. \end{aligned}$$

An increase in t_T increases both T_{AB} and T_{BA} and hence decreases the outputs of both firms.

As a result, GHG emissions from goods production as well as from transport decrease. This implies that a carbon tax in the transport sector generates a negative carbon leakage to the manufacturing sector. Thus, in the type-II equilibrium, a carbon tax in the transport sector necessarily decreases the global GHG emissions.

Figure 1 illustrates the relationship between t_T and GHG emissions when $x_{\alpha AB} > x_{\beta BA}$ holds at $t_T = 0$. Note that the equilibrium without any carbon tax is determined by the size of r.[13] The type-I equilibrium prevails if $t_T < t_T^{II}$, whereas the type-II equilibrium prevails if $t_T > t_T^{II}$. Panels (a), (b), and (c) illustrate how the tax rate t_T affects the emissions from transport, firm α's emissions, and firm β's emissions, respectively.

The effects of an increase in t_T on emissions in the type-III equilibrium are analogous to those in the type-I equilibrium, because the following hold in the type-III equilibrium:

$$\begin{aligned}\frac{\partial x_{\alpha AB}^{III*}}{\partial t_T} &= \frac{\partial x_{\beta BB}^{III*}}{\partial t_T} = 0, \quad \frac{\partial x_{\alpha AA}^{III*}}{\partial t_T} = \frac{1}{6a}, \quad \frac{\partial x_{\beta BA}^{III*}}{\partial t_T} = -\frac{1}{3a}, \\ \frac{\partial (x_{\alpha AA}^{III*} + x_{\alpha AB}^{III*})}{\partial t_T} &= \frac{1}{6a}, \quad \frac{\partial (x_{\beta BA}^{III*} + x_{\beta BB}^{III*})}{\partial t_T} = -\frac{1}{3a}.\end{aligned}$$

The equilibrium switches from Type III to Type II when t_T becomes large enough. We can draw figures similar to those in Figure 1. Note that a carbon tax in the transport sector increases the global emissions only if the backhaul problem is present (i.e., the equilibrium is either Type I or Type III).

We can obtain the following proposition when GHGs are emitted from both transport and production of the good.

Proposition 1 *Suppose that production and transport discharge GHG emissions and that a tax on transport is imposed. The tax decreases the GHG emissions from transport. In the type-I (III) equilibrium, an increase in the tax rate on transport reduces (increases) the GHG emissions from production in country A whereas it increases (decreases) those in country B. In the type-II equilibrium, the relationship between the tax rate and GHG emissions from production is negative in both countries and hence the carbon tax necessarily decreases the global emissions.*

Next we examine the case where goods consumption instead of production emits GHGs. In this case, the effects of the transport carbon tax on total consumption are the same as in

[13] If $x_{\alpha AB} = x_{\beta BA}$ holds at $t_T = 0$, the vertical axis is located to the right of t_T^{II}. In this case, the type-I equilibrium does not arise as long as $t_T \geq 0$.

the previous case:

$$\begin{aligned}
\frac{\partial(x^{I*}_{\alpha AA}+x^{I*}_{\beta BA})}{\partial t_T} &= 0, \quad \frac{\partial(x^{I*}_{\alpha AB}+x^{I*}_{\beta BB})}{\partial t_T} = -\frac{1}{6b}, \\
\frac{\partial(x^{II*}_{\alpha AA}+x^{II*}_{\beta BA})}{\partial t_T} &= \frac{\partial(x^{II*}_{\alpha AB}+x^{II*}_{\beta BB})}{\partial t_T} = -\frac{1}{6(a+b)}, \\
\frac{\partial(x^{III*}_{\alpha AA}+x^{III*}_{\beta BA})}{\partial t_T} &= -\frac{1}{6a}, \quad \frac{\partial(x^{III*}_{\alpha AB}+x^{III*}_{\beta BB})}{\partial t_T} = 0.
\end{aligned}$$

A carbon tax in the transport sector does not affect country A's (B's) emissions but decreases country B's (A's) emissions in the type-I (type-III) equilibrium. In the type-II equilibrium, a carbon tax in the transport sector decreases emissions in both countries. Thus, noting that a carbon tax in the transport sector reduces firm τ's emissions, the global emissions are mitigated under any equilibrium.

Proposition 2 *Suppose that transport and goods consumption discharge GHG emissions and that a tax on transport is imposed. In type-I (III) equilibrium, an increase in the tax rate does not change the GHG emissions from consumption in country A (B) but reduces those in country B (A). In the type-II equilibrium, an increase in the tax rate decreases the GHG emissions from consumption in both countries. In any type of equilibrium, the tax decreases the global emissions.*

3.2 Carbon taxes on manufacturing

In this subsection, we assume that GHGs are emitted from goods production and consider carbon taxes in the manufacturing sector. As the effects of carbon taxes in country B are similar to those in country A, we focus on country A's carbon taxes. Suppose that country A sets a specific carbon tax, t_P. The carbon tax raises the effective MC of firm α by t_P. In the type-I equilibrium, we obtain

$$\begin{aligned}
\frac{\partial x^{I*}_{\alpha AA}}{\partial t_P} &= -\frac{7}{12a}, \quad \frac{\partial x^{I*}_{\alpha AB}}{\partial t_P} = -\frac{1}{3b}, \quad \frac{\partial(x^{I*}_{\alpha AA}+x^{I*}_{\alpha AB})}{\partial t_P} = -\frac{4a+7b}{12ab}, \\
\frac{\partial x^{I*}_{\beta BA}}{\partial t_P} &= \frac{1}{6a}, \quad \frac{\partial x^{I*}_{\beta BB}}{\partial t_P} = \frac{1}{6b}, \quad \frac{\partial(x^{I*}_{\beta BA}+x^{I*}_{\beta BB})}{\partial t_P} = \frac{a+b}{6ab}, \\
\frac{\partial T^{I*}_{AB}}{\partial t_P} &= -\frac{1}{2}, \quad \frac{\partial T^{I*}_{BA}}{\partial t_P} = \frac{1}{4}.
\end{aligned}$$

As expected, an increase in t_P decreases the output of firm α and increases that of firm β. Thus, firm α's GHG emissions decrease, whereas firm β's GHG emissions increase. That is, carbon leakage occurs from firm α to firm β. However, it is noteworthy that both the decrease in firm α's GHG emissions and the increase in firm β's GHG emissions are mitigated because of the freight rate changes. Since the demand for transportation from country A to country B decreases, the capacity and freight rate from country A to B decrease. By contrast, because of the demand increase in transportation from country B to country A, the freight rate from country B to A increases. These freight rate changes mitigate both the decrease in firm α's exports to country B, and the increase in firm β's exports to country A. If the freight rate is constant, we would have $\partial(x^{I*}_{\alpha AA} + x^{I*}_{\alpha AB})/\partial t_P = -2(a+b)/3ab$ and $\partial(x^{I*}_{\beta BA} + x^{I*}_{\beta BB})/\partial t_P = (a+b)/3ab$. Note that as $x_{\alpha AB}$ decreases, firm τ's emissions also decrease in the type-I equilibrium.

In the type-I equilibrium, the global emissions decrease if and only if the following condition holds:

$$e_\beta \left(\frac{1}{6a} + \frac{1}{6b}\right) < e_\alpha \left(\frac{7}{12a} + \frac{1}{3b}\right) + \frac{e_\tau}{3b}. \tag{5}$$

As compared with the case of carbon taxes in the transport sector, the condition for global emissions to decrease is lax because the carbon leakage is mitigated by a change in the freight rate from country B to country A.

As t_P increases, $x_{\alpha AB}$ decreases but $x_{\beta BA}$ increases in the type-I equilibrium. Let t^{II}_P denote the tax rate at which $x_{\alpha AB} = x_{\beta BA}$: the equilibrium switches from Type I to Type II at t^{II}_P. The effects of an increase in t_P on outputs in the type-II equilibrium are given by

$$\begin{aligned}
\frac{\partial x^{II*}_{\alpha AA}}{\partial t_P} &= -\frac{5a+6b}{12a(a+b)}, \quad \frac{\partial x^{II*}_{\beta BB}}{\partial t_P} = \frac{1}{12(a+b)}, \\
\frac{\partial x^{II*}_{\alpha AB}}{\partial t_P} &= \frac{\partial x^{II*}_{\beta BA}}{\partial t_P} = -\frac{1}{6(a+b)}, && (6)\\
\frac{\partial (x^{II*}_{\alpha AA} + x^{II*}_{\alpha AB})}{\partial t_P} &= -\frac{7a+6b}{12a\,(a+b)}, \quad \frac{\partial (x^{II*}_{\beta BA} + x^{II*}_{\beta BB})}{\partial t_P} = -\frac{1}{12\,(a+b)}, && (7)\\
\frac{\partial T^{II*}_{AB}}{\partial t_P} &= -\frac{4a+3b}{4(a+b)}, \quad \frac{\partial T^{II*}_{BA}}{\partial t_P} = \frac{3a+2b}{4(a+b)}. && (8)
\end{aligned}$$

Thus, country A's carbon tax decreases GHG emissions from all firms including firm τ, implying there is negative carbon leakage. In general, a carbon tax in production tends to result in carbon leakage from firms subject to the tax to firms free from the tax. However, when considering the behavior of the transport firm explicitly, the leakage may not occur. The intuition behind this result is as follows. An increase in t_P decreases firm α's sales in both countries, which in turn increases firm β's sales in both countries with constant freight rates. However, as the demand for international transport from country A to B decreases, the transport firm reduces its capacity as well as the freight rate from country A to B. Thus, firm β is forced to reduce its exports to country A in the type-II equilibrium. This effect dominates the increase in firm β's sales in country B. In the type-II equilibrium, the global GHG emission obviously decreases because emissions from all sources decrease. Moreover, negative carbon leakage takes place in the sense that the carbon tax in country A decreases emissions from goods production in country B and from transport as well as emissions from goods production in country A.

It should be pointed out that a further increase in t_P may lead to $x_{\alpha AB} < x_{\beta BA}$. We let t_P^{III} denote the tax rate above which $x_{\alpha AB} < x_{\beta BA}$ holds. That is, the equilibrium switches from Type II to Type III at t_P^{III}. In the type-III equilibrium, we obtain

$$\begin{aligned}
\frac{\partial x_{\alpha AA}^{III*}}{\partial t_P} &= -\frac{7}{12a}, \quad \frac{\partial x_{\alpha AB}^{III*}}{\partial t_P} = -\frac{1}{3b}, \frac{\partial (x_{\alpha AA}^{III*} + x_{\alpha AB}^{III*})}{\partial t_P} = -\frac{4a+7b}{12ab}, \\
\frac{\partial x_{\beta BA}^{III*}}{\partial t_P} &= \frac{1}{6a}, \quad \frac{\partial x_{\beta BB}^{III*}}{\partial t_P} = \frac{1}{6b}, \quad \frac{\partial (x_{\beta BA}^{III*} + x_{\beta BB}^{III*})}{\partial t_P} = \frac{a+b}{6ab}, \\
\frac{\partial T_{AB}^{III*}}{\partial t_P} &= -\frac{1}{2}, \quad \frac{\partial T_{BA}^{III*}}{\partial t_P} = \frac{1}{4}.
\end{aligned}$$

Therefore, the effects of a change in t_P on the outputs are similar to those in the type-1 equilibrium. In the type-III equilibrium, however, an increase in t_P raises the shipping capacity, meaning GHG emissions from transport increase. In the type-III equilibrium, carbon leakage takes place from firm α not only to firm β but also to firm τ. Thus, the carbon tax in the manufacturing sector is less effective in the type- III equilibrium than in the other two types. The global GHG emissions decrease if and only if the following condition holds:

$$e_\beta \left(\frac{1}{6a} + \frac{1}{6b} \right) + \frac{e_\tau}{6a} < e_\alpha \left(\frac{7}{12a} + \frac{1}{3b} \right), \tag{9}$$

which is more stringent than (5).

Figure 2 illustrates the relationship between t_P and the emission levels when $x_{\alpha AB} > x_{\beta BA}$ holds at $t_T = 0$.[14] Panels (a), (b), and (c) illustrate how the tax rate t_P affects emissions from transport, firm α's emissions, and firm β's emissions, respectively. Note that the relationship between t_P and firm β's emissions and that between t_P and firm τ's emissions are not monotonic, which may lead to an expansion of the global emissions. Moreover, the market size of country A is smaller (larger) than that of country B in the type-I (type-III) equilibrium. Thus, a comparison between the conditions for the global emissions to decrease in the type-I and type-III equilibria ((5) and (9)), reveals that global emissions are more likely to increase when a country with a larger market size increases the carbon tax rate

[14] If $x_{\alpha AB} = x_{\beta BA}$ holds at $t_T = 0$, the vertical axis is located between t_P^{II} and t_P^{IIL}. If $x_{\alpha AB} < x_{\beta BA}$ holds at $t_T = 0$, the vertical axis is located to the right of t_P^{IIL}.

than when a country with a smaller market does.

Thus, we obtain the following proposition.

Proposition 3 *Suppose that transport and goods production discharge GHG emissions and that a tax on manufacturing is imposed in country A. The tax decreases the GHG emissions from production in country A. In the type-I equilibrium, an increase in the tax rate decreases the GHG emissions from transport but increases those from the production in country B. In the type-II (III) equilibrium, an increase in the tax rate decreases (increases) the GHG emissions from both transport and production in country B.*

3.3 Carbon taxes on goods consumption

In this subsection, we assume that GHGs are emitted from goods consumption and consider specific carbon taxes on consumption, which reduce goods demand and hence the intercept of (1) (i.e., a decrease in "A" for country A's carbon tax and "B" for country B's carbon tax). Because the effects of a carbon tax in country B are analogous to those in country A, we consider country A's carbon tax in the following analysis.

Suppose that country A sets a carbon tax, t_C, which decreases "A" by t_C. In the type-I equilibrium, we obtain

$$\begin{aligned} \frac{\partial(x^{I*}_{\alpha AA}+x^{I*}_{\beta BA})}{\partial t_C} &= -\frac{7}{12a}, \quad \frac{\partial(x^{I*}_{\alpha AB}+x^{I*}_{\beta BB})}{\partial t_C}=0, \\ \frac{\partial x^{I*}_{\alpha AB}}{\partial t_C} &= 0, \quad \frac{\partial x^{I*}_{\beta BA}}{\partial t_C}=-\frac{1}{6a}. \end{aligned} \tag{10}$$

Thus, emissions in country A decrease while emissions in both country B and the transport sector do not change. The carbon tax on country A's consumption only affects emissions in country A and hence no carbon leakage is generated. From (10), country A's carbon tax does not affect the equilibrium type. That is, the equilibrium remains Type I even if country A introduces a carbon tax in consumption.

In the type-II equilibrium, we obtain

$$\begin{aligned} \frac{\partial(x^{II*}_{\alpha AA}+x^{II*}_{\beta BA})}{\partial t_C} &= -\frac{7a+6b}{12a(a+b)}, \quad \frac{\partial(x^{II*}_{\alpha AB}+x^{II*}_{\beta BB})}{\partial t_C}=-\frac{1}{12(a+b)}, \\ \frac{\partial x^{II*}_{\beta BA}}{\partial t_C} &= \frac{\partial x^{II*}_{\alpha AB}}{\partial t_C}=-\frac{1}{6(a+b)}, \end{aligned}$$

implying that country A's carbon tax on consumption decreases emissions from both countries and transport. Thus, the carbon tax on country A's consumption results in negative cross-country and cross-sector carbon leakage. Note that a high tax rate may shift the equilibrium from Type II to Type I.

In the type-III equilibrium, the effects of country A's consumption carbon tax on emissions in the two countries are the same as those in the type-I equilibrium. However, in contrast to the type-I equilibrium, emissions from transport decrease. Thus, an increase in t_C may shift the equilibrium from Type III to Type II or Type I.

We let t_C^{II} denote the tax rate above (below) which the type-I (type- II) equilibrium holds, and t_C^{III} is the tax rate above (below) which the type-II (type-III) equilibrium arises. Panels (a), (b), and (c) in Figure 3 illustrate how the tax rate t_C affects the emissions from transport, in country A, and in country B. Proposition 4 summarizes the results discussed above.

Proposition 4 *Suppose that transport and goods consumption discharge GHG emissions and that a carbon tax on consumption is introduced in country A. The tax decreases the GHG emissions from consumption in country A. In the type-III equilibrium, an increase in the tax rate decreases the GHG emissions from transport but does not change those from consumption in country B. In the type-II (I) equilibrium, an increase in the tax rate decreases (does not change) the GHG emissions from both transport and consumption in country B. In any type of equilibrium, the tax decreases the global emissions.*

4 Presence of FDI

In this section, we introduce the possibility of horizontal FDI in the basic model. In other words, manufacturing firms have an option to build a foreign plant. However, the complete analysis of FDI is rather complicated and tedious because there are many possible cases to consider.[15] Thus, this section aims not to provide a complete analysis in the presence of FDI but to show novel findings that could not be obtained in the previous section. We specifically indicate strategic manipulations by firm τ which affect global emissions.

To this end, we focus on the case where only firm α can build its plant in the foreign country. By undertaking FDI, firm α can save transport costs to serve the foreign country, but has to incur FCs for FDI.[16] We assume for simplicity that FDI affects neither firm α's original marginal production costs nor its per unit emissions. Firm α has two options regarding FDI. The first option is to have two plants (2-plant FDI). a domestic and foreign

[15]There are many possible cases because in addition to two firms, three types of equilibrium, and two sources of GHG emissions, we consider two kinds of FDI, as explained below.

[16]Daniels and Ruhr (2014) find that shipping costs have a positive and significant relationship with US manufacturing FDI.

plant; that is, country i is served from the plant in country i ($i = A, B$). The second option is to have a single plant in the foreign country (single-plant FDI); that is, both countries are served from the foreign plant. We assume that the FC associated with FDI is identical between the 2 types of FDI and equals F. Moreover, assuming that no emission from consumption is generated, we focus on the case in which carbon is emitted during goods production and transport.

The stages of decisions are as follows. In the first stage, taking carbon tax as given, firm τ sets the freight rates. In the second, firm α decides whether to build a foreign plant. In the third, firms α and β compete in countries A and B. We now consider carbon tax on transport and country A's carbon tax on manufacturing.

4.1 Carbon taxes on transport

We consider a carbon tax on transport. We specifically assume that the type-I equilibrium prevails in the absence of FDI.[17]

When t_T is small and, accordingly, T_{AB} is low, firm α has no incentive for FDI. The relationships between the tax rate and GHG emissions of each firm are the same with those without FDI. There is a threshold freight rate at which firm α switches its mode of serving country B from "exports" to "FDI." At this threshold, the profits of firm α from serving country B through exports equal those through FDI. Note that firm α keeps serving country A from its plant in country A, even if αit operates a new plant in country B, because serving country A from the new plant in country B raises the effective MC to serve country A. This implies that single-plant FDI never arises with carbon tax on transport. In the presence of firm α's 2-plant FDI, firm β faces the lower effective MC of firm α in country B because the transport cost is saved. Firm β also faces a higher T_{BA} because only firm β uses transport services.

As firm τ loses from firm α's 2-plant FDI, firm τ may deter it. We consider this possibility below. When firm α chooses 2-plant FDI instead of exports, only firm β uses international transport services. Thus, the equilibrium with 2-plant FDI is given by

$$\begin{aligned} T_{BA}^{F*} &= \frac{A + 2(r + t_T) + c_\alpha - 2c_\beta}{4}, \\ x_{\alpha AA}^{F*} &= \frac{5A - 7c_\alpha + 2c_\beta + 2(r + t_T)}{12a}, \quad x_{\beta BA}^{F*} = \frac{A + c_\alpha - 2c_\beta - 2(r + t_T)}{6a}, \\ x_{\alpha BB}^{F*} &= \frac{B - 2c_\alpha + c_\beta}{3b}, \quad x_{\beta BB}^{F*} = \frac{B + c_\alpha - 2c_\beta}{3b}, \end{aligned}$$

[17] In the type-I equilibrium, an increase in t_T increases T_{AB} but does not affect T_{BA}. Thus, firm β has no incentive for FDI, even if it can undertake FDI.

where the superscript F denotes the case with firm α's 2-plant FDI.

When firm α chooses exports, an increase in t_T increases T_{AB}. We let T^L_{AB} denote the threshold freight rate from country A to country B, above which firm α would switch its mode of serving country B from exports to FDI. T^L_{AB} satisfies

$$\frac{(B-2(c_\alpha+T^L_{AB})+c_\beta)^2}{9b}=\frac{(B-2c_\alpha+c_\beta)^2}{9b}-F.$$

Let $T^{I*}_{AB}\big|_{t_T}$ represent the equilibrium freight rate T^{I*}_{AB} given tax rate t_T. We define t^L_T at which the freight rate becomes $T^L_{AB}(\equiv T^{I*}_{AB}\big|_{t^L_T})$. When $t_T \geq t^L_T$, firm τ has two options: deterrence or accommodation of firm α's FDI. When choosing deterrence, firm τ must fix the freight rate from country A to country B at T^L_{AB}. Otherwise, firm α undertakes FDI. By contrast, when choosing accommodation, firm τ sets its capacity equal to $x^{F*}_{\beta BA}$, and the freight rate from country B to country A at T^{F*}_{BA}. If firm τ were to accommodate FDI at t^L_T, its profits would decrease discontinuously. Thus, as long as the gap between t_T and $t^L_T(<t_T)$ is sufficiently small, firm τ has no incentive to accommodate firm α's FDI. If firm τ deters firm α's FDI, the outputs remain

$$\begin{aligned}
x^{I*}_{\alpha AA} &= \frac{5A-7c_\alpha+2c_\beta}{12a}, \quad x^{I*}_{\beta BA}=\frac{A+c_\alpha-2c_\beta}{6a},\\
x^{I*}_{\alpha AB}\big|_{t^L_T} &\equiv \frac{B-2c_\alpha+c_\beta-2(r+t^L_T)}{6b}, \quad x^{I*}_{\beta BB}\big|_{t^L_T}\equiv\frac{5B+2c_\alpha-7c_\beta+2(r+t^L_T)}{12b}.
\end{aligned}$$

The profits of firm τ are given by

$$\Pi^{I*}_\tau\big|_{T^L_{AB}} \equiv T^L_{AB}\; x^{I*}_{\alpha AB}\big|_{t^L_T}+T^{I*}_{BA}x^{I*}_{\beta BA}-(r+t_T)\; x^{I*}_{\alpha AB}\big|_{t^L_T}$$

when deterring firm α's FDI, and

$$\begin{aligned}
\Pi^{F*}_\tau &= (T^{F*}_{BA}-(r+t_T))x^{F*}_{\beta BA}\\
&= \left(\frac{A+2(r+t_T)+c_\alpha-2c_\beta}{4}-(r+t_T)\right)\frac{A+c_\alpha-2c_\beta-2(r+t_T)}{6a}
\end{aligned}$$

when accommodating firm α's FDI.

With $t_T \geq t^L_T$, we obtain

$$\frac{d\,\Pi^{I*}_\tau\big|_{T^L_{AB}}}{dt_T}=-\,x^{I*}_{\alpha AB}\big|_{t^L_T}=-\frac{B-2c_\alpha+c_\beta-2(r+t^L_T)}{6b}<0$$

when firm τ deters firm α's FDI. By contrast,

$$\frac{d\Pi_\tau^{F*}}{dt_T} = -\frac{A + c_\alpha - 2c_\beta - 2(r + t_T)}{6a} < 0$$

when firm τ accommodates firm α's FDI. Moreover, $d^2 \, \Pi_\tau^{I*}\big|_{T_{AB}^L} / d(t_T)^2 = 0$ when choosing deterrence, whereas $d^2\Pi_\tau^{F*}/d(t_T)^2 > 0$ when choosing accommodation. Thus, there may be another threshold, $t_T^H (> t_T^L)$, at which firm τ switches its strategy from deterrence to accommodation of firm α's FDI.[18] Thus, in the range of t_T, $t_T^L \leq t_T \leq t_T^H$, firm τ fixes its freight rate from country A to country B at T_{AB}^L. Noting $x_{\alpha AB} > x_{\beta BA}$, T_{BA} is independent of $r + t_T$. Thus, both $x_{\alpha AB}$ and $x_{\beta BA}$ are constant when $t_T^L \leq t_T \leq t_T^H$.

In sum, as long as $t_T^L < t_T < t_T^H$ holds, a small increase in t_T never affects the outputs of both firms and the shipping volumes of firm τ, and hence the GHG emissions of firms τ, α, and β do not change (see Figure 4). That is, we can claim the "ineffectiveness" of a carbon tax in the transport sector.

Proposition 5 *Suppose i) production and transport discharge GHG emissions, ii) a tax on transport is imposed, iii) firm α has an opportunity for FDI, and iv) the type-I equilibrium prevails without FDI. Firm τ deters firm α's FDI with $t_T^L < t_T < t_T^H$. With deterrence of firm α's FDI, GHG emissions from transport, production, and consumption of goods remain at the level with $t_T = t_T^L$.*

Next we consider how GHG emissions change if firm α switches its mode of serving country B from exports to FDI at t_T^H. The output of each firm with deterring firm α's FDI is given by

$$X_\alpha^{I*} = \frac{5A - 7c_\alpha + 2c_\beta}{12a} + \frac{B - 2c_\alpha + c_\beta - 2(r + t_T^L)}{6b}, \tag{11}$$

$$X_\beta^{I*} = \frac{A + c_\alpha - 2c_\beta}{6a} + \frac{5B + 2c_\alpha - 7c_\beta + 2(r + t_T^L)}{12b}, \tag{12}$$

where $X_l (l = \alpha, \beta)$ denotes the total output of firm l. By contrast, if firm α chooses FDI at t_T^H, then the output of each firm is given by

$$X_\alpha^{F*} = \frac{5A - 7c_\alpha + 2(c_\beta + r + t_T^H)}{12a} + \frac{B - 2c_\alpha + c_\beta}{3b}, \tag{13}$$

$$X_\beta^{F*} = \frac{A + c_\alpha - 2(c_\beta + r + t_T^H)}{6a} + \frac{B + c_\alpha - 2c_\beta}{3b}. \tag{14}$$

[18](i) $x_{\alpha AB} > x_{\beta BA}$, and (ii) FDI by firm α never hold simultaneously, because $x_{\alpha AB} = 0$ with firm α's FDI.

We also have $x^{F*}_{\beta BA} < x^{I*}_{\beta BA} (< x^{I*}_{\alpha AB})$ at t^H_T, implying that FDI lowers GHG emissions from firm τ. This is because FDI reduces demand for international transport. However, FDI increases the output of firm α and reduces that of firm β. Consequently, GHG emissions from production can increase. Thus, carbon leakage from the transport sector to the manufacturing sector can occur. The smaller the relative size of the per unit emission by firm α, the more likely it is that global GHG emissions decrease because of the mode shift. The condition for the global GHG emissions to decrease is given by

$$e_\alpha \left(\frac{r + t^H_T}{6a} + \frac{B - 2c_\alpha + c_\beta + 2(r + t^L_T)}{6b} \right) < e_\beta \left(\frac{r + t^H_T}{3a} + \frac{B + 2c_\alpha - c_\beta - 2(r + t^L_T)}{12b} \right)$$
$$+ e_\tau \frac{2aB - 2bA - 2(a+b)c_\alpha + (4b+a)c_\beta + 4b(r + t^H_T) - 2a(r + t^L_T)}{12ab}. \quad (15)$$

When $t_T > t^H_T$, an increase in t_T lowers $x_{\beta BA}$, increases $x_{\alpha AA}$ and does not affect $x_{\alpha BB}$ and $x_{\beta BB}$. Thus, the global GHG emissions may or may not decrease. We can readily verify that the condition for the global GHG emissions to decrease is $e_\alpha < 2e_\beta$.

From the above analysis, we obtain the following proposition. Figure 4 shows how firms' GHG emissions change as t_T rises.

Proposition 6 *Suppose i) production and transport discharge GHG emissions, ii) a tax on transport is imposed, iii) firm α switches its mode of serving country B from exports to FDI at t^H_T, and iv) the type-I equilibrium prevails without FDI. At t^H_T, GHG emissions from transport and firm β drop, whereas those from firm α increase. With $t_T > t^H_T$, an increase in the tax rate decreases GHG emissions from transport and firm β but increases those from firm α.*

4.2 Carbon taxes on manufacturing

We consider a carbon tax on manufacturing in country A. Again we specifically assume that the type-I equilibrium prevails in the absence of FDI. A carbon tax raises firm α's effective MC of production in country A by t_P. Although an increase in t_P decreases T_{AB}, firm α's effective MC of exports (i.e., $c_\alpha + t_P + T_{AB}$) rises. Firm α's effective MC of production in country B remains c_α. Thus, if the tax rate is high, firm α may have an incentive for FDI.

As in the case of a carbon tax on the transport sector, there is a threshold tax rate, t^{FL}_P, at which firm α would switch its mode of serving country B, from exports to FDI. Again, firm τ has two options: deterring firm α's FDI or accommodating it. However, there are two types of FDI: 2-plant FDI and single-plant FDI. In the following, we consider each case.

First, we consider the case in which firm τ deters firm α from undertaking FDI. In this case, firm τ sets the freight rate such that the effective MC of exports is constant at $c_\alpha + t_P^{FL} + T_{AB}|_{t_P^{FL}}$. As t_P increases, firm τ lowers the freight rate. Thus, an increase in t_P decreases firm α's sales in country A, increases firm β's sales in country A, and does not affect either firms' sales in country B. GHG emissions from firm α decrease, but those from firm β increase. Although the shipping from country A to B is constant, that from country B to A increases. However, as long as $x_{\alpha AB} > x_{\beta BA}$, GHG emissions from transport remain constant. We can readily verify from the equilibrium sales in country A under firm τ's deterrence that the global GHG emissions decrease if and only if $e_\beta < 7e_\alpha/2$.

Proposition 7 *Suppose i) production and transport discharge GHG emissions, ii) a carbon tax on manufacturing is imposed in country A, iii) firm α has an opportunity for FDI, and iv) the type-I equilibrium prevails without FDI. If firm τ deters firm α's FDI, then an increase in the tax rate decreases GHG emissions from firm α, increases those from firm β, and does not affect those from firm τ.*

Next, we consider the case in which firm τ accommodates firm α's FDI. We begin with the case with 2-plant FDI. The equilibrium outputs with 2-plant FDI are given by

$$\begin{aligned} T_{BA}^{F*} &= \frac{A + 2r + c_\alpha + t_P - 2c_\beta}{4}, \\ x_{\alpha AA}^{F*} &= \frac{5A - 7(c_\alpha + t_P) + 2(c_\beta + r)}{12a}, \quad x_{\beta BA}^{F*} = \frac{A + c_\alpha + t_P - 2(c_\beta + r)}{6a}, \\ x_{\alpha BB}^{F*} &= \frac{B - 2c_\alpha + c_\beta}{3b}, \quad x_{\beta BB}^{F*} = \frac{B + c_\alpha - 2c_\beta}{3b}. \end{aligned}$$

Firm α's effective MC of production in country A is $c_\alpha + t_P$, whereas that in country B (i.e., under FDI) is c_α. Thus, an increase in t_P decreases firm α's emissions in country A, does not affect firm α's emissions in country B, and increases the emissions of firms β and τ, implying carbon leakage from firm α to firms β and τ.[19] The global GHG emissions decrease if and only if $e_\beta + e_\tau < 7e_\alpha/2$.

We now consider the case with single-plant FDI. We specifically assume that firm τ can set different freight rates between firms α and β when they export from country B to A. Given the freight rate of shipping from country B to A, we obtain firm l's ($l = \alpha, \beta$) sales in the two countries as follows:

$$\begin{aligned} x_{\alpha BA}^{f} &= \frac{A - 2(c_\alpha + T_{\alpha BA}) + c_\beta + T_{\beta BA}}{3a}, \quad x_{\beta BA}^{f} = \frac{A + (c_\alpha + T_{\alpha BA}) - 2(c_\beta + T_{\beta BA})}{3a}, \\ x_{\alpha BB}^{f*} &= \frac{B - 2c_\alpha + c_\beta}{3b}, \quad x_{\beta BB}^{f*} = \frac{B + c_\alpha - 2c_\beta}{3b}, \end{aligned}$$

[19]As firm α serves country i ($i = A, B$) from its plant in country i, only firm β uses transport services.

where T_{lBA} is the freight rate for firm l to ship its product from country B to A, and the superscript f denotes the case with firm α's single-plant FDI. Note that for both firms, the effective MC of production does not depend on the tax rate in country A, because they produce only in country B. The profits of firm τ are given by

$$\Pi_{\tau}^{f} = (T_{\alpha BA} - r)\frac{A - 2(c_\alpha + T_{\alpha BA}) + c_\beta + T_{\beta BA}}{3a} + (T_{\beta BA} - r)\frac{A + (c_\alpha + T_{\alpha BA}) - 2(c_\beta + T_{\beta BA})}{3a}.$$

We obtain

$$T_{\alpha BA}^{f*} = \frac{1}{2}(A + r - c_\alpha), \quad T_{\beta BA}^{f*} = \frac{1}{2}(A + r - c_\beta),$$

and hence

$$x_{\alpha BA}^{f*} = \frac{A - r - 2c_\alpha + c_\beta}{6a}, \quad x_{\beta BA}^{f*} = \frac{A - r + c_\alpha - 2c_\beta}{6a}.$$

Therefore, country A's carbon taxes are not effective in this case.

However, we have another case of single-plant FDI. We consider this case below. Firm τ can profit from shipping good α with single-plant FDI if and only if $T_{\alpha BA} > r$. Thus, given that firm τ accommodates firm α's FDI, firm τ prefers single-plant FDI to 2-plant FDI if $t_P > r$ holds; that is, firm τ lets firm α undertake 2-plant FDI if $t_P < r$, but has an incentive to deter firm α's 2-plant FDI if $t_P > r$. However, if $T_{\alpha BA}^{f*} > t_P$ holds, firm τ cannot set $T_{\alpha BA}^{f} = T_{\alpha BA}^{f*}$. This is because any freight rate $T_{\alpha BA}$ greater than t_P results in firm α's 2-plant FDI. Thus, firm τ needs to set $T_{\alpha BA}^{f} = t_P$ to deter firm α's 2-plant FDI. The following lemma specifies which type of FDI occurs.

Lemma 1 *Suppose that firm τ accommodates firm α's FDI. Then 2-plant FDI arises with $t_P < r$ whereas single-plant FDI arises with $t_P > r$. With single-plant FDI, $T_{\alpha BA}^{f} = t_P$ holds if $t_P < T_{\alpha BA}^{f*}$ and $T_{\alpha BA}^{f} = T_{\alpha BA}^{f*}$ holds if $t_P \geq T_{\alpha BA}^{f*}$.*

With $T_{\alpha BA}^{f} = t_P$, we have

$$\begin{aligned}
T_{\beta BA}^{f*}\Big|_{T_{\alpha BA}^{f}=t_P} &= \frac{1}{4}(A + r + c_\alpha + 2t_P - 2c_\beta),\\
x_{\alpha BA}^{f}\Big|_{T_{\alpha BA}^{f}=t_P} &= \frac{5A + r - 6t_P - 7c_\alpha + 2c_\beta}{12a},\ x_{\beta BA}^{f}\Big|_{T_{\alpha BA}^{f}=t_P} = \frac{A - r + c_\alpha - 2c_\beta}{6a},\\
x_{\alpha BB}^{f}\Big|_{T_{\alpha BA}^{f}=t_P} &= x_{\alpha BB}^{f*}, \quad x_{\beta BB}^{f}\Big|_{T_{\alpha BA}^{f}=t_P} = x_{\beta BB}^{f*},
\end{aligned}$$

which implies that both the freight rate and firm α's sales in country A depend on t_P.[20]

[20] Firm β's sales to country A are not influenced by t_P. On the one hand, an increase in t_P decreases firm α's domestic sales. As outputs are strategic substitutes, this effect leads to an increase in firm β's sales in country A. On the other hand, the freight rate from country B to country A increases, which leads to a decrease in firm β's sales in country A. The two effects just cancel each other out.

Interestingly, even though both firms produce in country B, a carbon tax on manufacturing in country A affects emissions: an increase in t_P lowers the emissions of firms α and τ and hence the global emissions.

These results are summarized in the following proposition.

Proposition 8 *Suppose i) production and transport discharge GHG emissions, ii) a carbon tax on manufacturing is imposed in country A, and iii) firm α has an incentive for FDI, which firm τ accommodates. With $t_P < r$, an increase in the tax rate decreases GHG emissions from firm α but increases those from firms β and τ. With $t_P > r$, an increase in the tax rate decreases GHG emissions from firms α and τ if $r < t_P < T^{f*}_{\alpha BA}$ but does not affect GHG emissions from all firms if $t_P \geq T^{f*}_{\alpha BA}$.*

Figure 5 shows a possible case where as t_P increases, firm α's strategy shifts from a single plant in country A to two plants, and then to a single plant in country B. If $0 \leq t_P < t_P^{FH}$, firm α serves country B through its exports. In particular, the firm τ deters firm α's FDI with $t_P^{FL} \leq t_p < t_P^{FH}$. If $t_P^{FH} \leq t_P < t_P^{fL}$, firm α has two plants (i.e., a single plant in each country). If $t_P^{fL} \leq t_P$, firm α has a single plant in country B. Firm τ deters firm α's 2-plant FDI with $t_P^{fL} \leq t_P < t_P^{fH}$. With t_P^{FH}, GHG emissions from firm α increase dramatically, but those from firms β and τ drop. With t_P^{fL}, the GHG emissions from firm τ increase dramatically.

5 Conclusion

We studied the effects of carbon taxes on GHG emissions from international transport, production, and consumption of traded goods. The theoretical model takes endogenous transport costs, the transport firm's market power, and the backhaul problem into account. These features of international transport affect carbon leakage. If the backhaul problem is absent, any carbon tax is effective because GHG emissions from both transport and goods production/consumption and hence the global emissions are reduced. Carbon taxes on goods consumption are effective even with the backhaul problem. Carbon taxes on goods production result in cross-sector and/or cross-border carbon leakage when the backhaul problem is present. However, endogenous transport costs mitigate cross-border carbon leakage. Carbon taxes on transport decrease the global GHG emissions without the backhaul problem but may increase them with it. Thus, the backhaul problem is the key to the effectiveness of carbon taxes.

The opportunity of FDI also matters in assessing the effectiveness of carbon taxes. The carrier may have an incentive to deter FDI or induce single-plant FDI. The carrier's manipulation of freight rates affects both cross-sector and cross-border carbon leakage. In an extreme case, an increase in the carbon tax on transport does not affect GHG emissions at all. Another interesting case is that an increase in the carbon tax on goods production in a country where there is no goods production decreases the emissions from goods production in the other country.

In conclusion, four final remarks are in order. First, we have focused on carbon taxes in our analysis, though the essence of our main results remains valid with any emission regulation which increases the MC of transport or goods production/consumption. However, minor modifications may be necessary.[21] For example, the regulator may impose an emission standard, which forces the carrier to use fuel with less carbon. In this case, even if an increase in the carbon tax on transport does not affect carbon emissions with FDI deterrence, the tightening standard reduces carbon emissions.

Second, we have assumed that GHGs are discharged from either production or consumption. However, both production and consumption may discharge GHGs. We can also consider this case. In particular, we can readily verify that a carbon tax on goods production in one country lowers the emissions from goods consumption in both countries in all types of equilibrium and that a carbon tax on goods consumption in one country decreases the emissions from goods production in both countries in all types of equilibrium. Thus, we can conclude that a carbon tax on goods consumption in one country always reduces the global GHG emissions.

Third, we have considered the possibility of manufacturers' FDI when facing a high tax. However, manufacturers may be engaged in abatement activities instead of FDI. We have not considered the possibility of abatement activities in order to highlight the role of endogenous transport on carbon leakage.[22] Moreover, we have considered only horizontal FDI. It may be worth examining abatement activities and vertical FDI in our model.

Finally, our findings follow from a theoretical framework that addresses the interlinkage between trade, transport, and the environment by considering the transport sector explicitly. They indicate another benefit of comprehensive emissions regulations on both production (or consumption) and transport. Empirically, this interlinkage may identify room for improving the accounting of trade-related emissions. It may also help quantify the extent of carbon leakage under various scenarios of international cooperation on carbon pricing. Investigation along these lines of enquiry is relegated to future research.

[21] For details, see Appendix B.

[22] Cheng and Ishikawa (2021) take both abatement investment and FDI into account in the analysis of carbon taxes. However, they do not consider international transport.

Appendix A: Bertrand Competition

In this appendix, we consider the three equilibria (i.e., types I, II, and III equilibria) under Bertrand competition with differentiated goods. We call the good produced by firm l good l ($l = \alpha, \beta$). Once the equilibria are obtained, straightforward calculation reveals that Propositions 1-4 are still valid.

We begin with country A's market. We assume that inverse demand for goods α and β in country A are given by

$$P_{\alpha A} = A_\alpha - a_\alpha x_{\alpha AA} - \gamma_A x_{\beta BA}, P_{\beta A} = A_\beta - a_\beta x_{\beta BA} - \gamma_A x_{\alpha AA},$$

where γ_A is the degree of substitutability between goods α and β and $a_l > |\gamma_A|$ holds. The demand for goods α and β in country A become

$$\begin{aligned} x_{\alpha AA} &= \frac{a_\beta A_\alpha - \gamma_A A_\beta - a_\beta P_{\alpha A} + \gamma_A P_{\beta A}}{a_\alpha a_\beta - \gamma_A^2}, \\ x_{\beta BA} &= \frac{-\gamma_A A_\alpha + a_\alpha A_\beta + \gamma_A P_{\alpha A} - a_\alpha P_{\beta A}}{a_\alpha a_\beta - \gamma_A^2}. \end{aligned}$$

The profits of firm l obtained in country A, π_{lA}, are

$$\pi_{\alpha A} = (P_{\alpha A} - c_\alpha)x_{\alpha AA}, \pi_{\beta A} = (P_{\beta A} - c_\beta - T_{BA})x_{\beta BA}.$$

Given the freight rate from country B to country A (T_{BA}), we can obtain the prices and sales of each firm as follows:

$$\begin{aligned} P_{\alpha A} &= \frac{(2a_\alpha a_\beta - \gamma_A^2)A_\alpha - a_\alpha \gamma_A A_\beta + 2a_\alpha a_\beta c_\alpha + a_\alpha \gamma_A (c_\beta + T_{BA})}{4a_\alpha a_\beta - \gamma_A^2}, \\ P_{\beta A} &= \frac{-a_\beta \gamma_A A_\alpha + (2a_\alpha a_\beta - \gamma_A^2)A_\beta + a_\beta \gamma_A c_\alpha + 2a_\alpha a_\beta (c_\beta + T_{BA})}{4a_\alpha a_\beta - \gamma_A^2}, \\ x_{\alpha AA} &= \frac{a_\beta \left\{(2a_\alpha a_\beta - \gamma_A^2)A_\alpha - a_\alpha \gamma_A A_\beta - (2a_\alpha a_\beta - \gamma_A^2)c_\alpha + a_\alpha \gamma_A (c_\beta + T_{BA})\right\}}{(a_\alpha a_\beta - \gamma_A^2)(4a_\alpha a_\beta - \gamma_A^2)}, \\ x_{\beta BA} &= \frac{a_\alpha \left\{-a_\beta \gamma_A A_\alpha + (2a_\alpha a_\beta - \gamma_A^2)A_\beta + a_\beta \gamma_A c_\alpha - (2a_\alpha a_\beta - \gamma_A^2)(c_\beta + T_{BA})\right\}}{(a_\alpha a_\beta - \gamma_A^2)(4a_\alpha a_\beta - \gamma_A^2)}. \end{aligned}$$

Similarly, given the freight rate from country A to country B (T_{AB}), we obtain the prices and sales in country B:

$$
\begin{aligned}
P_{\alpha B} &= \frac{(2b_\alpha b_\beta - \gamma_B^2)B_\alpha - b_\alpha\gamma_B B_\beta + 2b_\alpha b_\beta(c_\alpha + T_{AB}) + b_\alpha\gamma_B c_\beta}{4b_\alpha b_\beta - \gamma_B^2}, \\
P_{\beta B} &= \frac{-b_\beta\gamma_B B_\alpha + (2b_\alpha b_\beta - \gamma_B^2)B_\beta + b_\beta\gamma_B(c_\alpha + T_{AB}) + 2b_\alpha b_\beta c_\beta}{4b_\alpha b_\beta - \gamma_B^2}, \\
x_{\alpha AB} &= \frac{b_\beta\left\{(2b_\alpha b_\beta - \gamma_B^2)B_\alpha - b_\alpha\gamma_B B_\beta - (2b_\alpha b_\beta - \gamma_B^2)(c_\alpha + T_{AB}) + b_\alpha\gamma_B c_\beta\right\}}{(b_\alpha b_\beta - \gamma_B^2)(4b_\alpha b_\beta - \gamma_B^2)}, \\
x_{\beta BB} &= \frac{b_\alpha\left\{-b_\beta\gamma_B B_\alpha + (2b_\alpha b_\beta - \gamma_B^2)B_\beta + b_\beta\gamma_B(c_\alpha + T_{AB}) - (2b_\alpha b_\beta - \gamma_B^2)c_\beta\right\}}{(b_\alpha b_\beta - \gamma_B^2)(4b_\alpha b_\beta - \gamma_B^2)}.
\end{aligned}
$$

From firm τ's profit maximization, the equilibrium freight rates in each equilibrium are obtained as follows:

$$
\begin{aligned}
T_{AB}^{I*} &= \frac{(2b_\alpha b_\beta - \gamma_B^2)B_\alpha - b_\alpha\gamma_B B_\beta - (2b_\alpha b_\beta - \gamma_B^2)c_\alpha + b_\alpha\gamma_B c_\beta + (2b_\alpha b_\beta - \gamma_B^2)r}{2(2b_\alpha b_\beta - \gamma_B^2)}, \\
T_{BA}^{I*} &= \frac{-a_\beta\gamma_A A_\alpha + (2a_\alpha a_\beta - \gamma_A^2)A_\beta + a_\beta\gamma_A c_\alpha - (2a_\alpha a_\beta - \gamma_A^2)c_\beta}{2(2a_\alpha a_\beta - \gamma_A^2)};
\end{aligned}
$$

$$
\begin{aligned}
T_{AB}^{II*} &= \frac{1}{b_\beta(2b_\alpha b_\beta - \gamma_B^2)} \cdot \big\{b_\beta(2b_\alpha b_\beta - \gamma_B^2)B_\alpha - b_\alpha b_\beta\gamma_B B_\beta - b_\beta(2b_\alpha b_\beta - \gamma_B^2)c_\alpha \\
&\quad + b_\alpha b_\beta\gamma_B c_\beta - (b_\alpha b_\beta - \gamma_B^2)(4b_\alpha b_\beta - \gamma_B^2)x_{\alpha AB}\big\}, \\
T_{BA}^{II*} &= \frac{1}{a_\alpha(2a_\alpha a_\beta - \gamma_A^2)}\big\{-a_\alpha a_\beta\gamma_A A_\alpha + a_\alpha(2a_\alpha a_\beta - \gamma_A^2)A_\beta + a_\alpha a_\beta\gamma_A c_\alpha \\
&\quad - a_\alpha(2a_\alpha a_\beta - \gamma_A^2)c_\beta - (a_\alpha a_\beta - \gamma_A^2)(4a_\alpha a_\beta - \gamma_A^2)x_{\beta BA}\big\};
\end{aligned}
$$

$$
\begin{aligned}
T_{AB}^{III*} &= \frac{(2b_\alpha b_\beta - \gamma_B^2)B_\alpha - b_\alpha\gamma_B B_\beta - (2b_\alpha b_\beta - \gamma_B^2)c_\alpha + b_\alpha\gamma_B c_\beta}{2(2b_\alpha b_\beta - \gamma_B^2)}, \\
T_{BA}^{III*} &= \frac{-a_\beta\gamma_A A_\alpha + (2a_\alpha a_\beta - \gamma_A^2)A_\beta + a_\beta\gamma_A c_\alpha - (2a_\alpha a_\beta - \gamma_A^2)c_\beta + (2a_\alpha a_\beta - \gamma_A^2)r}{2(2a_\alpha a_\beta - \gamma_A^2)}.
\end{aligned}
$$

Substituting the equilibrium freight rates into the prices and sales of each firm above, we can obtain equilibrium sales and prices. For example, we have

$$
\begin{aligned}
x^{II*}_{\alpha AB} &= x^{II*}_{\beta BA} = \frac{1}{\Omega}\cdot\big\{-a_\alpha a_\beta b_\beta \gamma_A(2b_\alpha b_\beta-\gamma_B^2)A_\alpha + a_\alpha b_\beta(2a_\alpha a_\beta-\gamma_A^2)(2b_\alpha b_\beta-\gamma_B^2)A_\beta \\
&\quad a_\alpha b_\beta(2a_\alpha a_\beta-\gamma_A^2)(2b_\alpha b_\beta-\gamma_B^2)B_\alpha - a_\alpha b_\alpha b_\beta\gamma_B(2a_\alpha a_\beta-\gamma_A^2)B_\beta \\
&\quad -a_\alpha b_\beta(2b_\alpha b_\beta-\gamma_B^2)((2a_\alpha a_\beta-\gamma_A^2)-a_\beta\gamma_A)c_\alpha \\
&\quad -a_\alpha b_\beta(2a_\alpha a_\beta-\gamma_A^2)((2b_\alpha b_\beta-\gamma_B^2)-b_\alpha\gamma_B)c_\beta \\
&\quad -a_\alpha b_\beta(2a_\alpha a_\beta-\gamma_A^2)(2b_\alpha b_\beta-\gamma_B^2)r\big\},
\end{aligned}
$$

where $\Omega \equiv a_\alpha(2a_\alpha a_\beta-\gamma_A^2)(b_\alpha b_\beta-\gamma_B^2)(4b_\alpha b_\beta-\gamma_B^2)+b_\beta(2b_\alpha b_\beta-\gamma_B^2)(a_\alpha a_\beta-\gamma_A^2)(4a_\alpha a_\beta-\gamma_A^2)$.

Appendix B: Variable Emission Coefficients

In the main analysis, we consider increases in the effective marginal costs of production, transport, and consumption as a result of specific carbon taxes, and assume that per unit GHG emissions (i.e., emission coefficients) are constant. The analysis can also be applied to the case of emission regulations such as emission standards which increase the effective marginal costs. However, per unit GHG emissions may decrease in such a case. In this appendix, we consider the case with variable emission coefficients.

The point is that an emission regulation decreases the emission coefficient the regulation targets. For example, an emission regulation in the transport sector leads to a decrease in e_τ. Similarly, emission regulation in the manufacturing sector in country A decreases e_α for firm α's production in country A. With variable emission coefficients, the necessary and sufficient conditions for emissions to decrease are replaced by sufficient conditions.

We first confirm this in the case without FDI. For simplicity, we assume that there are no GHG emissions from goods consumption. The analysis in Section 3.1 reveals that with $0 < t_T < t_T^{II}$, a carbon tax in the transport sector decreases the global GHG emission if and only if $e_\beta \leq 2(e_\alpha + e_\tau)$. However, if an emission regulation decreases e_τ, this condition becomes a sufficient condition when per unit GHG emission is variable. To be precise, the necessary and sufficient condition in this case is given by:

$$e_\beta \leq 2(e_\alpha + e_\tau) + x^{I*}_{\alpha AB}\frac{\partial e_\tau}{\partial r}.$$

Analogously, equations (5) and (9) become sufficient conditions for global GHG emissions to decrease with an emission regulation in the manufacturing sector which decreases e_α.

We next consider the case with FDI. Unless an emission regulation gives rise to firm α's mode shift ("from export to FDI for serving country B" or "from two plants to single plant for serving country A"), we obtain the same results as in the case of no FDI: an emission regulation is more likely to decrease local and global GHG emissions when emission coefficients are variable. Moreover, this result survives the mode shift when we consider only an emission regulation in the transport sector, because e_τ does not change even if firm α changes the location of production.

However, in the case of an emission regulation in the manufacturing sector, firm α's mode shift increases the global GHG emissions more with variable emission coefficients than with fixed emission coefficients. For example, consider the case in which a tighter emission regulation in the manufacturing sector in country A induces firm α's mode shift from exports to FDI for serving country B. Proposition 8 reveals the possibility that this mode shift increases the global GHG emissions even when firm α's emission coefficient is fixed. With variable emission coefficients, this possibility becomes higher because firm α's plant in country B is free from the emission regulation in country A, and hence the emission coefficient of firm α's plant in country B is higher than that in country A.

References

Abe, K., K. Hattori, and Y. Kawagoshi (2014): "Trade liberalization and environmental regulation on international transportation," *Japanese Economic Review*, 65, 468–482.

Baylis, K., D. Fullerton, and D. H. Karney (2014): "Negative Leakage," *Journal of the Association of Environmental and Resource Economists*, 1, 51–73.

Bohm, P. (1993): "Incomplete international cooperation to reduce CO2 emissions: alternative policies," *Journal of Environmental Economics and Management*, 24, 258–271.

Böhringer, C., K. E. Rosendahl, and H. B. Storrøsten (2017): "Robust policies to mitigate carbon leakage," *Journal of Public Economics*, 149, 35–46.

Copeland, B. R. and M. S. Taylor (2005): "Free trade and global warming: A trade theory view of the Kyoto protocol," *Journal of Environmental Economics and Management*, 49, 205–234.

Cristea, A., D. Hummels, L. Puzzello, and M. Avetisyan (2013): "Trade and the greenhouse gas emissions from international freight transport," *Journal of environmental economics and management*, 65, 153–173.

Daniels, J. P. and M. Ruhr (2014): "Transportation Costs and US Manufacturing FDI," *Review of International Economics*, 22, 299–309.

Dijkstra, B. R., A. J. Mathew, and A. Mukherjee (2011): "Environmental regulation: an incentive for foreign direct investment," *Review of International Economics*, 19, 568–578.

Eichner, T. and R. Pethig (2015): "Unilateral consumption-based carbon taxes and negative leakage," *Resource and Energy Economics*, 40, 127–142.

Felder, S. and T. F. Rutherford (1993): "Unilateral CO2 reductions and carbon leakage: The consequences of international trade in oil and basic materials," *Journal of Environmental Economics and Management*, 25, 162–176.

Fischer, C. (2015): "Options for avoiding carbon leakage," *Geneva Reports on the World Economy*, 2015, 297–311.

Hummels, D., V. Lugovskyy, and A. Skiba (2009): "The trade reducing effects of market power in international shipping," *Journal of Development Economics*, 89, 84–97.

Hummels, D. and A. Skiba (2004): "Shipping the Good Apples Out? An Empirical Confirmation of the Alchian-Allen Conjecture," *Journal of Political Economy*, 112, 1384–1402.

International Maritime Organization (2020): *Fourth IMO Greenhouse Gas Study 2020*, International Maritime Organization, London.

Irarrazabal, A., A. Moxnes, and L. D. Opromolla (2015): "The Tip of the Iceberg: A Quantitative Framework for Estimating Trade Costs," *Review of Economics and Statistics*, 97, 777–792.

Ishikawa, J. and K. Kiyono (2006): "Greenhouse-gas emission controls in an open economy," *International Economic Review*, 47, 431–450.

Ishikawa, J., K. Kiyono, and M. Yomogida (2012): "Is emission trading beneficial?" *Japanese Economic Review*, 63, 185–203.

——— (2020): "Emissions Trading and International Trade," *Discussion Paper Research Institute of Economy, Trade and Industry (RIETI)*, 20-E-080.

Ishikawa, J. and T. Okubo (2011): "Environmental product standards in north–south trade," *Review of Development Economics*, 15, 458–473.

——— (2016): "Greenhouse-gas emission controls and international carbon leakage through trade liberalization," *International Economy*, 19, 1–22.

——— (2017): "Greenhouse-gas emission controls and firm locations in north–south trade," *Environmental and Resource Economics*, 67, 637–660.

Ishikawa, J. and N. Tarui (2018): "Backfiring with backhaul problems: Trade and industrial policies with endogenous transport costs," *Journal of International Economics*, 111, 81–98.

Jakob, M., R. Marschinski, and M. Hübler (2013): "Between a rock and a hard place: a trade-theory analysis of leakage underproduction- and consumption-based policies," *Environmental and Resource Economics*, 56, 47–72.

Kayalica, M. O. and S. Lahiri (2005): "Strategic environmental policies in the presence of foreign direct investment," *Environmental and Resource Economics*, 30, 1–21.

Kiyono, K. and J. Ishikawa (2004): "Strategic emission tax-quota non-equivalence under international carbon leakage," in *International Economic Policies in a Globalized World*, Springer, Berlin, Heidelberg, 133–150.

——— (2013): "Environmental management policy under international carbon leakage," *International Economic Review*, 54, 1057–1083.

Markusen, J. R., E. R. Morey, and N. D. Olewiler (1993): "Environmental policy when market structure and plant locations are endogenous," *Journal of Environmental Economics and Management*, 24, 69–86.

——— (1995): "Competition in regional environmental policies when plant locations are endogenous," *Journal of Public Economics*, 56, 55–77.

Naegele, H. and A. Zaklan (2019): "Does the EU ETS cause carbon leakage in European manufacturing?" *Journal of Environmental Economics and Management*, 93, 125–147.

Olsthoorn, X. (2001): "Carbon Dioxide Emissions from International Aviation: 1950–2050," *Journal of Air Transport Management*, 7, 87–93.

Shapiro, J. S. (2016): "Trade costs, CO 2, and the environment," *American Economic Journal: Economic Policy*, 8, 220–54.

Smith, T., D. Baresic, J. Fahnestock, C. Galbraith, C. V. Perico, U. Rojon, and A. Shaw (2021): "A Strategy for the Transition to Zero-Emission Shipping," Report submitted to the Getting to Zero Coalition, Global Maritime Forum.

Vöhringer, F., J.-M. Grether, and N. A. Mathys (2013): "Trade and climate policies: do emissions from international transport matter?" *The World Economy*, 36, 280–302.

Zeng, D.-Z. and L. Zhao (2009): "Pollution havens and industrial agglomeration," *Journal of Environmental Economics and Management*, 58, 141–153.

Figure 1. Carbon tax on transport

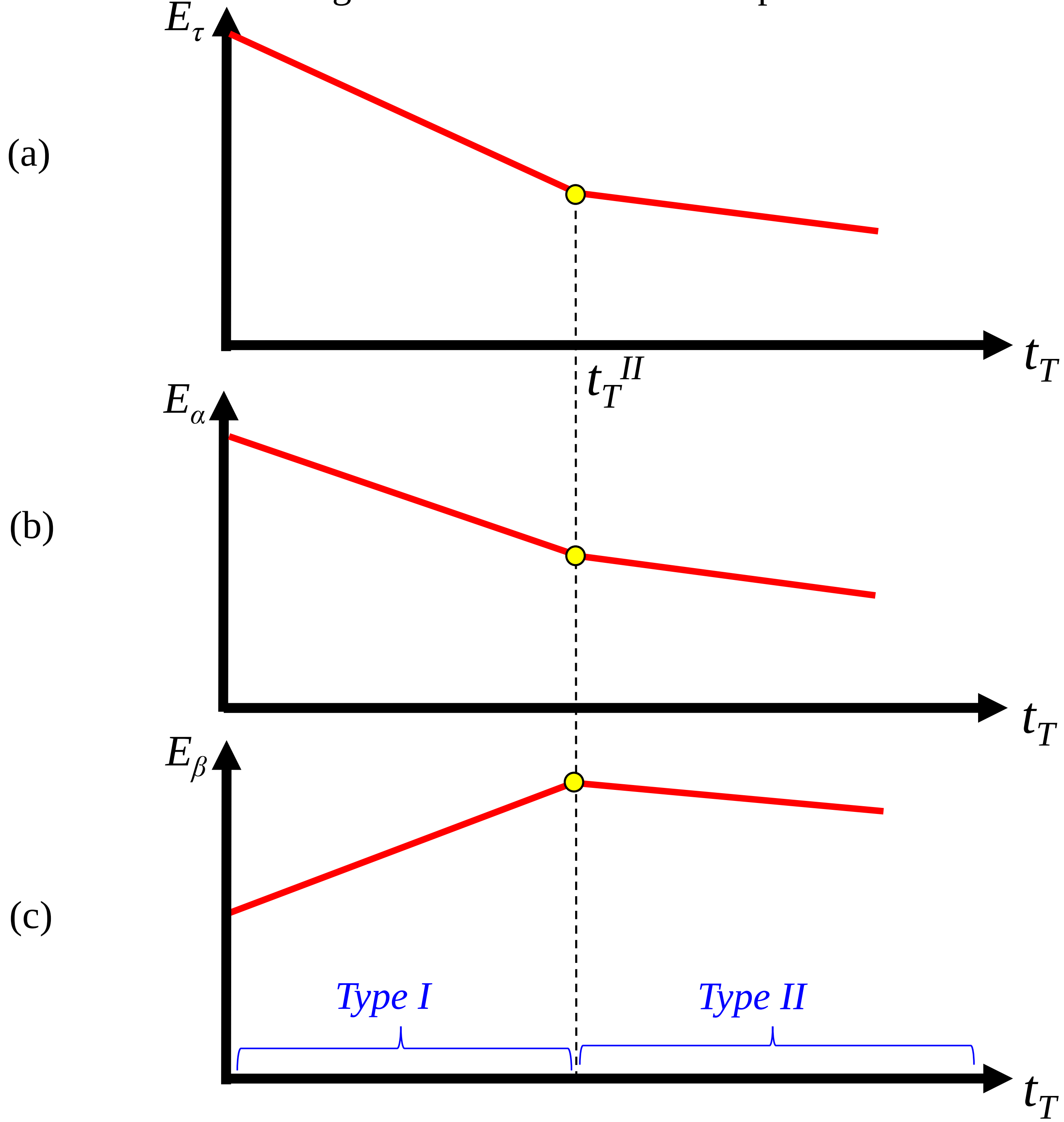

Figure 2. Carbon tax on production in country *A*

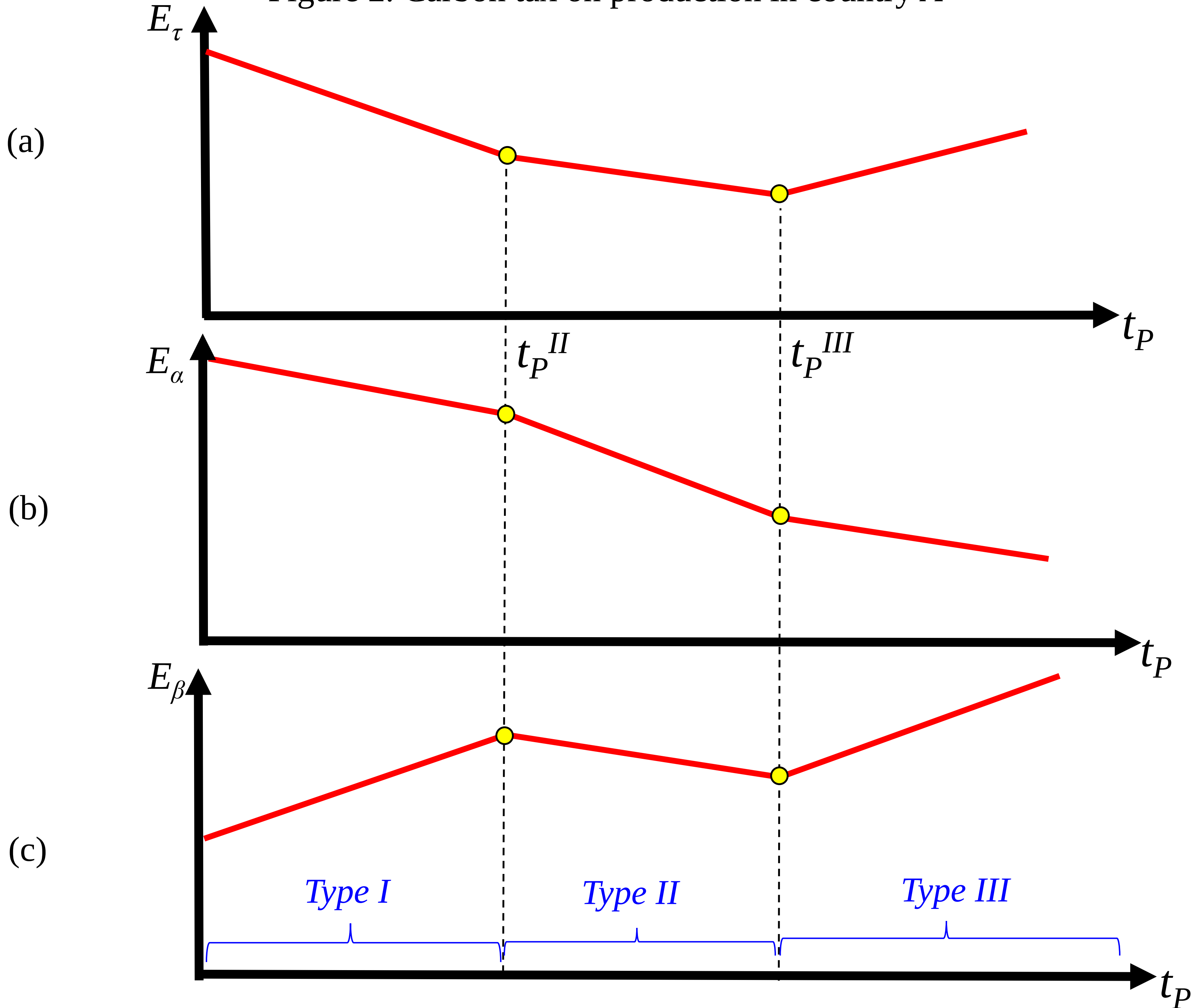

Figure 3. Carbon tax on consumption in country *A*

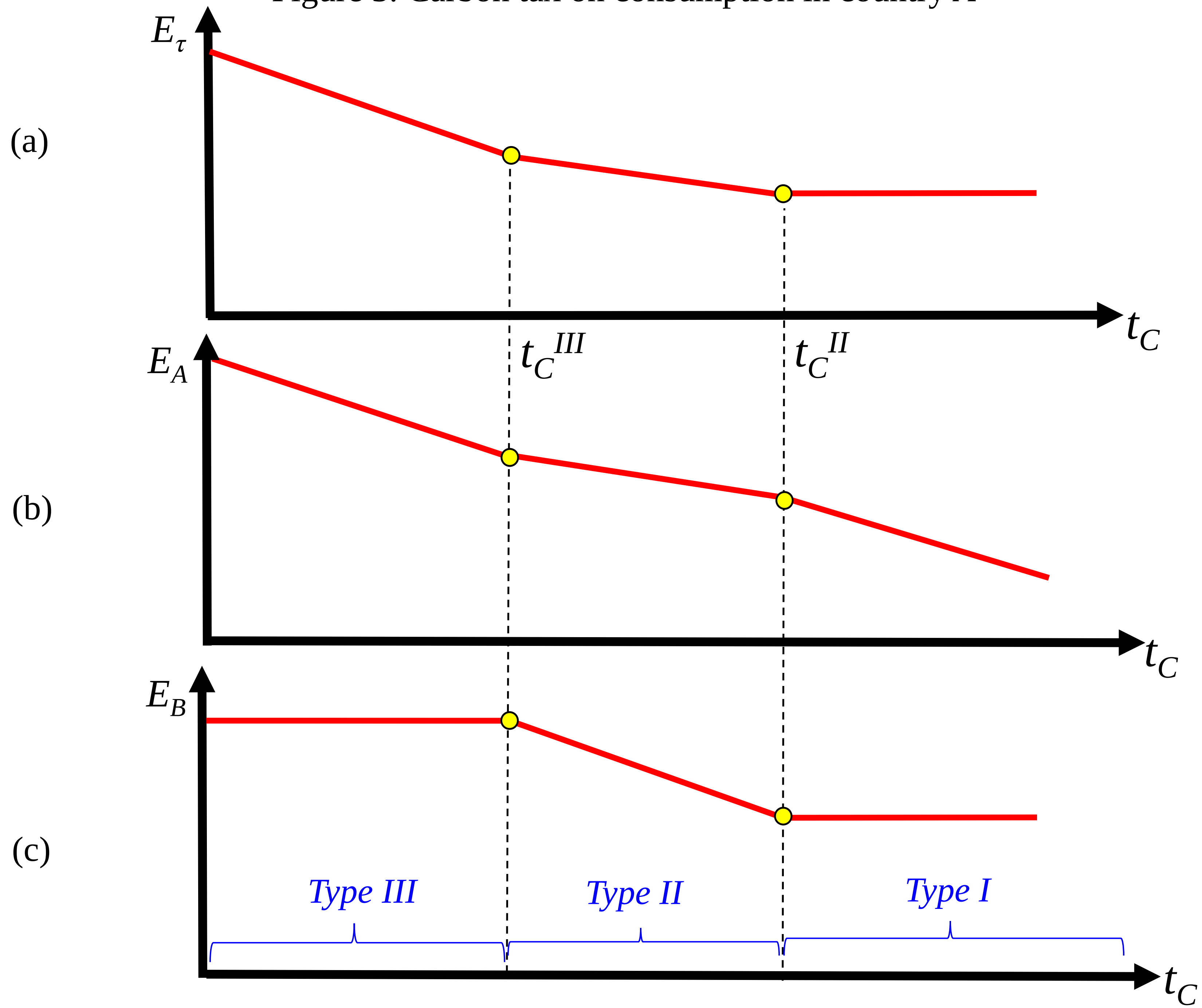

Figure 4. Carbon tax on transport with FDI

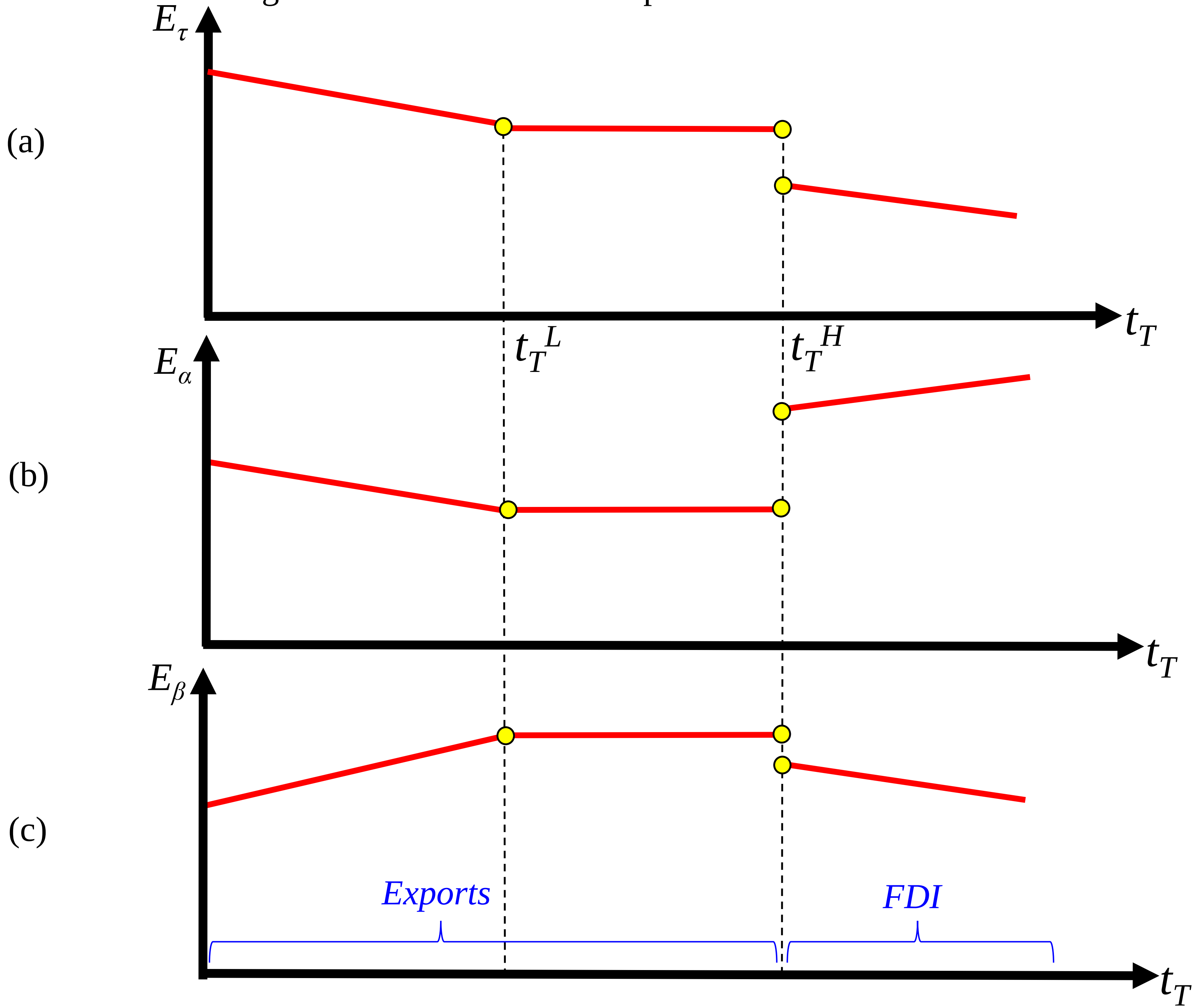

Figure 5. Carbon tax on production in country *A* with FDI