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National gasoline and diesel demand elasticities and regional effects of carbon taxes in Sweden

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Abstract: This study estimated national and regional-level gasoline and diesel demand elasticities in Sweden using county-level panel data obtained between 2001 and 2015, which were used to estimate regional effects of a cost effective achievement of the Swedish targets for CO_2 emissions in the transport sector. The national-level elasticities were estimated by employing fixed effect (FE) and general method of moments (GMM) estimators, while county-level elasticities were calculated by considering the weight of each fuel type share at regional and national levels. Results from the national level indicated that per capita income, own and substitute prices, and per capita vehicle stocks were statistically significant in determining gasoline demand, while per capita income and own price were statistically significant in determining diesel demand. The calculated regional elasticities showed a variation between counties, with the highest being approximately 40 % higher than the lowest in absolute terms. A simulation of fuel taxes to achieve the Swedish 2030 emission target for the transport sector indicated considerable differences between counties in demand responses and private costs in relation to disposable income.

Keywords: Fuel demand, carbon tax, elasticity, dynamic panel data, region, Sweden

JEL codes: Q41, Q48, Q52, R48

1. Introduction

Gasoline and diesel consumption account for 35 % of total CO_2 emissions by OECD countries (IEA, 2017). For this reason, various climate policy instruments have been recommended in order to reduce emissions from the transport sector. For instance, the implementation of a fuel tax is regarded as an effective policy to limit CO_2 emissions from gasoline and diesel (Bruvoll and Larsen, 2004; Sterner, 2007, 2012; Lin and Li, 2011). In this regard, countries such as Finland, Netherland, Sweden and Norway have been pioneers in adopting taxes on fuel consumption (Lin and Li, 2011; Sumner *et al.*, 2011). Subsequently countries such as the United Kingdom, United States and Canada have introduced a carbon tax to reduce emissions of greenhouse gases (GHG) (Sumner et al., 2011). Developing countries, such as Costa Rica, Indonesia and Chile, have also implemented carbon taxes to reduce pollutant emissions and ease urban traffic congestion (Blackman et al., 2010; Parry and Strand, 2012; Yusuf and Resosudarmo, 2015).

Several studies have examined the incidence of fuel taxes, in particular on gasoline, using homogenous elasticity estimates obtained from nationally aggregated data (Sterner, 2007; Kim *et al.*, 2011; Lin and Li, 2011). However this approach may not be effective at achieving the desired emission reduction for a number of reasons. First, pooled estimates may not represent cross-sectional or regional heterogeneity. For instance, the study by Wadud *et al.* (2009) demonstrates that elasticities from aggregate data are limited in capturing detailed cross-sectional heterogeneity. Second, the assumption of identical slopes for all cross-sectional units in a dynamic panel data model could overestimate the speed of adjustment parameters, while the mean effects of exogenous covariates could be underestimated (Robertson and Symons, 1992; Maddala et al., 1997). The implication is that a tax-based climate policy using elasticities from pooled models may be inappropriate when looking at regional distributional effects (Verde and Tol, 2009; Grainger and Kolstad, 2010; Jiang and Shao, 2014; Vandyck and Van Regemorter, 2014).

The objective of this paper was threefold: to estimate gasoline and diesel demand elasticity in Sweden using both national and regional-level elasticity estimates, to derive the national tax required to achieve a CO_2 emission reduction target for the transport sector in Sweden, and to calculate regional distributional effects of the tax. A balanced panel dataset on gasoline and diesel consumption, real per capita income, real gasoline prices and fleet size from 21 Swedish counties over the period of 2001-2015 was used. Fixed effect (FE) and generalized method of moment (GMM) estimators were employed to derive national homogenous elasticity estimates, which were used to calculate a cost effective CO_2 tax to reach the emission target for the transport sector in Sweden. A framework to derive regional elasticity estimates at a national level, developed by Graham and Glaister (2006), was used in this study. Regional level gasoline and diesel demand elasticities were then computed for each region represented by the counties of Sweden, which were used to calculate regional effects in terms of demand responses and private costs of the CO_2 tax. The same methodology was employed by Crôtte *et al.* (2010) in Mexico to estimate gasoline per vehicle demand elasticities, and a significant variation was found in terms of magnitude between national and local levels.

The main contribution of this study is to estimate consistent gasoline and diesel demand elasticities in Sweden and derive the corresponding regional level elasticities considering the relative variation in the share of each fuel type in total fuel consumption at a national and regional level. In this regard, most of the previous studies estimated gasoline and diesel demand elasticities for Sweden based on nationally aggregated time series data (*e.g.* Dahl, 2012; Brännlund, 2013), which may not capture the potential effect of spatial heterogeneity. In addition, results from the study provide a contribution to policy by examining the distributional effects at the regional level to achieve the national emission reduction target in the transport sector.

The remainder of this study is organized as follows In Section 2, data descriptions are presented. Section 3 elaborates the empirical strategy used to estimate national elasticities, while the corresponding results are presented in Section 4. Section 5 derives the regional price elasticities for the 21 counties of Sweden and illustrates the regional implication of cost-effective national fuel taxes in order to reach the Swedish 2030 emission reduction targets for the transport sector. Finally, Section 6 presents a brief discussion and the conclusions of this study.

2. Data description

Following the literature, this study used annual aggregated data on the quantity of gasoline and diesel consumption, real per capita income, gasoline and diesel prices, and per capita vehicle stock to estimate the gasoline and diesel demand function (see Dahl 2012 for a review). The data consist of a panel comprising 21 Swedish counties between 2001 and 2015, which were collected from multiple sources. County-level deliveries of annual gasoline and diesel products to final consumers (1000 m^3) were obtained from the SCB (2016). Annual real prices for gasoline and diesel (SEK/litre) were collected from the SEA (2016). Data on county level per capita income at current prices (1000 SEK) (1 Euro = 9.36 SEK in average in 2015) were obtained from the SCB (2016). These were then converted into 2015 prices using the consumer price index. Table 1 presents summary statistics for variables used in the regression equations.

Table 1: Summary of descriptive statistics for the variables in the regression

Variables	Obs.	Mean	Std. Dev.	Min	Max
Per capita gasoline consumption (m3/year)	315	0.808	0.168	0.400	1.189
Per capita diesel consumption (m3/year)	315	0.838	0.248	0.321	1.838
Per capita income (1000 SEK[a]/year)	315	320	52.40	233.3	584.9
Real price of gasoline (SEK[a]/L)	315	12.90	1.341	10.69	14.98
Real price of diesel (SEK[a]/L)	315	12.30	1.863	8.950	14.81
Per capita vehicle stock (number)	315	0.491	0.040	0.381	0.600

[a] 1 Euro = 9.36 SEK in average in 2015

The consumption pattern of gasoline and diesel in the Swedish economy has undergone substantial change in the past fifteen years. Gasoline consumption in the transport sector fell by an average of 3 % per year, whereas diesel consumption increased by 4 % between 2001 and 2015 (SEA, 2016). The relatively rapid fall in gasoline consumption has largely been attributed to tax-incentivised dieselisation of EU regulations regarding CO_2 emissions for new cars, which favours diesel vehicles and thus reduces the relative diesel price (*e.g.* IEA, 2013). Following an approach similar to Brännlund (2013), this trend was captured in the regression by including substitute prices as an additional explanatory variable. Efficiency improvements in the thermodynamic performance of diesel engines may also have made diesel cars more attractive to consumers (see Pock, 2010).

Real prices of gasoline and diesel increased between 2001 and 2015, with an annual average rise of 2 % for each fuel type (SEA, 2016). The average price of gasoline was higher than diesel during the study period (SEA, 2016).

3. Econometric strategy

For the national estimates, two methods were used and compared: a fixed effect model and a partial adjustment model, with the latter estimated using a general method of moment (GMM) estimator. The fixed effect model was implemented as a baseline model that shows the expected sign and magnitude of elasticity estimates. However, estimates from the GMM model were considered the ultimate results due to its robustness with regard to the issue of endogeneity, which is a concern with lagged dependent variable as an explanatory variable. In addition, the GMM estimator allows short-run and long-run elasticity estimates to be derived.

3.1. Fixed effect model

The analysis stated by estimating the baseline model through applying fixed effect estimator as follows:

$$\log f_{it}^{k} = \log\phi + \alpha\log p_{it}^{o} + \beta\log p_{it}^{s} + \theta\log y_{it} + \lambda\log pv_{it} + T + \eta_{i} + \varepsilon_{it} \tag{1}$$

where f_{it}^{k} is a per capita fuel consumption for k fuel type, *i.e.* gasoline and diesel, p_{it}^{o} is the own real fuel price, p_{it}^{s} is the real substitute price, y_{it} is real per capita income, and pv_{it} denotes the per capita vehicle stock. The term η_i represents a county-specific time-invariant individual specific component. In recent years, technological progress has increasingly been made to vehicle engines, which has potentially contributed to the reduction in gasoline demand in most European countries. This effect was captured in equation (1) by adding a time trend, T, as an additional covariate. The term ε_{it} denotes the stochastic error term. The parameters α, β, θ, and λ can be interpreted as elasticities for own price, substitute price, per capita income and vehicle stock respectively. The subscripts i and t represent county and year respectively. The variable representing own price is expected to have a negative effect on fuel demand, whereas per capita income and substitute price are expected to have a positive effect. The average vehicle stock is expected to have either a positive or negative effect on per capita fuel consumption.

Equation (1) can consistently estimate the parameter of interest if the idiosyncratic errors ε_{it} are uncorrelated with the regressors (Cameron and Trivedi, 2009). However, the presence of any potential unobserved factors, such as inter-county mobility that varies over time, could make the elasticity estimates inconsistent. In addition, estimates based on equation (1) may not provide reliable elasticity estimates if, for instance, there is a relatively high level of adjustment by consumers to supply shocks in the gasoline and diesel market. To overcome this limitation, elasticity estimates are presented based on the partial adjustment model.

3.2. Partial adjustment model

One of the key features of the partial adjustment model is related to the consistent estimation of long-run and short-run elasticities. This is based on the assumption that consumers are expected to adjust their consumption level over time by taking into account various shocks, such as a change in real income, price level and technology (Baltagi and Griffin, 1983; Dahl and Sterner, 1991; Pock, 2010). This implies that the observed k fuel type consumption level at a time t is adopted to the desired level f_{it}^{k*} through the familiar adjustment mechanism (see Houthakker and Taylor, 1966) as:

$$\frac{f_{it}^{k}}{f_{it-1}^{k}} = \left(\frac{f_{it}^{k*}}{f_{it-1}^{k}}\right)^{\psi}, \qquad 0 < \psi < 1 \tag{2}$$

After combining equations (1) and (2), the log-linearised dynamic fuel demand equation that includes the lagged dependent variable is given as (Appendix A):

$$\log f_{it}^{k} = \psi \log \phi + \psi\alpha \log p_{it}^{o} + \psi\beta \log p_{it}^{s} + \psi\theta \log y_{it} + \psi\lambda \log v_{it} + (1-\psi) \log f_{it-1}^{k} + u_{it} \tag{3}$$

where the total error term, u_{it} is defined in three distinct error components as:

$$u_{it} = \eta_i + v_t + \varepsilon_{it} \tag{4}$$

with η_i representing a county-specific fixed effect, v_t a time-specific effect and ε_{it} a white noise component. Dynamic specification allows a differentiation between short-run and long-run fuel demand elasticity estimates. Accordingly, the parameters $\psi\alpha, \psi\beta, \psi\theta, \psi\lambda$ and $\psi\omega$ represent the short-run elasticities for own fuel price, substitute price, per capita income and average vehicle stock respectively. The corresponding long-run elasticities, *i.e.* α, β, θ and λ, are derived by considering the speed of adjustment parameter given by the coefficient of lagged dependent variable $1 - \psi$. This parameter is supposed to be statistically significant and positive in the case where there is a dynamic process.

3.3. Identification strategy

The analysis started by applying the FE estimator on equation (1), which can provide a reliable elasticity estimate controlling for any potential individual specific time invariant unobserved heterogeneities. This occurs when the observed covariates in the model are exogenous. Similarly, the existence of unobserved individual specific heterogeneities that vary over time could make the FE model inconsistent. The implication is that estimating the dynamic specification of equation (3) using the FE estimator gives inconsistent fuel demand elasticities because the included lagged dependent variable is correlated with the error term u_{it} and becomes endogenous (Blundell and Bond, 2000; Drukker, 2008; Cameron and Trivedi, 2009).

However, theoretically consistent fuel demand elasticity can be obtained by applying the two-step general method of moment (GMM) estimator put forward by Arellano and Bond (1998). There are a number of advantages to using the GMM estimator. First, it corrects endogeneity caused by the inclusion of the lagged dependent variable by constructing an internal instrument. Second, the estimator addresses the issue of Nickell bias[1] in the estimation. Third, it provides robust estimates given that the study covers a short time (T=15) and a large cross-section (N=21). Finally, it considers the issue of finite sample correction to the reported standard errors, which are no longer downward biased (see Windmeijer, 2005). Essentially, the GMM estimates are required to satisfy the Arellano-Bond test for no autocorrelation in first-differenced errors and the Hansen test of overidentifying restriction, which

[1] Nickell bias is an important concern in the estimation since a correlation between the lagged dependent variable and country fixed effect cannot be ruled out given that the study only covers a short period of time (T=15).

complements the required theoretical and statistical properties of dynamic panel data estimation (Roodman, 2006).

4. Regression results

Table 2 presents gasoline and diesel demand elasticity estimates for the whole of Sweden. The implemented baseline estimates, *i.e.* FE estimates, showed the expected coefficient sign for the variables in the regression. In order to obtain more consistent estimates, the GMM estimator was employed in equation (3). The result showed that both the short-run and long-run estimates had the expected signs, with higher long-run estimates in absolute terms. Essentially, the model passed the AR(2)[2] test for autocorrelation and the Hansen test for instrument validity where the null hypotheses were not rejected, indicating an absence of autocorrelation and validity of the internal instruments respectively.

Table 2: Gasoline and diesel demand elasticity estimates in Sweden

	Gasoline demand			**Diesel demand**		
	FE	**GMM: Short run**	**Long run**	**FE**	**GMM: Short run**	**Long run**
Log of per capital GDP	0.394***	0.104***	0.406***	0.048	0.269***	0.984
	(0.050)	(0.023)	(0.064)	(0.226)	(0.127)	(0.618)
Log of gasoline price	-0.271	-0.322***	-1.260***	-0.330*	0.648	2.373**
	(0.196)	(0.032)	(0.216)	(0.171)	(0.396)	(1.195)
Log of diesel price	0.102	0.054***	0.212***	1.430***	-0.555*	-2.034***
	(0.111)	(0.018)	(0.074)	(0.412)	(0.285)	(0.871)
Log of vehicle stock per capita	-1.311***	-0.061***	-0.238***	0.935**	0.016	0.058
	(0.004)	(0.009)	(0.018)	(0.426)	(0.182)	(0.660)
Time trend	-0.031***	0.009***			-0.006**	
	(0.004)	(0.002)			(0.002)	
Lagged dep. variable		0.744***			0.727***	
		(0.030)			(0.054)	
Constant	6.897*	-0.972***		-1.371***	-3.776***	
	(3.545)	(0.262)		(4.317)	(0.504)	
Adj R^2	0.91			0.558		
AR(2)		1.560			0.477	
Hansen test		18.55			16.81	
Observations	315	294		315	294	

Note: The standard errors for the long-run elasticities were calculated from the short-run estimates using the delta method. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

[2] The Arellano-Bond test was applied to the residuals in differences and a check carried out to identify serial correlation of order *i* in levels by looking for correlation of order *i + 1* in differences (see Roodman (2006)). Thus the test for AR (2) in first differences became more important because it could detect an autocorrelation in levels.

The effect of per capita income on gasoline demand was positive and statistically significant at the 1 % level in all models. The effect of real gasoline and diesel price was also statistically significant at 1 % level for the GMM estimates, where an increase in gasoline price by 1 % leads to approximately a 0.32 % decrease in gasoline demand. This estimate was close to the price elasticity reported in the study by Dahl (2012). In addition, the estimate for per capita vehicle stock had a negative effect on gasoline demand, which was similar to the estimates reported in previous studies (*e.g.* Baltagi and Griffin, 1997; Pock, 2010). A unit rise in average per capita vehicle stock reduced gasoline demand by 0.06. The speed of adjustment parameter became statistically significant at 1 % significance level with a value of 0.74. This indicated a high level of persistence with consumers adjusting their long-run consumption by approximately 26 % within the first period.

With respect to diesel demand, the baseline model (FE) showed expected signs of the estimates for real per capita income, real diesel price, per capita vehicle stock and gasoline price. The corresponding short-run and long-run estimates showed the expected sign. The diesel price was statistically significant at 1 % and 5 % level in the short run and long run respectively. Accordingly, a 1 % increase in diesel price could lead to 0.56 % and 2 % reduction in diesel demand in the short and long run respectively. The larger long-run diesel price elasticity estimate could be linked to the increasing number of alternative vehicle types in the transport sector, shifting consumer choice towards public transport or other vehicle types for a small diesel price change (*e.g.* see Lim *et al.*, 2012). Similarly, the gasoline price becomes positive and statistically significant in the long run. Estimates for real per capita income were statistically significant in the short run, with a 1 % increase in per capita income resulting in a 0.27 % increase in short-run diesel demand.

The estimates representing per capita vehicle stock were positive and statistically significant in the case of the FE model, but statistically insignificant in the partial adjustment model. The effect of time trend, which is expected to capture technological progress, was positive and statistically significant at a 5 % level. This could be linked to the potential rebound effect where diesel consumption has been increasing, although there was an indication of improvement in vehicle technology. Importantly, the speed of adjustment parameter was statistically significant at a 1 % level with a value of 0.73. This indicates that consumers are expected to adjust their consumption level to the long-run equilibrium at the rate of approximately 27 % within the first period. Furthermore the GMM estimates were robust as they passed the Arellano-Bond test for zero autocorrelation and the Hansen test for instrument exogeneity.

5. Regional effects of national carbon fuel taxes

The national fuel taxes are calculated from the Swedish climate policy framework in which emissions from transport, excluding domestic aviation[3], are to be reduced by at least 70 % from the 2010 level by 2030 (MEE, 2017, IEA, 2013). This regulation is part of the EU's priority to create a fossil fuel-free transport fleet by 2030. This study calculated the necessary carbon dioxide tax and national price increases for gasoline and diesel required to achieve this target based on estimated price elasticities. It was then assumed that the price increases were introduced in 2015.

Calculated total emissions from consumption of fuels amounted to 25783 kton in 2015 based on the consumption of fuels presented in Table C1 and an average emission per 1000 m^3 of 2.67 kton CO_2 and 2.81 kton CO_2 for gasoline and diesel respectively (Miljöfordon, 2015). This is close to the reported emission of 26233 kton from domestic and foreign transports in 2015, which correspond to almost half of the total territorial emissions in Sweden (SEPA, 2018). Emissions of CO_2 from transports in 2015 were reduced by 17 % compared to emissions in 2010 (SEPA, 2018), which implies an emission reduction of 64 % in 2015 emissions to obtain the 2030 target. Furthermore, reductions in emissions from the transport sector will occur between 2015 and 2030 due to expected population growth, GDP growth, technology development and recent developments in fuel prices. According to Capros *et al.* (2016) the annual rate of decrease in emissions is 0.0156 for the period 2015-2020 and 0.0081 for the years between 2020 and 2030. If these projected emission reductions take place, the required reduction from the 2015 emission level would be 58 %.

It is further assumed that the Swedish government minimizes total social cost for achieving the target where costs are measured by reductions in consumer surplus. The decrease in consumer surplus from the tax at the cost effective consumption level is then excluded since it is regarded as a transfer. To simplify calculations, linear demand functions are derived by means of the elasticity estimate at the price and demand levels in 2015. Logarithmic functions are difficult to evaluate for relatively large reductions in fuel demand. Given these assumptions, the cost-effective carbon dioxide charge amounts to .5.6 SEK/kg CO_2 emission (Appendix B). The cost effective charges on gasoline and diesel are 15.1 SEK/l and 15.8 SEK/l, respectively, which imply increases in the 2015 price corresponding to 116% and 132% (Appendix B).

Estimates of regional price elasticities are needed in order to assess the regional effects in terms of reductions in fuel demand and private costs of the national fuel taxes. Graham and Glaister (2006) introduced a method to derive local-level elasticity estimates from the national level that can reflect regional differences. Using spatially disaggregated data in the UK's cities and towns, the study

[3] Domestic aviation is not included in the goal because it is included in the European Union Emissions Trading System.

examined the spatial implications of road user charging and how road users may respond to a change in the price of travel according to a variety of different charging regimes. The crucial assumptions in the analyses by Graham and Glaister (2006) were that prices are constant between regions, the symmetry condition hold on the compensated cross price derivatives, and that the relationship in impact between two transport modes is proportional to their shares of total transport demand. In this study, the prices are constant among regions and gasoline and diesel fuel were the transport modes. Given that the assumptions hold, the relationship between county-level and national elasticities is written as:

$$\eta_{i,j}^{R} = \eta_{i}^{N} \left(\frac{Q_{i}^{N} / \sum_{i} Q_{i}^{N}}{Q_{i,j}^{R} / \sum_{i} Q_{i,j}^{R}} \right) \tag{5}$$

where $\eta_{i,j}^{R}$ and η_{i}^{N} represent the regional and national-level elasticity estimates respectively, Q_i refers to the consumption of fuel *i* where *i*=gasoline, diesel. According to eq. (5), the regional elasticity of fuel *i* is determined by the national elasticity weighted by the relationship in the shares of fuel *i* of total fuel consumption at the national and regional level. The regional elasticity is high when the share of fuel *i* of total fuel consumption is low at the regional level and *vice versa*.

In this study, regional elasticities were calculated for the 21 counties in Sweden (Figure C1), and the weights were evaluated based on the consumption of the fuel types in 2015 (Table C1). The shares of gasoline and diesel at the national level amounted to 0.383 and 0.617 respectively. The calculated weight for gasoline ranged between 0.824 (Stockholm) and 1.582 (Norrbotten) for the counties. Counties with a relatively low weight because of the high share of gasoline had a high weight for diesel. The corresponding weight for diesel then shows a similar range, with the lowest weight for Norrbotten (0.814) and the highest for Stockholm (1.152).

Regional calculations were made for the own price elasticities since these estimates were more robust than the estimates of the cross price elasticities, as discussed in Section 4 (Table 2). The reductions in gasoline and diesel consumption from the introduction of the fuel taxes range between 37% and 65% for gasoline and between 58% and 80% for diesel (Table 3). When calculating the distributional effects of these changes, total costs are calculated which include the total reduction in consumer surplus.

Table 3: Calculated regional short-run price elasticities, percent reductions in fuel consumption and costs of the fuel taxes, and total costs in percent of disposable income, 2015 weights.

County	Absolute value of price elasticities:		% reduction in fuel consumption:		Private cost of fuel taxes. MSEK:		Tot. private cost in % of disp. income
	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	
Blekinge	0.290	0.596	37	74	860	942	6.23
Dalarna	0.321	0.556	41	68	1479	2080	6.60
Gävleborg	0.382	0.506	48	60	1428	2949	8.31
Gotland	0.291	0.594	37	73	340	378	6.63
Halland	0.349	0.530	44	64	1463	2481	5.85
Jämtland	0.331	0.545	42	66	691	1044	7.17
Jönköping	0.348	0.530	44	64	1657	2803	6.64
Kalmar	0.356	0.524	45	63	1157	2047	7.10
Kronoberg	0.292	0.593	37	73	915	1021	5.24
Norrbotten	0.509	0.452	65	52	968	3643	9.33
Örebro	0.348	0.530	44	64	1237	2091	6.08
Östergötland	0.337	0.540	43	65	1855	2920	5.52
Skåne	0.298	0.585	38	72	5605	6577	4.67
Södermanland	0.295	0.588	38	72	1392	1603	5.56
Stockholm	0.265	0.640	34	80	8050	6990	2.93
Uppsala	0.315	0.563	40	69	1420	1903	4.67
Värmland	0.356	0.524	45	63	1323	2354	7.01
Västerbotten	0.409	0.490	52	58	1008	2402	6.92
Västernorrland	0.388	0.502	49	60	1108	2372	7.43
Västmanland	0.317	0.561	40	68	1282	1744	5.87
Västra Gotaland	0.317	0.560	40	68	6815	9324	4.87
National	0.322	0.555	42	68	42055	59667	5.06

The results in Table 3 show that the total private cost of the fuel taxes corresponds to 5.06% of disposable income for Sweden as a whole. Stockholm county faces the highest total cost but the disposable income in this county is high, and the cost in percent of disposable income (2.93%) is lowest for this county. On the other hand, the percentage is higher for the northern counties and amounts to 9.33% for the Norrbotten county where disposable income is relatively low compared with the private cost of the fuel taxes.

6. Discussion and conclusions

This study estimated gasoline and diesel demand elasticities in Sweden at a national level, which were then used to obtain regional estimates of private costs to reach the Swedish emission targets of CO_2 for the transport sector in 2030. Fixed effects and GMM estimators where used and robust results were that per capita income, own and cross prices, and per capita vehicle stock had the expected sign in the fuel demand models, with a relatively higher magnitude for gasoline price in absolute terms. The estimated short-run and, in particular, long-run price elasticities of gasoline were in the same order of magnitude as several other studies, but the corresponding price elasticities of diesel were in the upper range (in absolute values).

As a member of the EU's comprehensive climate change mitigation plan, Sweden has developed emission reduction goals where a key target is a 70 % reduction in emissions from the transport sector by 2030 from the 2010 level. The calculations in this study showed that the necessary national fuel taxes for a cost-effective achievement of the target correspond to 116% and 132% of the consumer prices of gasoline and diesel, respectively. Private costs at the county level were calculated by deriving regional price elasticities from the national level estimates. The calculations showed that the private costs in percent of disposable income ranged between 2.93% and 9.33%, being lowest in the Stockholm county, where the capital of Sweden is located, and highest in the northern region with relatively low population density and disposable income.

The results rest on several crucial assumption. One is the choice of short run price elasticities for evaluating the national tax and regional effects because of the relatively high (in absolute value) levels of the long run elasticities. If the long price elasticities were used, the necessary tax would amount to 1.80 SEK/kg CO_2 emission and the price on gasoline and diesel would increase by 26% and 41% respectively. The private cost would in average amount to 1.42% of disposable income but the relative differences between the counties would remain the same (Table C2).

The weights used for calculating regional price elasticities were calculated at the fuel consumption levels in 2015. It could be argued that they should reflect a longer time perspective. Calculations were therefore made with weights calculated at the average level (between 2003 and 2015) for the counties (Table C3). These weights had a minor impact on the average private cost in percent of disposable income, but reinforced regional distributional impacts where the cost of a northern county (Norrbotten) increased by 0.21 percentage point and that of the Stockholm region decreased by 0.06 percentage point. Similar results were obtained with long run price elasticities and weights based on average consumption (Table C4).

Another assumption was a cost effective achievement of the Swedish target for the transport sector and not for total emissions in Sweden. Depending on the marginal cost of reductions in CO_2 compared with other sectors, such as agriculture and carbon sink enhancement in forestry, the level of the fuel charges may be either higher or lower. This is partly accounted for in this study by evaluating national carbon taxes and associated regional effects based on different national price elasticities, which amounted to SEK 1.8/kg CO_2 emission or SEK 5.6/kg CO_2 under the long and short run price elasticity, respectively. A common result of all simulations was that the private costs in relation to disposable income in northern regions with relatively low population density were more than twice as large as that of the densely populated regions. The regressive effects of carbon pricing is a well-known phenomenon in the literature (e.g. Dorband et al. 2019). Without any policies combatting these effects, they could mitigate the implementation and enforcement of cost-effective climate policies in the transport sector.

Appendix A: Derivation of dynamic fuel demand equations

Suppose the log-linearised demand function for *k* fuel type in region *i* at time *t* is given as follows:

$$\log f_{it}^{k*} = \alpha \log X + \omega_{it} \tag{A1}$$

where f_{it}^{k*} denotes a *1xN* vector of the desired fuel consumption, α is a 1xK vector of parameters to be estimated, X is a *KxN* vector of variables explaining fuel demand, and ω a 1xN vector representing the error term. Following Houthakker and Taylor (1966), the desired level of *k* type fuel demand in county *i* at time *t*, f_{it}^{k*}, through the familiar adjustment mechanism, is also given as:

$$\frac{f_{it}^{k}}{f_{it-1}^{k}} = \left(\frac{f_{it}^{k*}}{f_{it-1}^{k}}\right)^{\psi}, \qquad 0 < \psi < 1 \tag{A2}$$

$$\log\left(\frac{f_{it}^{k}}{f_{it-1}^{k}}\right) = \psi \log\left(\frac{f_{it}^{k*}}{f_{it-1}^{k}}\right)$$

$$\log f_{it}^{k} - \log f_{it-1}^{k} = \psi \log f_{it}^{k*} - \psi \log f_{it-1}^{k}$$

$$\psi \log f_{it}^{k*} = \log f_{it}^{k} - \log f_{it-1}^{k} + \psi \log f_{it-1}^{k}$$

$$\log f_{it}^{k*} = \frac{1}{\psi}\log f_{it}^{k} - \frac{1}{\psi}\log f_{it-1}^{k} + \log f_{it-1}^{k}$$

$$\log f_{it}^{k*} = \frac{1}{\psi}\log f_{it}^{k} + \left(1 - \frac{1}{\psi}\right)\log f_{it-1}^{k} \tag{A3}$$

Combining equations (A1) and (A3) gives the dynamic fuel demand equation as follows:

$$\frac{1}{\psi}\log f_{it}^{k} + \left(\frac{\psi - 1}{\psi}\right)\log f_{it-1}^{k} = \alpha \log X + \omega_{it}$$

$$\frac{1}{\psi}\log f_{it}^{k} = \left(\frac{1-\psi}{\psi}\right)\log f_{it-1}^{k} + \alpha \log X + \omega_{it}$$

$$\log f_{it}^{k} = (1-\psi)\log f_{it-1}^{k} + \psi\alpha \log X + \omega_{it} \tag{A4}$$

Equation (A4) represents the dynamic fuel demand equation, *i.e.* similar to equation (3).

Appendix B: Calculations of cost-effective national fuel price increases

The cost in terms of decreases in consumer surplus for each fuel f=gasoline, diesel with a linear demand function is defined $C^{f} = (P^{f} - P^{f,BAU})(Q^{f,BAU} - Q^{f})/2$ where *f=G,D* for gasoline and diesel respectively. Recognizing that $P^f = A^f - b^f Q^f$ when disregarding cross price elasticities, the decision maker can choose the cost effective levels of Q^f for reaching the emission target $\overline{E}$ according to:

$$\underset{Q^f}{Min} \quad C = \sum_f C^f \qquad s.t. \quad \sum_f e^f Q^f \leq \overline{E} \tag{B1}$$

where P^f and Q^f are the prices and quantities, respectively, of, the superscript BAU reflects the actual prices and quantities in 2015, and e^f are the conversion factors of fuels into CO_2 emissions .

The first-order conditions are:

$$\frac{\partial C}{\partial Q^f} = 2b^f Q^f - b^f Q^{f,BAU} - A^f + P^{f,BAU} = e^f \lambda \quad for \;\; f = G, D \tag{B2}$$

Expressions for b^f and A^f are found from the own price elasticity estimates and BAU levels of P^f and Q^f according to:

$$b^f = \frac{P^{f,BAU}}{\varepsilon^f P^{f,BAU}} \qquad A^f = b^f Q^{f,BAU} + P^{f,BAU} \tag{B3}$$

Solving for the cost effective level of Q^G gives:

$$Q^G = \left(\frac{2b^D \overline{E}}{2b^G} + H^G \right) \Big/ K^G \tag{B4}$$

where $H^G = A^G - A^D + P^{D,BAU} - P^{G,BAU} + b^G Q^{G,BAU} - b^D Q^{D,BAU}$ and $K^G = 2\left(\frac{b^G e^D}{e^G} + \frac{b^D e^G}{e^D} \right)$.

The optimal level of Q^D is obtained from the emission constraint in eq. (B1).

Inserting the estimated values of short-run elasticities $\varepsilon^G=0.322$, $\varepsilon^D=0.555$, $P^{G,BAU}=13$, $P^{D,BAU}$, $Q^{G,BAU}=3578$, $Q^{D,BAU}=5776$, $e^G=2.67$, $e^D=2.81$, $\overline{E}$ =10829 (a reduction by 58%), gives the optimal levels $Q^G=2149$ and $Q^D=1811$. The cost effective CO_2 tax as shown by the Lagrange multiplier λ amounts to SEK 5.6/ kg CO_2 emission. The necessary tax on gasoline is then 15.1 SEK/l and that on diesel is 15.8 SEK/l, which imply price increases of 116 % and 132 % of the BAU prices of gasoline and diesel, respectively.

Appendix C: Figure C1 and Tables C1-C4

Figure C1: Counties in Sweden. Source: www.lansstyrelsen.se

Table C1: Fuel consumption in 2015 and average fuel consumption (2001-2015) and regional weights for different counties

County	Consumption in 2015. Gasoline	Diesel	Consumption average. Gasoline	Diesel	Price elasticities at 2015 weights Gasoline	Diesel	Price elasticities at average weights Gasoline	Diesel
Blekinge	70.90	95.60	87.3	72.2	0.899	1.075	0.922	1.094
Dalarna	125.7	201.6	173.8	165.9	0.997	1.002	0.986	1.015
Gävleborg	129.1	270.7	159.9	196.4	1.186	0.911	1.124	0.899
Gotland	28.1	38.3	35.9	36.6	0.905	1.070	1.018	0.982
Halland	127.8	233.7	175.7	174.5	1.083	0.954	1.005	0.995
Jämtland	59.3	100	83.2	91.7	1.029	0.983	1.060	0.946
Jönköping	144.7	264.1	193.1	207.0	1.082	0.955	1.045	0.958
Kalmar	101.8	191.7	136.4	156.9	1.104	0.945	1.084	0.927
Kronoberg	75.6	103.3	104.7	113.6	0.906	1.069	1.052	0.952
Norrbotten	101.1	316.4	138.4	223.2	1.582	0.814	1.318	0.803
Örebro	108	197	146.5	147.1	1.082	0.955	1.011	0.989
Östergötland	160.2	278	212.0	203.5	1.048	0.973	0.988	1.012
Skåne	465.6	658.6	603.4	534.6	0.925	1.053	0.951	1.055
Södermanland	115.4	161.1	151.2	118.9	0.918	1.059	0.901	1.126
Stockholm	648.5	747.4	781.5	586.9	0.824	1.152	0.883	1.156
Uppsala	119.9	186	161.5	136.9	0.977	1.015	0.932	1.080
Värmland	116.5	220.2	161.9	181.5	1.107	0.943	1.070	0.938
Västerbotten	93.8	217	131.8	168.7	1.269	0.884	1.150	0.883
Västernorrland	100.9	216.8	145.3	168.9	1.206	0.904	1.090	0.922
Västmanland	108.5	170	138.5	120.6	0.983	1.011	0.943	1.065
V. Götaland	577	908	809.3	864.4	0.986	1.009	1.043	0.960
National	3578.4	5775.5	4730.9	4669.7				

Table C2: Calculated regional long run price elasticities, percent reductions in fuel consumption and costs of the fuel taxes, and total costs in percent of disposable income, 2015 weights

County	Absolute value of long-run price elasticities: Gasoline	Diesel	% reduction in fuel consumption: Gasoline	Diesel	Private cost of fuel taxes, MSEK: Gasoline	Diesel	Total private cost in % of disp. income
Blekinge	1.133	2.186	39	79	196	285	1.66
Dalarna	1.257	2.037	43	67	338	661	1.85
Gävleborg	1.494	1.853	51	52	329	989	2.50
Gotland	1.140	2.176	39	78	77	115	1.77
Halland	1.365	1.941	46	59	336	812	1.70
Jämtland	1.296	1.999	44	64	158	336	2.04
Jönköping	1.363	1.943	46	59	380	917	1.93
Kalmar	1.391	1.921	47	57	266	674	2.08
Kronoberg	1.142	2.173	39	78	208	310	1.40
Norrbotten	1.993	1.656	68	35	229	1283	3.06
Örebro	1.363	1.943	46	59	284	684	1.77
Östergötland	1.320	1.978	45	62	425	945	1.58
Skåne	1.165	2.142	40	76	1277	2018	1.26
Södermanland	1.156	2.154	39	77	317	490	1.50
Stockholm	1.039	2.344	35	92	1826	1983	0.74
Uppsala	1.231	2.064	42	69	324	600	1.30
Värmland	1.395	1.919	47	57	304	775	2.06
Västerbotten	1.599	1.797	54	47	234	817	2.13
Västernorrland	1.519	1.839	52	51	256	798	2.25
Västmanland	1.239	2.056	42	68	293	551	1.64
V. Götaland	1.242	2.052	42	68	1557	2949	1.36
National	1.260	2.034	42	68	9614	18991	1.42

Table C3: Calculated regional short-run price elasticities, percent reductions in fuel consumption and private costs of the fuel taxes, and total costs in percent of disposable income, average weights.

County	Absolute value of price elasticities: Gasoline	Diesel	% reduction in fuel consumption: Gasoline	Diesel	Private cost of fuel taxes, MSEK: Gasoline	Diesel	Total private cost in % of disp. income
Blekinge	0.297	0.607	39	75	836	929	6.11
Dalarna	0.317	0.563	42	69	1454	2062	6.52
Gävleborg	0.362	0.499	47	59	1430	2970	8.35
Gotland	0.328	0.545	43	66	322	400	6.65
Halland	0.324	0.552	43	67	1470	2421	5.78
Jämtland	0.341	0.525	45	63	670	1067	7.18
Jönköping	0.336	0.532	44	64	1644	2798	6.62
Kalmar	0.349	0.514	46	62	1142	2069	7.11
Kronoberg	0.339	0.528	44	64	857	1098	5.29
Norrbotten	0.424	0.446	55	51	1050	3666	9.54
Örebro	0.325	0.549	43	67	1240	2048	6.01
Östergötland	0.318	0.562	42	69	1852	2849	5.44
Skåne	0.306	0.586	40	72	5445	6568	4.61
Södermanland	0.290	0.625	38	78	1370	1534	5.39
Stockholm	0.284	0.641	38	80	7741	6973	2.87
Uppsala	0.300	0.600	40	74	1410	1825	4.54
Värmland	0.344	0.521	45	63	1313	2361	7.01
Västerbotten	0.370	0.490	48	58	1030	2403	6.97
Västernorrland	0.351	0.512	46	61	1130	2347	7.42
Västmanland	0.304	0.591	40	73	1272	1685	5.74
V. Götaland	0.336	0.533	44	64	6558	9609	4.88
National	0.322	0.555	42	68	41235	59683	5.02

Table C4: Calculated regional long run price elasticities, percent reductions in fuel consumption and costs of the fuel taxes, and total costs in percent of disposable income, average weights

County	Absolute value of long-run price elasticities: Gasoline	Diesel	% reduction in fuel consumption: Gasoline	Diesel	Private cost of fuel taxes, MSEK: Gasoline	Diesel	Total private cost in % of disp. income
Blekinge	1.379	2.226	47	82	195	276	1.63
Dalarna	1.279	2.065	43	69	339	649	1.83
Gävleborg	1.133	1.829	39	50	335	1001	2.53
Gotland	1.238	1.998	42	64	75	128	1.88
Halland	1.254	2.024	43	66	343	772	1.65
Jämtland	1.191	1.923	41	57	157	351	2.10
Jönköping	1.207	1.949	41	60	384	912	1.93
Kalmar	1.168	1.885	40	54	267	687	2.11
Kronoberg	1.200	1.937	41	59	200	359	1.52
Norrbotten	1.012	1.633	34	34	248	1295	3.12
Örebro	1.247	2.012	42	65	289	655	1.73
Östergötland	1.275	2.059	43	69	432	898	1.54
Skåne	1.330	2.146	45	76	1268	2011	1.26
Södermanland	1.419	2.290	48	88	319	445	1.42
Stockholm	1.456	2.351	50	93	1798	1972	0.73
Uppsala	1.361	2.198	46	80	328	549	1.23
Värmland	1.182	1.908	40	56	307	779	2.07
Västerbotten	1.113	1.796	38	47	242	817	2.15
Västernorrland	1.162	1.876	40	54	264	781	2.23
Västmanland	1.342	2.166	46	78	296	512	1.57
V. Götaland	1.209	1.952	41	60	1533	3129	1.41
National	1.260	2.034	42	68	9620	18978	1.42

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