Transport, spatio-economic equilibrium and global sustainability

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Received 23 June 1995; in revised form 10 March 1996

Abstract. In this paper we investigate interdependencies between transport, spatial economy, and the environment in the context of policies aimed at a global environmental target. A small-scale spatial price equilibrium model is formulated and used to perform a number of numerical simulations, and to investigate market-based versus environmentally sound spatioeconomic configurations with first-best and second-best policies, and with endogenous environmental technologies. We thus present a modelling framework capable of dealing with complexities associated with the simultaneous regulation, first-best and second-best, of multiple interdependent sectors in a spatial setting.

1 Introduction

Along with the growing environmental and social pressures of transport, a large number of studies have appeared on the external effects of transport, in particular, environmental externalities (notably emissions of CO_2, CO, VOCs, NO_x, and particulates), noise annoyance, accidents, and congestion. A lot of effort has been put into the valuation of these external costs of transport (see Gastaldi et al, 1997; Kågeson, 1993; Verhoef, 1994, for surveys on this field). Others have focused on the regulation of such transport externalities [see, among others, Button (1993); Verhoef et al (1995a) on second-best regulation ('flat pricing') of road transport externalities; Wilson (1983) and d'Ouville and McDonald (1990) on optimal road capacity supply with suboptimal congestion pricing; Braid (1989) and Arnott et al (1990) on uniform versus stepwise pricing of a bottleneck; Arnott (1979), Sullivan (1983), and Fujita (1989, chapter 7.4) on congestion policies through urban land-use policies; Arnott et al (1991), Glazer and Niskanen (1992), and Verhoef et al (1995b) on regulatory parking policies; and Verhoef et al (1996) on congestion pricing with an untolled alternative].

Except for the studies focusing on the dependencies between congestion and urban land use, the above-mentioned analyses typically consider transport in isolation. However, a partial equilibrium approach to transport ignores the fact that transport demand is often a derived demand, depending critically on issues such as the spatial organization of economic activities, and on spatial and modal characteristics of infrastructure supply. Therefore, 'optimal' levels of transport and 'optimal' Pigouvian transportation taxes derived in such partial analyses may in fact often suffer from considerable second-best biases, as first-best policies may require adaptions in the phenomena just mentioned. Indeed, considering transport in isolation is equivalent to assuming that first-best conditions apply for the entire spatioeconomic system. Apart from this, emissions from different, economically related regions or sectors may often infringe on the same global environmental goals (such as emissions of greenhouse gases). As a consequence, regulation on the level of a subsystem may often, indirectly, either benefit from synergetic side effects, or suffer from counterproductive compensatory effects in related subsystems. It is important to investigate the potential

impacts of such interdependencies upon the effectiveness of environmental regulation aimed at global targets, especially when performed under second-best circumstances.

In this paper these issues are discussed. The analysis is focused on interdependencies between transport, spatial economy, and the environment in the context of environmental policies aimed at a global environmental target. The spatial price equilibrium (SPE) approach is used for this purpose. A small-scale SPE model is formulated and used to perform a number of numerical simulations and to investigate market-based versus environmentally sound spatioeconomic configurations with first-best and second-best policies and with endogenous environmental technologies. We thus present a modelling framework capable of dealing with complexities associated with the simultaneous regulation, first-best and second-best, of multiple interdependent sectors. By considering (freight) transport as one of the polluting sectors, we have added an explicit spatial dimension to the model.

The paper is organized in the following manner. In section 2 a general conceptual framework is introduced for studying transport, spatial economy, and the environment in one analytical setting. In section 3, these ideas are translated into a spatial price equilibrium model. The SPE methodology and the simulation model to be used are discussed briefly. In section 4 we focus on the optimal spatioeconomic system and compare it with the market-based configuration. In section 5, second-best transport policies are considered, namely, the case where the transport regulator has no control over regulation in other sectors. In section 6, endogenous environmental technologies are introduced, which allows for comparisons between taxation of emissions and taxation of activities. Section 7 contains the conclusions.

2 Transport, spatial economy, and the environment: a conceptual framework
The analysis of environmental regulation of transport in relation to the spatioeconomic system will require a rather comprehensive approach. Figure 1 illustrates the types of interactions that can be distinguished. Four different but interacting layers are distinguished, jointly representing the spatial incidence of the issues considered. As a starting point, consider the second layer, which represents the spatial organization of (economic) activities. The parentheses indicate that we use a broad definition of the term 'economic', including all possible kinds of productive and consumptive activities. It is assumed that these activities are located somewhere in space, and therefore various nodes are indicated and labelled A–D. At this level of abstraction, a node may also represent a more spatially dispersed 'node' such as an agricultural sector. In general, owing to specialization of these nodes, fed by comparative advantages, scale economies, or agglomeration economies, the nodes will not be self-sufficient: the bundle of goods and factors supplied within a node is not the same as the bundle demanded at prevailing local market prices, and therefore internodal trade takes place. This trade is made possible by the presence of infrastructure (the third layer) and gives rise to all sorts of transport activities (the fourth layer). The top layer represents the ecological sphere.

The arrows indicate various interactions that may occur in the system considered. The arrows on the right-hand side describe issues which are traditionally at the heart of the regional and transport economics. The arrow labelled *1a* indicates that the demand for transport is a derived demand, following from the spatial organization of economic activities. Conversely, arrow *1b* represents the effect of transportation (costs) on the spatial distribution of activities. Arrows *2a* and *2b* show that the (spatial) construction of infrastructure depends on the spatial distribution of economic activities, but that the (spatial) supply of infrastructure may in turn affect the (spatial) development of the economic system. Next, arrow *3a* represents the restrictions that
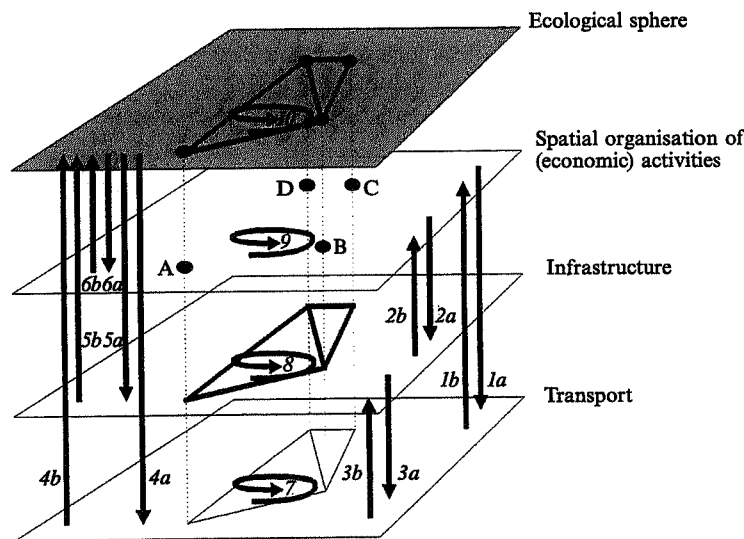
Figure 1. Transport, infrastructure, spatial economy, and the environment in a multilayer approach.

the existing infrastructure imposes upon transportation activities, whereas arrow *3b* indicates that an increasing demand for transport may eventually result in the construction of additional infrastructure (for instance, if transport volumes between A and C grow sufficiently large, it may be desirable to add the 'missing link' A–C).

The arrows on the left-hand side represent the additional interactions involved when the question of environmental quality is considered. The three ascending arrows (*4b–6b*) indicate the environmental impacts of transport activities, the existence of infrastructure, and the performance of economic activities, respectively. These effects will to some extent be localized, which is represented by the imprint of the spatial structure of the other layers in the ecological sphere. Other environmental externalities will be nonlocalized, which is represented by the shading of the ecological layer. The three descending arrows (*4a–6a*) indicate that the state of the environment may in turn affect the other three layers. In particular, environmental degradation may affect both the productivity and the utility in the second layer. Additionally, the productivity in the transportation sector, and the quality of and possibilities for infrastructure supply may depend on environmental characteristics.

Interactions may occur within each layer. The curved arrows may, for instance, represent: congestion effects in transport (*7*); intermodal and intramodal network dependencies in infrastructure (*8*); any form of spatioeconomic interdependencies such as trade (*9*); and physical interactions within the ecosystem (*10*).

It is now clear that the analysis of first-best and second-best environmental regulation in such a spatial system results in the adoption of a quite complex modelling system of multilateral interactions. Any change, in any one layer, can have different impacts on any other layer, as well as indirect impacts (via other layers, or because of substitution effects within that same layer). For instance, a decline in transport costs would lead to more transport, with direct impacts on the environment, but will also affect the spatioeconomic organization, leading to additional indirect environmental impacts, which can of course be negative or positive. Likewise, an expansion of a certain industry may have direct environmental impacts, as well as indirect impacts, via backward and forward linkages with other industries (the same layer) and because of induced transportation (another layer).

Clearly, figure 1 could be expanded further, for instance, by including a (tele-) communications layer to investigate substitution (or complementarity!) with transport. For the time being, however, it seems that an approach accounting for the effects indicated in figure 1 may be a sufficiently comprehensive extension of partial approaches towards the regulation of transport, which usually concentrate on arrow *4b* only. In the following sections we will translate the ideas represented in figure 1 into a more formal modelling framework.

Before proceeding, it is important to outline here that in doing so we will focus on global environmental impacts only, represented by the shading of the environmental layer in figure 1. These are the sorts of effects for which sectoral, spatial, and therefore also policy interdependencies will in particular be directly relevant. In modelling such global environmental targets, we will use the concept of the so-called 'environmental utilization space' (see Opschoor, 1992; Siebert, 1982). This represents a set of upper limits to the present generation's allowable emissions and claims on natural resources, not based on valuations and individual preferences of this generation but rather reflecting the care for the future quality of the environment, typically the global environment, for the sake of future generations. It is therefore related closely to the concept of sustainable development, which has become a key concept in environmental policy debates since the publication of the 'Brundtland report' (WCED, 1987).

The rationale for adapting environmental standards not based on intertemporal optimization is that a satisfactory treatment of future impacts of current environmental claims in terms of intertemporal externalities seems to be beyond reach, because of fundamental difficulties associated with uncertainty, consumer sovereignty, and discount rates (also see van den Bergh, 1996). The specification of the environmental utilization space should instead be based on ecological phenomena, such as carrying capacities of ecosystems, and should be the domain of the sciences of ecology and biology rather than economics. Moreover, in many countries, environmental policies are largely based on targets. Below we consider a global environmental utilization space: all sectors may cause certain emissions affecting the same global environmental characteristic. A good example here could be the emission of greenhouses gases. For the present model, in the derivation of optimal tax rules there is no fundamental difference between the use of marginal external costs or an environmental utilization space in the treatment of global environmental issues, as satisfaction of the latter implies a shadow price directly comparable with marginal external costs. Given the static nature of the model, however, there is a difference so far as overall welfare is concerned. Future impacts of current emissions would directly affect current welfare when treated in terms of externalities, and do not directly affect current welfare when treated in terms of an environmental utilization space. For that reason, the latter option was chosen.

It is worth stressing that, although the 'environmental utilization space' may provide a useful means for the operationalization of the concept of global environmental sustainability, we stick to a static approach in this paper, concentrating on economy-wide and spatial interactions. Consideration of dynamic aspects such as endogenous productivity growth, investment planning, irreversibilities, cumulative and delayed environmental impacts—all essential for the analysis of sustainable development—would certainly be worthwhile but would introduce huge complexities that would divert attention from the primary questions addressed in this paper, those related to spatial and sectoral issues. Indeed, dynamic models of sustainable development are usually aspatial one-sector models and do not easily lend themselves to spatial or sectoral disaggregation (see Toman et al, 1994). Nevertheless, dynamics may be addressed in future work.

3 Transport, spatial economy, and the global environment in a spatial price equilibrium approach

In Verhoef and van den Bergh (1996) the implications of the issues raised in the previous section for environmental transport policies were considered within the framework of a static SPE approach. The same starting point is now taken when regulation is considered in a, albeit small-scale, fully closed spatioeconomic system with a global environmental restriction. This exogenous restriction will be referred to as the environmental utilization space.

The SPE methodology, first presented by Samuelson (1952) and developed further by Takayama and others (Takayama and Judge, 1971; Takayama and Labys, 1986), has the property that equilibrating transport flows between two nodes come into existence as soon as the difference between nodal prices exceeds transport costs. Both nodes can be shown to benefit from such trade, and overall efficiency also increases. Usually, and also in this paper, SPE models are used to analyze spatial interactions in terms of commodity flows, with flexible prices clearing spatial excess demands and supplies for given transport cost structures and local demand and supply structures. A more general interpretation of SPE can embrace flows of production factors and intermediates, and even passenger transport. For our purpose, an advantage of the SPE approach is its close relation with traditional modelling as practised in welfare economics and it thus lends itself to formulations in terms of welfare maximization, and derivations of associated optimal policies. Furthermore, all four layers distinguished in figure 1 can be included, enabling consideration of the full policy complications of the possible interactions.

The SPE model presented below is based on the methodology presented in Verhoef and van den Bergh (1996). The model discussed there is multinodal, multisectoral, multimodal, and general in its functional specification, and thus allows for quite general conclusions. Also the environmental part of the model is richer, and includes localized emissions (relevant, for instance, to the issue of pollutant concentrations) in addition to the global environmental utilization space. In contrast, the model presented here is restricted to two nodes, two sectors, one mode with a given infrastructure capacity, one global environmental restriction, and is cast in explicit functions, but enables a more thorough comparative static analysis of the impact of some key parameters on the behaviour of the spatial system considered. The price to be paid is in terms of a decreasing level of generality and dimensionality: the functional forms of the different relations and the number of sectors, modes, and nodes are made explicit here. The two papers are, therefore, highly complementary. Many of the first-order conditions used below were derived and interpreted in Verhoef and van den Bergh (1996) and will not be discussed in depth here.

Figure 2 (see over) gives the diagrammatic representation of SPE. Two nodes are considered: A and B. The left panel depicts the local demand and supply curves, D_A and S_A, for a certain good in node A, where Y_A gives local consumption and Q_A local production (note that figure 2 is a back-to-back diagram, so that Y_A and Q_A increase as we move leftwards from the origin). In autarky (denoted with superscript a), equilibrium is given by $Q_A^a = Y_A^a$, and the local market price P_A^a would prevail. The right panel shows the same for node B, where the autarky equilibrium is given by Y_B^a, Q_B^a, and P_B^a. Let us assume that transport cost between the nodes is equal to t, which is less than the autarky price difference between the two nodes. Then it will become profitable to transport some goods from the lower price to the higher price region. In figure 2, it is assumed that $P_A^a > P_B^a$, and that $P_A^a - P_B^a > t$. In order to determine the after-trade equilibrium (denoted with superscripts t, for nodes R, where R = A, B, an excess demand or supply curve $X_R (F_R)$ is constructed
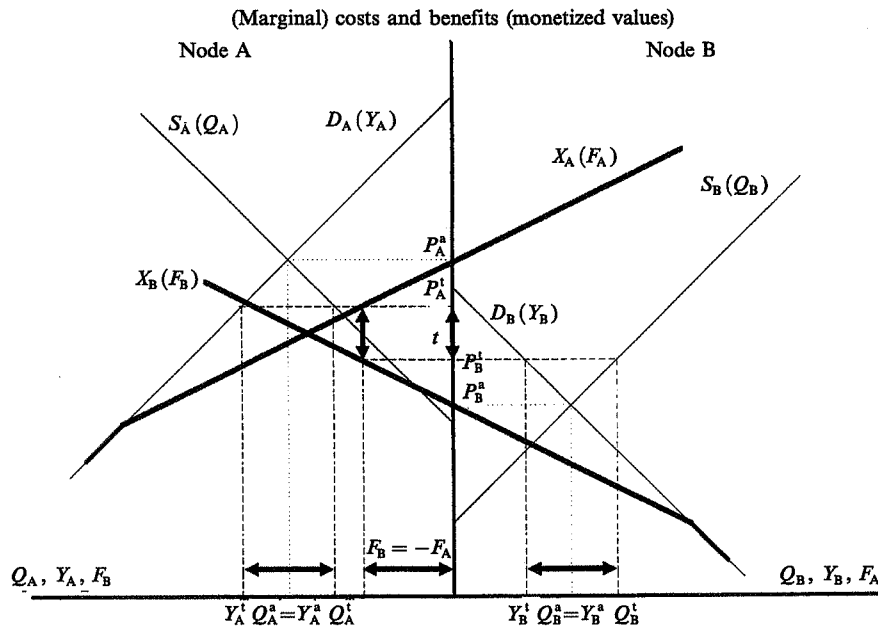
Figure 2. Spatial price equilibrium with one good and two nodes. (Note: the variables are described in the text.)

by horizontal subtraction of the supply curve from the demand curve. Hence, for each after-trade nodal price $P_A^t > P_A^a$, X_A gives the net export F_A that node A would supply to node B; for $P_A^t < P_A^a$, negative values of F_A (hence, positive net imports) imply that node A would be a net demander. In a closed system, the same holds for node B and the after-trade equilibrium is given by $F_A = -F_B$, and $|P_A^t - P_B^t| = t$. In figure 2, $P_A^t - P_B^t = t$, and $Q_B^t - Y_B^t = F_B = -F_A = Y_A^t - Q_A^t$: node B is the net exporter.

The simulation model used is consistent with figure 2. We consider two nodes, one good, and one transport mode, and price-taking behaviour throughout the system. The two nodes are assumed to be spaceless points, so that transport occurs only between not within the nodes. In addition, we consider one single type of environmental degradation. Production in both nodes leads to pollution, and so does transport. This pollution afflicts the global environment. The maximum allowable level of emissions, or the environmental utilization space, is set at E^*.

We specify for both regions the following affine nodal demand (D_R) and supply (S_R) relations, which are in line with the 'quadratic welfare approach' to spatial price equilibrium analyses as discussed by Takayama and Judge (1971):

$$D_R = d_R - a_R Y_R, \quad R = A, B, \tag{1a}$$

$$S_R = s_R + b_R Q_R, \quad R = A, B, \tag{1b}$$

where d_R and s_R are intercepts with the vertical axis, and all parameters and variables are nonnegative. If we assume that $d_R > s_R$, the autarky equilibria are given by:

$$Y_R^a = Q_R^a = \frac{d_R - s_R}{a_R + b_R}, \quad R = A, B, \tag{1c}$$

and

$$P_R^a = d_R \frac{b_R}{a_R + b_R} + s_R \frac{a_R}{a_R + b_R}, \quad R = A, B; \tag{1d}$$

P_R^a in turn defines the intercept of X_R (F_R). Recalling that these excess demand or supply curves are constructed by horizontal subtraction of the supply curve from the demand curve, and that F_R takes on positive values if R is a net exporter, we have (for internal solutions where nodal demand and supply are positive for both nodes):

$$X_R = P_R^a + x_R F_R,$$

with

$$x_R = \left(\frac{1}{a_R} + \frac{1}{b_R}\right)^{-1}, \quad R = A, B. \tag{2a}$$

The after-trade equilibrium can now be summarized as follows: if $|P_A^a - P_B^a| \leqslant t$, the equilibrium is given by equations (1c) and (1d); if $|P_A^a - P_B^a| > t$, label the region with the lower autarky price O (origin) and with the higher autarky price D (destination) and find, by the use of equation (2a) for R = O and R = D,

$$F_O = -F_D = \frac{P_D^a - P_O^a - t}{x_D + x_O}, \tag{2b}$$

$$P_D^t = P_D^a \frac{x_O}{x_D + x_O} + P_O^a \frac{x_D}{x_D + x_O} + t \frac{x_D}{x_D + x_O}, \tag{2c}$$

$$P_O^t = P_D^a \frac{x_O}{x_D + x_O} + P_O^a \frac{x_D}{x_D + x_O} - t \frac{x_O}{x_D + x_O}. \tag{2d}$$

From equations (2c) and (2d) we find that $P_D^t - P_O^t = t$, and that $P_D^t = P_O^t$ when transport costs are equal to zero. Nodal consumption and production after trade can be found by substituting back equations (2c) and (2d) into the respective demand and supply relations. For solutions where nodal consumption or production in at least one of the nodes is zero, the after-trade equilibria can be derived in the same manner.

The environmental emissions model in its most simple form—that is, with exogenous environmental technology—is as follows. There is one type of emission (represented by parameters e_i) which depends in a linear, source-specific fashion on production and transport, where the transport volume T equals total trade, $|F_A| = |F_B|$. Hence, total emissions E are given by

$$E = e_A Q_A + e_B Q_B + e_T T, \qquad \text{with } T = |F_A| = |F_B|. \tag{3}$$

The environmental utilization space E^* is given exogenously and the global target is met when $E \leqslant E^*$. In the absence of environmental technologies, the first-best policy mix of optimal nodal production taxes π_R and the optimal transport tax τ can be found by maximizing net social welfare (the sum of region-specific gross benefits, $B_A^{gros} + B_B^{gros}$, measured as the area under the Marshallian demand curves, minus the sum of region-specific production costs, $C_A^{prod} + C_B^{prod}$, minus total transport costs C^{tran}); subject to the constraint implied by the environmental utilization space; given the market behaviour of the actors involved under regulation; and subject to appropriate nonnegativity conditions concerning prices, production, consumption, and transport. This Kuhn–Tucker problem can be represented as:

$$\text{maximize } [B_A^{gros} + B_B^{gros} - C_A^{prod} - C_B^{prod} - C^{tran} + \lambda_E (E^* - E)],$$

subject to

$$\lambda_E \geqslant 0, \qquad E^* - E \geqslant 0, \qquad \text{and} \quad \lambda_E (E^* - E) = 0,$$

individual maximizing behaviour under regulation-appropriate nonnegativity conditions,

where λ_E is the Langrangian multiplier associated with the environmental constraint.

This multiplier will henceforth be referred to conveniently as the 'environmental shadow price'. This maximization problem is presented formally in Verhoef and van den Bergh (1996). The following optimal production taxes π_R and transport tax τ can be derived for the present model:

$$\pi_R = e_R \lambda_E, \quad R = A, B, \tag{4a}$$

$$\tau = e_T \lambda_E. \tag{4b}$$

The optimal second-best regulatory transport tax τ, where the regulator cannot affect environmental regulation in the origin and destination nodes but aims at meeting the environmental constraint in the most efficient way, is given by

$$\tau = e_T \lambda_E + \frac{e_O \lambda_E - \pi_O^0}{(1 + b_O/a_O)} - \frac{e_D \lambda_E - \pi_D^0}{(1 + b_D/a_D)} \tag{5}$$

(see Verhoef and van den Bergh, 1996). In equation (5) π_R^0 denotes the now exogenously given level of producer taxation in node R.

In the model with endogenous environmental technology, it is assumed that application of such measures in the production process shifts the cost curves for the good upwards, whereas it will increase the cost of private transport t. To model the costs of abatement technologies, therefore, the marginal costs of emission reductions per unit of production are assumed to be independent of the total level of production and the marginal costs of emission reductions per unit of transport are assumed to be independent of the total level of transport activities Consequently, such improvements affect marginal production and transport costs and are therefore assumed to be embodied in products and transport activities. In an alternative formulation, abatement technologies could be assumed to be embodied in fixed capital, which would merely affect fixed costs, leaving marginal production and transport costs unaltered.

The private gains of environmental improvements are assumed to be solely in terms of reductions in the regulatory tax sum to be paid. This is in line with the assumption that the environmental utilization space is an external constraint and not an argument in current actors' individual utility functions (that is, environmental degradation is not defined in terms of instantaneous external costs but E^* is to be met only for the sake of future generations). Also, it reflects that the global natural environment is in many instances a public good, implying that 'free riding' is the rational strategy for individual actors. It is assumed here that in each of the three sources of emissions (the two production sectors and transport) actors can reduce the value of e_i below the initial nonintervention value e_i^0 by quadratically increasing cost, $\frac{1}{2}k_i(e_i^0 - e_i)^2$, under the restriction that negative values of e_i are not possible. With optimal emission taxation, the actors will then set e_i to solve:

$$\underset{e_i}{\text{minimize}} \left[\frac{1}{2}k_i(e_i^0 - e_i)^2 + \lambda_E e_i \right]. \tag{6a}$$

Price-taking behaviour is reflected here by actors not considering the impact of their behaviour on λ_E. From equation (6a) it can be shown that emission taxation provides the first-best incentives to undertake the socially optimal level of environmental investments (given the environmental target): the first term gives the economic costs of such investments, whereas the second term gives the (social) economic costs of not undertaking them. Minimizing equation (6a) is thus in line with overall efficiency and leads to the following equilibrium levels of e_i:

$$e_i^* = \text{maximum} \left\{ 0, e_i^0 - \frac{\lambda_E}{k_i} \right\}. \tag{6b}$$

When λ_E is sufficiently larger or k_i is sufficiently small at equilibrium, e_i^* will be zero, whereas it will approach e_i^0 in the opposite cases. A comparison of the model in equations (4a) and (4b) to the one in equations (6a) and (6b) not only enables an assessment of the potential impacts of endogenous environmental technological development, but can also be interpreted as comparing the features of 'emission taxation', in the model given by equations (6a) and (6b), to 'activity taxation' (that is, production and transport taxation), in the model given by equations (4a) and (4b). In many instances, regulatory tax schemes are not, or cannot, be based on actual emissions but are based on related variables such as total production or total mobility instead (a fixed environmental tax per product or per vehicle mile). Such taxes do not directly induce technological solutions to environmental problems, as actors do not receive a direct reward for their efforts because the tax does not depend on actual emissions. In such cases price-takers will not undertake environmental investments, and the model given by equations (4a) and (4b) remains valid.

A final model is based on the second-best case given by equation (5), with transport emission taxation rather than transport activity taxation. Here, equations (6a) and (6b) only hold for the transport sector (although e_T^* will generally have a different value than in the case of first-best policies and should for that reason actually be replaced by, for instance, e_T^{**}) while e_A^0 and e_B^0 remain valid.

Although the above model can be criticized on several grounds (such as the linearity of the marginal functions and the consideration of only a single good), it still offers the possibility of assessing the basic comparative static equilibrium interactions between transport, spatioeconomic development, the environment, and environmental technology within a tractable model. This is the purpose of the following sections.

4 Market-based versus first-best regulated spatioeconomic configurations in the absence of environmental technologies

In this section, some simulation results based on the model developed in the previous section are discussed. However, first we will discuss briefly the 'base case' of the simulations, for which the following parameter values are ·chosen. The demand functions for the good are assumed to be identical for both nodes, with $d_R = 80$ and $a_R = 0.5$. The production side of the two nodes are different, with $s_A = 25$ and $b_A = 1.5$; and $s_B = 5$ and $b_B = 0.5$. Production is more efficient in node B than it is in node A. In autarky, $Q_A^a = Y_A^a = 27.5$, with $P_A^a = 66.25$; and $Q_B^a = Y_B^a = 75$, with $P_B^a = 42.5$. Transport costs are equal to 5, which is smaller than the autarky price difference, and hence equilibrating transport flows will exist. As expected, in trade equilibrium, B will be the net exporter ($F_B = 30$), which compensates exactly for the nodal imbalances implied by $Q_A^t = 20$ and $Y_A^t = 50$ at $P_A^t = 55$; and $Q_B^t = 90$ and $Y_B^t = 60$ at $P_B^t = 50$. In comparison with the autarky situation, total welfare in node A increases from 756.25 to 925, and in node B from 2812.5 to 2925. Note that welfare is a narrowly defined concept, measured as the sum of consumer and producer surpluses, and does not include any environmental values because environment is treated as a constraint rather than as a temporal externality. Both nodes, therefore, benefit from trade; as they would from voluntary trade. By setting $e_A = e_B = 10$, and $e_T = 15$, total emissions of 1550 result in the unregulated trade equilibrium: $E_A = 200$; $E_B = 900$, and $E_T = 450$. Transport accounts for approximately 30% of the emissions. The enviromental utilization space E^* is set at 1000.

To illustrate the SPE methodology in combination with the environmental model, in the first simulation the two production structures are gradually interchanged. On the right-hand side of figure 3 the base case is found, whereas on the left-hand

side $s_A = 5$ and $b_A = 0.5$; and $s_B = 25$ and $b_B = 1.5$. As we move towards the right, s_A (s_B) is increased (decreased) by 1 in each step; and b_A (b_B) is increased (decreased) by 0.05 in each step. The simultaneous variation of the four parameters is summarized along the horizontal axis by considering their impact on the autarky price difference $P_A^a - P_B^a$. Given the identical demand structures, this simulation will yield symmetric results with completely identical nodes (as reflected by $P_A^a - P_B^a = 0$) at the centre.

Figure 3 focuses on environmental issues. From the curvature of the nonintervention emission (E^{NI}), it is clear that the more the two nodes differ the higher these emissions will be, owing to the induced transportation flows. Alternatively, when the two nodes are identical, in the centre of the figure E^{NI} decrease within the environmental utilization space E^*, and the environmental shadow price λ_E is zero. The basic relation between E^{NI}, E^*, and emissions and λ_E under integral activity regulation (IAR) is illustrated. So long as $E^{NI} < E^*$, no regulation is needed and emissions under IAR are equal to E^{NI}. As soon as $E^{NI} > E^*$, regulation becomes necessary in order to prevent emissions from exceeding E^*. This is reflected in a positive environmental shadow price λ_E. The larger the difference $E^{NI} - E^*$, the higher the value of λ_E.
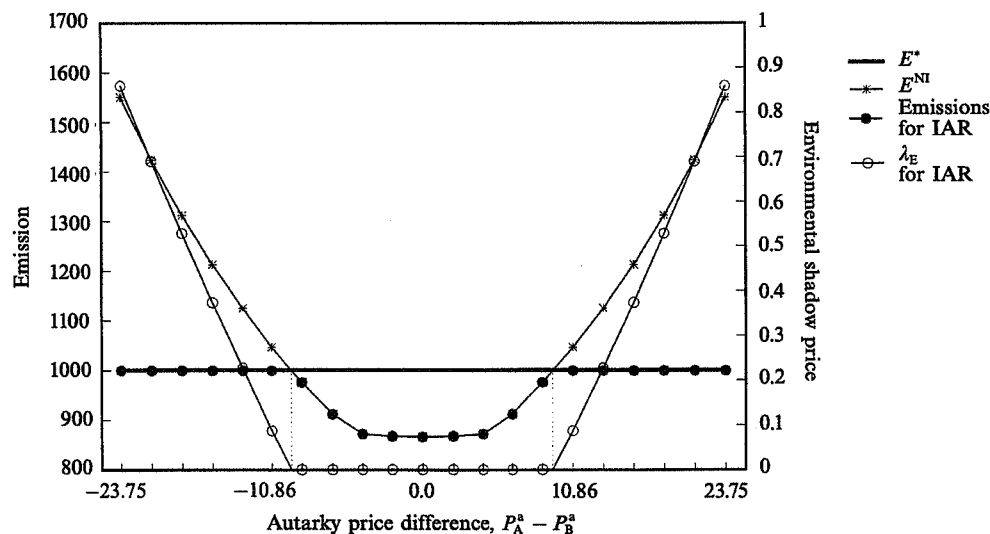

Figure 3. Emissions in the case of market-based spatial equilibrium and under integral activity regulation, and the environmental shadow price. (Note: the variables and abbreviations are described in the text.)

The spatioeconomic impacts of regulation, as well as some typical SPE characteristics, are shown in figure 4. With identical nodes and autarky prices, no trade takes place; when the autarky price difference exceeds the transport costs, the node with the lower autarky price becomes the net exporter. When E^{NI} exceed E^*, free-market activity levels are excessive. Figure 4 shows that the greater the difference between the nodes, the larger the discrepancy between nonintervention and optimal levels of trade and nodal specialization. For the optimal spatial configuration, production and transport have to be increasingly restricted. Given the identical demand structures, this implies a relatively stronger restriction in production of the exporting node than in the importing node, as can be seen at both ends of figure 4.
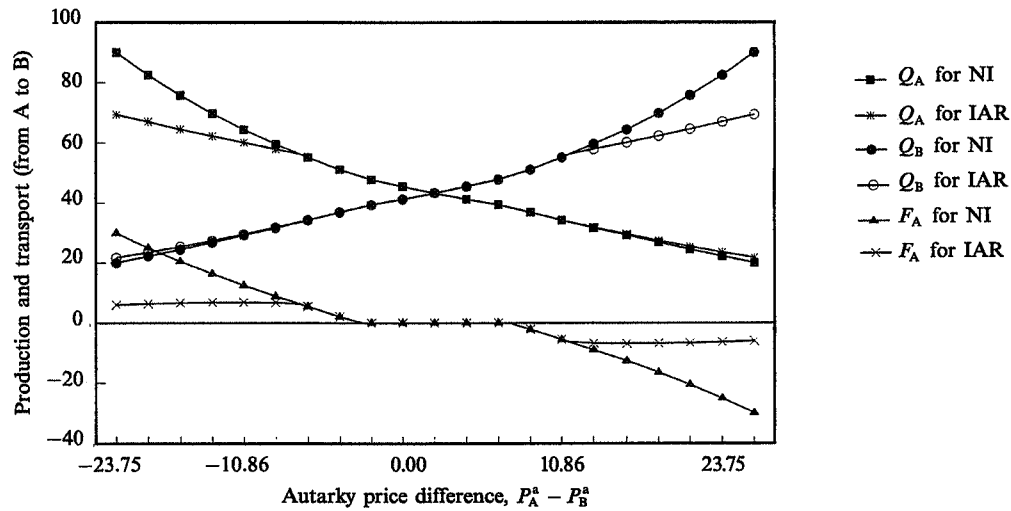
Figure 4. Production and transport from node A to node B in the case of market-based spatial equilibrium and under integral activity regulation. (Note: the variables and abbreviations are described in the text.)

5 Second-best transport volume regulation

We now turn to the case where the regulator is not capable of affecting regulation in the two production sectors but can only conduct transport policies to meet the environmental constraint. This could, for instance, correspond to the situation of a relatively small transit region, concerned with the impact of its 'throughput' on some global environmental amenity, but unable to influence environmental policies in the origin and destination nodes directly. The Netherlands is a good example. Although such a regulator cannot affect production and consumption directly, its transport policies will affect overall production and consumption indirectly. In the simulation discussed below, we focus on how the underlying spatioeconomic system might affect the efficiency and effectiveness of such second-best transport policies— as given in equation (5a)—in comparison with the first-best situation where the regulator can set an optimal policy mix of transport and production taxes.

Figure 5 shows emissions and environmental shadow prices under both types of regulation. Along the horizontal axis, the emission coefficient e_A in the destination node is raised from 0 to 45 (with a jump from 18 to 36); in comparison with the base case, e_T is set at 5 rather than 15. Furthermore, $\pi_A = \pi_B = 0$. The underlying spatioeconomic structure has an enormous impact on the performance and potential of second-best regulation. On the left-hand side, this structure is seen to be relatively favourable for such policies. Second-best transport volume regulation (TVR) not only has a favourable direct impact on emissions of transport itself, but it also induces a shift from consumption of imported goods towards the purchase of locally produced goods in node A—which are produced in a relatively environmentally friendly way compared with production in node B. Towards the right-hand side, however, his favourable indirect effect of transport policies is increasingly eroded. Up to the point where $e_A = 9$, this shows in an increasing discrepancy between the environmental shadow prices λ_E for both policies. This shadow price depends not only on the extent to which E^{NI} exceed E^*, as illustrated by the gradual increase of λ_E for IAR, but also on the efficiency and effectiveness of regulation itself.

When e_A exceeds the value of 9 we end up in the range where TVR is no longer sufficient for meeting the environmental constraint. In this regime, 'optimal' TVR
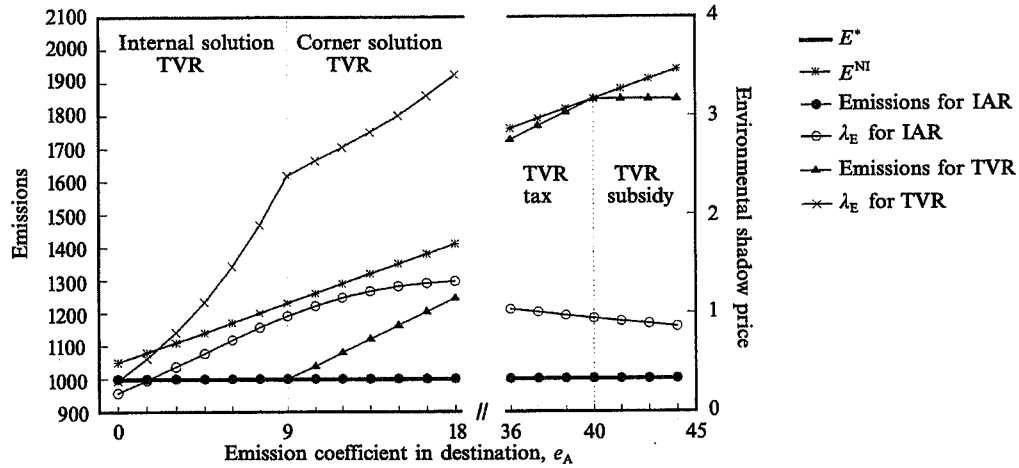
Figure 5. Emissions and environmental shadow prices under integral activity regulation (IAR) and transport volume regulation (TVR) as functions of the emission coefficient in the destination node. (Note: the variables are described in the text.)

consists of the solution of prohibitive taxation with zero transport (figure 6). This explains the kink in the curvature of λ_E for TVR, which is no longer sufficient for meeting the environmental target. The effectiveness and efficiency of TVR increasingly falls short of those of IAR, as shown by the increasing difference of emissions and λ_E for both policies in figure 5. With prohibitive transportation taxation, total regulatory tax revenues will be zero. With IAR, internal solutions will generally result, implying positive tax revenues for the regulator (figure 6).

When e_A increases further, a point will be reached where TVR becomes completely ineffective and inefficient. In this simulation, $e_A = 40$ creates that particular unfavourable combination of parameters where transport regulation has no effect whatsoever on total emissions. In this case, the direct environmental impacts on emissions from transport are completely compensated for by additional emissions from increased local production in the destination node, an increase induced by the transport policy itself. Here, λ_E for TVR approaches infinity, reflecting the complete inefficiency of the policy.
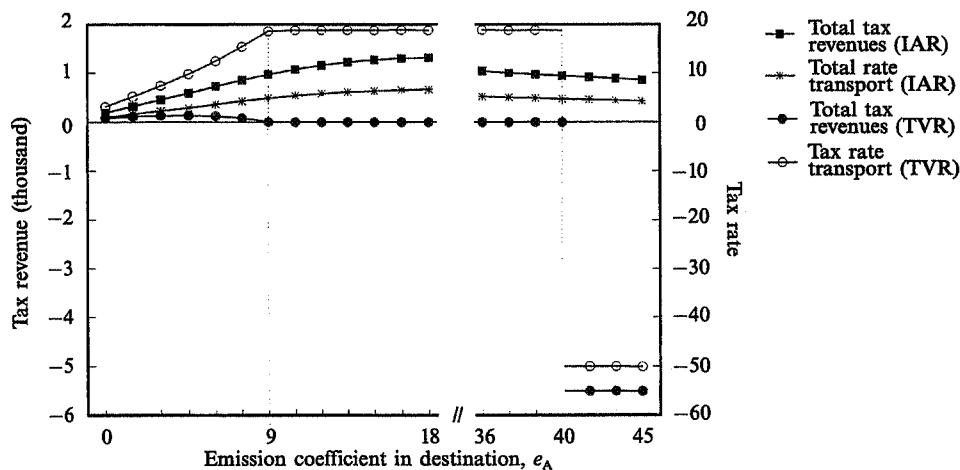

Figure 6. Regulatory tax rates and revenues under integral activity regulation (IAR) and transport volume regulation (TVR) as functions of the emission coefficient in the destination node.

When moving beyond this point, we end up in a third regime, where second-best TVR is in the form of transport subsidization rather than taxation. Transport taxation would be counterproductive, as it induces more emissions from production in the destination node than the transport emissions it reduces. As shown in figure 6, the best thing the TVR regulator can do is to subsidize transport in such a way that local production in node A is reduced to zero (in this case, TVR transport subsidies should be direction specific, which is never the case for transport taxes). The simulation results show that, in this regime, welfare under TVR falls considerably and is below welfare under IAR even though the environmental constraint is not met with TVR. Such TVR subsidization creates rather severe distortions in the spatioeconomic system.

The curvature of λ_E under IAR deserves some attention. The fact that it is rising on the left-hand side of figure 5 reflects that the economy as a whole becomes more polluting because of the increase in e_A. In light of this, the flattening of the slope of the curve on the left-hand side and its decline on the right-hand side may at first sight seem perverse. The explanation lies in the fact that the shadow price λ_E is attached to the factors e_i in the optimal tax rules. Therefore the increase in e_A in itself has a deflating impact on λ_E. The observed pattern arises from the combination of both effects.

Although one might argue that this situation of TVR subsidization is quite extreme and unrealistic because one would never expect a transport regulator in the sort of transit region considered actually to subsidize transport for environmental reasons, the simulation also has important implications for a less ambitious transport regulator. The underlying spatioeconomic equilibrium processes leading to the pattern seen in figure 5 simply cannot be ignored and will affect the effectiveness of any form of transport regulation. This is illustrated in figure 7, where the impact of four different levels of transportation taxes ($\tau = -4$, $-2, 2$, and 4) on total emissions is seen for various levels of e_A. On the left-hand side of the figure, taxes have a very favourable impact on total emissions because of their direct effect on transport, as well as the indirect impact of stimulating a production shift from node B to A; the impact naturally being higher the higher the tax. With an increasing emission coefficient, however, these impacts decline and beyond $e_A = 40$ the transport regulator would find that the total emissions increase with increases in the transport tax charged. Transport subsidization is necessary if TVR is to reduce total emissions. If the regulator is not inclined to subsidize transport, the best thing to do is keep transport taxes at zero.
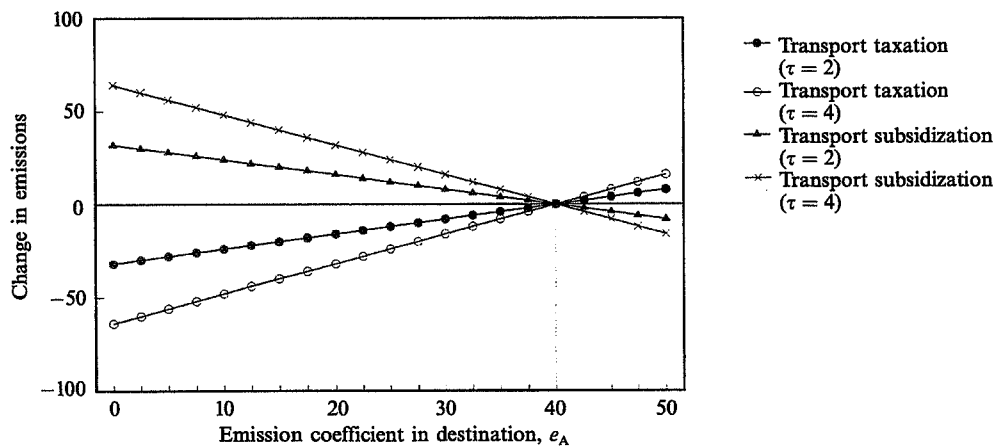

Figure 7. The effectiveness of transport volume regulation in a spatioeconomic setting.

These simulations demonstrate clearly the sometimes unexpected effects of regulation when considered in the context of a full spatioeconomic setting, including the interdependencies between the transport sector and the spatial pattern of economic activities.

6 Endogenous environmental technologies: emission charging versus activity regulation

Let us now consider simulations in a model where environmental technology is endogenous. Here, regulation by taxation based on production and transportation volumes is no longer first best, as it fails to provide any incentives to reduce emissions through cleaner environmental technologies. We will compare the impacts of such IAR with the first-best option of integral emission regulation (IER).

The most straightforward variables to consider are k_A and k_B, and k_T, which reflect the marginal costs of abatement technologies for each of the three sources of emissions. In the first simulation, these three parameters were raised simultaneously by a factor of 1.5 in each step, from 0.003 up to a level of 12, the base values of 0.2 being the central values. The impacts are as expected. For low values of k_S ($s = A$, B, T), the discrepancy between IAR and IER is large, whereas for high values the two forms of regulation practically converge. The higher the cost of implementing environmental abatement technologies, the more will producers and suppliers of transport services respond to regulation by reducing the size of their activities instead of adapting cleaner technologies. This follows directly from equation (6a) in accordance with which, under IER, suppliers will minimize the sum of the regulatory tax rate and the expenditures per unit on abatement technologies.

The effect on the environmental shadow price, not shown graphically, is that λ_E for IER will increase from almost zero for very low values of k_S up to the level for IAR (0.86) at very high values. This is closely related to the fact that with IER and at low values of k_S the original overall nonintervention levels and patterns of production and transportation can be maintained under regulation by meeting the environmental constraint through relatively cheap technological solutions, which directly implies a low environmental shadow price. Alternatively, when abatement becomes more expensive, technological solutions become less attractive and the environmental constraint will have to be met by adaptations in production and transport levels, as is the case under IAR. Figure 8 shows total levels of production and transport under nonintervention (NI), IAR, and IER.

Apart from k_S, other parameters will have their impact on the relative performance of IAR and IER. Figure 9 focuses on the impact of demand elasticity at the importing node on the levels of λ_E. Along the horizontal axis, the slope of the demand curve D_A, given by a_A in equation (1a), is gradually raised (by a factor of 1.5 in each step), while d_A is increased simultaneously in order to maintain the same nonintervention levels of consumption and production. In this way, the demand for the good and for transport becomes more inelastic as we move towards the right. As a result, it becomes increasingly difficult to restrict activity levels to meet the environmental constraint. This is reflected in the curvature of λ_E for IAR. Also λ_E for IER increases slightly as we move towards more inelastic demand at the destination node, but the increase is not as strong for IAR. This increasing discrepancy shows that, under IER, polluters have a greater incentive to invest in abatement technologies rather than to restrict production when demand is more inelastic. In this way, they keep the environmental shadow price relatively low. This implies that under first-best IER the total 'offer' that a society has to make to keep emissions at E^* is smaller than under IAR. Figure 9 shows a direct link between the relative values of λ_E for both policies and the relative welfare reductions due to these policies. But, even from a private perspective, the producers of emissions can make considerable savings by trading off abatement against activity
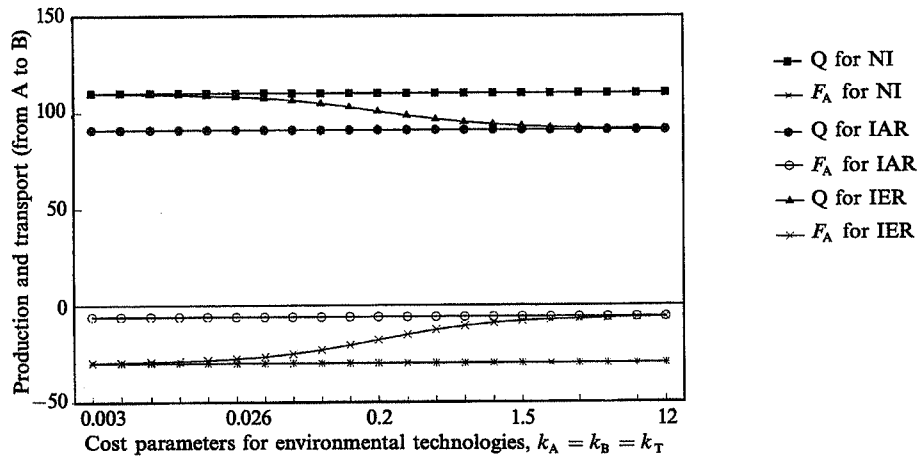
Figure 8. Overall production and transport from node A to node B under integral activity regulation (IAR) and integral emission regulation (IER). (Note: the variables are defined in the text.)
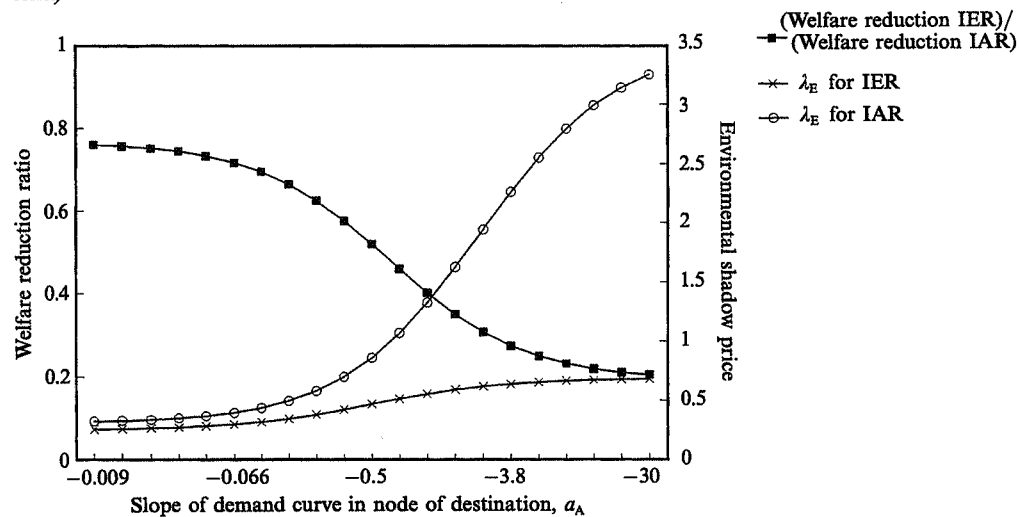

Figure 9. Environmental shadow prices and the ratio of welfare reduction for integral activity regulation (IAR) and integral emission regulation (IER). (Note: the variables are defined in the text.)

reductions. This is illustrated in figure 10 for tax rates and the expenditures per unit of production on abatement in the local production sector in node A. The same patterns are found for total tax sums and total expenditures on abatement.

The simulations discussed show that the environmental shadow price does not depend only on the extent to which nonintervention emissions exceed the environmental utilization space. One of the other key factors determining the value of this shadow price is the 'quality' of the environmental policies deployed to meet this restriction.

We will now use the simulation from section 4 for an integral comparison of TVR, IAR, IER, and the fourth possible form of regulation mentioned in section 2, namely, transport emission regulation (TER). In figure 11 the values of λ_E for the four policies are shown. So long as $E^{NI} \leqslant E^*$, these shadow prices are all equal to zero. When $E^{NI} > E^*$, however, the shadow prices diverge. As expected, λ_E for IER is lower than λ_E for IAR, and both fall short of the λ_E values for transport regulation. This shows that the more 'perfect' the regulation, the lower the environmental shadow price.
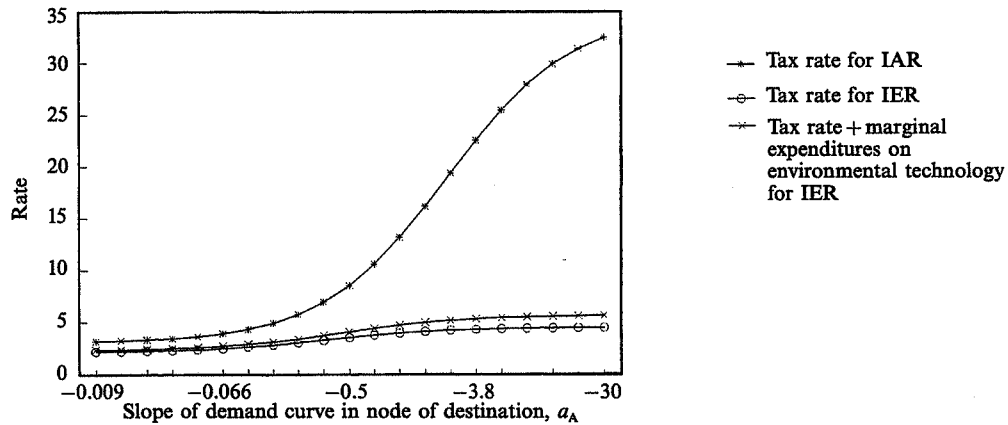
Figure 10. Marginal and total tax payments and outlays on abatement technology under integral activity regulation (IAR) and integral emission regulation (IER).
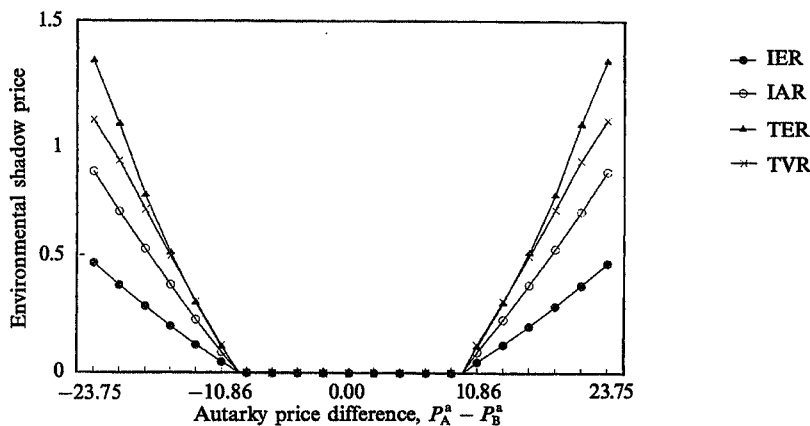

Figure 11. Environmental shadow prices for various types of regulation. (Note: the abbreviations are described in the text.)

More surprisingly, λ_E for TVR is, over a considerable range, lower than λ_E for TER, whereas one would expect the opposite for the same reason that TER seems closer to first-best standards than TVR. In fact, it is. The reason this is not reflected in λ_E is that λ_E is a marginal variable. At the margin, the environmental shadow price for TER is higher than it is for TVR, where the larger restriction in transport volumes has a greater indirect impact on production and emissions by the production sectors. This favourable side-effect of transport regulation is less significant when the suppliers of transport services are not confined to cutting down the overall transport volume, but can also respond to regulation by adopting abatement technologies. In the case of total welfare, however, not that evaluated merely at the margin, the impact of TER and TVR on overall welfare is almost identical (see figure 12). A close inspection of the numerical values of the welfare levels shows that welfare under TER is always above (or at least equal to) welfare under TVR. The differences, however, are small. Again, as expected, welfare under IER is the closest to welfare under non-intervention, with IAR between IER and both forms of transport regulation.

Figure 13 demonstrates that this ranking in welfare of the four types of regulation is closely connected to the extent to which the original spatioeconomic structure is affected by regulation. The ratio of total transport to total production is used for
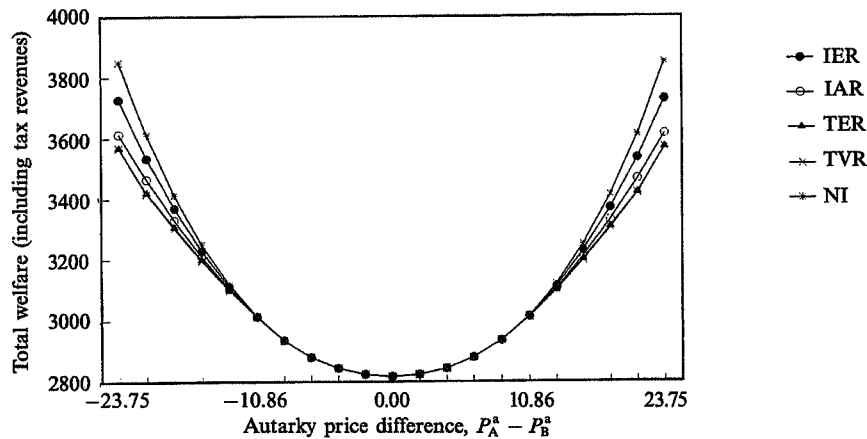
Figure 12. Total welfare (including tax revenues) for various types of regulation. (Note: the abbreviations are described in the text.)
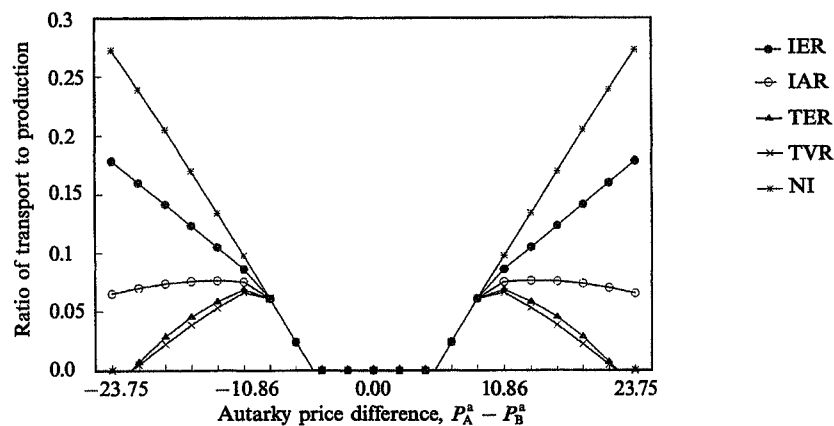

Figure 13. Ratio of transport to total production for various types of regulation. (Note: the abbreviations are described in the text.)

this purpose. With larger differences between the production structures of both nodes, nonintervention results in the greatest degree of specialization. Regulation in terms of IER, IAR, TER, and TVR will, in that order, restrict such specialization, where for extreme differences between the nodes in terms of production structure either form of second-best transport regulation may require a total prohibition of transport and trade.

7 Conclusion

In the foregoing analysis, interdependencies between transport, spatial economy, technology, and environment were investigated in the context of regulatory environmental policies aimed at a global environmental target, defined in terms of the environmental utilization space. A small-scale model based on the adapted spatial price equilibrium methodology presented in Verhoef and Van den Bergh (1996) served as an illustration of the formal analysis found in that paper. Notwithstanding the simple structure of the model, the simulation results are interesting in that they provide revealing comparative static insights into issues that are important in the formulation of environmental and transport policies.

A binding environmental utilization space results in a positive social 'environmental shadow price'. This can be interpreted as a counterpart to the concept of

marginal external costs in more traditional economic approaches to environmental policy. The value of this shadow price, however, not only depends on the extent to which nonintervention emissions exceed the environmental utilization space, but is also inversely related to the 'quality' of the environmental policies to be conducted. In particular, when the possibility of applying environmental abatement technologies in response to regulation is included, the lowest values for this shadow price, as well as the highest values of narrowly defined welfare after regulation, are found for the first-best policy mix of emission taxation in each of the three polluting sectors. In many instances, however, regulatory tax schemes are not, or cannot, be based on actual emissions but are based on related variables such as total production or total mobility instead. Such imperfect regulatory tax schemes result in higher environmental shadow prices and lower after-regulation levels of welfare. Consequently, the implicit price that a society has to pay for meeting environmental targets is directly dependent on the quality of the policies pursued.

Environmental transport policies conducted in isolation have indirect side-effects. These side-effects may be advantageous as a reduction in transport will generally lead to a reduction in overall trade and production. In some instances, however, notably if the local production sector in the importing node is relatively polluting, induced production shifts may partly or even completely offset the envisaged positive impacts of transport regulation. Furthermore, for transport policies conducted in isolation, the difference between overall efficiency of transport volume regulation and that of transport emission regulation need not be large. Whereas the latter has the advantage of inducing the application of abatement technologies in the transport sector, the former is likely to result in a larger reduction of transport volumes, which has a larger indirect impact on the spatioeconomic structure by its limiting impact on production and emissions associated with the production sectors.

Consequently, for the realization of global environmental targets, the formulation of isolated transport policies is not as straightforward as is sometimes believed. One would prefer to apply a first-best policy mix in which all sectors can be regulated simultaneously. If this is not possible, the transport regulator should consider closely the environmental implications associated with the induced shifts in the spatioeconomic structure due to the planned transport policies.

The above analysis could obviously be extended in many directions. Indeed it seems as if only after expanding the partial analysis towards a more realistic setting one becomes aware of the far-reaching, often implicit, assumptions behind the standard economic representation of the problem of transport externality regulation. One important extension that we would like to study in future work concerns the role of dynamics. Such an extension would allow us to consider dynamic processes in terms of, for instance, regional specialization and endogenous spatioeconomic development. This would require a distinction between short-run and long-run cost curves, the first of which were considered in this paper, in relation to transport and the environment. In such an analysis, the environmental utilization space E^*, as well as the environmental shadow price λ_E could be endogenized, thus taking the model a step further into the directions of the study of sustainable spatial development.

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