Transportation Pricing and Market Power in the Natural Gas Industry*

Remco van Eijkel†
Marco A. Haan‡
José Luis Moraga-González§

February 2008

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Abstract

We study the role of transportation pricing in shaping the incentives of gas producers with market power. Two downstream gas producers, each located at one of the ends of a pipeline, serve two markets connected by the pipeline. When pipeline capacity is relatively large, there exists a symmetric equilibrium where the pipeline is not fully utilized. In this case, nodal pricing is not optimal: a budget-constrained and welfare-maximizing transportation operator (TSO) adjusts transportation tariffs upwards to account for the presence of downstream market power. When capacity is relatively small, an (essentially) unique asymmetric equilibrium exists where one firm lowers its exports until the pipeline is used at full capacity. In this case, gas flows into the market where the price is lower and it is optimal for the TSO to subsidize the reverse flow and tax the dominant one so as to mitigate market power to the extent possible. In this case too, second-best tariffs differ from the nodal pricing system. Our results therefore suggest that the use of seasonal tariffs is optimal.

Keywords: gas transport, market power, pipeline, congestion

JEL Classification: L13, L51, L95

*We thank Henk Jaap Nooteboom and Joost Wempe for their useful remarks.

†Department of Economics and Econometrics, University of Groningen, E-mail: r.van.eijkel@rug.nl

‡Department of Economics and Econometrics, University of Groningen, E-mail: m.a.haan@rug.nl

§Department of Economics and Econometrics, University of Groningen and CESifo, E-mail: j.l.moraga.gonzalez@rug.nl

1 Introduction

Energy industries have undergone a liberalization process worldwide. Traditionally, these industries were vertically integrated monopolies, state-owned or not, operating under regulatory constraints. Owing to the recent trend of privatization and liberalization in network industries, separation of transportation services from commodity production and distribution has taken place in a number of gas and electricity markets. In the production and distribution segments policymakers attempt to promote competition by facilitating market entry by emerging firms. To ensure successful entry into the market, pipelines and power networks must grant access to the transportation system to new players. After a process of entry and exit, in recent days, the gas and electricity markets are essentially oligopolistic, with a few firms operating at the supply side of the market.[1] Transportation services usually remain regulated because of the natural monopoly characteristics of most services offered by the transportation operator (TSO).

In the gas industry, the extent to which gas producers have access to pipelines relates to the scope of gas market competitiveness. Pipeline capacity and access prices are thus two valuable instruments available to the operator/regulator to enhance competition in the gas market. Since capacity of the pipelines is somewhat fixed in the medium run and in any case rather costly to alter, attention has been given to the institutional details regarding the transportation of the commodity as well as to the pricing of transmission services.

Optimal transmission pricing has been studied thoroughly in the economics literature on power markets. The seminal work of Schweppe et al. (1988) shows that with perfect competition, in the absence of congestion, equilibrium prices are equal in all nodes of the power network. In the most simple case where the TSO bears no cost of providing services at all, optimal transportation tariffs are equal to zero. If one or more lines in the network become congested, then the price of transmission services is just the price difference between the nodes that are connected by the congested line. This pricing scheme, referred to as "nodal pricing," implies that an energy supplier receives its local price for all energy sold, independent of where its output is consumed.

Although nodal pricing is optimal in a perfectly competitive environment, it has also been used in models studying market power in energy industries. For example, Borenstein, Bushnell and Stoft (2000) consider an electricity network in which generators have market power and assume the existence of a fringe of arbitrageurs which ensure there are no price differences between nodes if the network is not congested. When the network becomes congested, the transportation tariffs are again equal to the difference in prices. The crucial

[1]Several empirical studies have shown that energy-supplying firms have the ability to set prices above the price that would prevail under perfect competition (see e.g. Wolfram, 1999; Borenstein and Bushnell, 1999; Borenstein, Bushnell and Wolak, 2002). In a recent report, the European Commission (EC, 2007) states that consumers cannot reap the full benefits of the recent EU-energy market liberalization because suppliers still have substantial power to manipulate market outcomes.

assumption in electricity studies using nodal pricing is that arbitrage opportunities are exhausted so there are no price differences across nodes in a non-congested network. Clearly, this assumption is justified if the market structure is one of perfect competition. However, in contrast to most electricity markets, possibilities for arbitrage in the gas industry are still fairly limited. Among the most important institutional factors preventing the exercise of arbitrage in gas markets are the absence of liquid hubs, physical bottlenecks in the network, and shippers' contractual obligations vis-à-vis consumers (see EC, 2007).

Another feature that distinguishes the gas industry from the market for electricity is that the physical laws governing the transmission of the commodities over the networks are not the same. The technical distinction, put forward neatly by Wilson (2002, p. 1301), has economic consequences:

> *Power transfers are complicated by the difficulty of directing flows in transmission systems with alternating current. [...] The absence of point-to-point transmission has had the economic consequence that property rights are not assigned by title (in contrast, title to gas is tracked continuously, even though it is perfectly homogeneous). No one owns power per se; rather, qualified market participants obtain privileges to inject or withdraw power from the network at specific locations.*

The fundamental difference between the two markets is that while gas producers typically have control over the gas flows, power producers generally do not. As a result, a gas producer can decide where it will inject the gas in the system and where it will take it out, thus being able to target output plans to distinct gas markets. In electricity, by contrast, the decision of a producer of power is just how much to inject in the system. This dissimilarity between industries, together with the lack of full arbitrage, implies that the existing models of nodal pricing developed for the electricity sector do not apply straightforwardly to the gas industry.

In this article, we study the incentives of gas producers and the role of transportation prices to foster competition in the gas market. We consider a setting where two downstream gas producers serve two distant markets connected by a pipeline, which is under control of a regulated TSO. Each producer is located at one of the ends of the pipeline and chooses gas supplies for the local and for the distant market. The fact that gas suppliers can control the gas flows in real-world markets has led to some important institutional details that we incorporate in our four-stage game. At the beginning of the market interaction, the TSO announces transmission tariffs for direct and reverse gas flows. In the second stage of the game, firms book transmission capacity for the gas they intend to sell in the distant market. In the third stage of the game, the TSO allocates transmission rights by netting out the reserved capacities and taking into consideration the overall pipeline capacity.[2] In the last stage, firms produce gas and inject it into the system; the consumers withdraw it and consume it.

Our model is similar in spirit to that in Cremer and Laffont (2002).[3] Their paper shows how the standard notion of nodal pricing has to be modified to account for the particular cost structure of gas pipelines.[4] The main differences are that we allow for market power in each node and that we do not adopt nodal pricing as the transportation pricing system. These differences imply that the booking system for capacity and the allocation mechanism for transmission rights need to be spelled out in detail. If the transmission line had no capacity whatsoever, firms would be monopolists in their own local markets, while if capacity were sufficiently large, the market would be fully integrated and each firm would behave as a duopolist in a large global market. Pipelines of limited capacity and the possibility of netting give firms an incentive to restrict their transmission bookings thereby also restricting the actual exports of the rival firm and increasing local market power.

The first part of the paper focuses on situations where pipeline capacity is large. In this case, a symmetric equilibrium exists in which flows are netted out so the pipeline is not fully utilized. In the absence of pipeline congestion, attaining the first-best calls for negative transportation prices, thus effectively lowering the cost of producing gas intended for exports and thereby raising exports till competitive levels. The first-best tariffs then correct for market power and are therefore smaller than corresponding first-best nodal prices (Cremer and Laffont, 2002). More interesting is the case in which the TSO operates under a budget constraint (second-best pricing). In this situation too, nodal pricing is not optimal: relative to nodal prices, a budget-constrained and welfare-maximizing TSO adjusts its transportation tariffs upwards to account for the presence of downstream market power. This is because gas producers with market power supply too little output relative to the competitive level, which implies that the tax base of the TSO is smaller and so nodal prices would generate a loss for the TSO. As a result, our second-best tariffs are higher than nodal prices. Finally, we examine the nature of profit maximizing transportation tariffs. We find that a profit-maximizing TSO charges tariffs that are too large from the viewpoint of society. This result arises because a profit-maximizing TSO does not internalize the effects of its tariffs on consumer's surplus and profits of the downstream firms.[5]

The second part of the article deals with the case where pipeline capacity is relatively small. In this situation, an (essentially) unique asymmetric equilibrium is shown to exist.

[2] With netting, flows in opposite directions cancel out and the line only has to let through the (physical) net flow, that is, the difference between the booked flow from 1 to 2 and the booked flow from 2 to 1.

[3] A similar framework is used in Joskow and Tirole (2000) and Gilbert, Neuhoff and Newbery (2004) to study the role of transmission contracts in the power sector. Likewise, Borenstein, Bushnell and Stoft (2000) use this model to examine the effects of pipeline capacity in the electricity market.

[4] See also Cremer, Gasmi and Laffont (2003) for the case of competitive gas markets and a three-node network.

[5] Results on asymmetric markets to be added.

Relative to the symmetric equilibrium, in this asymmetric situation one of the firms continues to lower its gas exports till the pipeline is congested. Interestingly, in equilibrium the commodity flows into the market where the price is lower. This result, which is at odds with the received wisdom from competitive markets, is not only a theoretical curiosity but has been observed in real world gas markets. For example, in the gas interconnector,[6] a two-way pipeline that links the UK (Bacton) and continental Europe (Zeebrugge), net flows have been seen to go from the UK to Belgium in a period where UK gas prices were significantly higher.[7] Our analysis suggests that this outcome can be a natural result of profit-maximizing behavior when demand is large relative to pipeline capacity.

In this case of small pipeline capacity where the equilibrium features pipeline congestion, it turns out that a budget-constrained and welfare-maximizing TSO has an incentive to subsidize the reverse flow and tax the dominant one. This second-best tariffs are meant to weaken the incentives of a firm to congest the pipeline in equilibrium, so that total supply on both markets increases and so does welfare. Since in equilibrium gas flows differ across markets, transportation tariffs are not equal to one another in absolute value. Therefore, also in this case of absence of excess pipeline capacity, our second-best tariffs differ from nodal prices.

In sum, our analysis shows that the market outcome, and so the nature of transportation pricing, crucially depends on the capacity of the pipeline. During summer seasons, demand is expected to be relatively low compared to capacity and so distinct geographic markets are expected to exhibit similar commodity prices. By contrast, if pipelines have not sufficient capacity, tough winters may lead to asymmetric equilibria and therefore to significant price differentials across separated geographic markets. Our results on optimal pricing suggests transportation tariffs should be seasonal.

The remainder of this paper is organized as follows. In the following Section we describe in detail the model we use for our analysis. In Section 3, we consider the case of no congestion and demonstrate that socially optimal tariffs differ from nodal prices. We also provide tariffs that maximize the profits of the TSO. Section 4 discusses second-best transportation prices when there is congestion and shows that in this case, tariffs are again not equal to nodal prices. Finally, section 5 gives the subgame perfect equilibrium of the game and section 6 concludes.

2 The model

We consider a gas network that consists of two nodes, labelled 1 and 2, which are connected by a pipeline with capacity K. There is demand for gas as well as gas production in both nodes. We focus on the case of symmetric demand, so $P_1(\cdot) = P_2(\cdot) = P(\cdot)$. Assume the

[6] See www.interconnector.com.

[7] In fact, this triggered a EU competition investigation of the operation of the interconnector during January 2001 (see European Commission, 2002).

common demand function is given by

$$P(Q_i) = a - Q_i$$

where Q_i is the aggregate quantity of gas consumed in node i with $i = 1, 2$. In each node, gas is produced by a single downstream firm, where firms are indexed by $i = 1, 2$. Due to the existence of the transmission line a producer cannot only sell gas in its local market but also in the distant market.[8]

To make clear the distinction between a producer's supply for its local market and its output targeted to the distant node, we refer to q_{ij} as the total output of a firm located in node i to serve demand in node j. Then $Q_1 = q_{11} + q_{21}$ and $Q_2 = q_{12} + q_{22}$. For the sake of clarity, q_{ii} and q_{ij}, $i \neq j$, are referred to as "local supply" and "exports" of firm i, respectively. In case the pipeline capacity is insufficient to accommodate the desired exports of the producers, a specific rationing rule has to be used by the TSO. We will introduce this rationing rule below when we spell out the booking system for transmission rights in the gas industry. The marginal cost of supplying gas (net of transportation charges) equals c for all firms, irrespective of whether it concerns domestic supply or exports. The cost function of downstream firm i is given by

$$C_i(q_{ii}, q_{ij}) = c(q_{ii} + q_{ij}) + t_{ij}q_{ij}, \text{ with } i \neq j \text{ and } i, j = 1, 2$$

where t_{ij} denotes the linear transportation tariff firms are charged to get one unit of their gas shipped from node i to j. Note that the pipeline is needed for gas exports and that firms can sell locally without using it. We shall assume that $|t_{ij}| \leq (a - c)/2$; if this assumption were not satisfied markets would be served by monopolies and the problem would not be so interesting.[9]

We consider a TSO having control over the pipeline and being able to charge firms for the use of the transportation services. Throughout the paper, we treat pipeline capacity as exogenous and assume that past investment outlays for capacity are sunk costs. The only costs for the TSO arise from shipping the (net) gas flow over the line and from pipeline maintenance; let c_O be the constant marginal cost of transporting the gas and $C(K)$ the fixed costs necessary to maintain the network operational. The pipeline is used by firms only to ship gas to the distant market. Moreover, as gas is completely homogeneous we assume that the operator is able to net out gross exports against each other. As a result, pipeline capacity has to be sufficiently large to let through the net flow, which equals the difference in gross exports, or $|q_{21} - q_{12}|$. The cost function of the TSO is then as follows:

$$C_O(q_{12}, q_{21}, K) = c_O\,|q_{21} - q_{12}| + C(K)$$

[8] Here we notice the difference between the gas industry and the market for electricity: while in the latter producers receive the local price for the total amount sold and therefore cannot sell in different consumer markets, in the former firms have the ability to target their output to geographically distinct markets.

[9] We get that if tariffs are very large, demand in a particular node is served only by the local firm. In contrast, when transportation prices become sufficiently negative there is no local supply and exports cover total demand in both nodes.

The core of the analysis focuses on the case in which the TSO is perfectly controlled by a welfare-maximizing regulator. As will become clear later, the first-best outcome would entail a loss for the TSO. To circumvent this problem, we let the TSO maximize welfare under the constraint that it has to break even. The resulting second-best tariffs are known as "Ramsey-Boiteaux" prices (see e.g. Laffont and Tirole, 2002). The paper also presents a comparison of profit-maximizing transportation prices with socially optimal tariffs.

We model the interaction in the market as a four-stage game. In the first stage, the TSO decides on transportation prices t_{ij} with $i \neq j$ and $i, j = 1, 2$. In the second stage, firms book transmission capacity to be able to export gas to the distant node. Let us denote these bookings by b_{ij} with $i \neq j$ and $i, j = 1, 2$. Then, in the third stage of the game, the TSO allocates transmission rights $\bar{b}_{ij}$ to the firms taking into account the transport capacity of the pipeline and the possibilities for netting the flows. In the last stage, production is realized and firms compete on both markets given their transmission rights and the tariffs set by the operator. In line with the actual practice in the industry, we assume that penalties for imbalances ensure that actual exports are always equal to the transmission rights granted to the firm, that is, $q_{ij} = \bar{b}_{ij}$. We define the last three stages of the game as the "gas market subgame", since throughout the paper these stages are discussed together. The game is solved by backward induction.

In what follows, we derive the subgame perfect equilibria (SPE) of this model. We first consider the case where in the gas market subgame, producers play strategies that yield an equilibrium in which the pipeline is not congested. Then, we determine for this gas market equilibrium first-best, second-best, and profit-maximizing tariffs. Thereafter, we move to the situation in which firm do bookings that lead to pipeline congestion and solve for the second-best tariffs.

3 Non-congested pipeline

In this section we study pipeline access in situations where the capacity of the pipeline is large and therefore there is not congestion in the market. We first consider the downstream gas

market subgame. Then we solve for the socially optimal and profit-maximizing transportation tariffs.

3.1 Equilibrium in the gas market

Here we characterize firm strategies that are part of an equilibrium without congestion. Proceeding backwards, we start with the last stage of the game. In this stage, taking as given the transportation tariffs set by the TSO and the transmission rights allocated to the firms, both gas producers compete in quantities. A firm i chooses the pair (q_{ii}, q_{ij}) to maximize its profits, which are given by

$$\pi_i(q_{ii}, q_{ij}; \cdot) = (a - (q_{ii} + q_{ji}) - c)q_{ii} + (a - (q_{ij} + q_{jj}) - c - t_{ij})q_{ij}$$

The existence of penalties for imbalances between the actual exports of a firm and its transmission rights ensures that firms do not withhold transmission rights in equilibrium, i.e. $q_{ij} = \bar{b}_{ij}$. This has the implication that the booking system serves as a commitment device and confers the rival exporter a first-mover advantage over its local counterpart. Therefore, the local supply q_{ii} of firm i is the best reply to the transmission rights allocated to firm j, i.e. $q_{ii} = BR(q_{ji}) = BR(\bar{b}_{ji})$. Equilibrium strategies in this stage are then given by

$$\begin{aligned} q_{ii}(\bar{b}_{ji}) &= \begin{cases} \frac{a-\bar{b}_{ji}-c}{2} & \text{if } \bar{b}_{ji} < a-c \\ 0 & \text{otherwise} \end{cases} \\ q_{ij}(\bar{b}_{ij}) &= \bar{b}_{ij} \end{aligned} \tag{1}$$

with $i \neq j$ and $i, j = 1, 2$.

We now move to describe the equilibrium of the third stage of the game. In this stage, anticipating that actual exports will be equal to the transmission rights allocated to the players, the TSO assigns transmission rights. For this, the TSO takes into account the capacity of the pipeline and the desired net export flow. Consider first a situation where firms request transmission rights b_{12} and b_{21} such that the net flow does not exceed the capacity of the pipeline. In this case, the amount of transmission rights granted to the firms equals the booked capacity. In case line capacity is not large enough to let through the desired net flow, the TSO rations the firm requesting the largest amount of transmission rights. In particular, this firm is allocated the maximum transmission capacity which is compatible with pipeline capacity. Therefore, the equilibrium TSO's mechanism for transmission rights allocation is:[10]

$$(\bar{b}_{12}, \bar{b}_{21}) = \begin{cases} (b_{12}, b_{21}) & \text{if } |b_{21} - b_{12}| < K \\ (b_{12}, b_{12} + K) & \text{if } b_{21} - b_{12} \geq K \\ (b_{21} + K, b_{21}) & \text{if } b_{12} - b_{21} \geq K \end{cases} \tag{2}$$

We now move to the second stage of the game. In this stage, firms book transmission capacities to maximize profits taking into account transportation tariffs and anticipating the equilibrium strategies in the continuation game. Consider the strategy profile (b_{12}, b_{21}). Figure 1 shows the congesting nature of different strategy profiles. When the difference between b_{12} and b_{21} does not exceed K, there is no congestion; otherwise either firm 1 or firm 2 is rationed by the TSO according to (2).

While studying whether a pair of booking strategies can be part of an equilibrium, it is useful to distinguish between booking profiles which result in no congestion of the

[10]This rationing rule is the only possible one in our model, since the TSO cannot force the firm that is booking the smallest amount to book more.

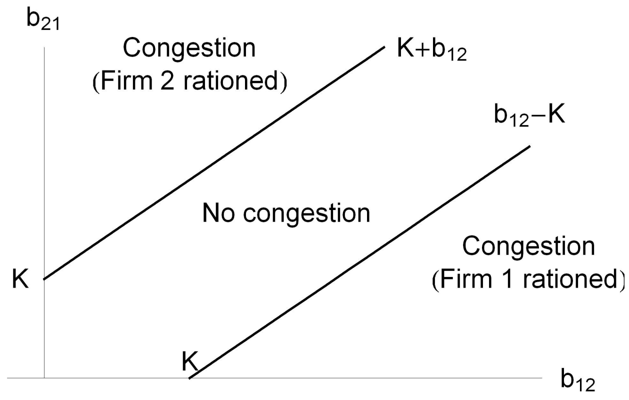


Figure 1: Booking strategies, pipeline congestion and implied rationing

pipeline and booking profiles resulting in congestion. We start by considering the set of booking profiles in the "No congestion" region of Figure 1. Later in Section 4 we consider booking strategy profiles which lead to pipeline congestion.

Let us study whether a booking profile (b_{12}, b_{21}) satisfying $|b_{21} - b_{12}| < K$ can be part of an equilibrium. Consider the problem of firm i. This firm chooses a booking b_{ij} to maximize its profits taking into account firm j's booking as well as the equilibrium strategies in the continuation game. Under the assumption $|t_{ij}| < (a-c)/2$, the reduced-form second-stage profits of firm i would be

$$\pi_i = \left(\frac{a - b_{ji} - c}{2}\right)^2 + \left(\frac{a - b_{ij} - c}{2} - t_{ij}\right) b_{ij},\ i \neq j,\ i,j = 1,2$$

where we note that $\bar{b}_{ij} = b_{ij}$ and $q_{ii} = BR(q_{ji})$. Taking the FOC and solving for b_{ij} gives

$$b^*_{ij} = \frac{a - c - 2t_{ij}}{2},\ i \neq j,\ i,j = 1,2. \tag{3}$$

Equation (3) describes the optimal capacity bookings of the firms (provided transportation rates are lower than $(a-c)/2$ for otherwise firms would prefer not to export at all). Note that booking the amounts in (3) does not lead to pipeline congestion as long as $|t_{21} - t_{12}| < K$.

If these strategies were part of an equilibrium, aggregate production, prices and profits would be given by

$$Q^*_i = b^*_{ji} + q^*_{ii} = \frac{3(a-c) - 2t_{ji}}{4} \tag{4}$$

$$p^*_i = \frac{a + 3c + 2t_{ji}}{4} \tag{5}$$

$$\pi^*_i = \frac{(a - c + 2t_{ji})^2}{16} + \frac{(a - c - 2t_{ij})^2}{8},\ i \neq j,\ i,j = 1,2. \tag{6}$$

We note that these outcomes do not depend on K, since there is no congestion and both firms are able to ship to the distant market their desired levels of exports.

We now examine the conditions under which firms cannot profitably deviate from the strategies in (3). We first consider a deviation by firm 1. Given firm 2's equilibrium booking b_{21}^*, consider firm 1 deviates by lowering its booking so as to generate pipeline congestion, i.e, firm 1 deviates by booking an amount $b_{12}^d \in [0, b_{21}^* - K)$.[11] This deviation is potentially profitable for firm 1 because by doing so this firm in effect controls the amount of exports flowing into its market, which increases its local market power.

In the third stage, following the deviation by firm 1, the TSO allocates transmission rights to the firms equal to $\bar{b}_{12} = b_{12}^d$ and $\bar{b}_{21} = b_{12}^d + K < b_{21}^*$. Therefore, the deviant's reduced-form profits are given by

$$\pi_1^d(b_{12}^d, b_{21}^*) = \left(\frac{a - b_{12}^d - K - c}{2}\right)^2 + \left(\frac{a - b_{12}^d - c}{2} - t_{12}\right) b_{12}^d \tag{7}$$

Taking the FOC and solving for the optimal deviation yields

$$b_{12}^d \quad = \begin{cases} K - 2t_{12} & \text{if } t_{12} < K/2 \\ 0 & \text{otherwise} \end{cases}$$

Using this optimal deviating strategy, one obtains the profits of the deviant:

$$\pi_1^d(\cdot) \quad = \begin{cases} \frac{1}{4}(a - c - K)^2 + \left(\frac{K}{2} - t_{12}\right)^2 & \text{if } t_{12} < K/2 \\ \frac{1}{4}(a - c - K)^2 & \text{otherwise} \end{cases} \tag{8}$$

Comparing equilibrium profits in (6) with deviating profits in (8) yields

$$\pi_1^*(b_{12}^*, b_{21}^*) \geq \pi_1^d(b_{12}^d, b_{21}^*) \Leftrightarrow K \geq K_1(a, c, t_{12}, t_{21}) \tag{9}$$

where

$$K_1(\cdot) \equiv \begin{cases} \left(1 - \frac{1}{\sqrt{2}}\right) \frac{a-c}{2} + t_{12} - \frac{t_{21}}{\sqrt{2}} & \text{if } t_{12} < K/2 \\ a - c - \frac{1}{2}\sqrt{3(a-c)^2 + 4(a-c+t_{21})t_{21} - 8(a-c-t_{12})t_{12}} & \text{otherwise} \end{cases} \tag{10}$$

Proceeding analogously, we can compute the condition under which firm 2 does not deviate from the equilibrium strategy in (3). This condition is symmetric to the condition in (9) and therefore $K_2(\cdot)$ can be obtained from the expression for $K_1(\cdot)$ by interchanging the subindexes i and j.

We are now ready to state our first equilibrium result. For this purpose, we define the set of parameters

$$Z_{NC} \equiv \{(a, c, t_{12}, t_{21}, K) : K \geq K_1(\cdot);\ K \geq K_2(\cdot)\} \tag{11}$$

We then come to the following proposition:[12]

[11] Note that $b_{12}^d < b_{21}^* - K$ must hold, since otherwise firm 2 still gets transmission rights allocated equal to b_{21}^* and there would be no congestion.

[12] Note from (3) that a necessary condition for an equilibrium without congestion to exist is $|t_{21} - t_{12}| < K$. It is easy to see that this condition is satisfied if $(a, c, t_{12}, t_{21}, K) \in Z_{NC}$. Suppose, without loss of generality, $t_{12} \leq t_{21}$ so that $K_1(\cdot) \leq K_2(\cdot)$ and therefore that $(a, c, t_{12}, t_{21}, K) \in Z_{NC}$ if $K \geq K_2(\cdot)$. Simple computation shows that $K \geq K_2(\cdot) > |t_{21} - t_{12}|$, which implies that $|t_{21} - t_{12}| < K$ automatically holds when $(a, c, t_{12}, t_{21}, K) \in Z_{NC}$.

Proposition 1 *For any vector of parameters* $(a, c, t_{12}, t_{21}, K) \in Z_{NC}$ *there exists a downstream gas market equilibrium where firms book the amounts given in (3), transmission rights satisfy (2) and production levels are given by (1). In equilibrium, the net flow is less than* K *so there is no congestion. Firms obtain a profit given in (6).*

In this equilibrium, firms do not have an incentive to congest the line and thus play strategies *as if* pipeline capacity were unlimited.

To illustrate Proposition 1, Figures 2(a) and 2(b) show, for given a, c, and K, the space of transportation prices (t_{12}, t_{21}) for which a downstream market equilibrium with no congestion exists. Figure 2(a) is drawn for the case of relatively large pipeline capacity, while Figure 2(b) shows the case of small capacity. In both cases, for pairs of tariffs (t_{12}, t_{21}) that lie between the two bounds $K = K_1(\cdot)$ and $K = K_2(\cdot)$, the equilibrium described in Proposition 1 exists.

To get some intuition, consider the bound $K = K_1(\cdot)$. For all tariff combinations that lie on this bound, firm 1 is indifferent between deviating from the strategy given by (3) or not. Clearly, for any t_{12} to the left of this bound firm 1 strictly prefers not to deviate, since a lower t_{12} raises the profitability of exporting to market 2. Furthermore, any t_{21} above $K = K_1(\cdot)$ also makes that firm 1 does not have an incentive to deviate. This is because a higher t_{21} lowers the exports of firm 2 in case the line is not congested. Thus, for any pair of tariffs to the left and above of $K = K_1(\cdot)$ firm 1 does not have an incentive to deviate. A similar reasoning applies for the bound $K = K_2(\cdot)$: firm 2 does not deviate from the equilibrium strategy if the pair of tariffs is below and to the right of $K = K_2(\cdot)$.

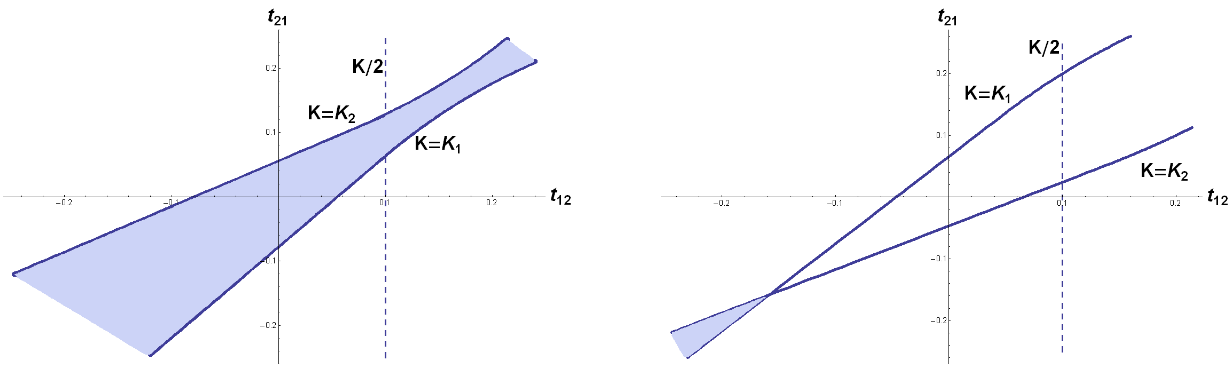
A comparison of Figures 2(a) and 2(b) reveals that the set of tariffs for which an equilibrium without congestion exists depends on pipeline capacity. When capacity is small, only negative transportation prices ensure that the pipeline is not congested (Figure 2(b)). The reason for this is that negative tariffs act as an export subsidy, which reinforces the incentives for firms to export a lot and makes congestion less attractive. By contrast, when capacity is large, positive transportation tariffs also allow for an equilibrium without congestion (Figure 2(a)). This is because when capacity is sufficiently large, it is not profitable for a firm to provoke congestion by lowering exports since the rival firm is anyway able to export an amount equal to (or close to) the desired amount.

3.2 Transportation pricing

Moving back to the first stage of the game, we now examine socially optimal transportation prices. We first consider the benchmark case of first-best transportation tariffs, then we study second-best tariffs. Finally, we discuss profit-maximizing transportation prices.

Social welfare equals

$$\begin{aligned} SW &= \int_0^{Q_1} \Big(a - x - c\Big) dx + \int_0^{Q_2} \Big(a - x - c\Big) dx \\ &- C_O(q_{12}, q_{21}, K) \end{aligned} \tag{12}$$



(a) Large pipeline capacity ($K = 0.2$) (b) Small pipeline capacity ($K = 0.1$)

Figure 2: An equilibrium with no congestion exists in the shaded areas ($a = 2; c = 1$)

where $C_O(\cdot) \equiv c_O|q_{21} - q_{12}| + C(K)$ is the total cost of the TSO. Notice that changing either transportation tariff has no direct effect on the level of social welfare. This is because transportation prices are just transfers from the firms to the TSO. However, transportation prices have a bearing on welfare via the quantities firms put in the market.

3.2.1 First-best tariffs

Without any restrictions on the revenues of the TSO, the problem of the operator is to set tariffs that maximize (12). Simple computations show that the first-best transportation prices equal

$$t_{12} = t_{21} = -\frac{a-c}{2} \tag{13}$$

To attain the socially optimal allocation, access charges should be negative. This is because negative transportation tariffs result in an increase in the exports, which has a positive effect on welfare. Note that with these transportation tariffs firms export an amount equal to the competitive output and do not supply any gas locally.[13]

Finally, we note that in our model transportation tariffs are used to stimulate production so they differ in nature from nodal prices. In fact, while in our case first-best transportation pricing entails the use of subsidies, first-best nodal prices are equal to zero (see e.g. Cremer and Laffont, 2002).

3.2.2 Second-best tariffs

The previous section shows that in order to obtain the first-best solution, the TSO has to set negative transportation prices. However, this pricing scheme entails losses for the

[13]Note that a similar aggregate outcome could be obtained if the government directly subsidized gas production instead of gas transportation. In that case, however, total public funding needed to obtain the social optimum would be lower. In fact, the production tax should be set to $t = -(a-c)/3$ and the total government expenditures would be $(a-c)^2/3$.

TSO. To get around this problem, we now assume that the TSO is not allowed to run a deficit.

The budget constraint of the TSO is given by

$$t_{12}q_{12} + t_{21}q_{21} - C_O(\cdot) \geq 0 \tag{14}$$

The TSO then maximizes (12) subject to (14), where the latter holds with equality at the optimum.[14] The resulting second-best transportation tariffs are Ramsey-Boiteaux prices, although adjusted for the presence of imperfect competition.

We consider the subset of tariffs that lead to the non-congested equilibrium (NCE) and ask which tariffs yield the highest level of social welfare. This set has been denoted Z_{NC} and its characterization is given in Proposition 1. Assume, without loss of generality, that $t_{12} \geq t_{21}$; this implies $q_{12}^* \leq q_{21}^*$, so that the problem of the TSO can be written as

$$\max_{(t_{12},t_{21})\in Z_{NC}} \quad \{SW = \int_0^{Q_1^*(t_{21})} \Big(a - x - c\Big) dx + \int_0^{Q_2^*(t_{12})} \Big(a - x - c\Big) dx - C_O(\cdot)\}$$

subject to:

$$t_{12}q_{12}^*(t_{12}) + t_{21}q_{21}^*(t_{21}) - C_O(\cdot) = 0$$

$$t_{12} \geq t_{21}$$

We then come to the following result.

Proposition 2 *For fixed parameters $a, c, K, c_O, C(K)$ consider the set $T_{NC}(a, c, K, c_O, C(K))$ of TSO's-budget-constraint-satisfying tariff combinations that lead to the NCE of Proposition 1:*

$$T_{NC}(a, c, K, c_O, C(K)) \equiv \{(t_{12}, t_{21}) \in \mathbb{R}^2 : (t_{12}, t_{21}) \in Z_{NC}(a, c, K); \sum t_{ij}q_{ij}^* \geq C_O\},$$

with q_{ij}^* given in Proposition 1. If $T_{NC}(a, c, K, c_O, C(K))$ is non-empty, the pair of tariffs

$$t_{12}^* = t_{21}^* = \frac{a - c - \sqrt{(a-c)^2 - 8C(K)}}{4} \tag{15}$$

dominates in terms of social welfare all other elements in this set $T_{NC}(a, c, K, c_O, C(K))$.

The proof is in the Appendix.

Proposition 2 gives the transportation prices (t_{12}^*, t_{21}^*) that maximize social welfare given that firms play strategies that lead to the equilibrium without congestion in the continuation game. It is easy to see that these tariffs are (i) increasing in the cost of the downstream firms and in the cost of capacity, and (ii) decreasing in the demand parameter a.[15] When there is no cost of capacity (maintenance), these tariffs are equal to zero. In smaller markets, the tax base is smaller so tariffs have to be raised to be able to cover capacity costs.

[14] To see that the budget constraint is binding at the optimum, suppose by contradiction that this constraint does not bind. But then one of the tariffs (or both) can be lowered without violating the budget constraint, since this constraint is continuous everywhere. Lowering the tariff increases welfare, which implies that the budget constraint binds at the optimum.

[15] Since there is no net flow in our symmetric equilibrium, tariffs do not depend on distance.

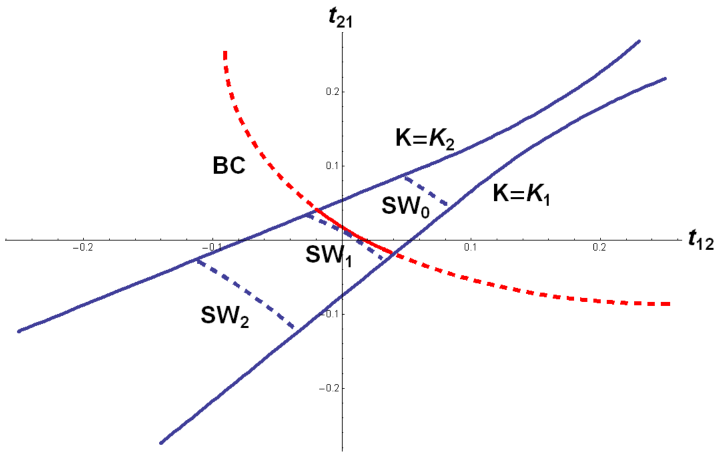


Figure 3: Optimal tariffs in the equilibrium without congestion ($a = 2, c = 1, K = 0.2, c_O = 0.01, C(K) = 0$)

The problem of the TSO and the reason why it chooses tariffs (t_{12}^*, t_{21}^*) can be illustrated by Figure 3. This Figure builds on Figure 2(a) above, which showed the region of parameters for which a NCE exists, by adding isowelfare levels and the TSO's budget constraint. The dashed concave and decreasing curves in the figure represent different isowelfare curves. To see why these isowelfare levels are decreasing, note that increasing (decreasing) a tariff has a negative (positive) effect on social welfare. Therefore, to keep welfare constant, a rise in one tariff has to be accompanied by a fall in the other tariff. Since social welfare decreases in tariffs, isowelfare levels increase as we move from the northeast of the (t_{12}, t_{21}) space to the southwest. The solid convex and decreasing curve represents the TSO's budget constraint. This curve is decreasing since a lowering of one tariff must be met by an increase in the other tariff to keep the budget in balance. The problem of the TSO consists of picking the point on the budget constraint that yields the highest social welfare and therefore, at the optimum the isowelfare curve is tangent to the budget constraint. Moreover, observe that this point lies above $K = K_1(\cdot)$ and below $K = K_2(\cdot)$ so that for tariffs (t_{12}^*, t_{21}^*) the equilibrium without congestion exists.

Now the question becomes how these transportation tariffs relate to tariffs that would be set if there were full competition in both nodes. From Cremer and Laffont (2002), we know that the second-best nodal prices are implicitly given by the difference in the consumer price and the producer price. With the demand and cost structure chosen in this paper, nodal prices are then given by

$$t_{12}^N = t_{21}^N = p_1^d - c = \frac{C(K)}{(a-c)^2}$$

where p_1^d is the consumer price in node 1. Comparing these nodal prices with the tariffs stated in Proposition 2 shows that if producers have market power, nodal prices are too low to cover the cost of the TSO. The reason for this is that under imperfect competition aggregate output is lower than under perfect competition, which also means that the tax

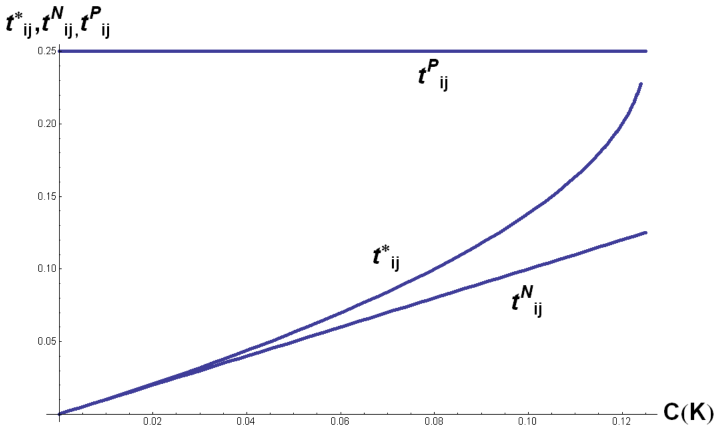


Figure 4: second-best tariffs and nodal prices ($a = 2, c = 1$)

base is lower. Therefore, the TSO has to increase tariffs to be able to meet the break-even constraint. Figure 4 illustrates the difference between nodal prices and the tariffs in Proposition 2. Observe that t_{ij}^N and t_{ij}^* diverge when $C(K)$ increases and that both prices are equal to each other only when $C(K) = 0$.

3.2.3 Profit-maximizing tariffs

Until now, we have assumed that the TSO acts as a benevolent social planner and thus implements transportation tariffs that maximize social welfare. Recently, however, there have been some attempts to privatize network operators.Therefore, it is useful to compare socially optimal tariffs with tariffs set by a profit-maximizing TSO. Notice that the solution of the gas market subgame still holds, so we only have to focus on the first stage of the game. The problem of the profit-maximizing TSO is then given by

$$\max_{(t_{12},t_{21})\in Z_{NC}} \{\pi^P = \frac{a-c-2t_{12}}{2}t_{12} + \frac{a-c-2t_{21}}{2}t_{21} - C_O(\cdot)\}$$

The following result describes the solution to this problem.

Proposition 3 *Consider the set of tariff combinations*

$$T_{NC} \equiv \{(t_{12}, t_{21}) \in \mathbb{R}^2 : (a, c, t_{12}, t_{21}, K) \in Z_{NC}\}$$

Then t_{12}^P and t_{21}^P denote the tariffs that generate the highest profit in this set, where

$$t_{12}^P = t_{21}^P \quad = \begin{cases} \frac{a-c}{4} & \text{if } K \geq \left(1 - \sqrt{11}/4\right)(a-c) \\ \frac{1}{6}(a-c) - \frac{1}{3}\sqrt{3K^2 + (a-c)^2 - 6(a-c)K} & \text{otherwise} \end{cases}$$

The proof is in the Appendix.

Comparing these tariffs with the tariffs set by a benevolent but budget-constrained planner, given by (15), one observes that profit-maximizing tariffs are excessive in terms of social welfare.

4 Congested pipeline

We now examine whether there are strategies that yield an equilibrium with congestion. We notice that the discussion on the equilibrium strategies of the last two stages in the previous section also applies here. So, there will be congestion in equilibrium only if firms' bookings violate the capacity constraint. After we have described the gas market equilibrium with congestion, we determine the second-best tariffs for this equilibrium.

4.1 Equilibria in the gas market

Let us turn to the question whether strategies b_{12} and b_{21} satisfying $|b_{21} - b_{12}| \geq K$ can be part of an equilibrium. Notice that if this were true, at the resulting equilibrium the pipeline would be congested. To start with, consider first a booking strategy profile such that $b_{12} \leq b_{21} - K$ (northwest of Figure 1), which implies that firm 2 will be rationed and obtain transmission rights $\bar{b}_{21} = b_{12} + K$. The second-stage profits of firm 1 equal

$$\pi_1(\cdot) = \left(\frac{a - b_{12} - K - c}{2}\right)^2 + \left(\frac{a - b_{12} - c}{2} - t_{12}\right) b_{12}$$

where we have substituted $q_{21} = \bar{b}_{21} = b_{12} + K$. Note that this profit expression is equal to the deviating profits expression we derived above in (7). The optimal booking of firm 1 is therefore given by

$$\widehat{b}_{12} = \begin{cases} K - 2t_{12} & \text{if } t_{12} < K/2 \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

Consider now the profits of firm 2. If the two producers' bookings satisfied $b_{12} \leq b_{21} - K$, firm 2 would obtain a level of profits given by the expression

$$\pi_2 = \left(\frac{a - b_{12} - K - c}{2} - t_{12}\right)(b_{12} + K) + \left(\frac{a - b_{12} - c}{2}\right)^2$$

Observe that the profits of firm 2 do not depend on its own booking b_{21} but on the rival's booking b_{12}. As a result, any booking strategy that satisfies $b_{21} \geq \widehat{b}_{12} + K$ is consistent with equilibrium. Therefore, any booking

$$\widehat{b}_{21} \geq x \equiv \begin{cases} 2K - 2t_{12} & \text{if } t_{12} < K/2 \\ K & \text{otherwise} \end{cases} \tag{17}$$

is an equilibrium strategy for firm 2.

If the strategies in (16) and (17) were part of an equilibrium, the aggregate market outcomes would be given by

$$\widehat{Q}_1 = \begin{cases} \frac{1}{2}(a - c) + K - t_{12} & \text{if } t_{12} < K/2 \\ \frac{1}{2}(a - c + K) & \text{otherwise} \end{cases} \tag{18}$$

$$\widehat{p}_1 = \begin{cases} \frac{1}{2}(a + c) + t_{12} - K & \text{if } t_{12} < K/2 \\ \frac{1}{2}(a + c - K) & \text{otherwise} \end{cases} \tag{19}$$

for market 1, and

$$\widehat{Q}_2 \quad = \begin{cases} \frac{1}{2}(a-c)+\frac{1}{2}K-t_{12} & \text{if } t_{12}<K/2 \\ \frac{1}{2}(a-c) & \text{otherwise} \end{cases} \tag{20}$$

$$\widehat{p}_2 = \begin{cases} \frac{1}{2}(a+c)+t_{12}-\frac{1}{2}K & \text{if } t_{12}<K/2 \\ \frac{1}{2}(a+c) & \text{otherwise} \end{cases} \tag{21}$$

for market 2. Furthermore, profits of firm 1 and firm 2 would, respectively, be equal to

$$\widehat{\pi}_1 \quad = \begin{cases} \frac{1}{4}(a-c-K)^2+\left(\frac{K}{2}-t_{12}\right)^2 & \text{if } t_{12}<K/2 \\ \frac{1}{4}(a-c-K)^2 & \text{otherwise} \end{cases} \tag{22}$$

$$\widehat{\pi}_2 \quad = \begin{cases} \frac{(a-c)^2}{4}+\frac{(a-c)K}{2}+2(t_{12}-K)t_{21}+3t_{12}K-\frac{7K^2}{4}-t_{12}^2 & \text{if } t_{12}<K/2 \\ \left(\frac{a-K-c}{2}-t_{21}\right)K+\left(\frac{a-c}{2}\right)^2 & \text{otherwise} \end{cases} \tag{23}$$

To see whether the strategies in (16) and (17) are in fact part of an equilibrium, we have to find conditions under which neither firm has an incentive to deviate. For convenience, let us first check when firm 2 does not have an incentive to deviate. Consider firm 2 deviates by booking an amount b_{21}^d. We start by noting that a deviation by firm 2 can only be profitable if $b_{21}^d<\widehat{b}_{21}$. Indeed, as mentioned above, we can ignore upward deviations since all booking strategies $b_{21}>\widehat{b}_{21}\geq\widehat{b}_{12}+K$ yield the same profit to firm 2. We next observe that any deviation $b_{21}^d\in[\widehat{b}_{12}-K,\widehat{b}_{12}+K)$ cannot be profitable either. This is because this deviation results in a lowering of firm 2's exports to market 1 and it does not constrain firm 1's exports in any way.[16]

These two observations imply that, if a deviation is profitable for firm 2, it must be the case that $b_{21}^d\in[0,\widehat{b}_{12}-K)$, or, using (16), $b_{21}^d\in[0,-2t_{12})$. Note that such a deviation, which is only possible for negative t_{12}, changes the direction of the net flow and leads to a situation where firm 1 is rationed. If deviating is possible, the best deviation b_{21}^d solves the problem:

$$\max_{b_{21}^d\in[0,-2t_{12})}\{\pi_2^d=-\left(\frac{a-b_{21}^d-c}{2}-t_{21}\right)b_{21}^d+\left(\frac{a-b_{21}^d-K-c}{2}\right)^2\} \tag{24}$$

Taking the first order condition yields

$$\frac{\partial\pi_2^d}{\partial b_{21}^d}=-\frac{b_{21}^d}{2}+\frac{K}{2}-t_{21},$$

which shows that deviating profits in (24) are monotonically decreasing in b_{21}^d when $t_{21}\leq K/2+t_{12}$ so no profitable deviation exists in that case. For other ranges of t_{21}, we get that deviation profits are maximized when

$$b_{21}^d \quad = \begin{cases} K-2t_{21} & \text{if } K/2+t_{12}<t_{21}<K/2 \\ 0 & \text{if } t_{21}\geq K/2 \end{cases} \tag{25}$$

[16]Note that profits of firm 2 are concave in q_{21} so that its profits are increasing in q_{21} for all $q_{21}\leq q_{21}^*$.

Substituting (25) into (24) yields the optimal deviating profits:

$$\pi_2^d = \begin{cases} \frac{1}{4}(a-c-K)^2 + \left(\frac{K}{2} - t_{21}\right)^2 & \text{if } K/2 + t_{12} < t_{21} < K/2 \\ \frac{1}{4}(a-c-K)^2 & \text{if } t_{21} \geq K/2 \end{cases} \tag{26}$$

Comparing (23) and (26), we conclude that firm 2 does not have an incentive to deviate whenever

$$\widehat{\pi}_2(\widehat{b}_{12}, \widehat{b}_{21}) \geq \pi_2^d(\widehat{b}_{12}, b_{21}^d) \Leftrightarrow K \geq \widehat{K}_2(a, c, t_{12}, t_{21})$$

where

$$\widehat{K}_2(\cdot) \equiv \begin{cases} 0 & \text{if } t_{21} \leq K/2 + t_{12} \\ \frac{2}{9}\left(a-c+3t_{12}-t_{21}-\sqrt{(a-c+3t_{12}-t_{21})^2-9(t_{12}-t_{21})^2}\right) & \text{if } K/2+t_{12}<t_{21}<K/2 \\ \frac{1}{4}\left(a-c+3t_{12}-2t_{21}-\sqrt{(a-c+3t_{12}-2t_{21})^2+8(2t_{21}-t_{12})t_{12}}\right) & \text{if } t_{21} \geq K/2 \end{cases} \tag{27}$$

Next, consider a deviation by firm 1 and let b_{12}^d denote its defection from the equilibrium strategy in (16). Since the equilibrium booking is the maximizer of the profits of firm 1 when $b_{12} \leq \widehat{b}_{21} - K$, a deviating booking can only be profitable if it decongests the pipeline, i.e. if $b_{12}^d > \widehat{b}_{21} - K$. Under such a deviation, firm 2 is not rationed any longer and is allocated transmission rights equal to $\widehat{b}_{21}$. Note furthermore that if firm 1 deviates by booking $b_{12}^d > \widehat{b}_{21} + K$, it will be rationed by the TSO. The deviant thus solves the following constrained maximization problem:

$$\max_{b_{12}^d \in [0, \widehat{b}_{21}+K)} \{\pi_1^d = (a - \widehat{b}_{21} - BR(\widehat{b}_{21}) - c)BR(\widehat{b}_{21}) + (a - b_{12}^d - BR(b_{12}^d) - c - t_{12})b_{12}^d\}$$

It is readily seen that the optimal deviation of firm 1 is

$$b_{12}^d = \min\{\widehat{b}_{21} + K, \frac{a-c}{2} - t_{12}\}$$

yielding profits equal to

$$\pi_1^d = \begin{cases} \left(\frac{a-\widehat{b}_{21}-c}{2}\right)^2 + \frac{(a-c-2t_{12})^2}{8} & \text{if } \frac{a-c}{2} - t_{12} \leq \widehat{b}_{21} + K \\ \left(\frac{a-\widehat{b}_{21}-c}{2}\right)^2 + \left(\frac{a-\widehat{b}_{21}-K-c}{2} - t_{12}\right)\left(\widehat{b}_{21} + K\right) & \text{otherwise} \end{cases}$$

Therefore firm 1 does not deviate from playing the strategy given by (16) if

$$\widehat{\pi}_1(\widehat{b}_{12}, \widehat{b}_{21}) \geq \pi_1^d(b_{12}^d, \widehat{b}_{21}) \Leftrightarrow K \leq \widehat{K}_1(a, c, t_{12}, \widehat{b}_{21})$$

where

$$\widehat{K}_1(\cdot) \equiv \begin{cases} \left(\frac{1}{2}-\frac{1}{\sqrt{2}}\right)(a-c)+t_{12}+\frac{\widehat{b}_{21}}{\sqrt{2}} & \text{if } \frac{a-c}{2}-\widehat{b}_{21}-K \leq t_{12} < K/2 \\ a-c-\frac{1}{2}\sqrt{\frac{3(a-c)^2}{8}+\left(\frac{1}{4}\widehat{b}_{21}-\frac{a-c}{2}\right)\widehat{b}_{21}+\left(\frac{1}{2}t_{12}-\frac{a-c}{2}\right)t_{12}} & \text{if } t_{12} \geq \max\{\frac{a-c}{2}-\widehat{b}_{21}-K, K/2\} \\ \frac{1}{2}\left(a-c-\widehat{b}_{21}-\sqrt{(a-c-2\widehat{b}_{21})(a-c)-4(\widehat{b}_{21}+t_{12})t_{12}}\right) & \text{if } t_{12} < \min\{\frac{a-c}{2}-\widehat{b}_{21}-K, K/2\} \\ \frac{2}{3}\left(a-c-\widehat{b}_{21}-t_{12}-\sqrt{(a-c-\widehat{b}_{21}-t_{12})^2-\frac{3}{4}(\widehat{b}_{21}+4t_{12})\widehat{b}_{21}}\right) & \text{otherwise} \end{cases} \tag{28}$$

Having derived the conditions under which no firm deviates from the strategies in (16) and (17), we are now ready to state our second equilibrium result. For this purpose, let us define the following set of parameters:

$$Z_C(x) \equiv \{(a, c, t_{12}, t_{21}, K) : K \leq \widehat{K}_1(a, c, t_{12}, x);\; K \geq \widehat{K}_2(\cdot).\}$$

The next proposition summarizes our second equilibrium result.

Proposition 4 *For any vector of parameters $(a, c, t_{12}, t_{21}, K) \in Z_C(x)$ there exists a continuum of gas market equilibria where firms' pipeline capacity bookings $(\widehat{b}_{12}, \widehat{b}_{21})$ satisfy (16) and (17) respectively, transmission rights allocated are given by (2) and production levels are stated in (1). In any equilibrium, bookings are such that the network is congested and firm 2 is rationed.*

Proposition 4 tells us that for some pipeline capacity and transportation prices, there exists an equilibrium in which firm 1 lowers its request for capacity such that the pipeline becomes congested. Firm 2 is then rationed, while the net flow is in the direction of node 1. Although it loses some profits from exporting, firm 1 gains local market power in this way since firm 2 cannot export as much as it wants to. Whether this gain outweighs the loss from lower exports depends on pipeline capacity and tariffs, as is discussed below.[17]

To illustrate further Proposition 4 we need to resolve somehow the indeterminacy of equilibria. In what follows we shall consider that $\widehat{b}_{21} = \dfrac{a-c}{2} - t_{21}$; arguably, this booking may be a natural focal point since it is the amount that firms would book in an equilibrium with no congestion.[18] Substituting this value for $\widehat{b}_{21}$ into (28) gives

$$\widehat{K}_1(\cdot) = \begin{cases} \left(1-\frac{1}{\sqrt{2}}\right)\frac{a-c}{2}+t_{12}-\frac{t_{21}}{\sqrt{2}} & \text{if } t_{21}-K\leq t_{12}<K/2 \\ a-c-\frac{1}{2}\sqrt{3(a-c)^2+4(a-c+t_{21})t_{21}-8(a-c-t_{12})t_{12}} & \text{if } t_{12}\geq \max\{K/2, t_{21}-K\} \\ \frac{1}{4}\left(a-c+2t_{21}-2\sqrt{2}\sqrt{(a-c+2t_{12})(t_{21}-t_{12})}\right) & \text{if } t_{12}<\min\{K/2, t_{21}-K\} \\ \frac{1}{3}\left(a-c+2(t_{21}-t_{12})-\sqrt{\frac{1}{4}(a-c)^2+(2t_{12}+t_{21})^2-(a-c)(10t_{12}-7t_{21})}\right) & \text{otherwise} \end{cases}$$

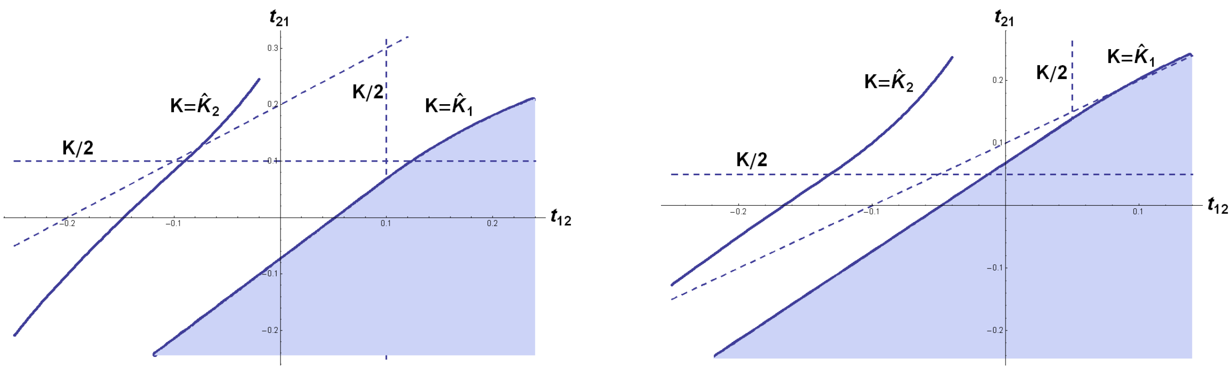
Figures 5(a) and 5(b), drawn for $\widehat{b}_{21} = \dfrac{a-c}{2} - t_{21}$, show the regions of parameters for which equilibrium described in Proposition 4 exists. Again, the left (right) figure corresponds to the case of large (small) capacity. All combinations of tariffs that lie below the two bounds lead to the congested equilibrium.

Some intuition can be gained if one considers the incentives for firm 1 to deviate from the equilibrium strategy. If t_{12} is relatively high, exporting, and therefore also deviating from equilibrium, becomes less attractive. Further, a relatively low t_{21} makes a defection

[17]This result is related to the study in Borenstein, Bushnell and Stoft (2000), who show that when capacity of the power network is small there does not exist an equilibrium without congestion.

[18]Indeed, since during the summer season there is typically no congestion in most markets while the opposite holds for the winter season, one may argue that summer bookings maybe natural bookings for the winter season in this case of indeterminacy. In addition, we note that $\widehat{b}_{21} = \frac{a-c}{2} - t_{21}$ is an equilibrium booking for firm 2 as long as $\frac{a-c}{2} - t_{21} \geq 2K - 2t_{12}$ if $t_{12} < K/2$ and $\frac{a-c}{2} - t_{21} \geq K$ if $t_{12} \geq K/2$, which in equilibrium indeed holds.

less beneficial, because in that case firm 2 would export a large amount to market 1. In regard to the deviating incentives for firm 2, observe that firm 2 also has no incentive to deviate from the equilibrium strategy if t_{12} is high and t_{21} is low, but for different reasons than firm 1. First, a deviation is not profitable for firm 2 when t_{21} is high. If this is the case, the exports of firm 1 are low and firm 2 does not gain much by changing the direction of the flow while it loses a lot due to the reduction in exports. Moreover, firm 2 does not deviate if t_{21} is low, since a low t_{21} makes it more profitable for firm 2 to export a large amount.



(a) Large pipeline capacity ($K = 0.2$) (b) Small pipeline capacity ($K = 0.1$)

Figure 5: Shaded areas: parameters for which an equilibrium with congestion exists ($a = 2; c = 1$)

Finally, comparing Figures 5(a) and 5(b) one sees that when pipeline capacity is small the set of tariffs for which the congested equilibrium of Proposition 4 exists is larger. To see why this is true, note that firm 2 can only export an amount $\bar{b}_{21} = b_{12} + K$ if it is rationed. Then, it is more often beneficial for firm 1 to provoke congestion in case of small capacity since the exports of firm 2 remain low no matter what.

In order to complete the analysis in this section, we need to examine booking strategy profiles satisfying $b_{21} \leq b_{12} - K$ (southeast of Figure 1). These strategy profiles lead to a situation where firm 1 will be rationed and obtain transmission rights $\bar{b}_{12} = b_{21} + K$. This case is similar to the case analyzed above in detail so, to save space, we do not present the derivations. The equilibria in which firm 1 is rationed exist when t_{12} is relatively low and t_{21} is relatively high.

4.2 Transportation pricing

We have shown in Proposition 2 that the pair of tariffs (t^*_{12}, t^*_{21}) is socially optimal if the pipeline is not congested. Note however that if pipeline is relatively small, setting these tariffs does not lead to an equilibrium without congestion. It also holds that in such a case, no other pair of tariffs satisfies both $K \geq \max\{K_1(\cdot), K_2(\cdot)\}$ and the budget constraint, which implies that the pipeline will be congested in the ensuing equilibrium. If this is so, it is no longer necessarily true that (t_{12}^*, t_{21}^*) are (constrained) welfare-maximizing.

4.2.1 Second-best tariffs

We now analyze the second-best transportation tariffs when firms' strategies in the continuation game lead to the congested equilibrium (CE) of Proposition 4, i.e. where firm 1 lowers its exports and firm 2 is rationed (the analysis is similar for the symmetric case where firm 1 is rationed instead). For fixed a, c, K, the TSO solves the following constrained maximization problem:

$$\max_{(t_{12},t_{21})\in Z_C(\cdot)} \quad \{SW = \int_0^{\widehat{Q}_1(t_{12})} \Big(a - x - c\Big)dx + \int_0^{\widehat{Q}_2(t_{12})} \Big(a - x - c\Big)dx - C_O(\cdot)\}$$

subject to:

$$t_{12}\widehat{q}_{12}(t_{12}) + t_{21}\widehat{q}_{21}(t_{12}) - C_O(\cdot) = 0 \tag{29}$$

This leads to the following result.

Proposition 5 *For fixed $a, c, K, c_O, C(K)$, consider the set $T_C(a, c, K, c_O, C(K))$ of TSO's-budget-constraint-satisfying pairs of tariffs that result in firms playing strategies that lead to the equilibrium with congestion of Proposition 4:*

$$T_C(a, c, K, c_O, C(K)) \equiv \{(t_{12}, t_{21}) \in \mathbb{R}^2 : (t_{12}, t_{21}) \in Z_C(\cdot); \sum t_{ij}\widehat{q}_{ij} \geq C_O\}$$

with $\widehat{q}_{ij}$ given in Proposition 4. If this set is non-empty, the element $(\widehat{t}_{12}, \widehat{t}_{21})$ that solves the system of equations

$$t_{12}\widehat{q}_{12}(t_{12}) + t_{21}\widehat{q}_{21}(t_{12}) - C_O(\cdot) = 0 \tag{30}$$

$$K - \widehat{K}_1(a, c, t_{12}, t_{21}, K) = 0 \tag{31}$$

yields the highest welfare.

The proof is in the Appendix.

Figure 6, which builds on Figure 5(a) above by adding isowelfare curves and the TSO's budget constraint, illustrates Proposition 5. Notice that the isowelfare curves are vertical and that welfare increases as we lower the tariff on firm 1's exports. As a result, welfare is maximized at the point where the line representing $K = K_1(\cdot)$ and the curve representing the budget constraint (BC) intersect. Observe that $\widehat{t}_{12} < 0$ and $\widehat{t}_{21} > 0$, so that the dominant flow is taxed while the reverse flow is subsidized.

In contrast to the situation described in Proposition 2 where firms play strategies that lead to no congestion, if the pipeline is congested optimal transportation prices are not equal to each other. More specifically, the dominant flow (firm 2's exports) is taxed while the reverse flow (firm 1's exports) is subsidized. As firm 2 does not respond to changes in tariffs when it is rationed, a raise in t_{21} has no effect on welfare. However,

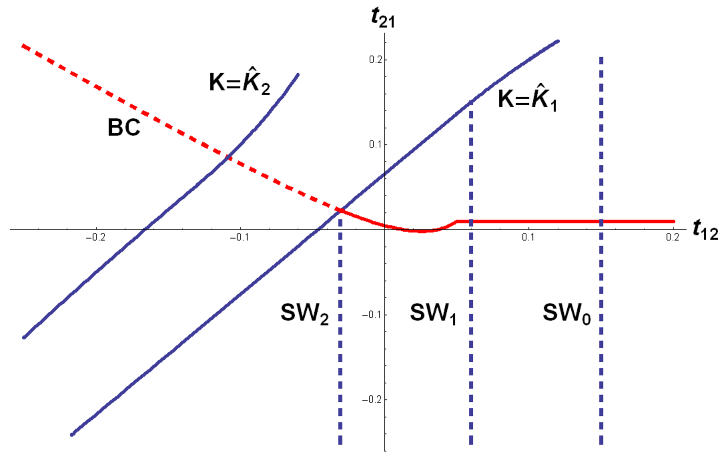


Figure 6: Optimal tariffs in equilibrium with congestion $(a = 2, c = 1, K = 0.2, c_O = 0.01, C(K) = 0)$

by increasing t_{21} the TSO generates more revenue coming from firm 2 thereby relaxing the budget constraint. This enables the TSO to lower t_{12}, which has a positive effect on aggregate output on both markets so that total welfare goes up. This cross-subsidization is in line with the principles of Ramsey-Boiteaux pricing, as the firm with the lower export elasticity (with respect to the transportation tariff) is taxed more heavily.

To compare the pair of tariffs $(\widehat{t}_{12}, \widehat{t}_{21})$ with nodal prices, for simplicity we focus on the case where $C(k) = 0$. Since under nodal pricing we would get $t_{12}^N = -t_{21}^N$ while we have $\widehat{t}_{12} \neq -\widehat{t}_{21}$, it is clear that $(\widehat{t}_{12}, \widehat{t}_{21})$ are not equal to nodal prices.

5 Subgame perfect equilibrium

We have derived the second-best tariffs in two cases, the case where firms equilibrium strategies lead to no congestion (Proposition 2) and the case where firms strategies lead to pipeline congestion and firm 2 is rationed (Proposition 5). The case where firm 1 is rationed is similar and has been omitted to save space. We also know that if for the tariffs (t_{12}^*, t_{21}^*) given in Proposition 2 an equilibrium without congestion does not exist, then no other TSO's-budget-constraint-satisfying tariffs exist such that firms play the NCE.

We now ask whether the level of welfare attained when the TSO sets (t_{12}^*, t_{21}^*) and firms play the NCE of Proposition 1 is higher or lower than in case the TSO sets $(\widehat{t}_{12}, \widehat{t}_{21})$ and firms play the CE of Proposition 4.

Lemma 1 *For fixed parameters $(K, c, c_O, C(K))$ such that $T_{NC}(\cdot) \neq \emptyset$ and $T_C(\cdot) \neq \emptyset$,*

$$SW_{NCE}(t_{12}^*, t_{21}^*) > SW_{CE}(\widehat{t}_{12}, \widehat{t}_{21}),$$

where SW_{NCE} and SW_{CE} are the levels of social welfare in the equilibrium without congestion and the equilibrium with congestion, respectively.

The proof is in the Appendix.

Lemma 1 shows that when the TSO can choose among the transportation tariffs that lead to the equilibrium without congestion and the tariffs that yield the equilibrium without congestion, then he prefers the symmetric equilibrium with no congestion.

This remarks allows us to state our final result in this section.

Proposition 6 *For fixed parameters $(a, c, K, c_O, C(K))$, we can distinguish two cases:*

(i) $(t^*_{12}, t^*_{21}) \in Z_{NC}(\cdot)$, in which case the (unique) SPE of the game is as follows: the TSO sets transportation tariffs $t^*_{12} = t^*_{21}$ given in (15), firms' exports are equal to the bookings and market outcomes are given by (4) and (5).

(ii) $(t^*_{12}, t^*_{21}) \notin Z_{NC}(\cdot)$, in which case there are two SPE with congestion. In one equilibrium, optimal tariffs are given by the solutions to (30) and (31), firm 1 provokes congestion, firm 2 is rationed and market outcomes are given by (18),(19),(20), and (21). The other equilibrium is the mirror of this SPE.

6 Conclusion

We have studied the role of transportation pricing in shaping the incentives of downstream gas suppliers with market power. The model has considered a setting where two downstream gas producers serve two distant markets connected by a pipeline, which is under control of a regulated TSO. Each producer is located at one of the ends of the pipeline and chooses gas supplies for the local and for the distant market.

Abstracting from any friction between the regulator and the TSO, the first-best solution calls for subsidies so as to induce producers to export the competitive quantity. However, such a transportation pricing system would lead to significant losses for the TSO. To circumvent this problem, we have studied tariffs that satisfy the TSO's budget constraint.

Which transportation prices maximize welfare depends on pipeline capacity, and indirectly on the profit-maximizing strategies of the downstream firms. When capacity of the pipeline is sufficiently large, neither firm has an incentive to deliberately congest the line and the second-best tariffs are the lowest ones that satisfy the budget constraint. When markets are similar, these tariffs are symmetric so the optimal transportation pricing system is non-discriminatory.

Yet, in case pipeline capacity is relatively small one of the gas suppliers has an incentive to lower its exports thereby provoking congestion in the transportation system. In this situation, the TSO finds it optimal to subsidize the such firm so as to weaken the distortions arising from congestion. To balance budget, the TSO charges the rival firm a strictly positive tariff. Therefore, with small pipeline capacity firms do not pay the same transportation tariffs and the optimal pricing system is discriminatory. Moreover, it follows the principles of Ramsey-Boiteaux pricing: the firm with the lowest supply elasticity faces the highest price for shipping its gas. These results on optimal transportation pricing show that when gas production is not competitive, socially optimal tariffs differ from transportation prices based on nodal pricing principles.

The paper has also presented a comparison of transportation prices that maximize the profits of the TSO with second-best transportation tariffs. Profit-maximizing prices are excessive from the point of view of social welfare maximization. As usual, when the TSO chooses tariffs to maximize its own profits, it does not take into account how tariffs influence consumer's surplus and the profits of the downstream gas suppliers.

Appendix

Proof of Proposition 2. We start by showing that $t_{12}^* = t_{21}^*$. As a first observation, note that the net flow in the NCE is zero if tariffs are equal to each other. In contrast, when tariffs are not the same the TSO deals with a positive net flow. Therefore, if optimal tariffs are symmetric in case $c_O = 0$ we know for sure that symmetry also holds in situations where the TSO incurs a cost of shipping the gas. We thus only have to prove for the case $c_O = 0$.

The FOC's that yield the solution for this case are as follows:

$$-\frac{1}{2}(a - Q_1^* - c) + \lambda\left(\frac{a - c - 4t_{21}}{2}\right) - \mu = 0$$
$$-\frac{1}{2}(a - Q_2^* - c) + \lambda\left(\frac{a - c - 4t_{12}}{2}\right) + \mu = 0$$

where λ and μ are the multipliers for the TSO's budget constraint and the condition $t_{12} \geq t_{21}$, respectively. Suppose now that the latter constraint does not bind; we then get $\mu = 0$ and

$$\frac{a - Q_1^* - c}{a - Q_2^* - c} = \frac{a - c - 4t_{21}}{a - c - 4t_{12}}$$

But the left hand side is smaller than one (since $Q_1^* > Q_2^*$) while the right hand side is larger than one, hence a contradiction. Therefore, the condition $t_{12} \geq t_{21}$ binds and optimal tariffs are symmetric.

We are now able to obtain exact expressions for the transportation prices. Since $t_{21} = t_{12}$, the net flow is zero and tariffs thus have to solve

$$2t_{12}q_{12}^* = C(K)$$

where we have substituted $t_{21} = t_{12}$. Solving for t_{12} gives the optimal transportation tariffs stated in Proposition 2.

As a final step, we prove that $T_{NC} = \emptyset$ if $(t_{12}^*, t_{21}^*) \notin T_{NC}$. First we show that when $(t_{12}^*, t_{21}^*) \notin T_{NC}$, no pair of asymmetric tariffs is in this set. Note that (t_{12}^*, t_{21}^*) is not in T_{NC} only if this combination does not yield the equilibrium without congestion, or if $(a, c, t_{12}, t_{21}, K) \notin Z_{NC}$. Hence, the vector of parameters $(a, c, t_{12}, t_{21}, K)$ is such that $K < \max\{K_1(\cdot), K_2(\cdot)\}$. But since $t_{12}^* = t_{21}^*$ and $K_2(\cdot)$ is just the mirror of $K_1(\cdot)$, we get $K < K_1(a, c, t_{12}^*, t_{21}^*) = K_2(a, c, t_{12}^*, t_{21}^*)$. Now it is easy to see that there is no pair of asymmetric tariffs included in the set. One could for example lower t_{12} such that $K \geq K_1(\cdot)$, but an increase of t_{21} is then required to again satisfy the budget constraint. This leads to an increase in $K_2(\cdot)$, so $K < K_2(\cdot)$ still holds. We still have to show that there are no other pairs of symmetric tariffs in the set. Clearly, lower symmetric tariffs violate the budget constraint and higher symmetric tariffs increase the critical values $K_1(\cdot)$ and $K_2(\cdot)$. Therefore, any combination of symmetric tariffs for which holds that tariffs are higher or lower than (t_{12}^*, t_{21}^*) are not in T_{NC} if the pair (t_{12}^*, t_{21}^*) itself is not in this set.

Q.E.D.

Proof of Proposition 3. Again, we have that optimal tariffs are equal to each other (which is shown below) so that it is sufficient to restrict the analysis to the case $c_O = 0$. Suppose that the constraint does not bind; from the FOC's we get that the profit-maximizing tariffs are given by the interior solution $t_{12}^P = t_{21}^P = \frac{a-c}{4}$. If, in contrast, the constraint is binding, we have that tariffs $t_{12}^P = t_{21}^P$ solve $K = K_1(\cdot) = K_2(\cdot)$, a corner solution. To see that the corner solution also yields tariffs being equal to each other, suppose, without loss of generality, that $t_{12} \leq t_{21}$ which implies that $K_1(\cdot) \leq K_2(\cdot)$. Clearly, $K_1(\cdot) \leq K_2(\cdot) < K$ cannot be profit-maximizing because the TSO can raise t_{21} without violating the constraint, thereby increasing its profits. We therefore must have that $K_1(\cdot) \leq K_2(\cdot) = K$. Suppose now that $t_{12} < t_{21}$ so that $K_1(\cdot) < K_2(\cdot) = K$. But then one can gain by increasing t_{12} such that constraint is still satisfied. As a result, $t_{12} = t_{21}$ and $K = K_1(\cdot) = K_2(\cdot)$. Since the TSO wants to set tariffs as high as possible (provided that for the corner solution it holds that $t_{12} = t_{21} < \frac{a-c}{4}$), the second part of (10) applies. Respecting that $t_{12} = t_{21}$ and rewriting a bit gives the corner solution stated in Proposition 3. *Q.E.D.*

Proof of Proposition 5. First observe from (29) that welfare in the CE (i) is constant in t_{21} and (ii) is decreasing (constant) in t_{12} for $t_{12} < K/2$ ($t_{12} \geq K/2$). Therefore, the TSO wants to set t_{12} as low as possible without violating the constraints stated in (29). We already know that at the optimum, the budget constraint binds. We complete this proof by showing that the condition $K = K_1(\cdot)$ also binds. First note that for $(a, c, t_{12}, t_{21}, K) \in Z_C(\cdot)$, we have $\widehat{K}_2(\cdot) \leq \widehat{K}_1(\cdot)$ so that $K \geq \widehat{K}_2(\cdot)$ is automatically satisfied if $K \leq \widehat{K}_1(\cdot)$ is binding. Suppose now by contradiction that the latter constraint does not bind, so $K < \widehat{K}_1(\cdot)$. But then we could gain in terms of social welfare by lowering t_{12} (and raising t_{21}) up to the point where the constraint becomes binding. Therefore, at the optimum the condition $K \leq K_1(\cdot)$ binds. *Q.E.D.*

Proof of Lemma 1. This proof consists of two steps. The first step is to show

$$SW_{NCE}(\widehat{t}_{12}, \widehat{t}_{21}) > SW_{CE}(\widehat{t}_{12}, \widehat{t}_{21})$$

It is obvious that this inequality holds, since for equal tariffs output in each node (and therefore welfare) is higher in the NCE than in the CE. Next, we have to prove

$$SW_{NCE}(t_{12}^*, t_{21}^*) > SW_{NCE}(\widehat{t}_{12}, \widehat{t}_{21})$$

For this, we first show that the pair of tariffs $(\widehat{t}_{12}, \widehat{t}_{21})$ is in the choice set of the TSO if firms play strategies that lead to the equilibrium without congestion. For the sake of clarification, let BC_{NCE} and BC_{CE} denote, respectively, the TSO's budget constraint in the NCE and CE. Then the following must hold:

$$BC_{NCE}(\widehat{t}_{12}, \widehat{t}_{21}) \geq 0$$

meaning that the TSO's budget constraint has to be satisfied when the pair of tariffs $(\widehat{t}_{12}, \widehat{t}_{21})$ is implemented and firms play strategies yielding the NCE. Substituting the equilibrium quantities gives

$$\widehat{t}_{12} q^*_{12}(\widehat{t}_{12}) + \widehat{t}_{21} q^*_{21}(\widehat{t}_{21}) - \Big| q^*_{21}(\widehat{t}_{21}) - q^*_{12}(\widehat{t}_{12}) \Big| c_O - C(K) \geq 0$$

To prove that this inequality holds, first notice that if the NCE with tariffs (t^*_{12}, t^*_{21}) exists, we have

$$K \geq K_1(a, c, t^*_{12}, t^*_{21})$$

This implies that tariffs $(\widehat{t}_{12}, \widehat{t}_{21})$ satisfying $K = \widehat{K}_1(a, c, \widehat{t}_{12}, \widehat{t}_{21})$ have to be such that $\widehat{t}_{12} \geq \widehat{t}_{21}$, as can be seen from (10). Note moreover that these tariffs also have to satisfy BC_{CE}, which is given by

$$\widehat{t}_{12} \widehat{q}_{12}(\widehat{t}_{12}) + \widehat{t}_{21} \widehat{q}_{21}(\widehat{t}_{21}) - K c_O - C(K) = 0$$

Since $\widehat{q}_{21}(\widehat{t}_{21}) > \widehat{q}_{12}(\widehat{t}_{12})$, we now also get that $\widehat{t}_{12} > |\widehat{t}_{21}|$. Now define, for given tariffs $\widehat{t}_{12}$ and $\widehat{t}_{21}$, the differences between quantities in the NCE and the CE as $\Delta_{12}(\widehat{t}_{12}) \equiv q^*_{12}(\widehat{t}_{12}) - \widehat{q}_{12}(\widehat{t}_{12})$ and $\Delta_{21}(\widehat{t}_{21}) \equiv q^*_{21}(\widehat{t}_{21}) - \widehat{q}_{12}(\widehat{t}_{21}) - K$. We then get

$$\Delta_{12}(\widehat{t}_{12}) - \Delta_{21}(\widehat{t}_{21}) = q^*_{12}(\widehat{t}_{12}) - q^*_{21}(\widehat{t}_{21}) + K > 0$$

where the inequality follows from the fact that in the equilibrium without congestion the net flow is smaller than K. As a final step, we rewrite the $BC_{NCE}(\widehat{t}_{12}, \widehat{t}_{21})$ as follows:

$$\begin{aligned}
& \Big(\widehat{t}_{12} + c_O\Big)\Big(\widehat{q}_{12}(\widehat{t}_{12}) + \Delta_{12}(\widehat{t}_{12})\Big) + \Big(\widehat{t}_{21} - c_O\Big)\Big(\Delta_{21}(\widehat{t}_{12}) + \widehat{q}_{12}(\widehat{t}_{12}) + K\Big) - C(K) \\
= \;& \widehat{t}_{12}\widehat{q}_{12}(\widehat{t}_{12}) + \widehat{t}_{21}\widehat{q}_{21}(\widehat{t}_{21}) - K c_O - C(K) + (\widehat{t}_{12} + c_O)\Delta_{12}(\widehat{t}_{12}) + (\widehat{t}_{21} - c_O)\Delta_{21}(\widehat{t}_{21}) \\
= \;& (\widehat{t}_{12} + c_O)\Delta_{12}(\widehat{t}_{12}) + (\widehat{t}_{21} - c_O)\Delta_{21}(\widehat{t}_{21})
\end{aligned}$$

where we have used $BC_{CE}(\widehat{t}_{12}, \widehat{t}_{21}) = 0$, or

$$\widehat{t}_{12} \widehat{q}_{12}(\widehat{t}_{12}) + \widehat{t}_{21} \widehat{q}_{21}(\widehat{t}_{21}) - K c_O - C(K) = 0$$

Now given $\widehat{t}_{12} > |\widehat{t}_{21}|$ and $\Delta_{12}(\widehat{t}_{12}) > \Delta_{21}(\widehat{t}_{21})$, we have $BC_{NCE}(\widehat{t}_{12}, \widehat{t}_{21}) > 0$. This shows that $\widehat{t}_{12}$ and $\widehat{t}_{21}$ are also in the choice set of the TSO if firms' bookings lead to the NCE. However, Proposition 2 tells us that the TSO prefers to choose the tariff combination (t^*_{12}, t^*_{21}) rather than implementing $(\widehat{t}_{12}, \widehat{t}_{21})$ if both pairs of tariffs are in its choice set. Therefore, we have

$$SW_{NCE}(t^*_{12}, t^*_{21}) > SW_{NCE}(\widehat{t}_{12}, \widehat{t}_{21}) > SW_{CE}(\widehat{t}_{12}, \widehat{t}_{21})$$

Q.E.D.

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