Implementing a Carbon tax in the transportation sector

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Abstract

A competitive equilibrium would drive the world economy to an inefficient outcome of increased greenhouse gas emissions, which shall be corrected by a carbon tax. However, imposing this tax based purely on externalities measurement suffers from an implementation drawback: the political sector is not prawned to implement it because lower deciles are characterized by intense use of pollutants, implying an increased tax burden on fragile segments of society. By maximizing social utility, we calculate optimal deviations from Pigouvian carbon taxes in the transportation sector. We find that these deviations imply a lower pricing for bus public transportation, that is intensively used by low-income individuals; on the other hand, they imply a higher gasoline tax. Implementing the proposed tax schedule reduces taxation inequality by 11 percent.

Key Words: pollution, carbon tax, transport sector.

JEL Classification Numbers: H23, Q21, Q28.

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1. Introduction

After the Glasgow Summit on environmental issues and the Sharm El Sheikh follow-up meeting, the call for action to avoid the damage caused by Greenhouse gas emissions has become imminent in the international arena.

There is a wide consensus among professional analysts on the need of imposing a Pigouvian carbon tax, which would internalize pollution effects on consumer's behavior. However, decisions on carbon tax are taken by politicians, who confront a difficult implementation problem. The imposition of a carbon tax implies imposing a high burden on many polluting fuel uses that are demanded by low-income individuals, which would hurt their consumer's surplus, implying a difficulty for politicians that are aware of the negative electoral impact of implementing such a reform. Coping with this issue requires an analysis of the externality issue combined with social considerations – which would transform the carbon tax idea into an implementable tool.

In this paper we aim at providing such a framework by analyzing the problem of a social planner that maximizes social utility, based on second-best solutions that improve the chance of carbon tax implementation.

To perform this task, we build a model for the transportation sector, and analyze the optimal deviation from Pigouvian tax rates when the available transportation means are both private cars and publicly regulated transportation, based on buses and trains.

The paper is organized as follows. In section 2 we show the model; section 3 shows the chosen parameters, based on a literature survey at OECD countries about price, cross-price and income elasticities of demand for car, bus and train rides. In section 3 we show the results of a simulation of optimal pricing, including the possibility of screening, by discriminating between low-income and high-income individuals through geographical destination of public transportation rides. Section 4 summarizes and concludes.

2. The Model

The government maximizes a social welfare function based on the sum of utility of individuals with income y that enjoy the consumption of private products, represented by their price p, subject to restrictions on greenhouse gas pollutants, E (see equation XIV in Appendix A):

$$(1)\quad W_1 = N \int U(p, y) f(y) dy + \lambda\big((\pi - s)E - F - D\big)$$

where N is the number of households, U is the indirect utility, p represents private products prices, λ is the Lagrange multiplier of the social planer budget constraint (shadow price of public funds), E is the total quantity of GHG emitted by the households when using services at the transport sector; $(\pi - s)E$ represents Trading Emissions Permits (TEPs) needed to produce all goods in the economy, where π is the price set by the government for each pollutant good, and s is the price of 1 ton of green-house gas pollution; F represents the fixed cost of operating the tax system; and D is the amount of money that is used to subsidize climate crisis mitigation and adaptation solutions by the tax system revenue. After setting the TEP's prices, the government covers the social cost of pollution, s (see equation 8 below).

According to this budget constraint tax revenue has three goals: 1. Self-financing; 2. Financing social costs of greenhouse gases, based on externalities such as treating various injuries, rewarding economic sectors harmed by climate crisis, etc.; and 3. Financing additional social goals of the social planner that are related to climate change, such as payment for various mitigation measures designed to reduce the amount of emissions; that includes education, installation of solar power facilities, etc., and payment for adaptation measures designed to reduce the expected social cost as a result of various natural phenomena related to climate change (strengthening cliffs on seashores, installing means to cool the environment, etc.).

In our model we show how to implement a carbon tax based on two means of transportation: private cars and publicly regulated transportation (buses and trains).

As shown in Appendix A, the pricing rules needed for setting the TEPs are (see equations XLIX and L):

$$(2)\qquad \theta_1 = \frac{\eta_{22}(R_1-\lambda)-\eta_{12}(R_2-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})} = \frac{\pi_1 - s}{\pi_1}$$

$$(3)\qquad \theta_2 = \frac{\eta_{11}(R_1-\lambda)-\eta_{21}(R_2-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})} = \frac{\pi_2 - s}{\pi_2}$$

When, η_{ij} is the elasticity of demand for i with respect to the price of j; $R_i = \frac{\int q_i(p,y)U_y f(y)dy}{\int q_i(p,y)U_y dy}$ is the "distributional characteristic", which is based on a weighted average of the marginal utilities of individuals that consume the good/service; i.e., each household's marginal utility of income weighted by that household's consumption of good/service i.[2] The pricing rules (2) and (3) reflect the socially optimal deviation from private sector marginal pricing, to be used by the government for imposing a carbon tax. These deviations are intended to cover the social cost of GHG emissions of private and public transportation. In other words, it shows, in percentages, how much different the optimal carbon tax rate is from the Pigouvian tax rate. The pricing rules depend on variables that are measurable and determinable.

To calculate the distributional characteristic of the final transportation good, we will use the following equation (Feldstein, 1972b):

$$(4)\quad R_i = \bar{y}^{-\beta}(1+V)^{1/2(\beta+\beta^2)}\,(1+V)^{-\beta\alpha_i}$$

Where $\bar{y}$ is the mean income; $V = \frac{\sigma_y^2}{\bar{y}^2}$ is the mean income relative variance; β is the normative distributional parameter; and α_i is the income elasticity of demand for i. That means that the pricing rule for the TEP of a final good/service depends also on the distributional parameters of the good's consumers alongside the good's type as inferior, necessity, or luxury good ($\alpha_i < 0, 0 \le \alpha_i \le 1\ and\ \alpha_i > 1$, respectively).

We can rewrite the distributional characteristic as follows:

[2] Feldstein 1972b, page 52.

(5) $R_i = \frac{R_{i<50\%}+R_{i\geq 50\%}}{2}$

$$= 0.5\left(\left(\overline{y_{\iota<50\%}}^{-\beta}(1+V_{i<50\%})^{\frac{1}{2(\beta+\beta^2)}}(1+V_{i<50\%})^{-\beta\alpha_i}\right)\right.$$

$$\left.+\left(\overline{y_{\iota\geq 50\%}}^{-\beta}(1+V_{i\geq 50\%})^{\frac{1}{2(\beta+\beta^2)}}(1+V_{i\geq 50\%})^{-\beta\alpha_i}\right)\right)$$

It means the characteristic is calculated first for the bottom and top 50 percentile income consumers of good/service i, which will show a more accurate picture that considers the weight of the income percentiles.

In the case where the cross elasticities of demand are equal to 0, the pricing rules become:

(6) $\theta_1 = \frac{1}{|\eta_{11}|}\left[1 - \frac{R_1}{\lambda}\right] = \frac{\pi_1 - s}{\pi_1}$

(7) $\theta_2 = \frac{1}{|\eta_{22}|}\left[1 - \frac{R_2}{\lambda}\right] = \frac{\pi_2 - s}{\pi_2}$

We can see that the optimal deviation from Pigouvian externality of GHG emissions depends on two factors that will determine whether there will be a price differentiation or not: i) an efficiency factor, $\frac{1}{|\eta_{ii}|}$, where η_{ii} is the price elasticity of demand for good i; this term is known as the "Ramsey rule" and it implies that the optimal social deviation from the price of GHG emissions varies inversely with the absolute price elasticity of demand. That means that when the price elasticity is high, the more significant the deadweight efficiency loss for any departure from marginal cost is, driving social planner to a lower optimal deviation from the price of GHG emissions. ii) a distributional factor, $\left[1 - \frac{R_i}{\lambda}\right]$, where R_i is the distributional characteristic of good i. That means the optimal deviation from the price of GHG emissions is lower than 0 if $R_i > \lambda$ and it is greater than 0 if $R_i < \lambda$. In other words, the optimal social price of GHG emissions will be greater than the price of GHG emissions (i.e., a positive deviation) only if the distributional characteristic of the good is lower than the shadow price of public funds (and vice versa). Moreover, the higher is the distributional characteristic (which means that the good is intensively consumed by low deciles of the income distribution), the higher the plausibility of a negative deviation from Pigouvian tax (i.e., providing a subsidy).

3. An Application to the Transportation Sector in Israel

3.1 Optimal deviations from Pigouvian tax

Equations 2 and 3 show the deviations from Pigouvian taxation in the case of two means of transportation. As explained above, we need to translate the deviations from Pigouvian tax for each transportation service.

For translating into a tax on a 1 km ride of transportation service m, we use the following equation:

$$(8) \qquad \tau_m = e_m \pi_m = e_m \, s \, (1 + \theta_m)$$

where e_m is the "emission factor" of m, or the amount of GHG emission emitted per 1 km of a ride (per passenger in transportation system) in transportation service m, for a 1-ton\$CO_2$eq of GHG.

According to our solution, to calculate the tax rates the following parameters are needed:

- The Social Cost of Carbon (SCC) and the emission conversion factors.
- The income elasticities of demand for private and public transportation (or bus and train rides).
- The mean income of private transportation users and public transportation (or of buses and trains) users.
- The relative variance of the mean income.
- The shadow price of public funds in Israel.

- The elasticity of demand for an additional distance of ride in private and public (or buses and trains) transportation with respect to the same method of transportation fare.
- The elasticity of demand for an additional distance of ride in private and public (or buses and trains) transportation with respect to the other method of transportation fare.

In the next sub-section we describe these variables, the data used to calculate the tax rates, and additional parameters.

3.2 Literature survey on elasticities

In this sub-section we show the results of different papers in relation to price, cross-price and income elasticities of transportation in private cars, in buses and in train.

Table 1 shows that own price elasticities vary in a range between 0.1 and 1.2.

In Table 2 we show the cross elasticities between car rides and public (bus or train) rides, which are remarkedly higher in the direction from public to private transportation (i.e., public transport is more sensible to changes in car ride prices).

This finding is remarkable, especially when we look at Goodwin (1992); in other words, people that use buses or train rides may change their way of acting when car rides are lowered/raised; this sensitivity is more intensive than the opposite way around.

Table 1: Price Elasticities of Demand for Transportation Methods

Method	Source	Value	Notes
Private Cars	de Jong and Gunn (2001)	-0.16 to -0.26	Car-Kms with respect to Fuel price, short-term to long-term
	Mayeres (2000)	-0.16 to -0.43	Essential trips, peak to off-peak
	Mayeres (2000)	-0.43 to -0.36	Optional trips, peak to off-peak
	Goodwin, Dargay and Hanly (2003)	-0.1 (0.06) to -0.3 (0.29)	Vehicle km (total) mean elasticity, short-term to long-term
Buses	Goodwin (1992)	-0.28 to -0.55	Bus demand with respect to fare short-term to long-term
	Mayeres (2000)	-0.19 to -0.29	Bus, Tram, Metro passenger-km, peak to off-peak
	Luk and Hepburn (1993)	-0.29	Bus demand and fare, short-term
	Small & Winston (1999)	-0.58 to -0.69	Bus Passenger Transport Elasticities, urban to intercity
Trains	Goodwin (1992)	-0.65 to -1.08	Railway demand with respect to fare short-term to long-term
	Mayeres (2000)	-0.37 to -0.43	Rail pass-km, peak to off-peak
	Luk and Hepburn (1993)	-0.35	Rail demand and fare, short-term
	Small & Winston (1999)	-0.86 to -1.2	Rail Passenger Transport Elasticities, urban to intercity

Table 2: Cross elasticities of demand for Transportation Methods

The elasticity of Demand for	Based on:	Location	Value	Source
Car ride	London bus fare Underground fare other local bus fare	London	0.0005 0.0006 0.0018	Acutt and Dodgson (1996)
Car ride	Bus single-fares Bus ten-fares Bus pass-fares	Newcastle, Australia	0.116 0.121 0.02	Hensher (1997)
Car ride	InterCity rails fares NSE rails fares Regional rail fares	London	0.0118 0.0026 0.0022	Acutt and Dodgson (1996)
Car ride	Train single-fares Train ten-fares Train pass-fares	Newcastle, Australia	0.196 0.092 0.335	Hensher (1997)
London bus fares Underground fares other local bus fares	Car ride price	London	0.02 0.017 0.013	Acutt and Dodgson (1996)
Bus single-fares Bus ten-fares Bus pass-fares	Car ride price	Newcastle, Australia	0.066 0.016 0.003	Hensher (1997)
InterCity rails fares NSE rails fares Regional rail fares	Car ride price	London	0.094 0.041 0.091	Acutt and Dodgson (1996)
Train single-fares Train ten-fares Train pass-fares	Car ride price	Newcastle, Australia	0.053 0.042 0.003	Hensher (1997)
Public transit	Petroleum price	Europe	0.34	Goodwin (1992)

In Table 3 we show a survey of income elasticities, which characterize an essential differentiation between private and public transportation. While the range of elasticities for car rides includes values that allow for denominating it a luxury good (f.e., Johanson and Schipper, 1997), in public transportation we found that elasticities are typically in a range that defines a "necessity"; interestingly, we found also estimates with negative values for the elasticity of public transportation, which mean that this service constitute an inferior good. [3]

A broad picture of estimated elasticities in OECD countries show a heterogeneous characterization for all three transportation means, which is based on diverse features related to specific conditions; for example, regarding price elasticities those include peak pricing and urban-intercity transportation; Meyers (2000) found a relatively high elasticity for car rides in the peak (-0.43).

From our point of view, the most important factor is to use an estimation of a long-run elasticity, that is based on an average behavior – including the previously mentioned two characteristics. The long-run feature is representative of the permanent use of the different transportation means, in accordance with the present paper goal. His estimate fits what Dargay et al. (2002) denominate long-run elasticity.

In the next sub-section we show what were our choices for the purpose of the simulation.

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[3] Note that public transportation as an inferior good is a plausible scenario: when income goes down (for example, in the retirement period under life cycle) individuals may switch from car rides to public transportation rides as a benchmark choice. Note also that Dargay et al. (2002) estimated a relatively high absolute value negative income elasticity in the long run using data from England.

Table 3: Income Elasticities of Demand for Transportation Methods

Method	Source	Value	Notes
Private Cars	Mayeres (2000)	0.7 1.53	Essential trips Optional trips
	Johansson and Schipper (1997)	0.05-1.6 (Best guess – 1.2)	Car Fuel Demand
	Johansson and Schipper (1997)	0.65-1.25 (Best guess – 1.2)	Car Travel Demand
	Johansson and Schipper (1997)	-0.1 to 0.35 (Best guess – 0.2)	Mean Driving Distance (Per car per year)
Bus, Tram, Metro	Mayeres (2000)	0.59	Pass-km (Europe)
Rail	Mayeres (2000)	0.84	Pass-km (Europe)
Public transit in England	Dargay et al. (2002)	-0.67 to -0.9 -069 to -0.95	Log-log, short run to long run Semi-log, short run to long run
Public transit in France	Dargay et al. (2002)	-0.05 to -0.09 -0.04 to -0.07	Log-log, short run to long run Semi-log, short run to long run
Public transit	Holmgren (2007) p. 1025	-0.82 to 1.18 (Mean: 0.17)	
Public transit	Holmgren (2007) table 7	-0.62	

3.3 Parameters of the simulation

The choice of parameters will be done according to long-run use of each transportation mean, to obtain a simulation that is of practical use for the policy maker. In table 4 we see our choice for the different parameters.

Table 4: Elasticities Rates Used to Determine the Tax Rates

Parameter	Value	Source
$\alpha_{private}$	1.2	Johansson and Schipper (1997)
α_{public}	0.17 -0.62	Holmgren (2007)
$\eta_{private}$	-0.28	de Jong and Gunn (2001) Goodwin, Dargay and Hanly (2003)
η_{bus}	-0.55	Goodwin (1992)
η_{train}	-1.08	Goodwin (1992)
$\eta_{public\_wrt\_private}$	0.34	Goodwin (1992)
$\eta_{private\_wrt\_bus}$	0.02	Hensher (1997)
$\eta_{private\_wrt\_train}$	0.335	Hensher (1997)

Table 5 summarizes the distributional characteristics for the different services analyzed in the paper. The highest distribution characteristic is obtained for bus transportation within the case in which bus rides are characterized as an inferior good. While low-income individuals use also train rides, its characteristic is in the middle between buses and private cars. Private car rides have the maximal distributional characteristic, which implies a higher deviation from Pigouvian taxation when compared to other transportation means.

Table 5: Distributional characteristics

Parameter	Value	
α_{public}	**0.17**	**-0.62**
$R_{private}$	0.13243	0.13243
R_{bus}	0.14859	0.15367
R_{train}	0.13953	0.14471

3.4 Simulation Results

3.4.1 Optimal pricing in different scenarios

To cover the maximal mapping of situations we show results for three models: i) Model 1 – compares optimal pricing of private facilities (private cars) against publicly regulated facilities (buses and train); ii) Model 2 – compares private cars to one alternative (buses or train) each time; iii) Model 3 – a comparison between the three transportation means (cars, buses and trains).

Table 6 shows results for the first model, in which as shown in table 4 the price elasticity is based on Goodwin (1992). In all simulations we will show results under two possible estimates of public transportation's income elasticity, as explained by Holgrem (2007): i) public transportation as a necessity ($\alpha = 0.17$); ii) public transportation as an inferior good ($\alpha = -0.62$). Moreover, we show results for two alternative cases: zero cross elasticities (equations 6 and 7) and positive cross elasticities (equations 8 and 9).

Results show that under deviations from Pigou pricing public transportation shall be subsidized between 20 and 33 percent, with a slightly lower subsidy when cross elasticities are relevant. This last result is consistent with Belan and Gauthier (2006), who show that optimal Ramsey pricing when there are alternatives is less extreme.

Table 6: Optimal pricing – Model 1: Public vs. Private transportation

	Value			
η_{ij}	Yes		-	
α_{public}	**0.17**	**-0.62**	**0.17**	**-0.62**
$\theta_{private}$	0.1699	0.1537	0.1931	
θ_{public}	-0.1946	-0.3295	-0.1941	-0.3271
$\pi_{private}$	163.78	161.52	167.04	
π_{public}	112.76	93.87	112.83	94.21
τ_{private}	0.02795	0.02757	0.02851	
τ_{Bus}	0.01088	0.00906	0.01089	0.00909
τ_{Train}	0.00400	0.00333	0.00400	0.00334

In Table 7 we show results doe Model 2, that compares optimal pricing when private transportation is compared to public one under separate alternatives.

Results show the the penalty (subsidy) for bus and train rides separately rises (decreases) when we compare private transportation to buses only or to train only.

In Table 8 we show results for all three transportation means. Note that this case provides similar results compared to the previous one.

Table 7: Optimal pricing – Model 2: Private vs. One Public Transportation Mean

	Value							
	Buses Only				Trains Only			
η_{ij}	Yes		-		Yes		-	
α_{public}	**0.17**	**-0.62**	**0.17**	**-0.62**	**0.17**	**-0.62**	**0.17**	**-0.62**
$\theta_{private}$	0.1852	0.1805	0.1931		0.1969	0.1559	0.1931	
θ_{bus}	-0.1106	-0.1765	-0.1116	-0.1775	0			
θ_{train}	0				0.0037	-0.0307	0.0031	-0.0312
$\pi_{private}$	165.93	165.27	165.27		167.57	161.83	167.04	
π_{bus}	124.52	115.29	124.38	115.15	140			
π_{train}	140				140.51	135.7	140.44	135.64
τ_{private}	0.02832	0.02821	0.02851		0.0286	0.02762	0.02851	
τ_{Bus}	0.01202	0.01113	0.012	0.01111	0.01351			
τ_{Train}	0.00497				0.00499	0.00482	0.00498	0.00481

To understand whether applying the proposed pricing has an impact on tax inequality, we use the Suits Index for the case in which cross-elasticities are positive. This index checks whether the tax policy improves income distribution (a positive value) or deteriorates it (a negative value). The implementation problem that we are analyzing comes from the fact that low-income deciles intensively make use of transportation services, a fact that drives to a negative Suits index when applying a carbon tax.

Table 8: Optimal pricing – Model 3: All three transportation means

	Value			
η_{ij}	Yes		-	
$\boldsymbol{\alpha_{public}}$	**0.17**	**-0.62**	**0.17**	**-0.62**
$\theta_{private}$	0.1293	0.1132	0.1526	
θ_{bus}	-0.1108	-0.1767	-0.1116	-0.1775
θ_{train}	0.0036	-0.0308	0.0031	-0.0312
$\pi_{private}$	158.10	155.84	161.36	
π_{bus}	124.49	115.26	124.38	115.15
π_{train}	140.50	135.68	140.44	135.64
τ_{private}	0.02698	0.02660	0.02754	
τ_{Bus}	0.01201	0.01112	0.01200	0.01111
τ_{Train}	0.00499	0.00482	0.00498	0.00481

The first conclusion is that in all scenarios our proposed optimal pricing reduces inequality in all scenarios: the index rises in a range between 2.9 and 9.25 percent. A second conclusion is that in terms of taxation, bus (train) riders enjoy from a 31 (41.9) percent reduction of their tax rate, which derive from efficiency (lower deadweight loss) and income distribution considerations. These results imply that introducing optimal deviations from a carbon Pigouvian tax has a substantial advantage for political implementation. Note also that similarly to previous results, the highest deviation is when we look at public transportation (train and buses) as a whole, compared to the alternative of private transportation.

In Table 9 we show the Suits indexes for the different alternatives.

Table 9: Suits Index under different models

		(1)	(2)	(3)	(4)	(5)
Model	α_{public}	**SUITS Index**	**Difference from Pigou SUITS Index (%)**	**One ton\\$CO_2$eq Tax Difference**		
				Private-Bus (%)	**Private-Train (%)**	**Train-Bus (%)**
Pigou		-0.1484	0	0	0	0
Model 1	**0.17**	-0.1383	6.80	31.15		0
	-0.62	-0.1347	9.25	41.88		0
Model 2 Buses	**0.17**	-0.1404	5.40	25.96	15.63	11.06
	-0.62	-0.1387	6.58	30.25	15.29	17.65
Model 2 Trains	**0.17**	-0.1432	3.54	16.45	16.15	0.37
	-0.62	-0.1441	2.90	13.49	16.15	-3.17
Model 3	**0.17**	-0.1407	5.19	29.97	14.21	11.38
	-0.62	-0.1392	6.22	28.62	15.99	15.04

The highest deviation of the Suits Index implies a 9.25 percent increase in progressivity.

3.4.2 A screening strategy

Another possibility to improve implementation is to adopt a screening strategy. By mapping poor destinations of bus and train rides, the government can target subsidies to poorer populations by implementing vouchers. The way we check this strategy is by imposing Pigou pricing for high income individuals and optimal deviations pricing for low-income individuals.

In Table 10 we show the results of implementing such a strategy, when high-income (low-income) individuals are this with an income higher (lower) than the median income.

Table 10: A Screening Strategy

		(1)	(2)	(3)	(4)
Model	α_{public}	**Pigou**	**Model 1**	**Screening**	
Income Levels	-	**All**	**All**	**High 50%**	**Low 50%**
$\Theta_{\mathbf{private}}$	**0.17**	0	0.170	0.170	0.170
	-0.62		0.154	0.154	0.154
$\Theta_{\mathbf{public}}$	**0.17**	0	-0.195	0	-0.195
	-0.62		-0.329	0	-0.329
$\pi_{\mathbf{private}}$	**0.17**	140	163.78	163.78	163.78
	-0.62		161.52	161.52	161.52
$\pi_{\mathbf{public}}$	**0.17**	140	112.76	140	112.76
	-0.62		93.87	140	93.87
$\tau_{\mathbf{private}}$	**0.17**	0.02389	0.02795	0.02795	0.02795
	-0.62		0.02757	0.02757	0.02757
$\tau_{\mathbf{Bus}}$	**0.17**	0.01351	0.01088	0.01351	0.01088
	-0.62		0.00906		0.00906
$\tau_{\mathbf{Train}}$	**0.17**	0.00497	0.004	0.00497	0.004
	-0.62		0.00333		0.00333
SUITS	**0.17**	-0.1484	-0.1383	-0.1367	
	-0.62		-0.1347	-0.1320	
Difference from Pigou (%)	**0.17**	0	6.8	7.9	
	-0.62		9.3	11.1	

Results report a substantial increase in the Suits index. The range of improvement rises from 6.8-9.3 to 7.9-11.1 percent; this result is clearly associated to a rise in the implementation chance of a carbon tax.

4. Summary and conclusions

In this paper we design a methodology for imposing a carbon tax in the transportation sector, considering a social planner that maximizes social utility. Such a social planner elaborates a correction for implementing the carbon tax, helping to solve its implementation issue in an unequal society; this issue makes difficult the application of a Pigouvian tax, because low-income individuals intensively use polluting final goods. Our simulation results imply a subsidy of up to 33% or for each 1-ton\$CO_2$eq of GHG emissions emitted by using public transportation and an extra fee of up to 19.7% for each 1-ton\$CO_2$eq of GHG emissions emitted by using private transportation.

Since the Pigouvian tax implies substantial regressiveness, we simulate Suits indices under different scenarios, to assess the distributional impact of proposed optimal tax rates. We found that our proposed tax scheme is significantly less regressive than the Pigouvian taxation model – with a gap of up to 9.25 percent.

Furthermore, we found that if the government is able to implement a screening strategy by subsidizing only public transportation emissions for low-income families while taxing high-income families by the Pigouvian tax rate at the same time, the regressivity level is reduced by up to 11.1 percent relatively to the full Pigouvian model.

A further direction for research would be to expand this methodology to all oil products, including low-income households uses, like cooking LPG gas, or kerosene for heating purposes during the winter.

Appendix A – Model's solution

Following Feldstein (1972), the production relation in the economy is:

(I) $$y = Mx + k$$

where M means the partitioned matrix:

(II) $$M = \begin{vmatrix} A \\ t \end{vmatrix}$$

A is $n \times n$ matrix of input coefficients in the production of goods, and t is the $n \times 1$ vector of the GHG emissions from the production of the goods; k represents final products with no inputs and y is the vector of final products. Concerning t, they are equal to the emission factor of each good (e_i). With a constant return to scale and perfect competition, the n-dimensional vector of private prices satisfies:

(III) $$p' = p'A + wl' + \pi e'$$

Where π will be determined by the government in the framework of Tradable Emission Permits (TEP's); l' is the vector of labor inputs per unit of output of each good, and w are the wages. From (III) we get:

(IV) $$p' = wl'(1 - A)^{-1} + \pi e'(1 - A)^{-1}$$

We then consider the vector of net direct and indirect inputs of TEPs per unit of good as:

(V) $$h' = e'(1 - A)^{-1}$$

The analogous vector of net direct and indirect labor inputs is:

(VI) $$z' = l'(1 - A)^{-1}$$

We can rewrite equation (IV) as:

(VII) $$p' = wz' + \pi h'$$

The households in the economy are rational agents that maximize their indirect utility $U(p, y)$ under the budget constraint of y and considering the prices of the goods, p. The households' income distribution is represented by the relative density function $f(y)$. It means that the total indirect consumer welfare can be represented by:

(VIII) $$\mathcal{U} = N \int U(p, y) f(y) dy.$$

Where N is the number of households. Total emissions of GHG from the production of all goods, or the total TEPs needed to produce all goods equals to:

(IX) $$E = \sum_i E_i = \sum_i e_i q_i$$

Where q_i represents the quantity of goods i produced and E_i represents TEPs needed to produce the goods. The Lagrange function that the social planer seeks to maximize is:

(X) $$\mathrm{W} = N \int U(p, y) f(y) dy + \gamma \sum_{i=1}^{n} c_i (p_i - a_i).$$

Where c_i is the aggregate consumption of good i, p_i is the price of good i that satisfies the constraint (VII) and a_i is the actual production cost of i. The private sector is competitive and sets prices at the marginal cost.

The social planner faces a budget constraint: the total TEPs' revenue R must be higher or equal to the total social price of GHG emissions in the economy, G; this outlay is additional to the fixed cost of operating the tax system, F, and to the subsidy for allowing anti-pollution tools in the amount of D.

In an economy with no waste, we impose the following equation:

(XI) $$G + F + D \leq R$$

That means that the constraint is:

(XII) $$0 \leq (\pi - s)E - F - D$$

Where s is the price of 1 ton of Greenhouse gases, which shall be covered by government pricing; and $(\pi - s)$ represents the additional price of each product beyond the Pigouvian component. In an economy with no waste, the social planer will choose a TEP's price that maximizes the following Lagrange function:

(XIII) $$W = N \int U(p, y) f(y) dy + \gamma \sum_{i=1}^{n} c_i (p_i - a_i) + \mu\big((\pi - s)E - F - D\big)$$

Note that in a competitive environment a_i will be set at the marginal price of production. Note also that the fact that prices are set to cover government needs implies that $\sum_{i=1}^{n} c_i (p_i - a_i) = (\pi - s)E$; thus, we re-write the Lagrange function as follows:

(XIV) $$W_1 = N \int U(p, y) f(y) dy + \lambda\big((\pi - s)E - F - D\big)$$

As explained above polluting goods are inputs for the final good, which in our case is based on transportation services; i.e., we look at polluting goods as intermediate goods. The F.O.C will then be:

(XV) $$\frac{\partial W_1}{\partial \pi} = N \int \sum_{i=1}^{n} \frac{\partial U}{\partial p_i} \frac{\partial p_i}{\partial \pi} f(y) dy + \lambda \left[E + (\pi - s) \frac{\partial E}{\partial \pi} \right] = 0$$

By using Roy's identity, the derivative of the consumer's indirect utility function with respect to the price of good i is:

(XVI) $$\frac{\partial U}{\partial p_i} = -q_i(p, y) \frac{\partial U}{\partial y}$$

where $q_i(p, y)$ is the quantity of good i consumed by a household with income y that faces prices p; $\frac{\partial U}{\partial y}$ is the marginal utility of income of that household.

Moreover, from (VII), we can get that:

(XVII) $$\frac{\partial p_i}{\partial \pi} = h_i$$

Next, we can set the price elasticity of demand for total TEPs as:

(XVIII) $$\eta = \frac{\partial E}{\partial \pi} \frac{\pi}{E}$$

Now we can use (XV), (XVI), and (XVII) to rearrange (XIV) into:

(XIX) $$N \sum_{i=1}^{n} \int h_i \sum_{i=1}^{n} q_i(p, y) \frac{\partial U}{\partial y} f(y) dy = E \left(\lambda \left[1 + (\pi - s) \frac{\partial E}{\partial \pi} \frac{1}{E} \right] \right)$$

Multiplying the right-hand side by $\frac{\pi}{\pi} = 1$ we get:

(XX) $$N \sum_{i=1}^{n} \int h_i \sum_{i=1}^{n} q_i(p, y) \frac{\partial U}{\partial y} f(y) dy = E \left(\lambda \left[1 + \left(\frac{\pi - s}{\pi} \right) \eta \right] \right)$$

Next, we will use the "distributional characteristic" of Feldstein (1982 a,b):

(XXI) $$\rho_i = \frac{\int q_i(p,y) U_y f(y) dy}{\int q_i(p,y) U_y dy}$$

Noting that the integral in the denominator of ρ_i is the average consumption per household of good i, so the aggregate consumption c_i equal N times this integral. We can write (XIX) as:

(XXII) $$\sum_{i=1}^{n} h_i c_i \rho_i = E \left(\lambda \left[1 + \left(\frac{\pi - s}{\pi} \right) \eta \right] \right)$$

Since $h'c = E$ (the vector of net direct and indirect inputs represented by TEPs), we can rewrite (XXI) as:

(XXIII) $\frac{\sum_{i=1}^{n} h_i c_i \rho_i}{\sum_{i=1}^{n} h_i c_i} = \lambda \left[1 + \left(\frac{\pi - s}{\pi}\right)\eta\right]$

The term in the left-hand side is a weighted average of the distributional characteristics of the goods, which we denominate $\bar{R}$:

(XXIV) $\bar{R} = \frac{\sum_{i=1}^{n} h_i c_i \rho_i}{\sum_{i=1}^{n} h_i c_i}$

We rewrite (XXIV) as:

(XXV) $\frac{\bar{R}}{\lambda} = \left[1 + \left(\frac{\pi - s}{\pi}\right)\eta\right]$

Which brings us to:

(XXVI) $\left(1 - \frac{\bar{R}}{\lambda}\right)\frac{1}{|\eta|} = \left(\frac{\pi - s}{\pi}\right)$

The left-hand side of equation XXVI is similar to the terms that appear in Feldstein (1972 a,b): a higher distributional characteristic and a higher price elasticity lower government pricing; note, however, that the in our case the elasticity stands for total TEP's, and that government pricing is based on TEP's.

Now we look at pollutants only at the transportation sector; i.e., there are two pollutants: private car rides and public transportation rides. Consequently, there are two types of TEPs – for public transportation rides ($i = 1$) and private car rides ($i = 2$), meaning that the TEPs can differentiate between both type of goods. In this case, we will rewrite the Lagrange equation as:

(XXVII) $W_2 = N \int U(p_i, y) f(y) dy + \lambda\big((\pi_1 - s)E_1 + (\pi_2 - s)E_2 - F - D\big)$

When π_1 and π_2 are the prices of TEP for public and private transportation, respectively, and $E_1 = q_1 e_1$ and $E_2 = q_2 e_2$ are the total quantity of GHG emitted by public and private transportation, respectively; that means that $G = E_1 + E_2$.

The new F.O.C. are:

(XXVIII) $\frac{\partial W_2}{\partial \pi_1} = N \int \sum_{i=1}^{n} \frac{\partial U}{\partial p_i} \frac{\partial p_i}{\pi_1} f(y) dy + \lambda \begin{pmatrix} E_1 + (\pi_1 - s)\frac{\partial E_1}{\partial \pi_1} + \\ (\pi_2 - s)\frac{\partial E_2}{\partial \pi_1} \end{pmatrix} = 0$

and

(XXIX) $$\frac{\partial W_2}{\partial \pi_2} = N \int \sum_{i=1}^{n} \frac{\partial U}{\partial \mathrm{p_i}} \frac{\partial p_i}{\pi_2} f(y)dy + \lambda \begin{pmatrix} E_2 + (\pi_2 - s)\frac{\partial E_2}{\partial \pi_2} + \\ (\pi_1 - s)\frac{\partial E_1}{\partial \pi_2} \end{pmatrix} = 0$$

Now, because the emission factors (e_1 and e_2) are constants and only the good's quantities change with the price, we can use the following additional notation:

(XXX) $$\eta_{11} = \frac{\partial E_1}{\partial \pi_1}\frac{\pi_1}{E_1} = \frac{\partial q_1 e_1}{\partial \pi_1}\frac{\pi_1}{q_1 e_1} = e_1 \frac{\partial q_1}{\partial \pi_1}\frac{\pi_1}{q_1 e_1} = \frac{\partial q_1}{\partial \pi_1}\frac{\pi_1}{q_1}$$

(XXXI) $$\eta_{12} = \frac{\partial E_1}{\partial \pi_2}\frac{\pi_2}{E_1} = \frac{\partial q_1 e_1}{\partial \pi_2}\frac{\pi_2}{q_1 e_1} = e_1 \frac{\partial q_1}{\partial \pi_2}\frac{\pi_2}{q_1 e_1} = \frac{\partial q_1}{\partial \pi_2}\frac{\pi_2}{q_1}$$

(XXXII) $$\eta_{21} = \frac{\partial E_2}{\partial \pi_1}\frac{\pi_1}{E_2} = \frac{\partial q_2 e_2}{\partial \pi_1}\frac{\pi_1}{q_2 e_2} = e_2 \frac{\partial q_2}{\partial \pi_1}\frac{\pi_1}{q_2 e_2} = \frac{\partial q_2}{\partial \pi_1}\frac{\pi_1}{q_2}$$

(XXXIII) $$\eta_{22} = \frac{\partial E_2}{\partial \pi_2}\frac{\pi_2}{E_2} = \frac{\partial q_2 e_2}{\partial \pi_2}\frac{\pi_2}{q_2 e_2} = e_2 \frac{\partial q_2}{\partial \pi_2}\frac{\pi_2}{q_2 e_2} = \frac{\partial q_2}{\partial \pi_2}\frac{\pi_2}{q_2}$$

(XXXIV) $$\theta_1 = \frac{\pi_1 - s}{\pi_1}$$

(XXXV) $$\theta_2 = \frac{\pi_2 - s}{\pi_2}$$

We rewrite the F.O.C for the transportation goods as follows:

(XXXVI) $$\frac{\partial W_2}{\partial \pi_1} = N \int \sum_{i=1}^{n} \frac{\partial U}{\partial \mathrm{p_i}} h_1 f(y)dy + \lambda E_1 \begin{pmatrix} 1 + (\pi_1 - s)\frac{\partial E_1}{\partial \pi_1} + \\ (\pi_2 - s)\frac{\partial E_2}{\partial \pi_1} \end{pmatrix} = 0$$

and

(XXXVII) $$\frac{\partial W_2}{\partial \pi_2} = N \int \sum_{i=1}^{n} \frac{\partial U}{\partial \mathrm{p_i}} h_2 f(y)dy + \lambda E_2 \begin{pmatrix} 1 + (\pi_2 - s)\frac{\partial E_2}{\partial \pi_2} + \\ (\pi_1 - s)\frac{\partial E_1}{\partial \pi_2} \end{pmatrix} = 0$$

Using equation V, Roy's identity and the definition of income distribution characteristics of final goods we obtain:

(XXXVIII) $$R_i - \lambda = \lambda\left(\theta_1 \eta_{11} + \theta_2 \eta_{21} \frac{q_2}{\pi_1}\right)$$

(XXXIX) $$R_i - \lambda = \lambda\left(\theta_2 \eta_{22} + \theta_1 \eta_{12} \frac{q_1}{\pi_2}\right)$$

In the problem we solve there are only two final goods; i.e., i=1,2. In addition, we ignore income effects and use the following generalized Slutsky relation:

(XL) $$\eta_{12} = \eta_{21}\left(\frac{q_2}{\pi_1}\right) \ ; \ \eta_{21} = \eta_{12}\left(\frac{q_1}{\pi_2}\right)$$

Which allows to write:

(XLI) $R_1 - \lambda = \lambda(\theta_1\eta_{11} + \theta_2\eta_{12})$

(XLII) $R_2 - \lambda = \lambda(\theta_2\eta_{22} + \theta_1\eta_{21})$

(XLI) and (XLII) can be solved for θ_1 and θ_2:

(XLIII) $\theta_1 = \frac{\eta_{22}(R_1-\lambda)-\eta_{12}(R_2-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})} = \frac{\pi_1 - s}{\pi_1}$

(XLIV) $\theta_2 = \frac{\eta_{11}(R_2-\lambda)-\eta_{21}(R_1-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})} = \frac{\pi_2 - s}{\pi_2}$

If $\eta_{12} = \eta_{21} = 0$

(XLV) $\theta_1 = \frac{\eta_{22}(R_1-\lambda)}{\lambda(\eta_{11}\eta_{22})} = \frac{\pi_1 - s}{\pi_1}$

(XLVI) $\theta_2 = \frac{\eta_{11}(R_2-\lambda)}{\lambda(\eta_{11}\eta_{22})} = \frac{\pi_2 - s}{\pi_2}$

The ratio of those pricing rules is:

(XLVII) $\frac{\omega_1}{\omega_2} = \frac{\frac{\eta_{22}(R_1-\lambda)-\eta_{12}(R_2-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})}}{\frac{\eta_{11}(R_2-\lambda)-\eta_{21}(R_1-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})}} = \frac{\eta_{22}(R_1-\lambda)-\eta_{12}(R_2-\lambda)}{\eta_{11}(R_2-\lambda)-\eta_{21}(R_1-\lambda)}$

If $\eta_{12} = \eta_{21} = 0$, the ratio will be:

(XLVIII) $\frac{\omega_1}{\omega_2} = \frac{\eta_{22}(R_1-\lambda)}{\eta_{11}(R_2-\lambda)}$

Similarly to Feldstein (1972a), the pricing rules are:

(XLIX) $\theta_1 = \frac{\eta_{22}(R_1-\lambda)-\eta_{12}(R_2-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})} = \frac{\pi_1 - s}{\pi_1}$

(L) $\theta_2 = \frac{\eta_{11}(R_2-\lambda)-\eta_{21}(R_1-\lambda)}{\lambda(\eta_{11}\eta_{22}-\eta_{12}\eta_{21})} = \frac{\pi_2 - s}{\pi_2}$

When η_{ii} is the price elasticity of demand for good i, η_{ij} is the cross elasticity of demand for good i with respect to the price of good j, R_i is the distributional characteristic of good i, π_i is the TEP price for good i, and θ_i is the deviation rate of the TEP price for good i from the SCC.

Appendix B

Table B.1: 2022 UK Government GHG Conversion Factors for Company Reporting: Business Travel – Land (DEFRA, 2022)

Activity	Defra Type	Unit	Total Ton CO_2eq per unit
Private Transportation	**Unknown (Average) car**	**Km**	**0.0001707**
	Diesel Car	Km	0.0001708
	Petrol Car	Km	0.0001705
	Hybrid Car	Km	0.00012
	Plug-in Car	Km	0.0000684
	Battery Electric Car	Km	0.0
	Motorbike (Average)	Km	0.00018274
Public Transportation	Regular taxi	Pass-km	0.00014876
	Local bus (not London)	Pass-km	0.00010778
	Local London bus	Pass-km	0.00007936
	Average local bus	Pass-km	0.00009650
	Coach	Pass-km	0.00002733
	National rail	Pass-km	0.00003549
	Light rail and tram	Pass-km	0.00002861
	International rail	Pass-km	0.00000446
	London Underground	Pass-km	0.00002781

Table B.2: Monthly Income and Consumption Expenditure in Quintiles of Households, by Net Income per Standard Person, in 2019[4]

	Quintiles					Total
	5	4	3	2	1	
Households in sample	1,846	1,632	1,525	1,467	1,357	7,827
Households in population (thousands)	539.6	539.8	539.9	539.2	540.5	2,699.0
Average persons in a household	2.63	2.94	3.23	3.36	4.01	3.23
Average standard persons in a household	2.34	2.52	2.69	2.74	3.08	2.67
Average earners in a household	1.63	1.69	1.66	1.33	0.89	1.44
The average age of the economic head of household	53.8	49.0	46.6	47.3	44.1	48.2
The average years of schooling of the economic head of household	15.6	14.5	13.8	13.1	12.8	14.0
Net income per household (NIS)	35,584	23,066	18,128	13,042	7,826	19,526
Net income per standard person (NIS)	15,411	9,132	6,756	4,758	2,577	7,301
Money expenditure per household (NIS)	18,912	14,158	12,826	10,398	9,005	13,059
Money expenditure per person (NIS)	7,184	4,818	3,974	3,094	2,247	4,038
Public transport (NIS), thereof:	91.2	67.2	73.8	79.9	111.0	84.6
Transport by bus (NIS)	23.3	23.2	41.5	49.9	76.9	43.0
Transport by train (NIS)	16.4	10.2	6.0	5.9	4.7	8.7
Transport by service taxi (NIS)	28.5	13.8	8.9	11.1	8.4	14.1
Transport by special taxi (NIS)	20.3	13.9	10.6	7.0	9.6	12.3
Expenditures on vehicles (NIS), thereof:	3,020.0	2,131.0	1,766.7	1,265.6	852.9	1,807.0
Fuel and lubricants for vehicles (NIS)	552.2	513.3	492.0	417.0	349.6	464.8

[4] From Table 1.1 in (CBS, 2022)

Table B.3: Average Distance Traveled in Transportation Methods, by Deciles of Income

		Distance					
		(1)	(2)	(3)	(4)	(5)	(6)
		Private Car (km)		Bus (Pass-km)	Train (Pass-km)	Public Transit (Pass-km)	Total
		CBS	Corrected				
	Min	0.0	0.0	0.0	0.0	0.0	0.0
Deciles	1	646.9	777.8	457.4	19.4	476.8	1254.6
	2	792.1	952.4	434.1	25.9	460.0	1412.4
	3	881.0	1059.3	416.8	24.6	441.4	1500.7
	4	1005.2	1208.6	250.9	29.6	280.5	1489.0
	5	1066.9	1282.8	232.1	19.0	251.1	1533.9
	6	1137.5	1367.6	294.6	23.1	317.7	1685.3
	7	1178.2	1416.5	138.2	25.8	164.0	1580.5
	8	1225.3	1473.2	144.6	50.5	195.1	1668.3
	9	1410.9	1696.4	157.6	78.5	236.2	1932.6
	10	1576.3	1895.2	104.9	52.1	157.0	2052.2
	max	14916.8	17935.0	23708.5	17031.2	23708.5	24799.0
	mean	1121.3	1348.1	250.8	36.5	287.4	1635.5

Table B.4: Average Emission Rates from transportation rides, by Transportation Methods, by Deciles of Income

		Emissions (ton\\$CO_2$eq)				
		Private Car	Bus	Train	Public Transit	Total
	Min	0	0	0	0	0
Deciles	1	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.1327	0.0441	0.0007	0.0448	0.1776
	3	0.1625	0.0419	0.0009	0.0428	0.2054
	4	0.1808	0.0402	0.0009	0.0411	0.2219
	5	0.2063	0.0242	0.0011	0.0253	0.2315
	6	0.2189	0.0224	0.0007	0.0231	0.2420
	7	0.2334	0.0284	0.0008	0.0292	0.2627
	8	0.2418	0.0133	0.0009	0.0143	0.2560
	9	0.2514	0.0140	0.0018	0.0157	0.2672
	10	0.2895	0.0152	0.0028	0.0180	0.3075
	max	0.3235	0.0101	0.0019	0.0120	0.3354
	mean	3.0610	2.2879	0.6044	2.2879	3.0610

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