# Unobserved Components of Fuel Consumption: Welfare Implications of Transport Price Changes

Hana Brůhová-Foltýnová* & Jan Brůha†

June 20, 2007

**Abstract**

We formulate and estimate a microeconometric model of household transport demand, which allows for latent separability of fuel consumption between urban and rural areas. Latent separability is crucial for transport price change assessments since external costs related to air pollution from fuel use differ between urban and rural areas. The estimation results are then used for calibration of a simulation model. The model assesses impacts of changes in passenger transport prices on fuel consumption, external effects of air pollution, household welfare and on public finance in a transition country. An exemplar calibration is taken for the five largest cities in the Czech Republic. We show that ignoring the different price elasticities of fuel consumption in the urban and rural areas can lead to serious errors.

**Keywords**: Fuel demand; Latent demand function; Urban transport; External costs of atmospheric pollution

**J.E.L. Classification**: H23, Q31, R48

*Corresponding author. Charles University Environment Center, U Kříže 8, Praha 5, 158 00, Czech Republic. Tel.: +420 251 080 246; fax: +420 251 620 441; email: bruhova@hotmail.com. Hana Brůhová-Foltýnová appreciates the support by a grant from the CERGE-EI foundation under a programme of the Global Development Network. All opinions expressed are those of the author and have not been endorsed by any funding institution, including CERGE-EI or the GDN.

†CERGE-EI, Joint Workplace of the Center for Economic Research and Graduate Education and the Economic Institute of the Academy of Science, Politických vězňů 7, Praha 1, 121 11, Czech Republic. Email: jan_bruha@yahoo.co.uk.

# 1 Introduction

For energy policy, environmental regulation and urban planning, it is worth understanding how prices influence passenger transport and its modal split. External costs of air pollution related to health and the environment (including climate change) are among the reasons why this task is important[1]. To do this rigorously, researchers face a number of methodological challenges. This paper contributes to the research agenda.

Health impacts and the related external costs of motor fuel use differ significantly between urban and rural areas. Thus, to assess the welfare consequences of price changes – no matter whether they are caused by policy interventions or exogenous factors - one has to estimate separate motor-fuel price elasticities for driving in urban and rural areas. Clearly, it is unsatisfactory to assume that the urban and rural price elasticities are similar: substitution possibilities differ in these areas. To estimate them separately is a difficult task since the databases usually available contain data on the total expenditures on motor fuels, but they do not directly provide the information on where the motor fuels are used. We handle the issue by considering an adequate demand system.

The concept of latent separability, which assumes that a single good may enter several utility aggregates and that only the total expenditure share on the good is observable, is a promising option. In the context of the above problem, the motor fuel can enter two utility aggregates: urban transport and transport outside urban areas (henceforth, rural transport). The crucial issue is the set of conditions under which a researcher is able to identify different price responsiveness of fuel consumption in the two areas even if not observing the expenditures on fuel consumption in the two areas separately.

Blundell and Robin (2000) develop a demand system with homothetic latent separability, where each aggregate is homothetic, and they show that the existence of exclusive commodities (i.e., for each aggregate there is a commodity, which enters only that aggregate) is sufficient for identification. Homothetic latent separability has been used in several studies in energy economics; see for instance Labeaga and Puig (2004).

Assuming urban and rural transport as two homothetic aggregates would allow to apply the model by Blundell and Robin (2000). The homothetic assumption is probably uncontroversial for studies which deal with relatively broadly defined commodities. However, this is not so the case, since we have to deal with transport modes: the choice of modes even in the individual aggregate is believed to be influenced by the households' income and expenditures. Therefore, we introduce an alternative model which relaxes the homotheticity of the aggregates. The cost of the extension is that identification is not automatically satisfied and we have to prove it before the model is estimated.

[1] Delucchi (2000) finds that environmental transport external costs are in a range of 1% to 10% per cent of the US GDP. Nash et al. (2001) argue that external costs of transport present a major problem in Western Europe. Central European transition countries face similar problems: e.g. the Ministry of the Environment (2001) identifies air pollution caused by transport as one of the most serious environmental problems in the Czech Republic.

The estimates are used for calibration of a simulation model. The goal of the model is to assess the influence of prices on fuel consumption, external effects of air pollution, household welfare (measured by compensating variation of price changes), and on public finance. The public finance impacts consist of changes in revenues and subsidies to public transport operators and tax revenues. To calibrate the model, we need estimates of (i) a demand system (as discussed above), (ii) the cost function of public transport operators and (iii) the quantification of external costs.

The model is calibrated for the five biggest Czech cities. We use Czech urban household data to estimate the demand system, data on Czech public transport operators to estimate the cost function, and external costs are taken from relevant previous studies.

Since most of the structural parameters of simulation exercises are estimated by econometric methods, we explicitly deal with uncertainty in these parameters. Most studies (e.g. Proost and Van Dender, 2001; Mayeres, 2000) rely on the certainty-equivalence principle and report results for the mean values of estimates. Instead, we use the Monte Carlo approach to derive the whole distribution of welfare consequences of selected scenarios. This enables not only to characterize the expected value of the welfare consequences, but also to characterize the probabilistic distribution conditional on estimated parameters and some risk-averse measures. This is important for two reasons:

1. If a model is nonlinear in parameters (and most models are), the expected values computed by integration of the whole distribution, as is the case in our paper, differ from the estimated welfare computed using mean values of estimates. It is worth exploring how large the simulation error can be.

2. Moreover, the public or policymakers might be risk-averse and therefore the mean computed using the certainty-equivalence approach overestimates the true mean of the distribution of the welfare; either because of the concave social utility function or because of the loss aversion.

The rest of the paper is organized as follows. Section 2 formulates the econometric model of transport behavior and reports on its estimation results. Section 3 defines simulation scenarios and methodology of their evaluation, and uses the results of Section 2 for model simulations with selected scenarios. The final section concludes.

## 2 Econometric Modeling and Calibration

To fulfil the task of the paper, we have to estimate key structural parameters. These parameters are (i) elasticities of the household transport demand, (ii) cost function of the transport providers, and (iii) the relevant external costs. This section describes these tasks.

## 2.1 Estimation of the transport demand model

For reasons explained in the Introduction, it is worth estimating separate price sensitivities of motor-fuel demand in urban and rural areas. The usual approach of using a demand system without latent separability cannot do this job. Indeed, household budget surveys and similar databases, consisting of repeated cross-section data on household expenditures and other characteristics, usually contain the aggregate motor-fuel expenditures only. Thus, without further assumption, it is impossible to identify the component of the motor-fuel demand used for driving in cities and outside cities.

Nevertheless, under suitable restrictions, it is possible to deal with the problem. One possibility is to use the homothetic latent separability approach suggested by Blundell and Robin (2000). The second possibility is to use a stage-budgeting approach by Brůha and Foltýnová (2006). We apply the latter approach and show that for the case presented here, the former model is a special case of the latter: this assertion does not hold generally, it is specific to the model used. In a general situation where the model by Blundell and Robin (2000) is identified, the model by Brůha and Foltýnová (2006) need not be identified and therefore the former approach should be used. However, when the model by Brůha and Foltýnová (2006) is identified, it encompasses the Blundell and Robin (2000) approach as a special case.

### 2.1.1 Model Formulation

We use budget-level restrictions on the demand system to identify the model. First, we assume that each household allocates desired expenditures among expenditures on urban transport, inter-urban transport, and other goods. The share of expenditures on urban transport (which includes public urban transport and motor-fuel expenditures used for urban traveling) shall be denoted by $\omega_U$, and the share of expenditures on rural transport (which includes expenditures on rail and buses and motor-fuel expenditures used for rural traveling) by $\omega_R$.

Assume that the shares satisfy the Almost Ideal Demand (henceforth, AID) system restrictions:

$$\omega_U = \alpha_U(h, \epsilon) + \gamma_{UU} \log\left(\frac{P_U}{P_O}\right) + \gamma_{UR} \log\left(\frac{P_R}{P_O}\right) + \beta_U \log\left(\frac{X}{P}\right), \quad (1)$$

$$\omega_R = \alpha_R(h, \epsilon) + \gamma_{UR} \log\left(\frac{P_U}{P_O}\right) + \gamma_{RR} \log\left(\frac{P_R}{P_O}\right) + \beta_R \log\left(\frac{X}{P}\right), \quad (2)$$

where $P_U$ is the Stone price index for urban transport (defined in more detail below), $P_R$ is the analogous Stone price index for rural transport (also defined in more detail below), $P_O$ is the price index for other goods approximated by the CPI, $X$ is the total expenditure, $\alpha_U(h)$, $\alpha_R(h)$ are intercepts which depend on household characteristics $h$ and a random-effect term $\epsilon$; $\gamma_{UU}$, $\gamma_{UR}$, $\gamma_{RR}$, $\beta_U$,

$\beta_R$ are the rest of the parameters, and $P$ is the Stone price index rewritten as:

$$\begin{aligned}\log P \quad = \quad & \alpha_0 + \alpha_U(h,\epsilon)\log\left(\frac{P_U}{P_O}\right) + \alpha_R(h,\epsilon)\log\left(\frac{P_R}{P_O}\right) + \log P_O + ... \\ & + \frac{1}{2}\gamma_{UU}\log^2\left(\frac{P_U}{P_O}\right) + \gamma_{UR}\log\left(\frac{P_U}{P_O}\right)\log\left(\frac{P_R}{P_O}\right) + \frac{1}{2}\gamma_{RR}\log^2\left(\frac{P_R}{P_O}\right).\end{aligned} \tag{3}$$

We explore the usual parametric restriction[2] of the AID system and write the system in a compact form (1) - (2), deleting the redundant third equation for the demand of the other goods.

After deciding on the expenditures on urban transport, rural transport and other goods, the household decides on the modal split of these two broad transport categories.

The expenditures on urban transport are divided between urban public transport (the share of public transport expenditures *in urban transport expenditures* is denoted as $\omega_P$), and motor-fuel expenditures for urban traveling (the corresponding share is $1-\omega_P$). These shares satisfy another AID system:

$$\omega_P = \alpha_P(h,\epsilon) + \gamma_P\log\left(\frac{P_P}{P_F}\right) + \beta_P\log\left(\frac{\omega_U X}{P_U}\right),$$

where $P_P$ is the price of public urban transport, $P_F$ is the consumer price of fuel, $\alpha_P(h,\epsilon)$, $\gamma_P$, $\beta_P$ are parameters (again the intercept depends on household characteristics and a random-effect term), and $P_U$ is the Stone price index for urban transport, derived from the AID specification:

$$\log P_U = \alpha_{0U} + \alpha_P(h,\epsilon)\log\left(\frac{P_P}{P_F}\right) + \log P_F + \frac{1}{2}\gamma_P\log^2\left(\frac{P_P}{P_F}\right).$$

This index enters the system (1) - (2).

Similarly, the expenditures on rural transport are divided between public transport such as bus and rail (the expenditure share of public transport in rural areas in expenditures on rural transport is denoted as $\omega_B$), and motor-fuel expenditures for rural traveling (the corresponding share is $1-\omega_B$). These shares satisfy yet another AID system:

$$\omega_B = \alpha_B(h,\epsilon) + \gamma_B\log\left(\frac{P_B}{P_F}\right) + \beta_B\log\left(\frac{\omega_R X}{P_R}\right),$$

[2] The restriction $\sum_k \gamma_{jk} = 0$ implies that the share equation

$$\omega_j = \alpha_j + \gamma_{jk}\sum_k \log P_k + \beta_j log(X/P)$$

can be rewritten as

$$\omega_j = \alpha_j + \gamma_{jk}\sum_{k,k\neq O}\log(P_k/P_O) + \beta_j log(X/P).$$

Also, Equation (3) already accommodates the parametric restrictions. Similarly, the second-stage equations derived further also accommodate the restrictions.

where $P_B$ is the price index of bus and rail rural transport, $P_F$ is the consumer price of fuel, $\alpha_B(h, \epsilon)$, $\gamma_B$, $\beta_B$ are parameters (yet again the intercept depends on household characteristics and a random-effect term), and $P_R$ is the Stone price index for rural transport, derived from the AID specification:

$$\log P_R = \alpha_{0R} + \alpha_B(h, \epsilon) \log \left( \frac{P_B}{P_F} \right) + \log P_F + \frac{1}{2} \gamma_B \log^2 \left( \frac{P_B}{P_F} \right),$$

which again enters the system (1) - (2).

Thus, the system is characterized by the multiple budgeting, where expenditures on public urban transport on the total urban-transport expenditures $\omega_P$ are independent on $\omega_B$, once the shares of greater commodities $\omega_U$, $\omega_R$ are determined (and vice versa). Precisely this 'independence' assumption identifies the model.

Denote the shares observable to researchers as follows: the share of public urban transport expenditures *in total expenditures* as $\sigma_P = \omega_P \omega_U$, the share of public non-urban transport as $\sigma_B = \omega_B \omega_R$, and the motor-fuel share as $\sigma_F = (1 - \omega_P)\omega_U + (1 - \omega_B)\omega_R$.

### 2.1.2 Estimation

If Stone price indexes $P$, $P_U$ and $P_R$ are observable (or if we approximate[3] them as in Brännlund and Nordström, 2004, or West and Williams, 2004) and if $\beta_P = \beta_B = 0$, it will be possible to write down a linear Seemingly Unrelated Regression (henceforth, SUR) system with the three observable shares as left-hand side variables and cross-products of relative prices and real expenditures as right-hand side variables.

Appendix A shows what exactly these SUR equations looks like and how it is possible to map reduced-form parameters of the SUR to structural parameters of the two-stage budgeting model. The appendix shows that for a set of reduced-form parameters, there is at most one set of structural parameters and the model is thus identified. Computing Stone indexes consistently makes the estimation problem inherently non-linear, but it does not threaten identification.

If some of the right-hand side variables are suspected to be endogenous, the instrumental-variable estimator should be used to estimate the reduced-form parameters. Fuel prices are usually suspected to be endogenous; and world oil prices are an obvious candidate as appropriate instruments. However, previous econometric expertise (Brůha and Ščasný 2003, 2006) suggests that energy and fuel prices are exogenous for Czech households, which probably reflects the openness of the Czech economy. Therefore, we do not opt for dealing with possible endogeneity of prices.

If stage-budgeting or latent demand are applied to a demand system with broadly defined commodities, such as fuels, energy, and transport, then it is

[3]Although the linear approximation to the Stone Index is often used in practice, it is known that it can bias estimation results substantially. Therefore, the use of the theoretically consistent Stone Index is preferable; Blundell et al. (1993).

reasonable to impose homotheticity of the latent aggregates (Blundell and Robin 2000). Indeed, in such a case, it may be uncontroversial to assume a one-to-one shift in the corresponding parts of the relevant commodities after an increase in the latent aggregate demand.

On the other hand, if commodities in a demand system are disaggregated, it is likely that the income effect will operate on the level of latent aggregates too. Indeed, an increase in demand for public transport due to an increase in planned expenditures may translate into a choice of urban transport modes too. It is quite possible that some transport modes are not normal goods even at the level of the latent classes. Therefore, we relax the assumption that $\beta_P = \beta_B = 0$. This adds additional reduced-form parameters, but the model remains identified. See Appendix A.

We apply the model to a panel of the five largest Czech cities for the years 1997-2004. Table 1 summarizes household data on average expenditure shares on the three types of transport.

We assume that parameters $\gamma_{UU}$, $\gamma_{UR}$, $\gamma_{RR}$, $\gamma_P$, $\gamma_B$, $\beta_R$, $\beta_U$, $\beta_P$, $\beta_B$ and $\alpha_{0U}$, $\alpha_{0R}$, $\alpha_{0P}$, $\alpha_{0B}$ are constant across cities and time, while $\alpha_U$, $\alpha_R$, $\alpha_P$, $\alpha_B$ differ across cities: they are treated as fixed effects. These fixed effects reflect unobserved characteristics of the cities (mainly demographic composition, and properties of the public transport networks), which are supposed to be constant across time. The researcher may not observe all the relevant city characteristics and the fixed effects can therefore fix the potentially serious bias due to a wrong econometric specification of city characteristics; see Murdock (2006) for an analogous treatment of unobserved site characteristics in a recreational demand model.

To characterize the price-responsiveness of households, we derive elasticities of expenditure shares with respect to prices. Since we introduce a stage-budgeting demand model, the derivation of elasticities may not be obvious. A recursive scheme is a tool to derive them. The recursion runs as follows. First, we derive elasticities of the Stone indexes $P_U$ and $P_R$ with respect to prices:

$$\frac{\mathrm{d}\log P_U}{\mathrm{d}\log P_P} = \alpha_P + \gamma_P \log\left(\frac{P_P}{P_F}\right),$$

$$\frac{\mathrm{d}\log P_U}{\mathrm{d}\log P_F} = 1 - \left[\alpha_P + \gamma_P \log\left(\frac{P_P}{P_F}\right)\right],$$

$$\frac{\mathrm{d}\log P_U}{\mathrm{d}\log P_B} = 0,$$

$$\frac{\mathrm{d}\log P_R}{\mathrm{d}\log P_P} = 0,$$

$$\frac{\mathrm{d}\log P_R}{\mathrm{d}\log P_F} = 1 - \left[\alpha_B + \gamma_B \log\left(\frac{P_B}{P_F}\right)\right],$$

$$\frac{\mathrm{d}\log P_R}{\mathrm{d}\log P_B} = \alpha_B + \gamma_B \log\left(\frac{P_B}{P_F}\right).$$

Then we use these results to derive elasticities of the Stone price index $P$:

$$\frac{\mathrm{d}\log P}{\mathrm{d}\log P_j} = \sum_{k\in\{U,R\}} \alpha_k \frac{\mathrm{d}\log P_k}{\mathrm{d}\log P_j} + \sum_{k\in\{U,R\}} \sum_{l\in\{U,R\}} \gamma_{kl} \log\left(\frac{P_k}{P_O}\right) \frac{\mathrm{d}\log P_l}{\mathrm{d}\log P_j},$$

for $j \in \{P, F, B\}$.

Given these elasticities of the price indexes, we derive the elasticities of the first-stage shares $\omega_U$ and $\omega_R$:

$$\frac{\mathrm{d}\log \omega_k}{\mathrm{d}\log P_j} = \frac{1}{\omega_k}\left[\gamma_{Uk}\frac{\mathrm{d}\log P_U}{\mathrm{d}\log P_j} + \gamma_{kR}\frac{\mathrm{d}\log P_R}{\mathrm{d}\log P_j} - \beta_k \frac{\mathrm{d}\log P}{\mathrm{d}\log P_j}\right],$$

for $j \in \{P, F, B\}$ and for $k \in \{U, R\}$.

These results are in turn needed to derive elasticities of the second-stage shares $\omega_B$ and $\omega_P$:

$$\frac{\mathrm{d}\log \omega_P}{\mathrm{d}\log P_j} = \frac{1}{\omega_P}\left[\gamma_P\left(\frac{\mathrm{d}\log P_P}{\mathrm{d}\log P_j} - \frac{\mathrm{d}\log P_F}{\mathrm{d}\log P_j}\right) + \beta_P\left(\frac{\mathrm{d}\log \omega_U}{\mathrm{d}\log P_j} - \frac{\mathrm{d}\log P_U}{\mathrm{d}\log P_j}\right)\right],$$

$$\frac{\mathrm{d}\log \omega_B}{\mathrm{d}\log P_j} = \frac{1}{\omega_B}\left[\gamma_B\left(\frac{\mathrm{d}\log P_B}{\mathrm{d}\log P_j} - \frac{\mathrm{d}\log P_F}{\mathrm{d}\log P_j}\right) + \beta_B\left(\frac{\mathrm{d}\log \omega_R}{\mathrm{d}\log P_j} - \frac{\mathrm{d}\log P_R}{\mathrm{d}\log P_j}\right)\right],$$

for $j \in \{P, F, B\}$.

The elasticities of the observable shares $\sigma_P$, $\sigma_B$ then satisfy:

$$\frac{\mathrm{d}\log \sigma_P}{\mathrm{d}\log P_j} = \frac{\mathrm{d}\log \omega_U}{\mathrm{d}\log P_j} + \frac{\mathrm{d}\log \omega_P}{\log P_j},$$

$$\frac{\mathrm{d}\log \sigma_B}{\log P_j} = \frac{\mathrm{d}\log \omega_R}{\mathrm{d}\log P_j} + \frac{\mathrm{d}\log \omega_B}{\log P_j}.$$

The derivation of motor-fuel elasticities is a bit involved:

$$\frac{\mathrm{d}\log \sigma_F^U}{\mathrm{d}\log P_j} = \frac{\mathrm{d}\log \omega_U}{\mathrm{d}\log P_j} - \frac{1}{1-\omega_P}\frac{\mathrm{d}\log \omega_P}{\mathrm{d}\log P_j},$$

$$\frac{\mathrm{d}\log \sigma_F^R}{\mathrm{d}\log P_j} = \frac{\mathrm{d}\log \omega_R}{\mathrm{d}\log P_j} - \frac{1}{1-\omega_B}\frac{\mathrm{d}\log \omega_B}{\mathrm{d}\log P_j},$$

and

$$\frac{\mathrm{d}\log \sigma_F}{\mathrm{d}\log P_j} = \frac{\sigma_F^U}{\sigma_F}\frac{\mathrm{d}\log \sigma_F^U}{\mathrm{d}\log P_j} + \frac{\sigma_F^R}{\sigma_F}\frac{\mathrm{d}\log \sigma_F^R}{\mathrm{d}\log P_j},$$

where $\sigma_F^U$, $\sigma_F^R$ are the motor-fuel expenditure shares used for traveling in urban and rural areas, respectively and $\sigma_F = \sigma_F^U + \sigma_F^R$ is the total motor-fuel expenditure share.

Given elasticities of these shares, one can easily derive compensated, uncompensated price demand elasticities and income elasticities. Table 2, based on Brůha and Foltýnová (2006), summarizes the results of the uncompensated price elasticities.

## 2.2 Estimation of the Cost Function of Public Transport Operators

To estimate the cost function of public transport operators, we follow the approach suggested by Williams (1979). We estimate the short-run cost function in the following form:

$$\log AC_{it} = \alpha_1 \log w_t + \alpha_2 \log \mathbb{P}_t + \beta \log Q_{it} + \varepsilon_{it}, \tag{4}$$

where $AC_{it}$ is the average cost of the operator in the city $i$ in the year $t$; $w_t$ is the wage rate in the transport sector in the year $t$; $\mathbb{P}_t$ is the price of fuels; $Q_{it}$ is the performance of the relevant provider; and $\varepsilon_{it}$ summarizes other variables, such as random effects, capital equipment, and pure disturbances. The parameter $\alpha_1$ is the elasticity of the average costs to labor costs; $\alpha_2$ is the elasticity of the average costs to the fuel prices; and the parameter $\beta$ measures the possible economies of scale (if $\beta < 0$, then there are increasing returns to scale, while $\beta > 0$ implies decreasing returns to scale).

We estimate this equation on the panel of data from urban public transport operators on 19 selected Czech cities for the time period 1997-2005. We obtained data on costs and on performance from the Association of Public Transport Operators; fuel prices and wages are from the Czech Statistical Office.

We do not have data on fuel prices for each city, we have only economy-wide fuel-price data. However, this probably does not present a major problem, since the dynamics of fuel prices are the same across cities and the level is influenced by idiosyncratic differences in the degree of competition in different locations.

We have various types of wage data in the transport sector. The reason is that a governmental reform took place in 2002, which replaced the old system of many relatively small districts (*okresy*) as basic regional units with a system consisting of only a few large regions (*kraje*). The Czech Statistical Office reflected the reform and since 2002 it has processed data based on the new larger regions. Ideally, we would like to have data on wages in the transport sector on the district level, since such wage data reflect the wage which transport firms in individual cities face. The data on average wages in the transport sector based on the regional level are too crude: each region usually consists of one main city and several smaller cities, and wages tend to be higher in that main city. Thus, the average regional wage is representative neither for the main city nor for the smaller cities[4]. Unfortunately, 2002-2005 district-level data on the transport-sector wages are not available to us. We develop the following approach to deal with such a situation. We construct artificial data for district average wages in the transport sector for the unavailable years 2002-2005. Basically, we assume that the average wage $\omega_{it}$ in the transport sector in the district $i$ in the year $t$ is linked to the economy-wide average wage in the transport sector $\varpi_t$ as follows:

$$\omega_{it} = \theta_i \varpi_t \eta_{it},$$

[4] For the overlapping years 2003 and 2004, we have data on economy-wide average wages both on district and regional levels. The comparison suggests that even dynamics on the two levels differ, which makes the use of regional data difficult.

where $\theta_i$ is the time-invariant district-specific constant, and $\log \eta_{it}$ is for each $i$ an i.i.d. zero-mean noise. We estimate the constants $\theta_i$ for the years 1994-2001, for which we have data on transport average wages on both district levels and economy level. Then, we use the estimated $\widehat{\theta_i}$ to impute district wages for 2002 - 2005 from the economy-wide average wage in the transport sector. We plug these generated data in estimating (4) as if these were true data. We use two estimation approaches: a fixed-effect model, and a random-effect model. Such a strategy is consistent, but standard errors are underestimated.

The coefficients are homogenous across all cities. Tables 1 and 2 summarize the results. The economies-of-scale parameter is positive (which suggests decreasing economies of scale) but insignificant. Results for the fixed-effect and random-effect models are very similar and the Hausmann test does not reject the hypothesis of the random effect (at 1%). Therefore, our simulations use the results based on the random-effect model.

We experiment with other empirical specifications as well. We use the national average wage in the transport sector for all cities and we formulate an unobserved component model (see Appendix B for details). Experience with various empirical specifications suggests the following:

1. Costs of public-transport agencies are more sensitive to wages than to fuel prices; this pattern is stable across the time-span, wage models and cities selected for estimation.

2. Point estimates of the economies-of-scale parameter $\beta$ vary substantially; nevertheless, in most cases the estimates are not significantly different from zero.

### 2.3 Quantification of External Costs

Theoretically consistent quantification of external costs of air pollution from transport is a relatively novel research agenda in the Czech Republic. To our knowledge, the only estimation to date has been calculated using the ExternE methodology (European Commission, 1999 and 2003) and is available in the research report on the project for the Ministry of the Environment of the Czech Republic 'Quantification of external costs of energy use for the Czech Republic' (CUEC 2005). These results are based on the 'impact-pathway' approach and apply a bottom-up analysis of emissions. Therefore, the estimated values depend on a wide range of parameters, such as the location of the emission (population density of the affected area), type of vehicle, vehicle fleet structure, fuel characteristics.

The population densities of the five analyzed cities differ from 23.6 inhabitants per hectare in Prague to 9.75 inhabitants per hectare in Olomouc. The structure of the vehicle fleet according to the EURO standards and the type of fuel (gasoline, diesel) is taken from the ATEM (2001) study of traffic flows, which was conducted in Prague and Pilsen. To estimate external costs in the other three cities, we assume the same vehicle fleet structure as in Pilsen (we use this assumption, since the income level, the area and transport performance of these three cities are close to the situation in Pilsen). Our external cost estimations are static: we do not change the structure of the vehicle fleet during the simulations. Table 5 shows the structure of the vehicle fleet used for the external cost estimation.

The monetary values of air pollution external costs are taken from CUEC (2005). The external costs of air pollution consist of the monetary value of the damage to health and the environment caused by vehicle emissions. We evaluate the following emissions: NOx, $SO_2$, hydrocarbons, and $PM_{10}$. The EURO standards do not include the $CO_2$ emission standards so we cannot identify the exact amount of $CO_2$ produced by different groups of vehicles using the EURO standards as is the case for the other evaluated emissions. For our analyses, we derive the amount of $CO_2$ emissions produced by cars from the average fuel consumption (for the figures, see Table 8). The average monetary values of external costs from air pollution per car-km are summarized in Table 6.

In our micro-simulation model, we use external costs per litre of fuel consumed. The total value of external costs of air pollution from cars is 20.49 CZK (0.74 EUR) per litre for urban areas for the middle-sized towns (Brno, Ostrava, Pilsen, and Olomouc), and 25.57 CZK (0.88 EUR) per litre for Prague (the difference in values is caused by a higher population density, which more than counterbalances the newer and less polluting car fleet operated in Prague). The external costs for rural areas are 10.24 CZK (0.37 EUR) per litre of fuel for a typical car operated by a middle-sized town inhabitant, and 9.13 CZK (0.31 EUR) for a car owned by an inhabitant of Prague.

The estimated external costs of public transport reflect the structure of the public transport vehicle fleet: the electrical traction (including trams, trolleybuses, and metro) are considered 'zero-emission' transport (as if their external costs were already internalized at the electricity producers), and external costs from air pollution are calculated only for buses[5]. The monetary values used for external costs of air pollution from public transport are summarized in Table 7.

# 3 Simulations

In this section, we define three scenarios and simulate our micromodel to evaluate their impacts. The scenarios are applied to the five largest Czech cities: Prague, Brno, Ostrava, Pilsen, and Olomouc (ranked according to the number of inhabitants, where Prague has 1,171 thousand and Olomouc 101 thousand inhabitants).

[5]The reason why Olomouc exhibits the greatest externality per km is that the public transport agency in Olomouc use electricity-based vehicles less than public transport agencies in the other cities do.

## 3.1 Definition of the Scenarios

As shown by Parry and Small (2005), the appropriate regulation tool of transport air pollution is fuel taxes. That is why impacts of increases in excise duty on fuels are assessed in Scenario 1. Fuel prices can increase not only as a consequence of a political decision (an increase in taxes). There are many external factors which influence the fuel prices, including a shock in the oil prices. Such a situation is simulated under Scenario 2. The last scenario (Scenario 3) focuses on a possibility to make public transport – as a less air-polluting substitute of cars – more attractive using subsidies to decrease fares.

We define our scenarios as follows:

**Scenario 1** is defined as an increase in the excise duty on fuels, which affects the consumer price of motor fuels. We distinguish between two subscenarios - the baseline involves an exemption for public transport operators from the increased duty (Scenario 1a), while the alternative formulation does not exempt public transport operators from this increased excise duty on fuels (Scenario 1b). Thus, the alternative scenario implies a cost increase for the public transport operators. We assume that fares in public transport will change to balance off the cost increase.

**Scenario 2** simulates a situation where the transport sector faces an unexpected rise in fuel prices (such as an exogenous shock to world oil prices). Although, similarly to Scenario 1, this implies an increase in the price of motor fuels and therefore in costs of public transport operators (and we assume that this rise is transmitted to fares), budgetary implications of these two scenarios differ. Because the fuel tax is based as an amount per litre (it is a unit tax), the revenues in Scenario 2 decrease as a consequence of raised fuel prices.

**Scenario 3** evaluates a decrease in public transport fares. This scenario is included since some environmentalists argue for a substantial reduction in public transport prices. This can, on the one hand, induce a shift toward a more environmentally friendly modal split for passenger transport; on the other hand, it may represent a serious budgetary pressure.

## 3.2 Methodology

Results of Section 2 enter the calculation of the change in the transport demand. We use estimation results from Section 2.2 to quantify the impact of fuel price changes on the average and total costs of public transport operators.

Given the estimation of the new quantities, the impact on the budget, which includes changed revenues from value added and excise taxes, can be calculated easily. Also, given the estimation of the changed quantities, we calculate changes in the external costs using an approximation which sets marginal externalities equal to average externalities. The last ingredient is an estimation of the compensating variation due to price changes. This is approximated using the Taylor expansion of the expenditure function.

Finally, we add up three welfare measures: the change in public funds (including the change in tax revenues and the change in costs of public transport operators), the change in external costs related to air pollution, and the compensating variation. These measures are summed into one Kaldor-Hicks type of social welfare measure with equal weights for all changes in the real incomes of individuals.

The changes in tax revenue receive a different weight than the changes in consumer surplus: we weight the change in public funds with 1.2. The reader should bear in mind that we include external costs related to air pollution only, thus welfare gains of motor fuel taxation are possibly underestimated (because of the uncounted costs of congestion).

## 3.3 Results of the Simulations

Simulation results are summarized in the Figures. All figures are organized as follows: there is a panel of five selected Czech cities (Prague, Brno, Ostrava, Pilsen, and Olomouc). Figures 1 - 4 display the total welfare of a price change in the five cities. Also, the welfare per inhabitant is displayed. The next four figures 5 - 8 display the distribution of the welfare disaggregated to the four components for a selected change, also in per capita terms. The distribution is obtained via Monte Carlo experiments by drawing a random sample of the size 5,000 from the underlying estimates (based on the asymptotic normal approximation). In these figures, the distribution is displayed as a histogram. Moreover, the mean is shown with a red star and the lower and upper 5 percentiles are denoted by green signs. Therefore, the interval between the two green signs covers 90% of the distribution.

Figure 9 compares the mean of the distribution (denoted as *true mean* in the figure legend) with (i) the welfare effect estimate based on the certainty-equivalence principle (denoted as *certainty equivalence*) and with (ii) the expected welfare effect under the assumption that the demand elasticities for motor fuels were equal in urban and rural areas (denoted as *naive elasticities*). Each scenario is evaluated for a 30% increase in the respective variable. The figure suggests that the difference among the three means can be significant. This indicates that (i) a blind usage of the certainty-equivalence principle can be dangerous, and (ii) that ignoring the different price elasticities of fuel consumption in the urban and rural areas can lead to important errors.

We employ the following convention: positive values mean an increase in the welfare; thus if a positive value of external costs is displayed, it means actually a decrease in negative external costs. Also, we display the total welfare effect, which is added as described above and which follows the same convention as its components. All welfare effects are measured in millions of CZK, while welfare in per capita terms is measured in CZK.

Figure 1 displays the results of expected welfare effects for **Scenario 1a**, which evaluates an increase in excise duty tax on fuels under the tax exemption for public transport. Figure 5 displays the whole distribution for a 30% increase of the tax rate for each component.

The simulations reveal that the change in total welfare is significantly negative for Prague and Brno (the two largest cities) for all the modeled changes in excise duty on fuel (i.e., the increase from 0% to 50%), while for the rest of cities, the 95% confidence interval contains zero. The positive welfare effect is caused by a decrease in the amount of transport emissions (because of the modal switch and a slight decrease in the total car traffic volume resulting from higher fuel prices), and an increase in tax revenues from excise duty and VAT. The total welfare is lowered by the negative compensating variation and higher requirements of subsidies for the public transport operators. The last effect is important especially for Prague. The expected increase in subsidies is even higher there than the expected increase in tax revenues. It is interesting that the value of the change in external costs is comparable to that in compensating variation in Prague, but it is lower in other cities. This reflects the higher population density in Prague.

Figures 2 and 6 display the results of **Scenario 1b**, which differs from Scenario 1a with the assumption that there is no exemption for public transport from the increased excise duty on fuels. Figure 2 displays the expected welfare effect of various increases in the tax rate, while Figure 6 displays the welfare distributions for the 30% increase.

We assume that the cost increase is transmitted to public transport fares. This implies that the modal split change is lower under this alternative. Air-pollution externalities, however, decrease in all cities because of the decrease in the traffic volume (the welfare change is positive for all cities). Since now fares rise as well, there occurs a bigger welfare loss for households (measured as the compensating variation) than in Scenario 1a. On the contrary the requirement of public transport subsidies is not as high as under Scenario 1a. The welfare compound from subsidies is negative, but lower than in Scenario 1a. The tax revenues are slightly higher under Scenario 1b. Summarizing the welfare components, the total welfare is significantly positive for all cities except of Prague. The 95% confidence interval of the welfare effect for Prague contains zero, which means that given the uncertainty in parameter values, we cannot be confident about the welfare effect of this scenario. In all other cities, the likely welfare effect is positive. In per capita terms, the highest numbers are attained for Ostrava and Olomouc. The explanation is that these cities have the lowest costs per an additional public-transport passenger.

**Scenario 2** evaluates the welfare implications of a shock to world fuel prices; the results are displayed in Figure 3. Figure 7 displays the welfare distributions for the 30% increase.

In this case, the budget would suffer a pure loss in revenues because of a decline in fuel consumption (the excise tax is a unit tax). The necessity to subsidy public transport increases to cover the rising costs of public transport operators. This welfare compound is negative. Similarly, the compensating variation is negative (it decreases the total welfare). On the contrary, a high positive contribution to the total welfare is made by a decrease in air-pollution externalities. The modal split change is small (the price shock is transmitted to fares) but the transport volume as such decreases. Still, this positive welfare compound does not overweigh the other negative welfare compounds and the total welfare change is negative for all cities for all fuel price increases (we simulate fuel price increases by 0 - 50%). When the price of fuel raises, the total welfare decreases. This decrease is the sharpest for Prague despite of the largest benefit due to the decrease in external costs. Apparently, the welfare distributions for this scenario have low variance comparing to other scenarios.

**Scenario 3** simulates a fall in public transport fares; see Figure 4 and 8. The impact of external costs and the compensating variation is rather small, since there is a small modal shift induced by this price change: for some cities, the fall in external costs is not even significantly positive. On the other hand, significant losses of public transport operators will result in the necessity of substantial subsidies and the total welfare effect is therefore negative. Thus, our simulations suggest that an increase in fuel taxation is likely a better policy than subsidy increases to public transport. The reason behind this result is the importance of the dead-weight loss of taxation needed to finance such subsidies.

We should point out that there are limitations connected to the simulation exercises. First, the welfare outcomes depend on the weights assigned to the different welfare components. The weights used in this paper are normative, in the sense that distributional issues are absent: the objective is efficiency. Second, we do not consider the political-economy perspective of subsidies to public transport operators, which is also an important issue for practical considerations.

# 4 Conclusions

The paper formulates a microeconometric model of passenger transport demand. The model allows for latent separability of transport demand without imposing the homothetic assumption on the aggregates. We show that the proposed model is identified, and outline an estimation strategy. Therefore, the paper shows a possibility of using latent separability or the stage budgeting approach without imposing constraints, which may be unrealistic in some situations.

The estimated results are used in a calibration of a microsimulation model for large cities in a transition country. The paper thus also complements studies which mostly deal with Western European countries or with the US. The model assesses impacts of price changes on fuel consumption, related external costs, public finance, and household welfare. We consider three scenarios, which include selected changes in policy variables (such as taxes and public transport fares) and in exogenous variables (such as shocks to world fuel prices).

Since most of the structural parameters in our simulation exercises are estimated by econometric methods, we explicitly deal with uncertainty in these parameters. Most studies rely on the certainty-equivalence principle and report results for the mean values of estimates. We regard this practise as incomplete because the public or policymakers might be risk-averse. Instead, we use the Monte Carlo approach to derive the distribution of welfare consequences of selected policies. This enables us to characterize the expected value of the welfare consequences, as well as other distributional characteristics (such as variance or percentiles). Numerical results suggest that uncertainty in the structural parameters are significant and should not be omitted. Moreover, we find that the certainty-equivalence approach is uncorroborated because of non-linearity of the model.

## References


ATEM, 2001. Survey on the vehicle fleet and related emission parameters in the Czech Republic. (in Czech, 'Zjištění aktuální dynamické skladby vozového parku a jeho emisních parametrů.) ATEM, October 2001.

Blundell, R., Pashardes, P., Weber, G., 1993. What Do We Learn About Consumer Demand Patterns from Micro Data? American Economic Review 83(3), 570-597.

Blundell, R., Robin, J.-M., 2000. Latent Separability: Grouping Goods without Weak Separability. Econometrica 68(1), 53-84.

Brännlund, R., Nordrström, J., 2004. Carbon Tax Simulation Using a Household Demand Model. European Economic Review, 48(1), 211 - 233.

Brůha, J., Foltýnová, H., 2006. A contribution to predicting the modal split in urban passenger transport under incomplete data. In: Proceedings from the Extra EURO Conference, Bari, 27 - 29 September, 2006, Technical University of Bari.

Brůha, J., Ščasný, M., 2003. Public Finance Aspects of a Green Tax Reform in the Czech Republic. Working paper of the 7th Joint Meeting of Tax and Environmental Experts. OECD Paris November 2003, OECD: COM/ENV/EPOC/DAFFE/CFA(2003)126.

Brůha, J., Ščasný, M., 2006. Distributional Effects of Environmental Regulation in the Czech Republic. Paper presented at the Third World Congress of the Association of Environmental and Resource Economists, June 2006, Kyoto.

CUEC, 2005. The Final report from the project of the R& D of the Czech Ministry of the Environment 'Quantification of external costs from energy use in the Czech Republic', No. VaV/320/1/03, Charles University Environment Centre, Prague.

Deaton A. S., Muellbauer, J., 1980. An Almost Ideal Demand System. The American Economic Review, 70(3), 312-36.

Delucchi, M.A., 2000. Environmental Externalities of Motor-Vehicle Use in the US. Journal of Transport Economics and Policy 34(2), 135-168.

European Commission, 1999. ExternE: Externalities of Energy. Vol.7: Methodology 1998 Update (EUR 19083); Vol. 8: Global Warming (EUR 18836); Vol. 9: Fuel Cycles for Emerging and End-Use Technologies, Transport and Waste (EUR 18887); Vol. 10: National Implementation (EUR 18528). Published by European Commission, Directorate-General XII, Science Research and Development. Office for Official Publications of the European Communities, L-2920 Luxembourg.

European Commission, 2003. External costs: Research results on socio-environmental damages due to electricity and transport. Published by European Commission, Directorate General for Research. Office for Official Publications of the European Communities, L-2920 Luxembourg.

Labeaga, J., Puig, J., 2004. Some practical implications of latent separability with application to Spanish data, working paper.

Mayeres, I., 2000. The Efficiency Effects of Transport Policies in the Presence of Externalities and Distortionary Taxes. Journal of Transport Economics and Policy, 3(2), 233-260

Melichar, J., 2006. Calculation of environmental costs. In: Foltýnová, H., Máca, V., Melichar, J., Report of the project Economy of implementation of alternative fuels in transport for 2005, No. 1F44E/022/210, Charles University Environment Center in Prague, January 2006 (in Czech).

Ministry of the Environment, 2001. Czech Environmental Policy, Prague.

Murdock, J., 2006. Handling unobserved site characteristics in random utility models of recreation demand. Journal of Environmental Economics and Management 51(1), 1-25.

Nash, C., Sansom, T., Still, B., 2001. Modifying transport prices to internalise externalities: evidence from European case studies. Regional Science and Urban Economics 31(4), 413-431.

Parry, I.W.H., Small, K.A., 2005. Does Britain or the United States have the Right Gasoline Tax? American Economic Review 95(4), 1276-1289.

Proost, S., Van Dender, K., 2001. The welfare impacts of alternative policies to address atmospheric pollution in urban road transport. Regional Science and Urban Economics 31(4), 383-411.

Williams, M., 1979. Firm Size and Operating Costs in Urban Bus Transportation. The Journal of Industrial Economics 28 (2), 209-218.

West, S.E., Williams, R.C., 2004. Empirical estimates for environmental policy making in a second-best setting. NBER working paper series, Working paper 10330, Cambridge, USA.

# A Identification of the Demand System

This appendix proves the identification of the demand system introduced in Section 2.1. To do that, it is necessary to prove that reduced-form parameters uniquely determine the structural parameters.

Expand the observable shares to the following reduced-form system:

$$
\begin{aligned}
\sigma_F \quad = \quad & [\alpha_U(1-\alpha_P)+\alpha_R(1-\alpha_B)] - \alpha_U\gamma_P \log\left(\frac{P_P}{P_F}\right) - \alpha_R\gamma_B \log\left(\frac{P_B}{P_F}\right) + ... \\
& + [(1-\alpha_P)\gamma_{UU} + (1-\alpha_B)\gamma_{UR}] \log\left(\frac{P_U}{P_O}\right) + ... \\
& [(1-\alpha_P)\gamma_{UR} + (1-\alpha_B)\gamma_{RR}] \log\left(\frac{P_R}{P_O}\right) + ... \\
& + [-\gamma_P\gamma_{UU}] \log\left(\frac{P_U}{P_O}\right) \log\left(\frac{P_P}{P_F}\right) + [-\gamma_P\gamma_{UR}] \log\left(\frac{P_R}{P_O}\right) \log\left(\frac{P_P}{P_F}\right) + ... \\
& + [-\gamma_B\gamma_{UR}] \log\left(\frac{P_U}{P_O}\right) \log\left(\frac{P_B}{P_F}\right) + [-\gamma_B\gamma_{RR}] \log\left(\frac{P_R}{P_O}\right) \log\left(\frac{P_B}{P_F}\right) + ... \\
& + [(1-\alpha_P)\beta_U - \alpha_U\beta_P + (1-\alpha_B)\beta_R - \alpha_R\beta_B] \log\left(\frac{X}{P}\right) + ... \\
& [\beta_U\beta_P + \beta_R\beta_B] \log^2\left(\frac{X}{P}\right) + ... \\
& + [-\gamma_P\beta_U] \log\left(\frac{X}{P}\right) \log\left(\frac{P_P}{P_F}\right) + [-\gamma_B\beta_R] \log\left(\frac{X}{P}\right) \log\left(\frac{P_B}{P_F}\right) + ... \\
& [-\gamma_{UU}\beta_P - \gamma_{UR}\beta_B] \log\left(\frac{X}{P}\right) \log\left(\frac{P_U}{P_O}\right) + ... \\
& [-\gamma_{UR}\beta_P - \gamma_{RR}\beta_B] \log\left(\frac{X}{P}\right) \log\left(\frac{P_R}{P_O}\right) + ... \\
& (-\beta_P)\omega_U \log\omega_U + (-\beta_B)\omega_R \log\omega_R.
\end{aligned}
$$

$$
\begin{aligned}
\sigma_P \quad = \quad & \alpha_U\alpha_P + \alpha_U\gamma_P \log\left(\frac{P_P}{P_F}\right) + \alpha_P\gamma_{UU} \log\left(\frac{P_U}{P_O}\right) + \alpha_P\gamma_{UR} \log\left(\frac{P_R}{P_O}\right) + ... \\
& + \gamma_P\gamma_{UU} \log\left(\frac{P_U}{P_O}\right) \log\left(\frac{P_P}{P_F}\right) + \gamma_P\gamma_{UR} \log\left(\frac{P_R}{P_O}\right) \log\left(\frac{P_P}{P_F}\right) + ... \\
& + (\alpha_P\beta_U + \alpha_U\beta_P) \log\left(\frac{X}{P}\right) + \beta_U\beta_P \log^2\left(\frac{X}{P}\right) + \gamma_P\beta_U \log\left(\frac{X}{P}\right) \log\left(\frac{P_P}{P_F}\right) + ... \\
& + \gamma_{UU}\beta_P \log\left(\frac{X}{P}\right) \log\left(\frac{P_U}{P_O}\right) + \gamma_{UR}\beta_P \log\left(\frac{X}{P}\right) \log\left(\frac{P_R}{P_O}\right) + \beta_P\omega_U \log\omega_U,
\end{aligned}
$$

$$
\begin{aligned}
\sigma_B \quad = \quad & \alpha_R\alpha_B + \alpha_R\gamma_B \log\left(\frac{P_B}{P_F}\right) + \alpha_B\gamma_{UR}\log\left(\frac{P_U}{P_O}\right) + \alpha_B\gamma_{RR}\log\left(\frac{P_R}{P_O}\right) + ... \\
& + \gamma_B\gamma_{UR}\log\left(\frac{P_U}{P_O}\right)\log\left(\frac{P_B}{P_F}\right) + \gamma_B\gamma_{RR}\log\left(\frac{P_R}{P_O}\right)\log\left(\frac{P_B}{P_F}\right) + ... \\
& + (\alpha_B\beta_R + \alpha_R\beta_B)\log\left(\frac{X}{P}\right) + \beta_R\beta_B\log^2\left(\frac{X}{P}\right) + \gamma_B\beta_R\log\left(\frac{X}{P}\right)\log\left(\frac{P_B}{P_F}\right) + ... \\
& + \beta_B\omega_R\log\omega_R + \gamma_{UR}\beta_B\log\left(\frac{X}{P}\right)\log\left(\frac{P_U}{P_O}\right) + \gamma_{RR}\beta_B\log\left(\frac{X}{P}\right)\log\left(\frac{P_R}{P_O}\right),
\end{aligned}
$$

The last terms in the share equations then revealed why the problem is inherently non-linear even under observability of the Stone indexes if $\beta_R \neq 0$ or $\beta_P \neq 0$. Now, we will discuss the identification issues.

First, assume that $\beta_P = \beta_B = 0$ and that we observe the Stone Indexes, then the system above is a linear SUR, with 28 reduced-form parameters, while the number of structural parameters is 14. For identification, it is necessary to have fewer structural than reduced-form parameters. Thus, the necessary condition for identification is met. This condition is not sufficient, though. To show that the system is identified (more precisely: overidentified), rewrite the system in the following form:

$$
\sigma_P = \delta_1 + \delta_2\log\left(\frac{P_P}{P_F}\right) + \delta_3\log\left(\frac{P_U}{P_O}\right) + \delta_4\log\left(\frac{P_R}{P_O}\right) + \dots
$$

$$
\dots + \delta_5\log\left(\frac{P_U}{P_O}\right)\log\left(\frac{P_H}{P_F}\right) + \delta_6\log\left(\frac{P_R}{P_O}\right)\log\left(\frac{P_P}{P_F}\right) + \dots
$$

$$
\dots + \delta_7\log\left(\frac{X}{P}\right) + \delta_8\log\left(\frac{X}{P}\right)\log\left(\frac{P_P}{P_F}\right),
$$

$$
\sigma_B = \delta_9 + \delta_{10}\log\left(\frac{P_B}{P_F}\right) + \delta_{11}\log\left(\frac{P_U}{P_O}\right) + \delta_{12}\log\left(\frac{P_R}{P_O}\right) + \dots
$$

$$
\dots + \delta_{13}\log\left(\frac{P_U}{P_O}\right)\log\left(\frac{P_B}{P_F}\right) + \delta_{14}\log\left(\frac{P_R}{P_O}\right)\log\left(\frac{P_B}{P_F}\right) + \dots
$$

$$
\dots + \delta_{15}\log\left(\frac{X}{P}\right) + \delta_{16}\log\left(\frac{X}{P}\right)\log\left(\frac{P_B}{P_F}\right),
$$

$$
\sigma_F = \delta_{17} + \delta_{18}\log\left(\frac{P_H}{P_F}\right) + \delta_{19}\log\left(\frac{P_B}{P_F}\right) + \delta_{20}\log\left(\frac{P_U}{P_O}\right) + \delta_{21}\log\left(\frac{P_R}{P_O}\right) + \dots
$$

$$
\dots + \delta_{22}\log\left(\frac{P_U}{P_O}\right)\log\left(\frac{P_H}{P_F}\right) + \delta_{23}\log\left(\frac{P_R}{P_O}\right)\log\left(\frac{P_H}{P_F}\right) + \dots
$$

$$
\dots + \delta_{24}\log\left(\frac{P_U}{P_O}\right)\log\left(\frac{P_B}{P_F}\right) + \delta_{25}\log\left(\frac{P_R}{P_O}\right)\log\left(\frac{P_B}{P_F}\right) + \dots
$$

$$\ldots + \delta_{26} \log\left(\frac{X}{P}\right) + \delta_{27} \log\left(\frac{X}{P}\right) \log\left(\frac{P_H}{P_F}\right) + \delta_{28} \log\left(\frac{X}{P}\right) \log\left(\frac{P_B}{P_F}\right).$$

Now, it can easily be checked that if $\widehat{\delta}_i$ are consistent for $\delta_i$, $i \in \{1, ..., 28\}$, then:

$$\widehat{\alpha}_R \equiv \frac{\widehat{\delta}_1 + \widehat{\delta}_9 + \widehat{\delta}_{17}}{1 + \frac{\widehat{\delta}_1 \widehat{\delta}_{11}}{\widehat{\delta}_4 \widehat{\delta}_9}},$$

$$\widehat{\alpha}_U \equiv \frac{\left(\widehat{\delta}_1 + \widehat{\delta}_9 + \widehat{\delta}_{17}\right) \left[\frac{\widehat{\delta}_1 \widehat{\delta}_{11}}{\widehat{\delta}_4 \widehat{\delta}_9}\right]}{1 + \frac{\widehat{\delta}_1 \widehat{\delta}_{11}}{\widehat{\delta}_3 \widehat{\delta}_9}} = \widehat{\alpha}_R \left[\frac{\widehat{\delta}_1 \widehat{\delta}_{11}}{\widehat{\delta}_4 \widehat{\delta}_9}\right],$$

$$\widehat{\alpha}_P = \frac{\widehat{\delta}_1}{\widehat{\alpha}_U},$$

$$\widehat{\alpha}_B = \frac{\widehat{\delta}_9}{\widehat{\alpha}_R},$$

are consistent for $\alpha_R$, $\alpha_U$, $\alpha_P$, $\alpha_B$. Given these estimates, it is easy to solve for consistent estimates of $\gamma_H$, $\gamma_B$, $\gamma_{UU}$, $\gamma_{UR}$, $\gamma_{RR}$, $\beta_U$ and $\beta_R$:

$$\widehat{\gamma}_{UU} = \widehat{\delta}_3 / \widehat{\alpha}_P,$$

$$\widehat{\gamma}_{UR} = \widehat{\delta}_4 / \widehat{\alpha}_P,$$

$$\widehat{\gamma}_{RR} = \widehat{\delta}_{12} / \widehat{\alpha}_B,$$

$$\widehat{\gamma}_P = \widehat{\delta}_5 / \widehat{\gamma}_{UU},$$

$$\widehat{\gamma}_B = \widehat{\delta}_{13} / \widehat{\gamma}_{UR},$$

$$\widehat{\beta}_U = \widehat{\delta}_7 / \widehat{\alpha}_P,$$

$$\widehat{\beta}_R = \widehat{\delta}_{15} / \widehat{\alpha}_B.$$

The general case of $\beta_P \neq 0$ or $\beta_B \neq 0$ can be obtained as an easy generalization of the just derived procedure: the same reasoning shows that the model would be overidentified. The only difference would be model nonlinearity even if the Stone Index were approximated by a linear index. Therefore, the nonlinear SUR should be used to estimate the model.

# B An Unobserved-Component Wage Model

As explained in the main text, we do not have ideal data on wages in the transport sector. The estimation results used in simulations are obtained by the strategy described in Section 2.2. Nevertheless, to check the robustness of the results, we approach the problem using other methods too. This appendix presents an unobserved-component model.

We assume that the average wage $\omega_{it}$ in the transport sector in district $i$ in the year $t$ is linked to the national average wage in the transport sector $\varpi_t$ as follows:

$$\log \omega_{it} = \vartheta_i + \log \varpi_t + \eta_{it}, \tag{5}$$

where $\vartheta_i = \log \theta_i$ is the time-invariant district-specific constant and $\eta_{it}$ is for each $i$ an i.i.d. homoscedastic mean-zero noise.

The difference is that we do not estimate the constants $\theta_i$ based on the years 1994-2001 **solely**. We do estimate the constants $\theta_i$ simultaneously with other structural parameters of the model (i.e. simultaneously with $\alpha_1$, $\alpha_2$ and $\beta$). This strategy has two advantages to it:

1. it increases the efficiency of the estimates;
2. it gets the standard errors right.

In short, we use a minimum-distance estimator. Its objective function is defined as follows:

$$\min \mathbb{W} = \sum_t \sum_i \widetilde{\varepsilon}_{it}^2 + \gamma \sum_{t>2001} \sum_i \widetilde{\eta}_{it}^2, \tag{6}$$

where $\widetilde{\varepsilon}_{it}$ are residuals of (4), $\widetilde{\eta}_{it}^2$ are residuals of (5) and the minimization is with respect to the structural parameters $\alpha_k$ and $\theta_i$. The efficient version of the estimator can be reaped using the notorious two-stage approach. In the first stage, we estimate (6) with $\gamma = 1$. The first-stage estimates are then used for estimating the variances of $\varepsilon_{it}$ and of $\eta_{it}$ and the second stage improves the efficiency by setting $\gamma = \sqrt{\frac{\sigma_\varepsilon^2}{\sigma_\eta^2}}$.

If we specified a stochastic process for $\theta_i$, we could use the Kalman filter instead of the two-step minimum-distance estimator[6]; this option, however, would diminish the degrees-of-freedom, which are low anyway and the short time span is not favorable for a statistical determination of the appropriate specification of the stochastic processes. Therefore, we do not opt for this option.

[6]The relative variances can be estimated simultaneously with other structural parameters by the maximum-likelihood principle, if normality of $\varepsilon_{it}$ and of $\log \eta_{it}$ is assumed.

Table 1: Summary statistics on household data

| City | Average expenditure share of | | |
|---|---|---|---|
| | public urban transport | motor fuels | public non-urban transport |
| Prague | 1.5% | 3.2% | 0.4 % |
| Brno | 1.7% | 2.8% | 0.3 % |
| Ostrava | 1.4% | 2.9% | 0.6 % |
| Pilsen | 1.3% | 3.7% | 0.3 % |
| Olomouc | 0.9% | 3.1% | 0.5 % |

Table 2: Calibration of uncompensated elasticities

| | Price elasticity of | | |
|---|---|---|---|
| | motor fuel used in | | public urban transport |
| | urban areas | rural areas | |
| w.r.t. fuel price | -1.04 | -0.40 | 0.30 |
| w.r.t. urban transport price | 0.28 | 0.03 | -0.65 |

Table 3: Results of the Fixed-Effect Model

| Variable | Coefficient | t-statistics | p-value |
|---|---|---|---|
| Log of the Fuel Price | 0.302 | 3.431 | 0.0008 |
| Log of the Wage Rate | 0.462 | 3.966 | 0.0001 |
| Log of the Output | 0.089 | 0.499 | 0.6185 |

Table 4: Results of the Random-Effect Model

| Variable | Coefficient | t-statistics | p-value |
|---|---|---|---|
| Log of the Fuel Price | 0.302 | 3.419 | 0.0008 |
| Log of the Wages Rate | 0.463 | 3.951 | 0.0001 |
| Log of the Output | 0.089 | 0.497 | 0.6197 |

Table 5: Vehicle fleet structure according to the EURO standards (2001)

| Vehicle fleet structure in | Prague | Pilsen |
|---|---|---|
| EURO 0 | 24.7% | 44.2% |
| EURO 1 | 25.1% | 23.5% |
| EURO 2 | 50.0% | 31.7% |

Source: ATEM (2001)

Table 6: Monetary values of external costs of air pollution from cars (in CZK per km, Czech Republic, urban areas, 2001)

| Monetary values CZK/km | $NO_x$ | $SO_2$ | HC | $PM_{10}$ | $CO_2$ | Total |
|---|---|---|---|---|---|---|
| Gasoline, EURO 0 | 1.53 | 0.0013 | 0.483 | 0.0015 | 0.13 | 2.14 |
| Gasoline, EURO 1 | 0.28 | 0.0015 | 0.025 | 0.0005 | 0.11 | 0.42 |
| Gasoline, EURO 2 | 0.12 | 0.0015 | 0.011 | 0.0005 | 0.10 | 0.24 |
| Diesel, EURO 0 | 0.56 | 0.0011 | 0.013 | 0.3330 | 0.11 | 1.02 |
| Diesel, EURO 1 | 0.28 | 0.0015 | 0.090 | 0.1641 | 0.10 | 0.56 |
| Diesel, EURO 2 | 0.12 | 0.0015 | 0.004 | 0.0791 | 0.09 | 0.30 |

Note: Costs of $CO_2$ are taken from Melichar (2006).

Table 7: Average monetary values of external costs of air pollution from public transport in Czech cities (in CZK per km, 2001)

| City | Air Pollution External Costs (CZK per km) | Air Pollution External Costs (EUR per km) |
|---|---|---|
| Brno | 38.26 | 1.28 |
| Prague | 36.66 | 1.22 |
| Pilsen | 32.89 | 1.10 |
| Olomouc | 62.62 | 2.09 |
| Ostrava | 47.32 | 1.58 |

Table 8: Baseline Parameter Assumptions

| Parameter | Value (in CZK) | Value (in EUR) |
|---|---|---|
| Excise Tax on Gasoline | 11.84 CZK/litre | 0.39 EUR/litre |
| Gasoline price | 26.73 CZK/litre | 0.89 EUR/litre |
| Excise Tax on Diesel | 9.95 CZK/litre | 0.33 EUR/litre |
| Diesel price in public transport | 18.68 CZK/litre | 0.62 EUR/litre |
| VAT on fuel | 22% | |
| VAT on public transport fares | 5 % | |
| Average diesel efficiency of buses | 48.1 litre/100 km | |
| Average gasoline efficiency of cars | 7 litre/100 km | |
| Costs of public funds | 20% | |

Note that the VAT does not apply to the fuel price of public transport operators.