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Traffic, Transportation, Infrastructure and Externalities - a Theoretical Framework for a CGE Analysis -

Klaus Conrad

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Universität Mannheim
A5, 6
D-68131 Mannheim

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Klaus Conrad, Mannheim University[à]

Abstract

In Europe traffic congestions make it impossible to estimate travel time. The increasing number of cars calls for a transportation policy towards an improved efficiency of the transportation system. However, extending road infrastructure to reduce the congestion externality implies another type of externality, air pollution. Designing a transportation policy in industrialized countries one has to consider this trade-off. Our objective is to investigate the role of transportation services and their prices within an interindustry framework. The authority wishes to minimize total cost of production with respect to the provision of infrastructure subject to an emission standard. By omitting a financial constraint to finance infrastructure we determine the size of infrastructure where no congestion occurs. The productivity effect of infrastructure and the cost savings from a dissolved congestion determine the optimal stock of infrastructure. Our congestion index is unity in that case of no financial constraint. If the extension of infrastructure has to be paid for by taxation, we obtain a lower level of infrastructure. In view of the trade-off between the benefit of a productivity gain from a dissolved congestion and the deadweight loss from taxation this lower level of infrastructure will result in an index of congestion higher than unity, implying a negative externality to the economy.

[◊] University of Mannheim, Department of Economics, Seminargebäude A 5, D-68131 Mannheim
Phone +49 621 181 1896, Fax +49 621 181 1893, e-mail: kconrad@rumms.uni-mannheim.de

Traffic, Transportation, Infrastructure and Externalities

- a Theoretical Framework for a CGE Analysis -

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1. Introduction[*]

In Europe, and especially in Germany, traffic congestions make it impossible to estimate travel time. The increasing number of cars and the location of Germany in the center of Europe call for a transportation policy to improve the efficiency of our transportation system.[1] However, extending road infrastructure to improve mobility and to reduce congestions implies another type of externality, air pollution. This trade-off will have to be considered for a transportation policy in industrialized countries. For decades the literature on congestion type externalities has suggested congestion tolling or highway tolls as instruments to correct congestion externalities (Walters (1961), Mohring (1965), Vickrey (1967), Wheaton (1978) and Wilson (1983)). The argument is that the price of private motor vehicle usage is well below its social marginal cost. In spite of this, there are no highway tolls in Germany. An alternative to the introduction of a toll system at a high cost would be an increase in the gasoline tax with the advantage of lower transaction cost.

In addition to using price levers, the flow of traffic could also be improved by an extension of the road infrastructure. However, this also needs a price instrument for its financing. The problem of an optimal capacity determination under congestion externalities has been analyzed in Mohring (1970), Wheaton (1978) and D'Ouville and McDonald (1990). In these papers capacity affects the

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variable costs of the input „road service flow“ and the question of how to finance the extension of the capacity leads to the distinction between first-best and second-best rules of extending highway capacity. The capacity determination of infrastructure is first-best, if the extension moves along with a congestion toll. Without the consideration of a congestion toll and the environmental impact of road traffic, marginal costs of road usage are below social marginal costs and a second-best extension of capacity, purely based on demand, takes place.

The size of the optimal capacity of infrastructure depends, of course, on the assumptions made in the corresponding models. In most models the service flow of road infrastructure enters only the utility function of the consumers (Mohring (1970), Wheaton (1978), Wilson (1983)). In view of the steadily increasing transportation by trucks with the just-in-time philosophy as the main source of congestion externality, a cost and production approach like D'Ouville and McDonald (1990) seems to be as relevant as a consumer model. However, the relevance of infrastructure and the congestion externality is usually neglected in the literature. The analysis of infrastructure and congestion is the objective of this paper. One of our main concerns is the trade-off between savings in private costs as a result of a good provision of transportation infrastructure and the related increase in social congestion costs from the more intensive usage of infrastructure (more trips per person and more motorvehicles). This aspect is investigated by Gronau (1994), where again the travelling consumer is the object of the analysis but not transportation as an input of the production process. In the urban economic literature models of consumers caught in the daily rush-hour traffic can be found (e.g. McConnell and Straszheim (1982)), but no economy-wide approaches are available dealing with trucks as an input and its possibility of substitution by other modes of transportation.

A third dimension has to be added to the two already mentioned dimensions - the trade-off between private gain in productivity from more infrastructure, and the resulting increase in congestion

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[1] Useful surveys of the traffic literature are Winston (1985) and Oum et al. (1992).

- namely environmental pollution. Decisions about capacity extension, the need to finance this (e. g. by a higher gasoline tax) and also decisions about the determination of emission standards have to be made simultaneously.

Our objective is to investigate the role of transportation services and their prices within an interindustry framework. We are not interested in traffic as a local problem[2] but in its role as an important intermediate input, as a main air pollutor and in its general equilibrium effect on the performance of an economy (see for example: van den Bergh (1993), van den Bergh and Nijkamp (1993) and Mayeres and Proost (1994)). Van den Bergh (1993) investigates the relationship between freight transportation, production and consumption in a two-sector equilibrium model. In addition to the objective of cost minimization in the production of transportation services, and the modeling of supply and demand of transportation services subject to congestion externalities, van den Bergh makes an attempt to integrate spacial aspects into a computable general equilibrium model (CGE) as well. This integration of CGE models with a multiregional transportation analysis (for the latter see Liew and Liew (1991)) is a first step towards a comprehensive quantitative study on transportation policy.

However, modeling congestion externalities is only sketched in van den Bergh, and infrastructure is exogeneous and not an instrument of a transportation policy. In van den Bergh and Nijkamp infrastructure is endogeneous and the economic costs of the transportation system are taken into account. The modeling of the effects of congestion and infrastructure is not yet satisfactory. The negative externalities, environment and congestion, are not treated separately. The paper elaborates theoretical elements for a general equilibrium analysis without building a CGE

[2] In view of our objective of a quantitative analysis of a transportation policy with environmental aspects within an 58 industry-input-output model we are not interested in aspects of peak-load pricing as a basis of a congestion fee (see Lee and Wilson (1990), Mohring (1970), Kraus, Mohring and Pinfold (1976), Singh (1992), Mumy (1994)). Otherwise we had to endogenize the traffic density (rush-hour; vacation) which requires a too complex model.

model. The work by Mayeres and Proost is the closest to ours. They use a simple CGE model to demonstrate the introduction of an optimal taxation of congestion externalities. One of the taxes is a toll on traffic flow in peak-load hours. As in our model infrastructure is an instrument to dissolve congestion. However, our methodological approach is to endogenize the size of the congestion externality and to find the determinants for an optimal extension of infrastructure. In that, we will differ from their procedure.

We begin our construction of a CGE model with a multi-input production function where aggregated transportation services are one of the inputs (section 2). Its components are ship, railway, purchased truck services and firm owned trucks treated as quasi-fixed capital input. Within the input structure of our input-output table an industry can use its own transportation equipment or it can purchase services from the suppliers of alternative modes of transportation. There are therefore also industries which use their transportation capital to supply transportation services. For all industries the congestion externality has an output reducing effect. From the duality in the theory of cost and production one can derive a variable cost function for transportation with equipment for transportation as a quasi-fix capital stock and congestion as cost increasing externality. From Shephard's Lemma we obtain price-dependent input coefficients for the four transportation modes. From the envelope condition the optimal stock of transportation equipment can be derived and can be compared with the actual one (section 3).

In a first step we minimize the total cost of production given the infrastructure and the congestion externality subject to a NO_x emission standard (section 4). From this centralized solution we can derive a price lever as an instrument to make a decentralized solution of this problem possible. In a second step we abandon the assumption of proportionality of stocks and flows and make the service flow of transportation equipment dependent on its stock and the provision of infrastructure. The authority now minimizes total cost of production with respect to the provision of infrastructure subject to an emission standard (section 5). By omitting a financial constraint for the provision of infrastructure we determine the size of infrastructure when no congestion occurs. The emission standard and the productivity effect of infrastructure as well as the cost savings from a dissolved congestion determine the optimal stock of infrastructure. Our congestion index is unity in that case. In a next step we introduce a financial constraint for extending infrastructure in terms of a gasoline tax. In view of a trade-off between the benefit of a productivity gain from a dissolved congestion and the deadweight loss from energy taxation, this level of infrastructure will be below the optimal one where financial constraints have been neglected. In that case our index of congestion is higher than unity, implying a negative externality.

2. Cost function and input coefficients for the aggregated inputs

We characterize the technology of a cost minimizing industry by nested CES cost functions. *C(X, PK, PL, PE, PM, PT)* is the cost function at the first stage with input prices for capital, labor, energy, material and transportation. Our production function is therefore assumed to be CES in the corresponding inputs. Figure 1 shows the nested production structure.

Insert Fig. 1

Profit maximization under constant returns to scale implies revenue $PX \cdot X$ equal to cost which explains the output price PX of domestic production in terms of a CES unit cost function:

$$PX = \left[d_K \cdot PK^{1-s_x} + d_L \cdot PL^{1-s_x} + d_E \cdot PE^{1-s_x} + d_M \cdot PM^{1-s_x} + d_T \cdot PT^{1-s_x} \right]^{\frac{1}{1-s_x}} . \qquad \textbf{(1)}$$

From Shephard's Lemma we derive the factor demand functions as variable input coefficients:

$$\frac{i}{X} = d_i \left(\frac{PX}{P_i} \right)^{\sigma_x}, \qquad i = K, L, M, E, T. \tag{2}$$

In principle, one could include all the input prices of the model in one CES unit cost function. This, however, would imply the assumption, that the elasticity of substitution is the same between all inputs. We therefore specify subcost functions for the energy aggregate, the material aggregate and the transport aggregate with different elasticities of substitution. The price function for the energy aggregate at the second level is:

$$PE = \left[d_{1E} \cdot PEL^{1-\sigma_E} + d_{2E} \cdot PF^{1-\sigma_E} \right]^{\frac{1}{1-\sigma_E}}. \tag{3}$$

The price-dependent composition of the energy aggregate is:

$$\frac{EL}{E} = d_{1E} \left(\frac{PE}{PEL} \right)^{\sigma_E} \quad \text{and} \quad \frac{F}{E} = d_{2E} \left(\frac{PE}{PF} \right)^{\sigma_E}. \tag{4}$$

In order to determine the fuel input coefficient, one has to multiply (4) by (2) with $i = E$.

We furthermore have a unit cost function for material in its m components, similar to (3) and with input coefficients, analogous to (4). Similarly, we choose a CES specification for the unit cost function for transportation. This function is, however, more complex and consists of a variable unit cost function based on a CES variable cost function with a service flow KT from the industry's capital stock of transportation equipment. This service flow is quasi-fixed and depends, as will be explained later, on the stock of transportation capital and on road infrastructure.

The subproduction function for T is:

$$T = \left[d_{T1} \cdot T_1^{-\rho} + d_{T2} \cdot T_2^{-\rho} + d_{T3} \cdot T_3^{-\rho} + d_{T4} \cdot \left(KT \cdot Z^{-\gamma} \right)^{-\rho} \right]^{-\frac{1}{\rho}} \tag{5}$$

where $Z \geq 1$ is a congestion index the construction of which will also be explained later.[3] Then the variable cost function is

$$CT = c_T(PT_1, PT_2, PT_3) \cdot f(T, KT, Z)^{-\frac{1}{\rho}} \qquad \textbf{(6)}$$

where

$$f(T, KT, Z) = T^{-\rho} - d_{T4}\left[KT \cdot Z^{-\gamma}\right]^{-\rho}$$

and

$$c_T(PT_1, PT_2, PT_3) = \left[\sum_{i=1}^{3} \delta_{2,i}\, PT_i^{1-\sigma_T}\right]^{\frac{1}{1-\sigma_T}} \qquad \textbf{(7)}$$

with $\sigma_T = \dfrac{1}{1+\rho_T}$ and $\delta_{2,i} = d_{T_i}^{\sigma_T}$. We have $\dfrac{\partial CT}{\partial Z} > 0$ and $\dfrac{\partial CT}{\partial KT} < 0$.

The unit cost function for the intermediate good transportation is

$$PT = \frac{CT(\cdot)}{T} + \frac{PKT \cdot KT}{T} \qquad \textbf{(8)}$$

where PKT is the user cost price of the service KT and will also be explained later.

From the derivatives of the cost function CT we obtain the cost-minimizing allocation of transportation to its three variable components:

$$\frac{T_i}{T} = \frac{\delta_{2,i} \cdot \left[\dfrac{c_T(PT_1, PT_2, PT_3)}{PT_i}\right]^{\sigma_T} \cdot f(T, KT, Z)^{-\frac{1}{\rho}}}{T} \quad . \qquad \textbf{(9)}$$

If a better infrastructure or a higher stock of vehicles in an industry increases the service flow KT, then the input coefficients (9) decline because a better service from the firm's own trucks reduces the demand for the substitutes T_1, T_2 and T_3.

The demand for the transportation service KT will be modeled in the next section. If we

[3] The industry which buys services from road transportation T_1, does not care about whether Z does affect T_1. Z does affect T_1, however if T in (5) is the T of the transportation sector.

multiply the overall input coefficient by the sub-input coefficient we obtain the input coefficients a_i:

$$a_i = \frac{T_i}{X} = \frac{T_i}{T}(\cdot)\cdot\frac{T}{X}(\cdot), \qquad i = 1,\ldots,3,$$

(10)

$$a_i = \frac{M_i}{X} = \frac{M_i}{M}(\cdot)\cdot\frac{M}{X}(\cdot), \qquad i = 4,\ldots,m, \qquad a_L = \frac{L}{X}(\cdot)$$

(11)

and

$$a_F = \frac{F}{X} = \frac{F}{E}(\cdot)\cdot\frac{E}{X}(\cdot), \qquad a_{EL} = \frac{EL}{X} = \frac{EL}{E}(\cdot)\cdot\frac{E}{X}(\cdot). \tag{12}$$

The $(\cdot)$ indicates that the coefficients depend on relative prices. In a CGE analysis for measuring the impact of transportation policy, the prices influence the input structure A = (a_{ij}) as well as final demand FD. The solution of the system $x = Ax + FD$ yields the output vector x of the economy.

3. The effect of traffic congestion on the cost of production

If an industry requires transportation as an input in producing its output, it can choose among the services of trucks, ships or trains, or it can use its own stock of transportation equipment. Let KT_j^o be the stock of trucks in industry j; its service flow KT_j depends on this stock as well as on the availability of infrastructure KI. We express this relation by $KT_j = KT_j\left(KT_j^o, KI\right)$ and assume the specification:

$$KT_j = KT_j^0 \cdot \exp\left(-\frac{\gamma_j}{KI}\right), \qquad \gamma_j > 0, \tag{13}$$

where $KI \to \infty$ implies a full utilization of the stock KT_j^0.

In section 2 we have assumed KT_j^o and KI to be fixed, and specified a CES production function for the transportation aggregate T (see (5)) and a variable CES cost function (see (6)). The industry can purchase T_i , i = 1, 2, 3 or it can produce the service KT_j, depending on relative prices. The service KT_j has to be interpreted as a congestion free input, i.e. it is ex ante expected that there are no negative externalities. There exists, however, a congestion externality which is defined as the ratio of two geometric means:

$$Z := \frac{z}{z^*} := \frac{\prod_{k=1}^{n+1} KT_k^{b_k}}{\prod_{k=1}^{n+1} KT_k^{*b_k}} \geq 1\,. \qquad \textbf{(14)}$$

KT_k is the service of transportation equipment in industry k under congestion-free conditions, i.e. there is an efficient provision of infrastructure. The contribution of the households to congestion is KT_{n+1} which will be determined in section 7. KT_k^* is the reduced service flow due to lack of sufficient

The expression gives the saving in variable costs of the substitutes by providing one more unit of transportation services, i.e. we took the derivative with respect to KT_j, the congestion free input. A high congestion weight g_j diminishes the cost reducing effect of KT_j (see (1- β_j γ_j) in (15)). If we treat, however, the cost price as a given ex-ante price, say PKT^{ante}, then we will be able to solve (15) for the desired service flow $\overline{KT}$:

$$\overline{KT} = \left[\frac{c_T(\cdot) f(\cdot)^{-1 \ldots} d_{T4} (1-\beta_j \gamma_j) Z^{\gamma_j}}{PKT^{ante}} \right].$$

Demand for services $\overline{KT}$ increases in T, Z or in the price of the substitutes and decreases in the user cost.[4] Given KI and Z, the firm would prefer to have acquired the stock $\overline{KT}_j^0$ (derived from (13)), but in the short run it has to operate with KT_j^0.

It is important to realize that within our general equilibrium analysis an industry j can be a manufacturing sector or a sector which produces transportation services. Furthermore, we could assume that a firm considers Z to be exogeneous, i.e. it believes not to contribute to the congestion ($b_j = 0$ in (15)). An industry „transportation“ on the other hand knows about its contribution to congestion and calculates the shadow cost according to (15).[5]

We next add some cost components to the user cost of truck transportation PKT. For this purpose we make use of the duality approach in terms of linked inputs and corresponding cost prices (see Conrad (1983)). We decompose fuel consumption into a part proportional to transportation with factor γ_F, and a disposible part $\tilde{F}$, required for other production purposes in the industry.

$$F = g_F \cdot KT + \tilde{F} \,. \qquad \textbf{(16)}$$

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[4] As KT enters $f(\cdot)$, this is not an explicit solution for KT. For our purpose it is sufficient to employ a lagged value in $f(T, KT_{-1}, Z)$.

[5] This is a plausible assumption on the aggregate firm level, e.g. for large transportation companies.

In a similar way, a truck and a truckdriver are linked or interdependent inputs, and we decompose the industry's labor input into transportation personnel $g_L \cdot KT$ and other labor input:

$$L = g_L \cdot KT + \tilde{L} \; . \qquad \textbf{(17)}$$

Furthermore, the motorvehicle tax T^{MV} is proportional to *KT*, and so is the fuel tax T^F:

$$T^{MV} = t_{MV} \cdot KT \; , \qquad \textbf{(18)}$$

$$T^F = t_F \cdot F = t_F (g_F \cdot KT) + t_F \tilde{F} \; . \qquad \textbf{(19)}$$

Finally, the user cost of capital is $PI\,(r + d)$, where *PI* is the price of an investment good (car), *r* is the rate of return on risk-free government bonds and *d* is the rate of replacement.

By adding all cost components, multiplied by their corresponding prices, we obtain

$$PKT \cdot KT = PI(r + d) \cdot KT + PF \cdot g_F \cdot KT + PL \cdot g_L \cdot KT + t_{MV} \cdot KT + t_F \cdot g_F \cdot KT. \qquad \textbf{(20)}$$

In terms of costs *PKT* per unit of *KT* we find:

$$PKT = PI\,(r + d) + PL \cdot g_L + t_{MV} + (PF + t_F)\, g_F \; . \qquad \textbf{(21)}$$

This cost price of the input *KT* includes all cost components which accrue if the firm uses a truck. It reflects the real cost of employing a truck. A higher fuel tax increases *PKT*, reduces the demand for transportation services and, as a consequence, the demand for the stock, i.e. for trucks.

We finally return to the determination of an optimal $\overline{KT}_j$ from the envelope condition. The shadow cost PKT^s in (15) has to be equal to the real cost of a unit of transportation, which include all the other cost components. The optimal (and therefore lower) $\overline{KT}_j$ should be based on the higher cost price in (21). The long run objective of a firm is:

$$\min_{KT} C\,(Y, PKE, PM, PL, PF, PT(\cdot))$$

With *PT* as defined in (8), but now with the higher price *PKT* from (21), we obtain the envelope condition[6] as stated in (15). Condition (15), solved for the desired transportation services with PKT from (21), enables us to determine the purchase of trucks and the stock of transportation equipment for the next period.

4. Cost efficiency, given the present infrastructure and a standard for NO_X emissions

Given market failure in terms of the congestion externality, we first look for an allocation of transportation services by a central authority. Its objective is to minimize the production costs of the economy with respect to the services KT_j subject to an environmental restriction. Infrastructure KI is given, a congestion free index Z is a goal, not yet realized, and the authority's objective is only to achieve an optimal allocation of the KT_j's over all sectors of the economy. Assuming proportionality of stocks and flows, the objective of the authority is equivalent to allocate transportation equipment across industries. The authority knows about the productive effect of KT_j as well as its contribution to the two negative externalities, congestion Z and air pollution. It therefore minimizes[7]

$$\min_{KT_1,\ldots,KT_n} \sum_{j=1}^{n} \left[c_{T,j}(\cdot)\cdot f_j(T_j, KT_j, Z)^{-1} + PKT_j \right] \cdot KT_j \qquad \textbf{(22)}$$

subject to

$$NO_X = e_{NO_X}\left(\sum_{k=1}^{n} KT_k\right) \le \overline{NO}_X \qquad \textbf{(23)}$$

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[6] Note that

$$\frac{\partial C}{\partial KT} = \left(\frac{\partial C}{\partial PT}\right)\left(\frac{\partial PT}{\partial KT}\right) = T\left(\frac{\partial PT}{\partial KT}\right)$$

[7] This problem is eqivalent to minimizing $\sum C_j\ (q) = \sum X_j\, q\, PX_j\, [PKE\ (q), PLMFT(PL, PF, PM(q), PT(q))]$. This follows from Shephard's Lemma and from (9).

where e_{NO_X} is the emission coefficient for NO_X per unit of KT. In principle, NO_X emissions should depend on congestion. In Germany, e.g. wasted gasoline, linked to congestion, accounts for 9 billion ECU. This is also a reason for the government to invest in infrastructure, besides its objective to minimize costs in the economy. However, for reasons of simplicity we have not included Z in (23).

The f.o.c. are (23) as a binding restriction and

$$\frac{CT_l}{f_l} d_{4,l} \left(KT_l - Z\right)^{-\eta_l - 1} = \frac{1}{KT_l} \left(PKT_l + \frac{\delta \eta_l}{KT_l} \Delta C_{cong} + \lambda e_{NO_X}\right) \qquad l = 1, \dots, n \tag{24}$$

where

$$\Delta C_{cong} = \sum_{j=1}^{n} \frac{CT_j}{f_j} \quad d_{4j} \cdot \eta_j \cdot \left(KT_j - Z\right)^{-\eta_j - 1} \tag{25}$$

are the social cost of congestion and λ is the shadow cost of the emission restriction. Using (15), the social cost of congestion are the ex-post cost of transportation, excluding its own congestion contribution ($\eta_j = 0$):

$$\Delta C_{cong} = \sum_{j=1}^{n} \eta_j \cdot \left(PKT_j^s - KT_j\right). \tag{26}$$

$\delta \eta_l \, \Delta C_{cong}$ are external transportation costs to the economy caused by firm l's increase in vehicle use. Equation (24) equates the saving in variable transportation costs from KT with three cost components:

private variable cost saving effect of KT_l	=	*cost of an unit of KT_l*
	+	*congestion costs per unit of KT_l*
	+	*environmental costs per unit of KT_l.*

Without considering the two externalities we would have obtained KT_l from the envelope condition in the usual way. Now, however, the user cost of KT_l is augmented by the cost components of the two externalities to signal the social costs of KT_l. This implies a lower optimal stock of transportation equipment, given infrastructure and our assumption of the proportionality of stocks and flows.

In order to achieve the optimal allocation of transportation equipment chosen by a central authority in a decentralized manner, a tax on KT_l is required in order to internalize the costs of the externalities. In this tax rate, the congestion term $(\beta_l / KT_l) \cdot C_{cong}$ varies across industries according to their contribution to congestion whereas the environmental component λ_{NO_X} is the same. The appropriate tax rate which controls the two negative externalities in a decentralized manner, is:

$$t_l = \frac{\beta_l}{KT_l} \cdot C_{cong} + \lambda_{NO_X} \ . \qquad \textbf{(27)}$$

Each firm minimizes costs with respect to KT_l :

$$\min_{KT_l} \quad CT_l = ((r + \delta) PKT_l + t_l)\, KT_l \ . \qquad \textbf{(28)}$$

If the size of the tax rate has been determined by solving the system in (24), the f.o.c. of each industry is identical to one of the n conditions from (24) because a single industry considers the congestion externality Z as exogeneous, although KT_l contributes to Z.[8] The standard problem in setting the right Pigou tax also holds in our case; the authority has to know the optimal values from (24) to determine the optimal tax rate. This rate has to be higher for those industries that have a large weight β_l in the formation of Z.

5. Optimal infrastructure under a standard for NO_X emissions

We next focus on infrastructure *KI* as an instrument of the government to improve the provision of services for the stock of transportation means. The services *KT* are determined by the size of the stock *KT°* and by infrastructure *KI* (see (13)).[9]

In the preceeding section the government allocated transportation services, given the stock of motorvehicles *KT°* and of infrastructure *KI*. In this section the government determines optimal infrastructure which influences indirectly the allocation of the KT_j's. The government minimizes total cost of production in the economy with respect to *KI*, i.e. $\sum C_j(X_j,...,PT_j[KT_j(KI)])$, given the stock of vehicles in the industries and subject to the environmental restriction (23). This problem is equivalent to

$$\min_{KI} \sum_j \left\{ \varepsilon_{Tj}(\theta) \cdot f_j(\theta)^{-1} \cdot PKT_j \cdot KT_j \right\} + PKI \cdot KI \tag{29}$$

subject to (23).

The goal is similar to (22), i.e. to find an optimal allocation of the services KT_j but this time *KI* is used as a lever across all industries. The simultaneous determination of *KI* and of the stocks KT_j° is not considered to be the task of the government. *PKI* is the society's cost of infrastructure and $Z(\theta)$ in (14) is a ratio of geometric means from ex-ante congestion free services $KT_k(\theta)$ and ex-post services $KT_k^*(\theta)$. Infrastructure raises the productivity of *KT°*, the ex-post experienced service KT^* increases as a result of the improvement of road capacity, and the congestion index $Z = z/z^*$

[8] It might be more realistic to model a game in Nash-of-road-use conjectures. Each firm assumes that other firms will not expand their road transport but all do and they end up in a Nash „equilibrium" with congestion.

declines, given z.

[9] We assume, or have to assume, that a *KI* measure can be constructed, that it can be controlled by the government and that all travellers benefit from a new investment in infrastructure. This assumption can be critizised for many reasons, but for highways it is not implausible.

A crucial question is how the congestion-free services in the numerator of Z, denoted by $\bar{z}$, can be found. For that purpose we assume that in the f.o.c. for (29) $\bar{z}$ in $Z = \bar{z}/z^*$ is a given aggregate obtained in a situation with optimal infrastructure. The goal of the government is to raise z^* up to Z = 1, so that in the optimum $z^* = \bar{z}$ holds. Since in (29) expenditure for KI need not be financed by taxes, one can expect that an optimal solution eliminates congestion inefficiencies because deadweight losses from a tax burden are not at issue. Therefore we set Z=1 in the corresponding f.o.c. for $\overline{KI}$, which minimizes (29). As $\bar{z}$ only appears in the f.o.c. as part of Z (which is equal to one right now), there is no need to find a value for $\bar{z}$. We determine a value for $\overline{KI}$ and construct the geometric mean z^*. This will be our congestion free index $\bar{z}$ in the numerator of Z for the further analysis of congestion. The f.o.c. is:

$$\frac{1}{\overline{KI}}\sum_{j=1}^{n}\frac{CT_j \cdot KT_j^{-1} \cdot d_{T4,j}}{f(T_j, KT_j, Z=1)}\varepsilon_{KT_j,KI} = PKI - \frac{\partial C_{cong}}{\overline{KI}}\sum_{k=1}^{n-1}\delta_k\,\varepsilon_{KT_k,KI}$$
$$+\sum_{j=1}^{n}\frac{PKT_j \cdot KT_j}{\overline{KI}}\varepsilon_{KT_j,KI} + \varphi \cdot e_{NO_X} \cdot \sum_{j=1}^{n-1}\frac{KT_j}{\overline{KI}}\varepsilon_{KT_j,KI} \qquad \textbf{(30)}$$

where $\varepsilon_{KT_j,KI}$ is the elasticity of transportation services with respect to infrastructure. Condition (30) sets the cost-saving productivity effect of infrastructure under optimal $\overline{KI}$ equal to the social cost of infrastructure (PKI) reduced by the cost saving congestion dissolution [10] plus the infrastructure related increase in the cost of transportation services due to a better utilization of the stocks KT_j^{*} plus the environmental costs of the rise in road traffic.

Condition (30) is an implicit equation for $\overline{KI}$ which has to be solved for $\overline{KI}$. Then $KT_k = KT_k(KT_k^{*}, \overline{KI})$ follows for constructing the numerator z in the defined congestion index

[10] For calculating ∂C_{cong} from (25), Z has to be set equal to 1.

Z in (14). We have assumed that without a budget restriction in (29), $\overline{KI}$ eliminates congestion, i.e. Z = 1 in (30). However, if we take a budget restriction into account, the corresponding stock of infrastructure can be expected to be lower than $\overline{KI}$ without any financial restriction. Let KI^* be the infrastructure under a budget restriction (see equation (31) below). We then obtain $KT_k^* = KT_k(KT_k^{\circ}, KI^*)$. With these KT_k^* we construct the denominator z^* of the index Z. This denominator expresses the insufficient provision of infrastructure experienced ex-post.

We next determine this stock of infrastructure KI^* when infrastructure has to be financed in part by an energy tax. The government then minimizes the following objective function:

$$\min_{KI} \sum_{j=1}^{n} \Bigg(c_{Tj}(\cdot)\left[T_j^{-1} - d_{T4,j}\right] KT_j(\cdot)\left[\left(\frac{Z}{z(\cdot)}\right)^{-\gamma_j} - 1\right]^{-1} + PKT_j^{*} \cdot KT_j(\cdot)\Bigg) + PKI \cdot KI \qquad \textbf{(31)}$$

where PKT^* is $PKT + t_E\, \theta\, \gamma_F$ with PKT from (21). The budget restriction is

$$s \cdot PKI \cdot KI = t_E \cdot E \qquad \textbf{(32)}$$

where $E = \gamma_F \sum_{j=1}^{n+1} KT_j$ is fuel consumption in the economy and the environmental NO_X-restriction is (23). The parameter $0 \le s \le 1$ represents the share of infrastructure which has to be financed by the energy tax. Next we express the tax t_E in PKT^* as a function of KI, using (32):

$$t_E = \frac{s \cdot PKI \cdot KI}{\gamma_F \cdot \sum_{j=1}^{n+1} KT_j}. \qquad \textbf{(33)}$$

Under the CES specification given in (31) we obtain an implicit function for KI^* with PKT^s as derived in (15):[11]

[11] The f.o.c. is:

$$\frac{1}{KI^*}\sum_{j=1}^{n} PKT_j^s \cdot KT_j \cdot \varepsilon_{KT_j,KI} = PKI - \frac{\Delta C_{cong}}{KI^*}\sum_{k=1}^{n+1} \beta_k\, \varepsilon_{KT_k,KI}$$

(34)

$$+\sum_{j=1}^{n} \frac{PKT_j^* \cdot KT_j}{KI^*}\, \varepsilon_{KT_j,KI} + s \cdot PKI \left\{ - \sum_{j=1}^{n+1} \frac{E_j}{E}\, \varepsilon_{KT_j,KI} \right\} + \lambda\, e_{NO_X} \sum_{k=1}^{n+1} \frac{KT_k}{KI^*}\, \varepsilon_{KT_k,KI}$$

Before interpreting (34) we show that $\overline{KI} > KI^*$; i.e. infrastructure without a financial restriction is larger than infrastructure partly financed by an energy tax. We have to compare the conditions (30) and (34) and check how they differ. One important difference is in the price PKT^* in (34) which exceeds the price PKT in (30) by the energy cost component $(_F\, q\, t_E$. If we substitute PKT_j^* in (34) by $PKT_j + (_F\, q\, t_E$, we got the following positive term which does not appear in (30):

$$s \cdot PKI \sum_{j=1}^{n} \frac{E_j}{E} \cdot \varepsilon_{KTj,KI} \qquad \textbf{(35)}$$

This term cancels out with the same term in (34), but negative. Therefore, the right hand side of (34) exceeds the right hand side of (30) by $s \cdot PKI$. We conclude that $s \cdot PKI$, added to PKI in (34), increases the cost of providing an unit of KI. Thus $KI^* < \overline{KI}$, and therefore $KT_j^* < \overline{KT}_j$ given the stocks KT_j^{0}. This implies $z^* < \bar{z}$ and Z>1. Ex ante the participants in road traffic expect the index $\bar{z}$, ex post they experience the index z^* and find themselves in a congestion because of $Z = \bar{z}/z^* > 1$.

We finally summarize all the economic aspects which play a role in providing one more unit of infrastructure to the private economy. The meaning of (34) is:

$$\sum_{j=1}^{n} \left\{ \frac{\partial CT}{\partial KT_j}\frac{\partial KT_j}{\partial KI} + \frac{\partial CT_j}{\partial z}\sum_{k=1}^{n+1}\frac{\partial z}{\partial KT_k}\frac{\partial KT_k}{\partial KI} + \frac{d\, PKT_j^*}{d\, t_E}\frac{d\, t_E}{d\, KI}\cdot KT_j \right.$$

$$\left. + PKT_j^*\frac{\partial KT_j}{\partial KI} \right\} + PKI + \lambda\, e_{NO_X}\sum_{k=1}^{n+1}\frac{\partial KT_k}{\partial KI} = 0$$

cost saving	=	*capital cost of infrastructure*
productivity effect of	-	*congestion costs reducing effect of KI*
infrastructure	+	*derived transportation cost increase from a better service flow from the stock of vehicles*
	+	*allocative effect of tax financed infrastructure*
	+	*additional environmental cost from a better infrastructure*

This is a full list of all the arguments which play a role in the policy discussion about extending the road network.

6. Some simple calculations for a CGE application

Since the mathematical formulation of the productivity, congestion and environmental effects of infrastructure provision looks somewhat complex, we make some assumptions to show that the approach can be used for a CGE analysis. Under the assumption that all elasticities $\eta_{KT_j KI}$ are equal, (34), used to determine *KI**, reads:

$$\frac{1}{KI^*}\eta_{KT,KI}\sum_{j=1}^{n} PKT_j^s \cdot KT_j = PKI + \frac{\eta_{KT,KI}}{KI^*}\cdot\left(\partial C_{cong} + \sum_{j=1}^{n} PKT_j^* \cdot KT_j + \lambda\cdot\varepsilon_{NO_X}\sum_{k=n+1} KT_k\right) + s\cdot PKI(\eta_{t,KI} - 1)$$

which can be solved for *KI**.[12]

$$KI^* = \frac{\eta_{KT,KI}\left[\sum_{j=1}^{n} PKT_j^s \cdot KT_j + \partial C_{cong} - \sum PKT_j \cdot KT_j - \lambda\cdot\varepsilon_{NO_X}\cdot\sum KT_K\right]}{PKI\,(1+s)} \qquad \textbf{(36)}$$

The essential aspects of a tranportation policy have the right qualitative impact on KI^*, the

[12] This calculation of *KI** is only an approximation because *KI* enters also in *KT (KT°, KI)* and influences KT_j, which in turn enters $CT(\cdot)$. For an application we can, however, neglect this complexity.

productivity effect and congestion costs raise KI^*, capital costs (private user cost of KT and social cost PKI), environmental costs and the tax incidence of financing KI lower KI^*. The optimal infrastructure $\overline{KI}$ without a budget restriction can be determined from (30) in an analogous way; i.e by setting $s = 0$ in (36). The tax rate for financing KI^* follows from (32).

$$t_E^* = \frac{s \cdot PKI \cdot KI^*}{E^*}, \qquad \textbf{(37)}$$

where $E^* = g_F \cdot \sum KT_j \left(KT_j^{\circ}, KI^* \right)$.

Finally, for constructing Z we had specified in (13) a functional form for $KT_j\,(KT_j^{\circ}, KI)$, i.e.

$$KT_j = KT_j^{\circ} \cdot \exp(-\varphi_j \,/\, KI), \qquad \varphi_j > 0, \qquad \textbf{(38)}$$

If we insert $\overline{KI}$ from (36) (s = 0) into (38), we obtain $\overline{KT}_j$ and hence $\bar{z}$. Inserting KI^* we obtain KT_j^*, i.e. z^*. This yields $Z = \bar{z} / z^*$. We conclude that the government determines infrastructure, the firm determines the optimal stock of motor vehicles, and the service flow follows from (38). This flow KT_j is multiplied by Z^{-g} to give the reduced effective service flow.

7. Private households, motor vehicle use and congestion externality

We characterize preferences of consumers by a Stone-Geary utility function from which the linear expenditure system can be derived.[13] Minimizing expenditure, given the utility level $\bar{u}$, yields:

$$\min_{C_1,\ldots,C_{n+1}} e = \sum_{i=1}^{n+1} P_i \cdot C_i \qquad \textbf{(39)}$$

subject to

---

[13] In calibrated, i.e. non-econometrically estimated CGE models, more complex demand systems like the AIDS-model can not be implemented.

$$\bar{u} = \prod_{i=1}^{n} \left(C_i - C_{0,i}\right)^{r_i} \left(C_{n+1} \cdot Z^{-\gamma}\right)^{r_{n+1}} \tag{40}$$

where C_i is consumption of commodity i, $C_{0,i}$ is the minimum required quantity of commodity i, $C_{n+1} = KT_{n+1}$ is the service flow of private cars and its minimum required quantity $C_{0,n+1}$ is zero. We consider again private transportation KT_{n+1} as quasi-fixed and choose the dual representation of preferences in terms of an expenditure function.

$$e\left(P, \bar{u}, KT_{n+1}, Z\right) = \sum_{i=1}^{n} P_i \cdot C_{0,i} + \bar{u} \cdot \left(KT_{n+1} \cdot Z^{-\gamma}\right)^{-r_{n+1}} \prod_{i=1}^{n} \left(\frac{P_i}{r_i}\right)^{r_i}. \tag{41}$$

Using Shephard's lemma we obtain the optimal consumption plan:

$$C_i = \frac{\partial e(\cdot)}{\partial P_i} = C_{0,j} + \frac{r_i}{P_i}\left(e - \sum_{i=1}^{n} P_i \cdot C_{0,i}\right) \tag{42}$$

The ex-post price of KT_{n+1}, i. e. willingness to pay for one more unit of KT_{n+1} is:

$$-\frac{\partial e(\cdot)}{\partial KT_{n+1}} = \frac{r_{n+1}}{KT_{n+1}}\left(e - \sum_{i=1}^{n} P_i \cdot C_{0,i}\right) \tag{43}$$

With a higher stock of KT^{o}_{n+1}, and hence KT_{n+1}, expenditures e for all commodities have to be reduced $\left(\frac{\partial e}{\partial KT_{n+1}} < 0\right)$ in order to keep the standard of living at $\bar{u}$. With a lower e, all C_i*'s* in (42) will be reduced. The congestion index Z raises expenditure $e(\cdot)$ in (41). Three expenditure components are modes of transportation services which will benefit from congestion. The other consumption categories benefit from congestion because the consumer gives up the idea of a car trip and instead enjoys an expensive dinner or a theatre-going. It is straightforward to add household expenditure to the minimization problem in (22) in order to include household's contribution to the cost of congestion and to the environmental externality.

As a money metric utility measure for evaluating transportation policy proposals the equivalent variation EV can be used:

$$EV = e\left(P^B, u^P, KT^P_{n+1}, Z^P\right) - e\left(P^B, u^B, KT^B_{n+1}, Z^B\right) + PKT_{n+1}\left(KT^P_{n+1} - KT^B_{n+1}\right) \quad \textbf{(44)}$$

where the index B stands for the base case and P for the policy case. If we consider the specification of $e(\cdot)$ in (41) and of $\bar{u}$ in (40) we obtain

$$EV = \prod_{i=1}^{n}\left(\frac{P_i^B}{r_i}\right)^{r_i}\left[\prod_{i=1}^{n}\left(C_i^P - C_{0,i}\right)^{r_i} - \prod_{i=1}^{n}\left(C_i^B - C_{0,i}\right)^{r_i}\right] + PKT_{n+1}\left(KT^P_{n+1} - KT^B_{n+1}\right). \quad \textbf{(46)}$$

As an example let us suppose infrastructure has been improved. This reduces congestion and the substitute activities for the reduced car usage will be lower (i. e. the C_i^P will be lower). The first difference in (45) is negative. The positive effect comes from a better service flow KT^P_{n+1}, i.e. the second difference is positive. If it dominates the negative effect then $EV > 0$. This is the amount the consumers are willing to pay at the most to see the infrastructure improved. A CGE analysis also takes the effects of the tax to finance infrastructure into account. The corresponding price and hence quantity effects will influence the change in the C_i^P as well.

8. Optimal infrastructure for industries and private households

In section 4 and 5 we mentioned KT_{n+1} which is transportation used by private households. It has affected the congestion externality and contributed to higher cost of production. In this section we extend our search for an optimal infrastructure by assuming that the government wishes to minimize cost of producers and expenditures of private households. Then instead of (33) its objective is:

$$\min_{KI} \sum_{j=1}^{n}\left[CT_j\left(T_1,\ldots,T_j,KT_j,Z\right)+PKT_j^{*}\cdot KT_j\right] + e\left(p,\bar{u},KT_{n+1},Z\right)+PKT_{n+1}^{*}\cdot KT_{n+1}+PKI\cdot KI \qquad \textbf{(46)}$$

subject to the emission standard (23) and the budget restriction (32). It is again $Z = \frac{\bar{z}}{z} \geq 1$ according to the considerations made in section 5. The f.o.c. for KI^* in (34) now reads:

$$\frac{1}{KI^*}\sum_{j=1}^{n} PKT_j^{s}\cdot KT_j\cdot \eta_{KT_j,KI} + \frac{\lambda_{n+1}}{KI^*}\left[e - \sum_{i=1}^{n} p_i C_{0,i}\right]\cdot \eta_{KT_{n+1},KI}$$

$$= PKI - \frac{1}{KI^*}\left[C_{cong} - \gamma\lambda_{n+1}\left(e - \sum p_i C_{0,i}\right)\right]\sum_{k=1}^{n+1}\delta_k\cdot \eta_{KT_k,KI}$$

$$+ \frac{1}{KI^*}\sum_{j=1}^{n+1} PKT_j\cdot KT_j\cdot \eta_{KT_j,KI} + s\cdot PKI$$

$$+ \mu\cdot \varepsilon_{NO_x}\sum_{k=1}^{n+1}\frac{KI_k}{KI^*}\,\eta_{KT_k,KI}\,.$$

with the analogue to (35) already incorporated.

In words:

	*productivity effect per KI**	=	*cost of KI*
+	*marginal willingness to pay for a*	-	*reduction of congestion cost*
	*marginal unit of KI**	+	*additional cost from the increased*
			service flow of vehicles
		+	*tax effect*
		+	*environmental costs per KI**.

The objective of the formal analysis is to reveal costs and benefits of the provision of infrastructure. Similar to the procedure in section 5 to determine the optimal stock $\widetilde{KI}$, we can drop the financial restriction in (46) for getting a congestion free road system. The CGE calculations in section 6, now extended by the consumer model, require to add $r_{n+1}\,(e - \sum p_i\, C_{0,i})(1 + g)$ within the bracket of the numerator of (36) which summarizes the willingness to pay for more KI and the corresponding benefit from less congestion.

We can derive the optimal stock of motorvehicles owned by private households given infrastructure KI^* and tax rate t^*. Households minimize expenditure with respect to KT_{n+1}:

$$\min_{KT_{n+1}} e\left(\bar{u}, KT_{n+1}, P\right) + PKT^*_{n+1} \cdot KT_{n+1}$$

where PKT^*_{n+1} includes the tax component $t_E \cdot g_F$. Using (43) and the specification of $e(\cdot)$ in (41) yields:

$$\widetilde{KT}_{n+1} = \left[\frac{\alpha_{n+1}}{PKT^*_{n+1}}\left(\bar{u} - \sum_i \alpha_i \ln P_i\right)\right]^{\frac{1}{1-\alpha_{n+1}}}.$$

The long-run optimal stock KT^0_{n+1} then follows from a specification similar to (38).

It might be useful to provide a summary description of our approach and complement it by a figure. Fig. 2 gives such an overview.

Insert Fig. 2

The government provides infrastructure KI^* which is partly financed by a tax. It could, in principle, provide sufficient infrastructure $\widetilde{KI}$ (no congestion) if no financial restriction exists. As $KT^* < \widetilde{KI}$, Z is greater than one and reduces the actual service flow from the stock of vehicles. The firms determine the size of their stock of vehicles on the basis that they can fully utilize it. This assumption can be justified by arguing that a firm would reduce its stock by 20 percent if it can use only 80 percent of its capacity and would purchase instead services from other modes of transportation.

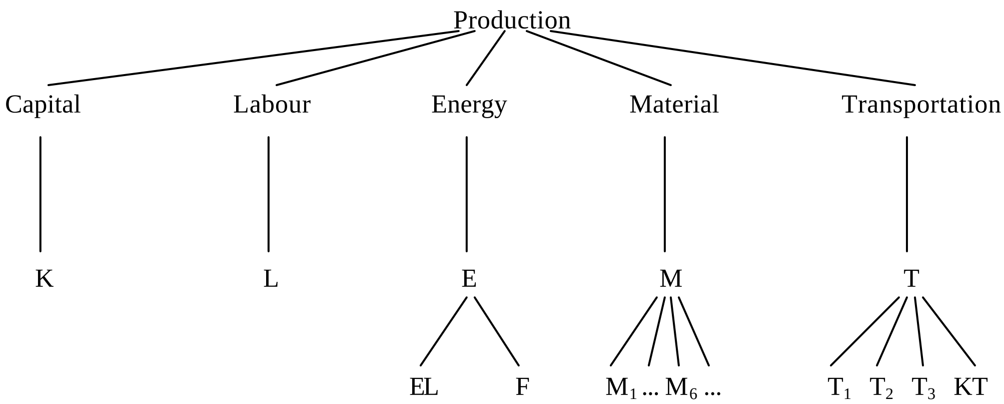
Infrastructure transforms the stock of transportation capital, $KT°$, to a service flow. As the length of highways in km does not say anything about its sufficiency, we construct an index of congestion. This index, in turn, is determined by the model in such a way that first an optimal stock $K\bar{I}$ is calculated which provides a congestion free flow of the stock of vehicles. Its size is hence not restricted by financial constraints and is solely based on the demand for transportation services by all sectors of the economy. However, since infrastructure has to be financed at least partly by (gasoline) taxes, the model determines an insufficient size of infrastructure, KI^*. The congestion index $Z > 1$ reduces productivity in all industries and hence raises the cost of production in the economy.

9. Summary and Conclusion

In this paper we have developed within a general equilibrium framework the impact of road infrastructure on the efficiency of the transportation system of an economy. Road transportation has external effects in two ways. First, it causes pollution and second, congestion occurs on the roads. The resulting load on the roads then leads to a smaller infrastructure productivity. As firms and consumers can procure transportation equipment or can purchase it from other industries (railway, ships, forwarding agencies), an analysis of the economic impact of the transportation system with its complements infrastructure, congestion, and pollution requires a CGE framework. The novel feature of this paper is the specification of cost and production functions and of a household expenditure function which include these obvious aspects and which permit to derive qualitative and quantitative results in a general equilibrium setting. Although modeling air pollution is straightforward, modeling congestion is not. We have developed a new approach to quantify congestion in such a way that the government can control it by investing in infrastructure. The degree of congestion is measured by a congestion index, which is the ratio between transportation services from the uncongested infrastructure system and the services from the actual congested infrastructure system.

A second novel feature is the extension of the standard user cost of transportation capital concept by adding operating costs like wages for drivers, costs for fuel and taxes on it, and a motorvehicle tax. If one of those cost components increases, the derived demand for transportation services from capital, owned by the firm, will decline. This extended user cost price plays a key role in our unified framework to endogeneous investment in both infrastructure and vehicles where the service flow of the latter depends on the quality of infrastructure. An important check of an optimization model is whether it can produce results which are useful in designing a better transportation policy. In this respect, our model produces all costs and benefits of expanding infrastructure in order to minimize the cost of production for all industries. The benefits are cost saving productivity effects for the economy and a reduction in the time cost of congestion. The costs of this policy are the capital cost of infrastructure, additional costs from the increased service flow of vehicles, the costs of tax distortion, and the costs of more air pollution due to the better infrastructure. In view of the high time cost of congestion in Europe - the estimate for Germany is 90 billion ECU or 5 percent of GDP - empirical analyses based on the theoretical framework suggested seem workable and worthwhile.

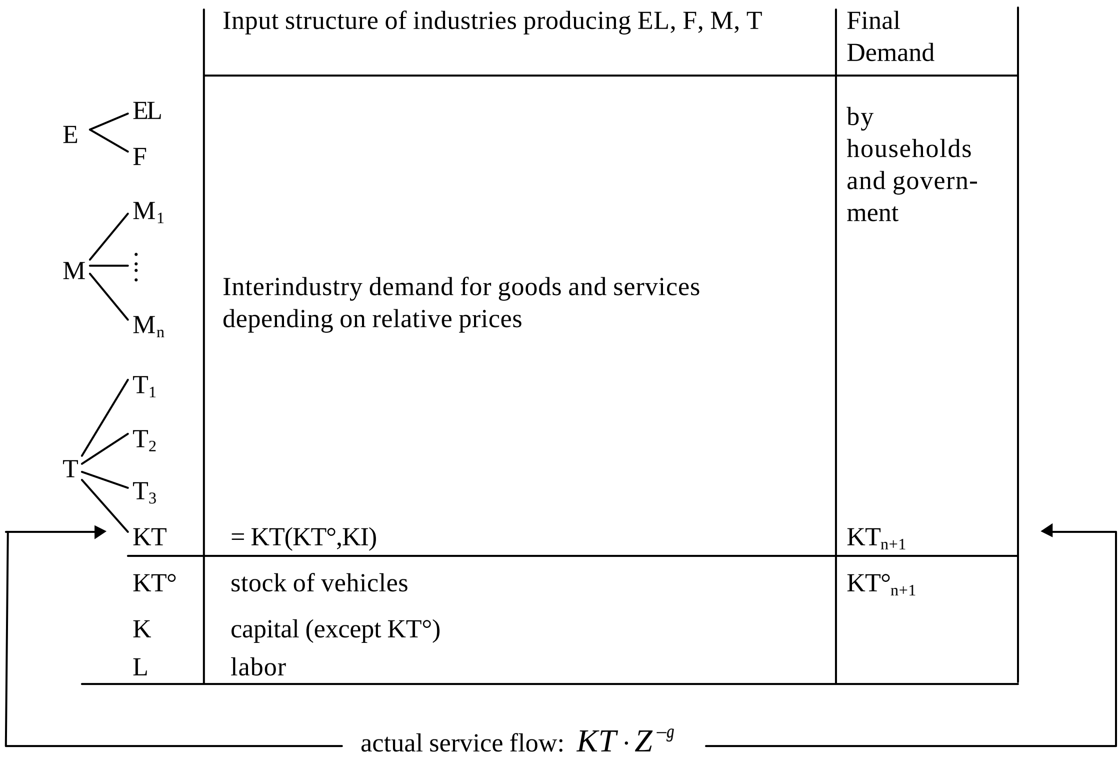
Fig. 1 The Nested Production and Factor Prices



where:

M_1 - iron and steel; M_2 - machinery; M_3 - construction; M_4 - motor vehicles; M_5 - shipbuilding; M_6 - light metal, trains, etc.; T_1 - road transportation; T_2 - water ways; T_3 - railways; *KT* -transportation capital services from stocks owned by the industry; *EL* - electricity; *F* - fuel.

Fig. 2 The Effect of Infrastructure on Congestion and of Congestion on Transport



Index of congestion: $Z = \dfrac{\sum KT_k(KT_k^{\circ}, KI)^{\alpha_k}}{\sum KT_k(KT_k^{\circ}, KI^{*})^{\alpha_k}} - 1$

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