Modelling the regional economic impacts of road pricing in an interregional general equilibrium framework

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1. Introduction
Road pricing is rapidly becoming an important political issue, largely because of its potential for reducing congestion and environmental externalities. The issue is also gaining importance because the technical possibilities upon which road pricing systems are based have expanded rapidly, reducing dramatically the implementation, operational and administrative costs of such systems. At the same time, road pricing will inevitably affect the labour market as it will influence choicer between leisure and work time. There are different forms of road pricing. The version considered here is the most general, where users pay for actual use of different stretches of road during a fixed period, such as a year. In the paper, the prime interest is in the regional economic effects of the introduction of a system of road pricing, using Denmark as a case example.

The theoretical approach adopted is to model the effects of road pricing on regional economies through the use of a Computable Interregional General Equilibrium model which permits analysis of changes in prices on economic activity in a regional system.

In section 2 the background for modelling the regional economic effects of road pricing is examined and the analysis presented here is defined. In section 3 the Interregional General Equilibrium model LINE is described, concentrating specifically on the interaction between transport activity and regional economies. Section 4 documents a simplified linear version of LINE is presented. In section 5 results of an initial analysis of some of the regional economic effects of road pricing in Denmark are presented and finally in section 6 the limitations of the analysis and future perspectives are examined.

2. The direct impacts of road pricing

2.1 Road pricing
Different road pricing systems exist. The four standard models are:
1. Point based
2. Road based
3. Network based
4. Area based

The first system involves payment for passing a point whilst the other three involve payment for use of a length of road. Combinations of the four types are possible. In Denmark at present a pilot project is being developed involving a combination of types 3 and 4. Technically, it is based on GPS technology, permitting precise identification of location and thereby, road use, related in turn to toll level for the

road. The toll level depends on road status in a road hierarchy and level of urbanization. Cars are to be fitted with receivers which function as meters, registering both current expenditure as the road is used and cumulated expenditure for a given period. The meter is read at periodic intervals and the user is charged.(see Herslund et al 2001, Nielsen 2000)

The analysis in this paper is developed to study the Danish case, based upon this road pricing system.

2.2 Traditional approaches to analysis of the economic effects of road pricing

A traditional approach would involve identification of changes in transport flows and changes in direct and indirect (time) costs for travellers. This information is then used to undertake a cost-benefit analysis of the changes in the regulation of the transport system, involving an evaluation of changes in direct costs, time savings and changes in other costs, such as accidents and environmental costs.

The central problem of this approach is the exogenous determination of the value of time for different categories of traveller. In addition, redistribution of benefits and costs on different categories of user is usually ignored.

2.3 The General Equilibrium approach to transport system changes

An alternative to the exogenous determination of the value of time is its endogenous determination within a General Equilibrium model. Changes in the transport system have consequences for costs and prices in the regional economy. In an Interregional General Equilibrium model cost and price changes are followed from place of production through the trade system to place of demand and further to place of residence of the consumers and to place of production as intermediate input, forming the first round in an (in principle) infinite number of circles, which describes the propagation of cost and price changes in the (inter) regional economy. These cost and price changes form the basis of the regional economic behaviour of consumers and producers. Implicitly, after adding up changes in income due to changes in transport cost, the value of time is determined endogenously.

The present paper has this long-term ambition, but limits itself to examination of redistribution of income by region. In LINE, data on changes in transport cost due to road pricing are fed in to the model and then redistributed to consumers and producers in other regions and sectors, which in turn are passed on to other consumers and producers in other regions in a never ending process. The resulting decline in disposable income reduces private consumption, and with this, also production and employment in Danish regions.

The present analysis does not model changes in behaviour due to these relative price and cost changes (except for changes due to reduction in real disposable income). In order to undertake a complete regional cost-benefit analysis these behavioural changes must be included together with assumptions concerning governmental reactions to increased tax revenues and possible consequences for international trade.

3. An Interregional General Equilibrium model (LINE)

3.1 Background

LINE is an interregional general equilibrium model which has been developed at The Local Government Research Institute (AKF) in Copenhagen (Madsen et al 2001a). In this section an overview of the LINE model is presented. First, the full model is shown graphically, followed by the more limited model where the transport component of LINE is examined.

The basic philosophy in the construction of LINE takes trade theory as the point of departure, combined with an input-output approach. The model develops both a circuit of real transactions, corresponding to the traditional Leontief real input-output model, described in figure 3.1 below, and a cost-price circuit, corresponding to an input-output price model, as described in figure 3.2.

To illustrate the overall model structure, a brief discussion of the characteristics of interregional general equilibrium models is undertaken. Interregional general equilibrium models are composite as on the one hand, they contain the two basic exchange circuits, the real and the cost/price circuits, which can, in principle, be modelled using linear relationships. On the other hand, such models usually contain a set of non-linear relations which reflect a priori, in a consistent and mathematically manageable manner, producers' and consumers' behaviour in a set of sub-models. These non-linear relationships model such elements as product variety and production externalities, elements which are of considerable importance in modelling in an urban context.

The choice made in the context of LINE is to begin with a linear model, in order to examine the effects of road pricing in a purely linear world and to extend the model through the successive inclusion of non-linear relationships, either by sequential inclusion, or by simultaneous inclusion, permitting analysis of their interaction. By following this strategy it will be easier to identify the specifically

urban elements, compared with changes which would occur in any regional system without urban characteristics.

3.2 LINE: an overview of the details

Figure 3.1 shows the general model structure, based upon the real circuit employed in LINE. The horizontal dimension is spatial: place of work, place of residence and place of demand. Production activity is related to place of work. Factor rewards and income to institutions are related to place of residence and demand for commodities is assigned to place of demand. The vertical dimension follows with its five-fold division the general structure of a SAM model (see: Madsen et al 2001b). Production is related to activities; factor incomes are related to i) activities by sector ii) factors of production by qualification, sex and age and iii) institutions (households and firms) iv) demand for commodities is related to wants (aggregates of commodities or components of final demand and intermediate consumption); v) commodities, irrespective of use.

The real circuit corresponds to a straightforward Keynesian model and moves clockwise in figure 3.1. Starting in cell AE in the upper left corner, production generates factor incomes in basic prices including the part of income used to pay commuting costs. This factor income is redistributed from activities to factors (cell AE to cell AG), where the labour force is divided into qualification, sex and age groups. Factor incomes are then transformed from place of production (AG) to place of residence (BG) through a commuting model. In this process transport costs are subtracted from factor income. Disposable income is calculated in a sub model where taxes are deducted and transfer and other incomes are added. Disposable incomes are distributed from factors (BG) to households and firms (BH). This is the basis for determination of private consumption in market prices, including transport, by place of residence (BW). Private consumption is assigned to place of demand (DW) using a shopping model. In this process transport costs related to shopping are subtracted. Private consumption, together with intermediate consumption, public consumption and investments constitute the total local demand for commodities (DV) in basic prices through a Use matrix. In this transformation from market prices to basic prices (from DW to DV) commodity taxes and trade margins are subtracted. Local demand is met by imports from other regions and abroad in addition to local production. Through a trade model exports to other regions and production for the region itself are determined (from DV to AV). Adding export abroad, gross output by commodity is determined. Through a Make matrix the cycle returns to production by sector (from AV to AE). The stylised version of the model with the real circle illustrated, as well as the price concepts used, is shown in figure 3.2.
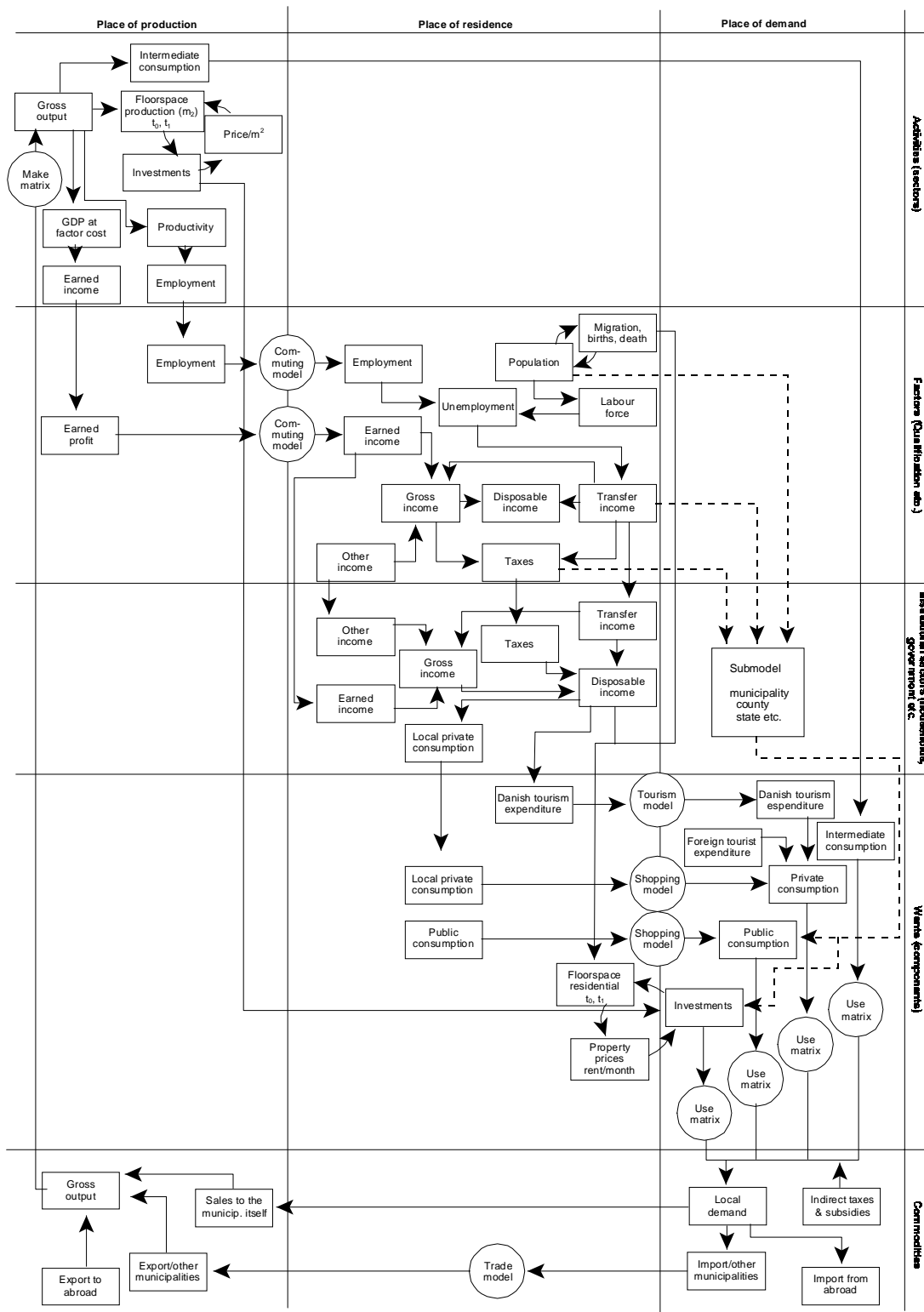
Fig. 3.1 The LINE model

	Place of production	Place of residence	Place of demand
Activities (Sectors)	Gross Output GDP at factor prices (AE)		
Factors of Production (education, gender, age)	Earned income Employment (AG)	Earned income Employment Unemployment Taxes and transfers Disposable income (BG)	
Institutions (households, firms, public sector)		Earned income Employment Taxes and transfers Disposable income (BH)	
Demand components		Local private consumption Residential consumption Tourist expenditure Public consumption Investments (BW)	Intermediate consumption Local private consumption Tourist expenditure Public consumption Investments (DW)
Commodities	Local production Exports to other municipalities Exports abroad (AV)		Local demand Imports from other municipalities Imports from abroad (DV)

————————— Constant prices

— — — — — — — Current prices

—

Fig. 3.2 Simplified version of LINE. The real circuit

	Place of production	Place of residence	Place of demand
Activities (Sectors)	Gross Output GDP at factor prices (AE)		
Factors of Production (education, gender, age)	Earned income Employment (AG)	Earned income Employment Unemployment Taxes and transfers Disposable income (BG)	
Institutions (households, firms, public sector)		Earned income Employment Taxes and transfers Disposable income (BH)	
Demand (components)		Local private consumption Residential consumption Tourist expenditure Public consumption Investments (BW)	Intermediate consumption Local private consumption Tourist expenditure Public consumption Investments (DW)
Commodities	Local production Exports to other municipalities Exports abroad (AV)		Local demand Imports from other municipalities Imports from abroad (DV)

_____ Basic prices (exclusive transport costs)

_ _ _ _ _ _ _ _ _ Market prices

▬▬▬▬▬ Basic prices (inclusive transport costs)

Fig. 3.3 Simplified version of LINE. The price circuit

Using again the stylised and complete version of the model shown in figure 3.2, the anticlockwise cost/price circuit shown in figure 3.3, corresponds to the dual problem. In cell AE sector basic prices (current prices) are determined by costs (intermediate consumption, value added and indirect taxes) though excluding transport costs. Through a reverse Make matrix, sector prices by sector are transformed into sector prices by commodity (from AE to AV). In the trade model lying between AV and

DV, transport costs related to trade are added transforming the value of commodities into basic prices including transport costs. These are then transformed into market prices through inclusion of retailing and wholesaling costs and indirect taxes (from DV to DW). This transformation takes place using a reverse Use matrix. Finally, private consumption is transformed from place of demand to place of residence in market prices including transport costs (from DW to BW).

In the description of the full model (Madsen et al 2001a) a more detailed treatment is to be found. In relation to analysis of transport, a number of significant elements can be identified.

3.2.1 Linking the transport and regional economic models
The link between LINE and a transport model can be seen in figure 3.4. The linked model is simultaneous as there are linkages in both directions. Spatial interaction forms the link from the regional economic model to the transport model and transport costs form the link in the opposite direction. Other linkages are to be found within the overall model. For example, demand for the transport commodity is determined in the transport model, whilst supply is met by interregional trade in the transport commodity.

In the following the main area of interest is the economic model and its linkages to the transport model. In relation to a traditional free-standing transport model the economic model has replaced the trip generation, attraction and distribution steps by an economic model for interaction (trade, commuting etc) and a model for trip frequency.

Figure 3.4 An ideal model: An integrated model for transport and regional economic change
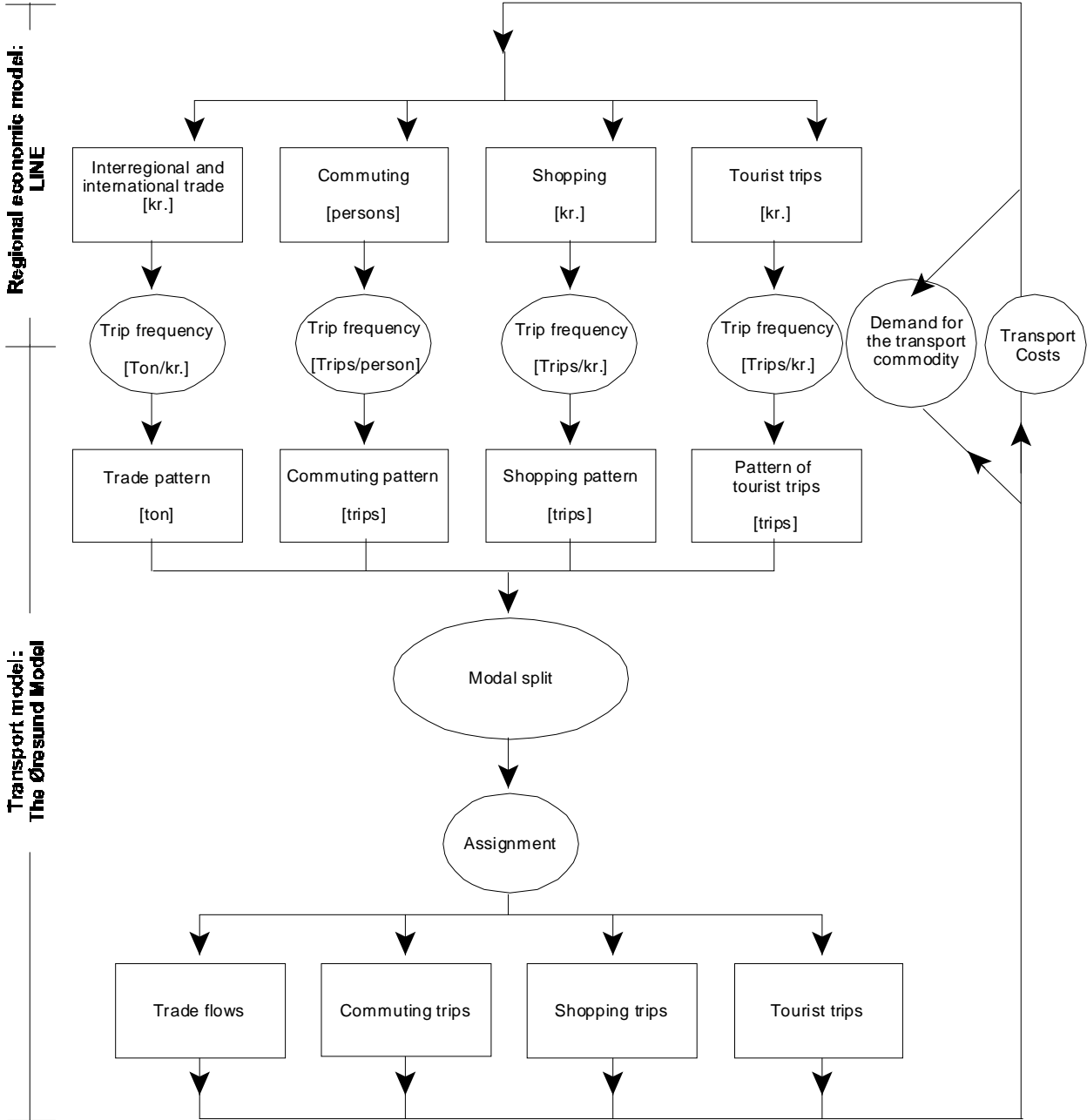
3.2.2 Transport inside LINE

A number of features of the treatment of transport inside LINE are important. First, the model distinguishes between mobile and immobile commodities. Mobile commodities are transportable commodities whilst for immobile commodities place of demand is by definition the same as place of production, including various forms of private and public service, for example hairdressing and hospitals. For immobile commodities the relation between demand and supply of commodities is direct as there is no interregional trade and therefore there are no transport costs. In the case of hairdressing the problem of transport costs is related to shopping trips. This is also the case for a number of components of consumption, for example services related to real estate.

Second, different price concepts are used. Commercial margins and net commodity taxes enter into the full model and in relation to the transport commodity this means that the price depends on the size of net commodity taxes (for example fuel taxation and road pricing).

Third, in a detailed version of LINE the transport sector can be subdivided into different transport subsectors, each has different productivity and employment levels.

For a general treatment of data construction and model structure, see Madsen et al 2001a and Madsen et al 2001b.

4. The linear model: simplified version

In the following, a simplified version of the linear model is described.

4.1 Defining the variables

Central elements in the model are the Make and Use matrices and the trade matrices. Tables 4.1-4.3 show the structure and notation on the Make, Use and Commodity Balance and Trade matrices used in the model. $\mathbf{V}$ is a Make matrix, $\mathbf{U}$ a Use matrix and $\mathbf{Z}$ an interregional trade matrix. The superscripts used are as follows: R denotes region of supply; S denotes region of demand; L denotes local (regional) origin of supply and demand; O denotes an other-region origin of supply and demand; F denotes foreign origin of supply and demand; D denotes domestic (all domestic regions). The subscripts used are as follows: V denotes commodity; E denotes sector; W denotes a component of final demand (or country group); IC denotes intermediate consumption; CP denotes private consumption; CO denotes public consumption; I denotes investment. In the equations which follow, the Use matrix in coefficient form is defined as $\mathbf{B}$, the Make matrix in coefficient form is defined as $\mathbf{D}$ and the trade matrix is $\mathbf{T}$. This is the same notation as used in Madsen & Jensen-Butler (1999). All variables are measured in fixed prices except for the case where there is a superscript

C, denoting current prices. The price index for a given variable in matrix or vector form is denoted by a prefix P.

Table 4.1 Make matrix by region

		Commodities	Total supply
Local output	By sector	$\mathbf{V}^{R,L}$	$\mathbf{V}^{R,L}_{E}$
	Total	$\mathbf{V}^{R,L}_{V}$	$\mathbf{V}^{R,L}_{V,E}$
Imports from abroad	By country	$\mathbf{V}^{R,F}$	$\mathbf{V}^{R,F}_{W}$
	Total	$\mathbf{V}^{R,F}_{V}$	$\mathbf{V}^{R,F}_{V,W}$
Total supply		$\mathbf{V}^{R}_{V}$	$\mathbf{V}^{R}$

Table 4.2 Use matrix by region

	Intermediate consumption		Private consumption		Public consumption		Investment		Local demand	Foreign exports		Total demand
Commodities	$\mathbf{U}^{S,L}_{IC}$	$\mathbf{U}^{S,L}_{V,IC}$	$\mathbf{U}^{S,L}_{CP}$	$\mathbf{U}^{S,L}_{V,CP}$	$\mathbf{U}^{S,L}_{CO}$	$\mathbf{U}^{S,L}_{V,CO}$	$\mathbf{U}^{S,L}_{I}$	$\mathbf{U}^{S,L}_{V,I}$	$\mathbf{U}^{S,L}_{V}$	$\mathbf{U}^{S,F}_{V}$	$\mathbf{U}^{S,F}_{V}$	$\mathbf{U}^{S}_{V}$
Total demand	$\mathbf{U}^{S,L}_{E,IC}$	$\mathbf{U}^{S,L}_{V,E,IC}$	$\mathbf{U}^{S,L}_{W,CP}$	$\mathbf{U}^{S,L}_{V,W,CP}$	$\mathbf{U}^{S,L}_{W,CO}$	$\mathbf{U}^{S,L}_{V,W,CO}$	$\mathbf{U}^{S,L}_{W,I}$	$\mathbf{U}^{S,L}_{V,W,I}$	$\mathbf{U}^{S,L}$	$\mathbf{U}^{S,F}_{W}$	$\mathbf{U}^{S,F}_{V,W}$	$\mathbf{U}^{S}$

Table 4.3 Commodity balance and trade

	The region itself	Other regions	Production for the domestic market	Export abroad	Total production
The region itself	$\mathbf{Z}^{R,L}_{V} = \mathbf{Z}^{S,L}_{V}$	$\mathbf{Z}^{R,O}_{V}$	$\mathbf{Z}^{R,D}_{V}$	$\mathbf{Z}^{R,F}_{V}(=\mathbf{U}^{S,F}_{V})$	$\mathbf{Z}^{R}_{V}(=\mathbf{V}^{R,L}_{V})$
Other regions	$\mathbf{Z}^{S,O}_{V}$	$\mathbf{Z}^{R,S,O}_{V}$			
Domestic demand	$\mathbf{Z}^{S,D}_{V}$				
Foreign imports	$\mathbf{Z}^{S,F}_{V}\ (=\mathbf{V}^{R,F}_{V})$				
Total demand	$\mathbf{Z}^{S}_{V}\ (=\mathbf{U}^{S,L}_{V})$				

[ ]: These four matrices constitute the gross intra and interregional trade matrix $\mathbf{Z}^{D}_{V}$

4.2 Conventional production - fixed prices[1]

First, gross value added (GVA) by place of production is determined by gross output (in figure 3.2 cell AE):

$$H^R = X^R - (i^V)' B_{IC}^{S,L} \hat{X}^R \qquad (1)$$

Where:

H^R : GVA by place of production, R

X^R : Gross output, by place of production R

$B_{IC}^{S,L}$: Intermediate consumption (IC), as a part of local demand (L), as share of gross output, at place of production S^2,

i^V : unity vector

$\hat{\ }$: denotes a diagonalised version of previously defined variable, in this case X^R

Gross value added by place of production is transformed into disposable income at place of residence by subtracting commuting costs from income (from cell AE to BE):

$$H^T = (i^R)'(1 - B_{V=tr,commuting,CP}^{R,T}) \# J^{R,T} \hat{H}^R$$
$$= (i^R)'(1 - B_{V=tr,commuting,CP}^{R,T}) \# H^{R,T} \qquad (2)$$

Where:

H^T : Disposable income (income net of transport expenditure) by place of residence T

$B_{V=tr,commuting,CP}^{R,T}$: Demand for transport commodity for commuting (as a part of private consumption) as share of factor income by place of residence T and place of production (work) R

$J^{R,T}$: Commuting coefficient matrix by place of residence T and place of production (work) R

$H^{R,T}$: Gross value added by place of production R and place of residence T

: Cell-by-cell multiplication

i^R : Vector containing 1's for summing away place of production, R

The input to this step ($B_{V=tr,commuting,CP}^{R,T}$) is data for commuting cost in value terms. In the following other elements of transport costs are used

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[1] In this section, almost all variables are in fixed prices. In the extended LINE disposable income etc. are modelled in current prices.

[2] Which is by definition equal to place of production R

Private consumption by place of residence is calculated as follows (cell BW):

$$U_{V,CP}^{T,L} = B_{V,CP}^{T,L} \hat{H}^T \qquad (3)$$

Where:

$U_{V,CP}^{T,L}$: Private consumption, CP, by commodity V, as part of local demand L, by place of residence T

$B_{V,CP}^{T,L}$: Private consumption CP, by commodity V, as a part of local demand, as a share of disposable income by place of residence T

Private consumption by place of demand is calculated (from cell BW to DW):

$$
\begin{aligned}
U_{V,CP}^{S,L} &= (i^T)'(1 - B_{V,tr=shopping,CP}^{T,S}) \# K_V^{T,S} \hat{U}_{V,CP}^{T,L} \\
&= (i^T)'(1 - B_{V,tr=shopping,CP}^{T,S}) \# U_{V,CP}^{T,S,L}
\end{aligned} \qquad (4)
$$

Where:

$U_{V,CP}^{S,L}$: Private consumption, CP, by commodity V, as part of local demand L, by place of demand S

$B_{V,tr=shopping,CP}^{T,S}$: Demand for transport commodity (as a part of private consumption), for shopping as share of private consumption by place of residence T and place of demand S

$K_V^{T,S}$: Shopping coefficient matrix by place of residence T and place of demand S

$U_{V,CP}^{T,S,L}$: Private consumption, CP, by commodity V, by place of residence T and place of demand S

Intermediate consumption is determined by gross output (from cell AE to DV):

$$U_{V,IC}^{S,L} = (i^E)' B_{IC}^{S,L} \hat{X}^R \qquad (5)$$

Where:

$U_{V,IC}^{S,L}$: Intermediate consumption, IC, by commodity V, as part of local demand L, by place of demand S

$B_{IC}^{S,L}$: Intermediate consumption, IC, by commodity and by sector, as a share of gross output, by place of demand S

Total local demand is given by (cell DV):

$$U_V^{S,L} = U_{V,IC}^{S,L} + U_{V,CP}^{S,L} + U_{V,CO}^{S,L} + U_{V,I}^{S,L} \qquad (6)$$

Where:

$U_V^{S,L}$: Total local demand L, by commodity V, by place of demand S. The subscripts IC, CP, CO and I represent the components of local demand: intermediate consumption, private consumption, public consumption and investment, respectively.

Public consumption and investment are given exogenously.

Local demand, which is supplied domestically, is determined by subtracting foreign imports (cell DV):

$$Z_V^{S,D} = U_V^{S,L} - Z_V^{S,F} \qquad (7)$$

Where:

$$Z_V^{S,F} = T_V^{S,F} \# U_V^{S,L} \qquad (8)$$

Where:

$Z_V^{S,D}$: Domestically supplied local demand D by place of demand S and commodity V

$Z_V^{S,F}$: Foreign imports F by place of demand S and commodity V

$T_V^{S,F}$: Foreign imports F as share of local demand by place of residence S and commodity V

Domestic production is determined by a trade model (from cell DV to AV):

$$Z_V^{R,D} = (i^S)'(1 - B_{V=\text{int.}trade,IC}^{R,S}) \# T_V^D \hat{Z}_V^{S,D}$$
$$= (i^S)'(1 - B_{V=\text{int.}trade,IC}^{R,S}) \# Z_V^{R,S,D} \qquad (9)$$

Where:

$Z_V^{R,D}$: Gross output for domestic demand D by place of production R and commodity V

$B_{V=tr,trade,IC}^{R,S}$: Demand for the transport commodity as an intermediate commodity as share of trade by place of demand S and place of production R.

T_V^D : Domestic (D) trade between place of production and place of demand as share of local demand for domestic production by commodity V

$Z_V^{R,S,D}$: Domestic trade between place of production R and place of demand S and by commodity V

Foreign exports are determined by subtracting transport costs (cell AV):

$$Z_V^{R,F} = (i^F)'(1 - B_{V=tr,foreign\ trade,IC}^{R,F}) \# T_V^{R,F} \hat{Z}_{V,MP}^{R,F}$$
$$= (i^F)'(1 - B_{V=tr,foreign\ trade,IC}^{R,F}) \# Z_{V,MP}^{R,F} \qquad (10)$$

Where:
$Z_V^{R,F}$: Foreign exports F by place of production R by commodity V

$B_{V=tr,foreign\ trade,IC}^{S,F}$: Demand for the transport commodity for transport as an intermediate commodity as share of foreign exports (F) by country group (as B is municipality x group of countries) and by place of production R

$T_V^{R,F}$: Foreign exports (F) by country group as share of total foreign exports, by commodity V and by place of production R

$Z_{V,MP}^{R,F}$: Foreign exports F by place of production R by commodity V, in market prices MP

By adding foreign exports, local production can be calculated (cell AV):

Where: $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ *(11)*

$V_V^{R,L}$, Z_V^R : Local gross output by place of production R, by commodity.

$V_V^{R,L} = Z_V^R = Z_V^{R,D} + Z_V^{R,F}$

Transforming gross output by commodity to gross output by sector closes the real circle:

$$X^R = (i^V)' D^{R,L} \hat{Z}_V^{R,L} \qquad\qquad (12)$$

Where:
$D^{R,L}$: Is the make matrix

4.3 Production in the transport sector – fixed prices

As can be seen in this model description, transport costs enter into the model in different ways. First, for households, transport costs appear in relation to commuting

as a deduction from household income and purchases of goods include transport costs involved with transporting the goods to place of residence. Second, for firms, wage costs are gross and include payment of commuting costs. It is assumed that the seller pays transport costs (fob). The firms' revenues from sale of commodities therefore exclude transport costs.

The approach used here is the inverse of the well-known *iceberg concept* (Samuelson 1954) implying the inverse of the idea that a part of the commodities disappear on the way to the market. The cost approach used here corresponds to an increase in the price of the product under transport to the market.

Demand for transport can be determined by adding up (relating interaction cells to cell VR):

$$U_{V=tr,commuting,CP}^{R,T} = B_{V=tr,commuting}^{R,T} \# H^{R,T} \qquad (13a)$$

$$U_{V=tr,shopping,CP}^{T,S} = B_{V=tr,shopping}^{T,S} \# U_{V,CP}^{T,S} \qquad (13b)$$

$$U_{V=tr,ir.trade,IC}^{R,S} = B_{V=tr,ir.trade}^{R,S} \# Z_{V}^{R,S} \qquad (13c)$$

$$U_{V=tr,for.trade}^{R,F} = B_{V=tr,for.trade}^{R,F} \# U_{V}^{R,F} \qquad (13d)$$

Where:

$U_{V=tr,xxx.yy}^{O,D}$: Demand for transport commodity for economic transactions between regions O and D for interaction type xxx and demand category yy. For interaction type commuting, xxx = commuting and demand category yy = CP (private consumption), O=R and D=T.

Assuming that demand for transport for commuting and shopping (private consumption) are related to place of residence T, the following holds:

$$U_{V=tr,CP}^{T,L} = (i^{R})'U_{V=tr,commuting,CP}^{R,T} + (i^{S})'U_{V=tr,shopping,CP}^{T,S} \qquad (14a)$$

For interregional trade and foreign trade, it is assumed that demand for transport (intermediate consumption) is related to place of production:

$$U_{V=tr,IC}^{R,L} = (i^{S})'U_{V=tr,ir.trade,IC}^{R,S} + (i^{F})'U_{V=tr,foreign.trade,IC}^{R,F} \qquad (14b)$$

From this step the transport commodities are treated in the same way as all other commodities: In the first step, private consumption of transport commodities is transformed into place of demand (shopping) and intermediate consumption of the transport commodities is added. In the second step, total demand, trade and production of transport commodities are determined like demand and production for

all other commodities. Third, gross output in the transport sector and other transport commodity producing sectors (e.g. the sector-internal production of transport commodities) is determined.

4.4 Conventional production - current prices[3]

In the simple version the real circuit is modelled almost exclusively in fixed prices. In the cost-price circle variables are transformed into current prices. Starting from the determination of labour supply, as a function of prices of commodities, wage rates and allocation of time, as described above, gross value added in current prices is determined.

Economic activities in current prices are modelled using a mark-up principle. Gross output in current prices is determined as follows (in figure 3.3 cell AE):

$$X^{R,C} = (i^V)' PUK_{IC}^{S,L} \# U_{IC}^{S,L} P\hat{U}_{V,demand,cat=IC}^{S,L} + H^{R,C} \qquad (15)$$

Where:
$PUK_{IC}^{S,L}$: Price correction matrix (PK) for intermediate consumption (U), by commodity and by sector and by place of demand S
$P\hat{U}_{V,demand.cat=IC}^{S,L}$: Commodity prices for intermediate consumption IC, by commodity V and place of demand S
$U_{IC}^{S,L}$: Intermediate consumption by commodity and sector at place of demand S
The superscript C denotes current prices.

An output price index can now be determined implicitly[4] (cell ER in figure 3.3):

$$PX^R = X^{R,C} / X^R \qquad (16)$$

Where:
PX^R : Price index by sector and by place of production R.

Gross output by sector in current prices can be transformed into gross output by commodity using a sector price index:

$$V^{R,L,C} = PVK^{R,L} \# V^{R,L} P\hat{X}^R \qquad (17a)$$

$$(17b)$$

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[3] In this section most variables are in current prices. Current price variables are indicated with an upper C.
[4] Intermediate consumption by commodity and sector can be derived implicitly from equation (5)

$$V_V^{R,L,C} = (i^E)' V^{R,L,C}$$

Where
$PVK^{R,L}$: Price correction matrix by commodity and by sector and by place of production R

An output commodity price index can now be determined implicitly (cell VR in figure 3.3):

$$PV_V^{R,L} = V_V^{R,L,C} / V_V^{R,L} \qquad (17c)$$

Where:
$PV_V^{R,L}$: Prices by commodity V, by place of production R

In a similar way, both sector prices and commodity prices for all sectors and commodities, including the transport sector and commodity, can be determined.

In the next step foreign exports in current prices are determined:

$$Z_V^{R,DF,C} = PZK_V^{R,DF} \# Z_V^{R,DF} P\hat{V}_V^{R,L} \qquad (18a)$$

Where:
$PZK_V^{R,DF}$: Price correction matrix for domestic and foreign sales by commodity V and by place of production R
$Z_V^{R,DF}$: Gross output divided between foreign and domestic demand by commodity V and place of production R

Basic prices for output produced both for foreign and domestic markets can now be determined:

$$PZ_V^{R,DF} = Z_V^{R,DF,C} / Z_V^{R,DF} \qquad (18b)$$

Where:
$PZ_V^{R,DF}$: Implicit basic price index for foreign (F) and domestic (D) sales by commodity V and place of production R

Now foreign market prices in current prices can be determined by adding transport cost in current prices:

$$Z_V^{R,F,C} = PZK^{R,F} \# Z^{R,F} PZ_V^{R,DF=F} + U_{V=tr,for.\exp ort,IC}^{R,F,C}$$

(19a)

A country-specific implicit price index for foreign market prices can be derived:

$$PZ_V^{R,F} = Z_V^{R,F,C} / Z_V^{R,F}$$

(19b)

Where:
$PZ_V^{R,F}$: Implicit market price index for foreign sales by country and by commodity V and place of production R

Interregional trade in current market prices can be calculated as follows:

$$Z_V^{D,C} = PZK_V^D \# Z_V^D (\P Z)_V^{R,DF=D} + U_{V=tr,ireg.trade,IC}^{R,S,C}$$

(20a)

$$Z_V^{S,D,C} = (i^R)' Z_V^{D,C}$$

(20b)

$$PZ_V^{S,D} = Z_V^{S,D,C} / Z_V^{D,C}$$

(20c)

By adding imports from abroad, local consumption in market prices can be determined:

$$U_V^{S,L,C} = Z_V^{S,D,C} + PZK_V^{S,F} \# Z_V^{S,F} (P\hat{Z})_V^{S,F}$$

(21a)

An implicit index for local market prices by commodity can now be derived:

$$PU_V^{S,L} = U_V^{S,L,C} / U_V^{S,L}$$

(21b)

Local demand for commodities can be divided into categories of demand. For each category the market price by commodity is calculated in the following manner:

$$U_{V,demand.cat}^{S,L,C} = PUK_{demand.cat}^{S,L} \# U_{V,demand.cat}^{S,L} (P\hat{U})_V^{S,L}$$

(22a)

$$PU_{V,demand.cat}^{S,L} = U_{V,demand.cat}^{S,L,C} / U_{V,demand.cat}^{S,L}$$

(22b)

Prices of intermediate commodities enter into output prices by sector, using the adding up principle – see equation 15. This closes the cost price-circle.

A number of other market price deflators can be calculated. The most important is the link between gross value added and private consumption. Deflation takes place from two sides.

From the side of production, gross value added is transformed to disposable income by deducting transport costs related to commuting and from the demand side by deducting transport costs related to shopping from commodity market prices by place of demand.

In the case of production and income, disposable income in current prices is calculated as follows:

$$H^{T,C} = (i^R)' PHK^{R,T} \# H^{R,T,C} P\hat{H}^R - U^{R,T,C}_{V=tr,commuting,CP} \qquad (23)$$

From the demand side, private consumption in current prices by place of residence can be calculated as follows:

$$U^{T,C}_{CP} = (i^S)' PUK^{S,T}_{CP} \# U^{S,T}_{CP} P\hat{U}^S_{CP} - U^{T,S,C}_{V=tr,shopping,CP} \qquad (24a)$$

The implicit price index for private consumption by place of residence can now be determined:

$$PU^T_{CP} = U^{T,C}_{CP} / U^T_{CP} \qquad (24b)$$

$$PU^T_{CP,TOTAL} = (i'U^{T,C}_{CP})(i'U^T_{CP}) \qquad (24c)$$

This price index can be used for deflating real disposable income:

$$H^T = H^{T,C} / PU^T_{CP,TOTAL} \qquad (25)$$

The remainder of the cost-price circle is developed along the same lines.

4.5 Production in the transport sector – current prices

In calculation of production in current prices, demand for transport commodities in current prices enters. Calculation of purchase of transport commodities in current prices is carried out by multiplying purchase of transport commodity in fixed prices (for example in equations 13a-13d) by a price index for transport commodities obtaining demand for transport commodities in current prices (equations 19a, 20a, 23). The demand for transport commodities in current prices and the price index for transport commodities are calculated in a similar way to the corresponding variables for other commodities. The point of departure is the production price index in the transport sector (and other transport commodity producing sectors), which is

transformed into production in current prices and a price index for transport commodities, which in turn is transformed into commodity demand in current prices and a price index by place of demand for transport commodities.

4.6 Linking the cost-price and real circles in LINE
In the simple version of LINE presented above, the cost-price circle does not have impacts on the real circle. Changes in local costs and prices only have an impact on economic activity measured in current prices, but local economic activity in fixed prices is unchanged. Application of the simple version of the model provides, therefore, only a limited number of effects, which are, however, not without interest. By incremental introduction of links between the two circles a more complete picture of effects of changes in the cost-price circle on the real circle can be obtained. These links are as follows:

i) Commodity markets effects

a) Changes in consumer prices in the cost-price circle will influence real disposable income. Road pricing will reduce disposable income, which will have the immediate effect of reducing private consumption
b) Changes in export and import prices will affect foreign exports and imports. Unilateral Danish road pricing will increase export price resulting in a loss of competitiveness and a decline in export, whilst the effects on import prices will be negligible. At the same time the prices of domestically produced commodities will rise, which implies increasing consumption of imported goods in relation to domestically produced goods.

ii)Factor market effects
a) Changes in disposable income imply changes in the relative lengths of working time, home production time and leisure time. This affects the supply of labour, the equilibrium wage and thereby costs of production. These cost changes in turn work their way through the cost-price circle, influencing a number of variables in the real circle, for example exports and imports.
b) Changes in consumption and earnings patterns will occur, because of the differential effects on transport intensive consumption (for example tourism) and transport intensive earning activities (for example long distance commuting).

5. Empirical results
The version of LINE at present in use has 16 regions, corresponding to the Danish counties, including the municipalities of Copenhagen and Frederiksberg, which have county status. Twelve sectors and 18 commodities are used, including the transport

commodity and sector, covering all types of transport. 15 components of private consumption are employed, including fuel for transport and transport services as two separate components. Factors are divided into wages and profits and the wage side is subdivided into seven educational groups. Institutions include households and the governmental sector, where households are subdivided into eleven different types by marital status and numbers of children.

The present version of LINE is based on exogenously given interregional transport costs. In the longer term, the aim is to establish interaction between LINE and the National Transport model, so that calculation of transport costs becomes endogenous. The matrices used here show the travel impedance between the 16 amter in Denmark in 2 different scenarios (with and without road pricing). The impedance is minimized with regards to the cost and the length and time matrices corresponding to the path found when minimizing the cost. A digital map of Denmark (VejdetDK) has been used for the calculation, where the network consists of 100,031 links and 79,476 nodes.

5.1 Road pricing
In this initial analysis, a simple road pricing principle has been used, where the following costs have been added to all links. In urban areas (dense urban and urban) 0.66 DKR/km and in rural areas 0.15 DKR/km. No differentiation has been made between different types of roads within the different types of area. The region-internal cost, length and travel time has been found as half of path along the longest diagonal in each zone.

5.2 Transport costs
Transport costs are based upon both time and distance where the generalised cost has been calculated as (Time x 200 KKR/h) + (Length x 2 KKR/km). Also included are costs of traveling by ferry and fixed links (Storebaelt).

Table 5.1 shows that transport costs for regions located around Copenhagen are most affected by road pricing.

Table 5.1 Percentage changes in transport costs with road pricing

	CopenM	FrbergM	CopenC	FrborgC	RoskC	WzealC	StStrmC	BornhC	FynC	SjutlC	RibeC	VejleC	RingkC	AarhusC	ViborgC	NjutlC
CopenM	9,74	8,56	11,21	12,90	13,84	8,48	7,41	1,95	5,09	5,02	5,04	5,27	5,69	5,59	5,38	5,40
FrbergM	8,56	8,42	11,26	13,02	14,34	8,48	7,37	2,13	5,04	4,97	5,00	5,22	5,66	5,55	5,34	5,36
CopenC	11,21	11,26	16,52	13,16	15,32	8,91	7,78	2,50	5,23	5,11	5,13	5,37	5,57	5,44	5,25	5,28
FrborgC	12,90	13,02	13,16	4,73	6,67	5,02	8,16	3,66	4,03	4,49	4,34	4,42	4,71	4,29	4,28	4,40
RoskC	13,84	14,34	15,32	6,67	8,15	4,94	4,75	3,74	3,35	3,81	3,98	3,98	4,19	4,30	4,29	4,42
WzealdC	8,48	8,48	8,91	5,02	4,94	4,19	4,82	3,90	2,75	3,57	3,80	3,76	4,07	2,96	3,96	4,09
StSTrmC	7,41	7,37	7,75	8,16	4,75	4,82	3,79	3,94	3,55	4,18	4,03	4,05	4,21	4,14	4,15	4,27
BornhC	1,95	2,13	2,50	3,66	3,74	3,90	3,94	3,76	3,52	3,74	3,82	3,82	4,25	3,94	3,97	4,06
FynC	5,09	5,04	5,23	4,03	3,35	2,75	3,55	3,52	5,46	4,68	4,82	5,51	5,19	5,35	4,91	5,42
SjutlC	5,02	4,97	5,11	4,49	3,81	3,57	4,18	3,74	4,68	4,40	4,58	4,91	4,51	5,09	4,74	4,89
RibeC	5,04	5,00	5,13	4,34	3,98	3,80	4,03	3,82	4,82	4,58	4,78	5,16	4,73	5,12	5,00	4,92
VejleC	5,27	5,22	5,37	4,42	3,98	3,76	4,05	3,82	5,51	4,91	5,16	4,46	4,87	5,32	4,76	4,93
RingkC	6,04	6,01	5,93	5,05	4,19	4,07	4,21	4,47	5,19	4,51	4,73	4,87	5,00	6,34	5,42	5,04
AarhusC	5,59	5,55	5,44	4,29	4,30	2,96	4,15	3,94	5,35	5,09	5,12	5,32	6,34	4,10	6,33	5,71
ViborgC	5,38	5,34	5,25	4,28	4,29	3,96	4,15	3,97	4,91	4,74	5,00	4,76	5,42	6,33	4,65	4,88
NJutlC	5,40	5,36	5,28	4,40	4,42	4,09	4,27	4,06	5,42	4,89	4,92	4,93	5,04	5,71	4,88	5,40

5.3 Effects on interaction in current prices (the cost-price circle)

These changes in transport costs affect both producers and households. Following the cost-price circuit shown in figure 3.3, demand met by domestic production by place of demand increases in current prices due to increased transport costs. As shown in Table 5.2, column 1, these increases are greatest in two distinct geographical situations. First, in peripheral regions, due to long-distance trade and second, regions with intensive intra-urban trade. Following the circle, these increases are transferred into market prices in retailing (column 2). The geographical pattern is similar to column 1, but at a lower level, because these prices are market prices. Continuing further, increased transport costs are also transferred to intermediate consumption in market prices (column 3), retaining the same basic structure. Gross output by sector and place of production (column 4) also increases. Finally, closing the circle, gross output by commodity and place of production (column 5) is identical with column 4. This process continues, generating not only a direct effect, but also redistribution of cost and price changes through the system of interregional trade. In Table 5.2 the total consequences, including the round-by-round effects are shown.

The effects of price changes on the real circuit is not included in table 5.2, but follows in table 5.3.

Table 5.2 Total effects of road pricing on costs and prices (percentage increase)

	Demand met by domestic production by place of demand. (DV in figure 3.3) Basic prices (1)	Private consumption by place of demand (DW in figure 3.3) Market prices (2)	Intermediate consumption by place of demand (DW in figure 3.3) Market prices (3)	Gross output by sector and place of production (AE in figure 3.3) Basic prices (4)	Gross output by commodity and place of production (AV in figure 3.3) Basic prices (5)
CopenM	0,45	0,28	0,42	0,19	0,19
FrbergM	0,38	0,25	0,30	0,11	0,11
CopenC	0,62	0,33	0,54	0,24	0,24
FrborgC	0,37	0,24	0,35	0,15	0,15
RoskC	0,44	0,25	0,38	0,17	0,17
WzealdC	0,40	0,26	0,36	0,18	0,18
StSTrmC	0,40	0,26	0,37	0,16	0,16
BornhC	0,70	0,46	0,57	0,25	0,25
FynC	0,40	0,24	0,34	0,16	0,16
SjutlC	0,50	0,40	0,43	0,22	0,22
RibeC	0,42	0,26	0,33	0,17	0,17
VejleC	0,37	0,22	0,31	0,16	0,16
RingkC	0,55	0,33	0,46	0,24	0,24
AarhusC	0,31	0,17	0,27	0,12	0,12
ViborgC	0,56	0,36	0,48	0,24	0,24
NjutlC	0,44	0,28	0,39	0,19	0,19

5.3 Effects on disposable income (from the cost-price circle to the real circle)

Table 5.2 provides results concerning price increases. The next step is to take into account their impact on real disposable income and private consumption, which is shown in table 5.3. Here, the effects of road pricing both on commodity trade and on shopping, tourism and commuting are included.

Table 5.3 Total effects of road pricing on private consumption and disposable income. Columns 1-4 show changes in nominal prices and column 5 shows real change in consumption. (All figures are percentage increases)

| | Local private consumption by place of residence (BW in figure 3.3) | Domestic tourists' consumption by place of residence (BW in figure 3.3) | Private consumption by place of residence (BW in figure 3.3) | Disposable income by place of residence (BW in figure 3.3) | Real disposable income by place of residence (BW in figure 3.3) |
	(1)	(2)	(3)	(4)	(5)
CopenM	0,95	1,46	0,96	-0,06	-1,02
FrbergM	0,80	1,57	0,84	-0,08	-0,92
CopenC	1,46	1,10	1,45	-0,08	-1,50
FrborgC	0,54	1,43	0,55	-0,07	-0,62
RoskC	0,68	1,16	0,69	-0,09	-0,80
WzealdC	0,60	1,72	0,61	-0,05	-0,68
StSTrmC	0,56	1,76	0,58	-0,05	-0,64
BornhC	0,63	2,33	0,64	-0,07	-0,73
FynC	0,66	1,16	0,67	-0,04	-0,72
SjutlC	0,58	1,13	0,59	-0,04	-0,64
RibeC	0,57	1,94	0,59	-0,05	-0,66
VejleC	0,56	1,46	0,57	-0,04	-0,62
RingkC	0,70	1,89	0,72	-0,04	-0,77
AarhusC	0,48	0,91	0,49	-0,04	-0,50
ViborgC	0,67	1,77	0,68	-0,04	-0,73
NjutlC	0,62	0,97	0,63	-0,03	-0,66

The table shows that price increases for local private consumption are greater than for private consumption by place of demand. This is because in the latter (table 5.2, column 1), only the effect of road pricing on trade is included, whilst in the former (table 5.3, column 1) the effects of road pricing on shopping is included. The general pattern is that Greater Copenhagen and peripheral regions face the greatest price increases. Column 2 shows that cost increases are higher for tourism , than is the case for local private consumption because in general, the distances involved are greater. The net effect (weighted) on private consumption can be seen in column 3. Column 4 shows disposable income by place of residence in current prices, reflecting the effect of road pricing on commuting. Finally column 5 shows real disposable income, adjusted for price increases in private consumption. Column 5 shows again the same pattern as earlier, that decline in real disposable income is greatest in the Copenhagen area and in peripheral regions.

5.4 Demand and supply (the real circle)

The decline in real disposable income has a number of consequences for the real economy. Private consumption declines, both at place of residence and place of demand, the effect appearing in the spatial components of the shopping and tourism submodels. These reductions appear in columns 1 and 2 in table 5.4 where it can be seen that the effects are somewhat smaller as are the differences between regions. Otherwise the general pattern of largest declines in the Copenhagen area and peripheral regions is again observable. Following the real circle in figure 3.2, columns 3-6 reveal that the effects of road pricing on total demand and production are relatively even in spatial terms. Interregional trade in both finished and intermediate goods, combined with the fact that industry is well represented in peripheral regions, at least in relative terms, lies behind this pattern.

Table 5.4 Total effects of road pricing on demand and supply. Columns 1-6 show changes in fixed prices. (All figures are percentage increases)

	Private consumption by place of residence (BW in figure 3.2)	Private consumption by place of demand (DW in figure 3.2)	Local demand by place of residence (DV in figure 3.2)	Local production by commodities (AV in figure 3.2)	Local production by sector (AE in figure 3.2)	Intermediate consumption by commodities (DV in figure 3.2)
	(1)	(2)	(3)	(4)	(5)	(6)
CopenM	-1,02	-0,57	-0,11	-0,13	-0,13	-0,13
FrbergM	-0,92	-0,72	-0,48	-0,40	-0,40	-0,38
CopenC	-1,49	-0,83	-0,16	-0,17	-0,17	-0,15
FrborgC	-0,61	-0,40	-0,14	-0,13	-0,13	-0,11
RoskC	-0,77	-0,54	-0,26	-0,22	-0,22	-0,20
WzealdC	-0,66	-0,45	-0,15	-0,12	-0,12	-0,11
StSTrmC	-0,62	-0,43	-0,19	-0,15	-0,15	-0,15
BornhC	-0,68	-0,61	-0,44	-0,27	-0,27	-0,26
FynC	-0,70	-0,42	-0,11	-0,11	-0,11	-0,09
SjutlC	-0,62	-0,45	-0,14	-0,11	-0,11	-0,09
RibeC	-0,63	-0,46	-0,14	-0,12	-0,12	-0,11
VejleC	-0,61	-0,40	-0,10	-0,10	-0,10	-0,09
RingkC	-0,75	-0,51	-0,13	-0,11	-0,11	-0,09
AarhusC	-0,50	-0,28	-0,07	-0,08	-0,08	-0,07
ViborgC	-0,71	-0,51	-0,16	-0,12	-0,12	-0,11
NjutlC	-0,65	-0,39	-0,09	-0,09	-0,09	-0,08

6. Limitations of the analysis

The above analysis represents one of the very first attempts using LINE to model the regional economic impacts of road pricing, which is why the analysis is limited in scope and the results are interim. However, it is possible to draw some initial conclusions. The principal limitations of the analysis are as follows.

The first set of limitations concern the treatment of transport costs.

Changes in transport cost depend on the price structure adopted for road pricing. In the present analysis it is assumed that road pricing affects lorries and cars equally and that the same price structure is used at all times of the day and year. One major problem is that time costs are at present a part of generalised transport costs, also for person transport. It would be more correct to eliminate time costs because household consumption is only influenced through the direct transport costs, such as fuel and ticket costs, wheras the time cost in the present analysis is treated as being exogenous. This means that the effects of road pricing on shopping, commuting and tourism are underestimated.

In calculation of the effects, no account has been taken of congestion externalities. Linking LINE to a transport model which includes congestion effects will in the future solve this problem. If road pricing reduces congestion, then the increase in transport costs will be more modest, reducing the negative effects.

No account has been taken of re-routing created by road pricing. This can result in an increase in transport costs, increasing the negative effects of road pricing on the regional economy. This problem can also be solved by linking LINE and a transport model.

The second set of limitations relate to the assumptions and structure of the regional economic model.

In the present version of the model, no account is taken of the effects of price increases in transport on households' consumption of transport and producers' intermediate consumption of transport. The model as yet does not include substitution effects. These effects include both changes in choice of destination and commodity substitution (for example staying at home rather than travelling on holiday). As substitution effects have not been included, consequences for production in the transport sector have not been presented, as the effects are minimal.

In the present analysis no account has been taken of the impact on public sector finances, which is especially relevant in relation to the above discussion of the double dividend. It can be assumed that the income from road pricing can be used to improve the transport system (governmental expenditure or investment). The income can also be used to reduce income tax, VAT or taxes on transport. All these financial questions have regional economic consequences and should be included in the final analysis. A more general discussion must assume that financial balances in other institutional sectors, such as households and firms, remain unchanged.

The effects of road pricing on competitivess in relation to foreign markets should also be included, especially if it is asssumed that road pricing is introduced unilaterally in Denmark. If this is the case, the cost/price changes will increase the price of Danish exports and create increased competition from imports. A fixed exchange rate model is relevant for analysis of regional economic impacts of road pricing. Deterioration of the balance of trade may lead to political initiatives, reducing domestic demand and improving competitiveness.

7. Conclusion

The paper has presented an interregional general equilibrium model, suitable for analysis of the regional economic effects of road pricing. First results of model runs have also been presented, indicating that regions surrounding the centre of Copenhagen and peripheral regions are those most negatively affected by road pricing. Further analyses will develop the sophistication of the model. A more differentiated road pricing system will be introduced together with the problems of congestion and re-routing. Substitution effects in relation to the transport commodity will be incorporated and institutional financial balance behaviour (for example tax reactions and tax policy) will be included in the model.

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