Working Paper No. 673

July 2020

Car ownership and the distributional and environmental policies to reduce driving behavior

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Abstract: Using the EASI demand system and Irish data, it is found that additional carbon taxation is not as regressive as previously found, when the externality cost associated with driving is included in the metric of the tax incidence. This result is in contrast with the existing literature. Affluent households are found to have the largest externality costs and the largest average emissions per kilometer. Based on estimated cross price elasticities between public and private transportation it is found that for low income households, these commodities are complementary and substitutes for high income levels. While subsidies for public transit can reduce emissions and the demand for private transportation, they are found to be regressive. A lump-sum transfer is found to perform better at compensating households after the carbon tax. However, it reduces the carbon savings by 1%.

Keyword(s): Household energy demand, energy taxes, microsimulation, private transportation

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Acknowledgements: The authors acknowledge funding from the Energy Policy Research Centre (EPRC).

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1 Introduction

In Europe, Greenhouse gas emissions (GHG) from the transport sector accounted for 25% in 2017 of total emissions[1]. In Ireland, the situation is similar, in 2018 60% of the GHG are energy related emissions and transportation accounted for 40% of them [2]. Increasing carbon taxes has emerged as a key policy instrument to reduce emissions in this sector. The economic literature shows that carbon taxes on road transport fuels can encourage drivers to take fewer car trips and encourage them to buy more efficient vehicles (see Borger and Rouwendal, 2014; Fullerton et al., 2015). In addition, it is argued that currently, taxes on fuels used in private transportation do not reflect the externalities (e.g. local pollution, congestion, accidents, etc) caused by vehicle use (Parry, 2015). However, most of the existing literature finds that low income households are disproportionately affected by carbon taxation (see Poterba, 1991; West, 2004, 2005; Fullerton and West, 2000). However, current research shows that the tax burden of low income households due to the regressive nature is not as severe as expected (Sterner, 2012) and can be overcome by revenue recycling policies (Bento et al., 2009). On the other hand, Sager (2019) shows that savings in CO_2 can be eroded when revenues are recycled. Carbon taxation alone will not be able to reduce the emissions at the level required by the Paris agreement. In this regard, Wijkander (1985) investigated the idea that complements or substitutes for externality-creating goods can also be taxed or subsidised to reduce externalities. Little attention in the economic literature has been placed on the estimation of cross effects between public and private transportation. This article provides new insights to the current debate about decarbonizing the transport sector by quantifying changes in the distance driven when implementing additional carbon taxes and subsidies for public transportation. In addition, the article computes the tax burden experienced by vehicle owners when the externality cost associated with driving is included. Jakob et al. (2017) found that public resistance to carbon taxes could be due to the fact that people prefer to tackle the environmental problems they caused themselves rather than delegating it to other people via paying carbon taxes. Consequently, creating awareness of the cost associated with driving could increase carbon tax acceptability.

Regarding non-carbon pricing policies, Beaudoin and Lin-Lawell (2018) found that an increase of 10% in infrastructure for public transportation in

[1]EUROSTAT, Greenhouse gas emission statistics
[2]ENERGY-RELATED CO2 EMISSIONS IN IRELAND 2005 – 2018

the U.S. over the years 1991-2011 led to an increase in auto travel of 0.4%. Yang et al. (2018) found that each of the subway openings in Beijing, drops vehicle congestion sharply. Regarding the distributive effects of subsidies for public transit, Börjesson et al. (2020) found that subsidies for public transportation are not effective as a redistribution policy in Stockholm. The same conclusion was reached by Bureau and Glachant (2011) using French data. Implementing major sustainable-mobility projects such as the expansion of the Dublin Area Rapid Transit (DART), Metro Link, and the Bus Connects Programme are important elements in the Irish Climate Action Plan. Bus Connects targets a 50% increase in bus passenger numbers over the lifetime of the project in the country major cities by investing in infrastructure to increase safety and comfort when travelling.

Carbon taxation will bring changes in the consumption patterns of the energy consumed for heating and transportation. In addition, subsidies for public transit will also affect the demand for private transportation. A demand system approach allows quantifying changes in energy demand for private transportation taking into account cross-price effects associated with changes in the price of other commodities (i.e. heating or public transportation). While there are numerous studies that use a demand system to analyse the distributional effects of carbon pricing is considerably large (see; Baker et al., 1989; Labandeira and Labeaga, 1999; Labandeira et al., 2006; Tiezzi and Verde, 2016; Böhringer et al., 2017; Creedy and Sleeman, 2006; Pashardes et al., 2014; Tovar Reaños and Wölfing, 2018), few studies are on the distributional effects of increasing taxes via fuel prices for private transportation. Even fewer analyse the relationship between public and private transportation. A demand system represents the demand of different commodities as a function of total expenditure and commodity prices. This approach requires assumptions about the income expansion paths, known as Engel curves. Engel curves describe how household expenditure on a particular commodity changes across different levels of income. The existing literature assumes linear (see Deaton and Muellbauer, 1980) or quadratic Engel curves (see Banks et al., 1997). The Affine Stone Index (EASI) implicit Marshallian demand system proposed by Lewbel and Pendakur (2009) allows for more flexibility when modeling Engel curves.

Regarding demand-system approaches that analyse the incidence of increasing taxes via fuel prices, West and Williams (2007) assumed linear Engel curves and compute the optimal schedules for petrol taxes under efficiency consideration. Nikodinoska and Schröder (2016) use a demand system approach to analyse the distributional effects of increasing taxes via petrol prices. They assume quadratic Engel curves and find that there is a trade off between equity and environmental targets when there is no revenue recycling. Tiezzi and Verde (2016) use a similar approach and find that changes in petrol taxes have significantly greater impacts on petrol demand than market-induced changes in petrol prices. They include public transportation in their estimation and find that these commodities are complements. Tiezzi and Verde (2019) analyse the equity implications of responses to market-induced and increasing petrol taxes. Tiezzi and Verde (2016, 2019) are the most recent studies that include public transportation in their model. They found that increases in petrol prices reduces demand for public transportation. Quantifying the tax burden when the cost of pollution is taken into account has not yet been examined. In this regard, Tovar-Reanos (2020) uses a one equation model for the distance driven (i.e. neglecting cross effects) and finds that when the cost of air pollution is included in the metric for the tax incidence, the tax burden decreases considerably.

The insights provided in this paper are threefold. First: own, cross and expenditure elasticities are estimated related to demand for petrol and diesel used for private transportation. Second, additional carbon taxes on fuels for heating and transportation are simulated to quantify the tax incidence experience by vehicle owners. The externality cost associated with driving is estimated and included when computing the tax incidence. Finally, we estimate the environmental and distributional effects of a lump-sum transfer and subsidies for public transportation.

The estimated cross price elasticities for private and public transportation show that while for low income households these commodities are complementary, for more affluent households they are substitute. Regarding welfare losses, it is found that the tax is regressive, as measured by equivalent variation, but recycling carbon taxation revenues to households can mitigate these regressive effects. Regressivity decreases considerably when the cost associated with the externalities of driving are taken into account. It is also found that affluent households have the largest average CO_2 emissions per kilometre. In addition, subsidies for public transportation has superior environmental outcomes but it is not a good instrument for distributing additional revenues. This paper is structured as follows. Section 2 describes the methodology and the models which we estimate later. Section 4 describes the data used in combination with descriptive statistics. The results are presented in Section 5. Section 7 concludes.

2 Methodology

2.1 The Affine Stone Index (EASI) implicit Marshallian demand system

The methodology employed here is similar to that of Tovar Reaños and Wölfing (2018) where after estimating the EASI demand system from micro-data, changes in welfare at the household and aggregated level are estimated. The EASI (Lewbel and Pendakur, 2009) provides a first-order approximation of an arbitrary expenditure function from which a demand system can be derived. The estimated expenditure function must have all the properties that hold for a theoretical expenditure function (Varian, 1992). Pothen and Tovar Reaños (2018) have recently used this approach to analyse the footprints associated with consumption patterns. The generalized method of moments (GMM) estimator or an iterated linear approximation can be used to estimate the demand system. Lewbel and Pendakur propose the following expenditure function:

$$\begin{aligned} \log\left[C(p,y)\right] = y &+ \sum_{i=1}^{I} m_i(y,z)\log(p_i) \\ &+ \frac{1}{2}\sum_{i=1}^{I}\sum_{j=1}^{I} a_{ij}\log(p_i)\log(p_j) \\ &+ \frac{1}{2}\sum_{i=1}^{I}\sum_{j=1}^{I} b_{ij}\log(p_i)y \\ &+ \sum_{i=1}^{I}\varepsilon_i\log(p_i) \end{aligned} \tag{1}$$

where

$$m_i = \sum_{r=0}^{R} b_r \log(y)^r + \sum_{l} d_{il} z_l \log(y) + \sum_{l} g_{il} z_l \tag{2}$$

and where p_i are commodity prices, y is the implicit household utility, and z_l are demographic characteristics. R is chosen by the modeller and determines the degree of the polynomial m_i. This specification allows for highly flexible Engel curves while still keeping the functional form quite comprehensible. $a_{i,j,l}$, $b_{i,j}$, $b_{i,r}$, $d_{i,l}$ and g_{il} are the parameters to be estimated.

ϵ_i represents, unobserved preference heterogeneity. Lewbel and Pendakur show that the implicit utility, y, can be expressed in the following way:

$$y = \frac{\log(x) - \sum_i w_i \log(p_i) + \frac{1}{2}\sum_i \sum_j a_{i,j} \log(p_i)\log(p_i)}{1 - \frac{1}{2}\sum_i \sum_j b_{i,j} \log(p_i)\log(p_j)} \tag{3}$$

By applying Shephard's lemma to the cost function embedded in expression (1)[3], the following set of equations for the budget shares w_i is obtained:

$$\begin{aligned} w_i = {} & \sum_j a_{i,j} \log p_j + \sum_j b_{i,j} \log y \\ & + \sum_{r=0}^{R} b_{i,r} [\log y]^r + \sum_l g_{i,l} z_l + \sum_l d_{i,l} z_l \log y + \epsilon_i. \end{aligned} \tag{4}$$

Lewbel and Pendakur show that (4) can also be estimated with an approximation of y, instead of using Equation (3). The authors approximate y by using $\log(x) - \sum_i \bar{w_i} \log(p_i)$ where $\bar{w_i}$ is the mean of the budget share. We use this approach in order to reduce the computational burden of estimating the parameters of the system. We estimate the parameters using three-stage least squares (3SLS).

As in West and Williams an inverse Mills ratio is computed to correct for the bias introduced by excluding households without a car in my sample. A two-step version of the Heckman correction procedure is used. In the first stage, a probit model on the dichotomous choice to own a vehicle is run to calculate the inverse Mills ratio for each household. In the second stage, the estimated Mills ratio is introduced in each of the equations in the demand system estimation. The probit model includes as independent variable whether there are dependent children in the household, the town size, whether there is a garage in the dwelling and the logarithm of the public transfers received by the households. Standard errors for the estimated coefficients of the demand system and elasticities are computed by using bootstrap methods.

[3] Note that $\log(x) = \log[C(p, y)]$

$$
\begin{aligned}
a_{i,j,l} = a_{j,i,l} \quad \text{and} \quad & \sum_i a_{i,j,l} = 0 \;\forall\; l, \\
b_{i,j} = b_{j,i} \quad \text{and} \quad & \sum_i b_{i,j} = \; 0, \\
\sum_i d_{i,l} = & \sum_i g_{i,l} = 0 \;\forall\; l, \\
\sum_i b_{i,r} = & \; 0 \text{ for } r \; \neq \; 0, \\
\sum_i b_{i,r} = & \; 1 \text{ for } r \; = \; 0,
\end{aligned} \tag{5}
$$

Lewbel (1989) is followed to create more variation in commodity prices and further improve identification of associated parameters. Once the parameters in equation 4 are estimated, own-price elasticities (OPE) and expenditure elasticities (EE) can be computed as follows:

$$
OPE = \left\{ \frac{\partial w_i}{\partial \log(p_i)} \right\} \frac{1}{w_i} - 1 \tag{6}
$$

$$
EE = \left\{ \frac{\partial w_i}{\partial \log(X)} \right\} \frac{1}{w_i} + 1 \tag{7}
$$

We can describe the impacts of changes in welfare by estimating Hicks's equivalent variation (HEV). $HEV = C(p^0, U^1) - C(p^0, U^0)$, where U is the level of household utility. This follows Creedy and Sleeman (2006) and Tovar Reaños and Wölfing (2018). The indices 0 and 1 represent the initial and post-tax periods.

$$
\begin{aligned}
EV = exp & \left\{ \sum_i {p_i}^0 w_i(y, {p_i}^0) - \kappa * [\sum_i {p_i}^1 w_i(y, {p_i}^1)] \right. \\
& \left. - [\frac{1}{2} \sum_{l=0}^{L} \sum_{i,j} a_{i,j,l} {p_i}^0 {p_j}^0 z_l - \kappa * \frac{1}{2} \sum_{l=0}^{L} \sum_{i,j} a_{i,j,l} p_i^1 p_j^1 z_l] + \kappa * X^1 \right\} \\
& - X^0,
\end{aligned} \tag{8}
$$

where

$$
\kappa = \frac{[1 - \frac{1}{2} \sum_{i,j} b_{i,j} {p_i}^0 {p_j}^0]}{[1 - \frac{1}{2} \sum_{i,j} b_{i,j} p_i^1 p_j^1]} \tag{9}
$$

”‘Equivalent income” (x^e) is the income level required in order to achieve the utility that prevails under the current income level, but at a different set of prices.[4] Tovar Reaños and Wölfing (2018) show that (x^e) can be estimated as $x^e = Total\ Expenditure - Hicks'equivalent\ variation.$ In my simulation exercise, a Gini coefficient is calculated to analyze changes in the distribution of equivalent income.

2.2 Tax revenues, emissions and driving behaviour

As in West (2004), the government has the following budget constrain. The right hand side of Equation (10) represents the additional revenues raised by the carbon tax on fuel i (i.e. i=fuels used for heating and private transportation) . The left hand side represents the lump-sum transfers. The demand system is used to provide changes in consumption patterns after taxes (i.e. Q^1_{ih}) for each household and commodity.

$$\sum_{h,i}(p_{i1} - p_{i0})Q^1_{ih} = \sum_{h} T_h \tag{10}$$

The level of CO_2 emissions associated with heating and private transportation is estimated using the 2016 wave of the Household Budget Survey (HBS). Weekly fuel expenditure is translated into CO_2 emissions using fuel prices and emissions factors provided by the Sustainable Energy Authority of Ireland (SEAI). Emission factors and energy prices used in the estimation are displayed in Table 1. Emission factors are taken from SEAI (2015) and the prices are weighted averages from my own estimation based on information provided by the SEAI.

Table 1: Emission factors and fuel prices

Fuel	Emissions (g CO_2/kWh)	Cost €/kWh
Gas	204.7	0.080
Oil (kerosene)	257.0	0.078
Solid Fuels	357.0	0.068
Petrol	252.0	0.144
Diesel	264.0	0.121

Data sources from SEAI (2015) and directly from SEAI

[4] Note that this definition is distinct from an unrelated definition of ‘equivalent income’ that appears elsewhere in the economic literature, namely that of a measure of income by a household member that accounts for household composition and economies of scale.

Changes in emission levels at household level h are estimated as follows:

$$\Delta emissions_h = \sum_i factor_i * (Q^0_{hi} - Q^1_{hi}) \quad (11)$$

where Q_i is the quantity demanded of energy for heating and private transportation, $factor_i$ is the emission factor per kWh. It is estimated using information displayed in Table 1 and it is assumed to be fixed across the simulation. The index i denotes the quantity demanded for heating and private transportation, and the indices 0 and 1 denotes the base and the simulated scenario.

2.3 Externality cost of driving

The cost associated with driving is computed using the costs in €per kilometre provided by van Essen et al. (2019). They provide cost for air pollution, climate change, noise and the cost associated with producing petrol and diesel. These values are provided for diesel and petrol cars in different categories of the ratio CO_2 gr/km. The values are also provided for rural and urban roads. For the cost associated with air pollution van Essen et al. (2019) include, damages in health, crop losses, material and building damages (e.g. damages of building facades through particles and dust) and biodiversity loss. As for climate change costs, they are defined as the costs associated with all of the effects of global warming, such as sea level rise, biodiversity loss, water management issues, more and more frequent weather extremes and crop failures. The externality cost at household level is estimated as follows:

$$Externality\ cost_h = \sum_k \frac{cost_k}{km} * wg_k * Km_h \quad (12)$$

where wg_k is the budget share devoted to the purchase of the k fuel (i.e. petrol and diesel). wg_k is needed given that the HBS does not provide information on the driven distance broken down by vehicle type. Km_h is the distance driven. The ratio CO_2 gr/km is estimated by dividing the emission estimated in the base scenario and the reported annual driven distance in the HBS. This is done in order to impute the externality costs provided by van Essen et al. (2019).

Changes in the driven distance is estimated using expression (13).

$$\Delta Km = \frac{km}{litre} * (Q^0_h - Q^1_h) \quad (13)$$

Where the ratio $\frac{km}{litre}$ is the household energy efficiency. Q_h^0 and Q_h^1 are estimated using the demand system.

3 Data Set and Descriptive Statistics

The dataset employed in this work is the Household Budget Survey (HBS), conducted by the Central Statistical Office (CSO) every five years. The purpose of the survey is to determine a detailed pattern of household expenditure, which in turn is used to update the weighting basis of the Consumer Price Index[5]. The waves from 1994, 1999, 2004, 2009 and 2015-2016 are used in a pooled cross-sectional manner. Indices for commodity prices for the same years provided by the CSO are also used. For the purpose of this study, the consumption goods were grouped into several categories: food, housing, lighting and heating (which we also term "heating" throughout the course of this paper), public transportation and communication (i.e. expenditure on bus, train, taxi, telephone and internet bills), fuel (i.e. petrol and diesel) education and leisure, and other goods and services. This aggregation is similar to that used in Tovar Reaños and Wölfing (2018). In addition, this aggregation minimizes corner solutions (i.e. zero reported expenditures). Public transportation and communication are also aggregated in one commodity in order to include in the estimation vehicle owners that do not use public transportation. This category is dominated by expenditure on transportation by bus, train and taxi, thereby we term this category "Public transportation" throughout the course of this paper). This grouping largely follows the Classification of Individual Consumption According to Purpose (COICOP). As in Baker et al. (1989), I do not include the purchase of vehicles and white goods appliances. Instead, dummy variables for ownership of these goods are included in the analysis. Summary statistics for the full dataset are shown in Table 9. In addition, dummy variables are included for whether a dwelling is in a rural area (according to the CSO classification of same), the age of the dwelling, whether the dwelling has gas fired central heating, a washing machine, and dishwasher and a fridge.

4 Microsimulation data and scenarios

The demand system estimated above is used to simulate the effect of carbon taxation on expenditure on the various commodity groups. For the purposes

[5]See https://www.cso.ie/en/methods/housingandhouseholds/householdbudgetsurvey/

Scenario	Description	Expenditure change	Price change
NoTax	No increase in tax	NO	NO
Tax	Tax	NO	YES
TaxRev	Tax and lump-sum	YES	YES
TaxSub	Tax and subsidy for public transportation	NO	YES

Table 2: Scenario overview

of the microsimulation, we use the 2015-2016 wave of the HBS as it has the most recent data available. We simulate the impact of increasing carbon taxation by 100 €per tonne, which according to Klenert et al. (2018) is the level required in order to reach the goals set in the Paris agreement. A carbon tax was introduced in 2010 in Ireland which applies to non-ETS emissions at €20 per tonne. Consequently, the simulated carbon tax is 120 €per tonne on the carbon contained in fuels for heating and private transportation. Note that only vehicle owners are considered in my simulation. Carbon taxes combined with a revenue recycling scheme are also simulated, where the revenue from carbon taxation is distributed via a lump sum payment to each household, colloquially known as a "green cheque". In addition, a reduction in 5% in the price of public transportation is also simulated. Table 2 summarises these scenarios and whether prices or household expenditure effects are expected .

5 Empirical Results

5.1 Elasticities

Tables 3 and 4 shows the own price and expenditure elasticities for each commodity group and for the first and fourth expenditure quartiles. In general the size of the estimated own price elasticities for fuels used in private transportation are in line with current studies (e.g. Graham and Glaister, 2002; Goodwin et al., 2004; Bureau, 2011; Tovar-Reanos, 2020). As for the rest of the own price elasticities, own price elasticities (OPE) for heating are in line with estimates found in the literature (see Pothen and Tovar Reaños, 2018; Salotti et al., 2015). Clements et al. (2006) study expenditure elasticities for 45 different OECD countries and report their average expenditure elasticity for transport as 1.58. My estimates are within these two estimates.

Table 3 shows also cross price elasticities for public and private transportation. One can see that while for low income households, subsidies for public transit will reduce the demand for fuels used for private transportation, for more affluent households, the opposite is the effect and it is very small. Regarding, fuels for heating, increases in the price of this commodity will increase the demand for private transportation for low and high expenditure levels. As for expenditure elasticities, we see in Table 4 that public transportation and petrol and diesel are necessity commodities given that expenditure elasticities are not greater than one. Consequently increases in the price of these commodities can be regressive.

Table 3: Own- and cross-price elasticities

	Food	Housing	Heating	Pub. Tran.	Fuel	Education	Other
				First quartile			
Food	-0.671	0.060	0.102	0.070	0.103	0.107	0.063
Housing	-0.083	-0.778	0.005	0.017	0.014	-0.016	0.143
Heating	-0.012	-0.016	-0.473	0.060	0.060	-0.027	-0.153
Pub. Tran.	-0.152	-0.026	0.014	-0.604	-0.064	0.015	-0.070
Fuel	-0.053	-0.041	0.025	-0.091	-0.567	-0.024	-0.055
Education	-0.095	-0.154	-0.126	-0.049	-0.087	-0.922	0.099
Others	-0.273	-0.177	-0.267	-0.245	-0.236	-0.185	-1.163
				Forth quartile			
Food	-0.930	0.009	0.043	0.080	0.038	0.076	-0.026
Housing	0.059	-0.704	0.093	0.082	0.085	0.010	0.073
Heating	0.032	-0.017	-0.515	0.107	-0.006	-0.138	-0.317
Pub. Tran.	0.096	-0.029	0.034	-1.026	0.005	0.019	-0.070
Fuel	-0.003	-0.042	-0.003	0.019	-0.695	-0.066	-0.092
Education	-0.057	-0.151	-0.109	-0.082	-0.103	-1.244	0.132
Others	-0.122	-0.104	-0.115	-0.108	-0.104	0.001	-1.117

All entries are statistically significant at the 5% level

Table 4: Expenditure elasticities

	Food	Housing	Heating	Pub. Tran.	Fuel	Education	Other
First quartile	0.581	0.678	0.035	0.809	0.510	1.643	1.732
Forth quartile	0.741	0.216	0.117	0.937	0.481	1.488	1.234

All entries are statistically significant at the 5% level

5.2 Welfare changes at household level

Table 5 shows the estimated Hicks Equivalent Variation (HEV) for vehicle owners relative to total expenditure for three type of households. Households with children have an average driving distance above the sample mean. In addition, households in retirement age might experience energy poverty (see Meier and Rehdanz, 2010) and carbon taxes on the price of fuels for heating and transportation can make their situation worse. One can see that carbon taxes imposes a disproportional burden on low income households when there is no revenue re-allocation and environmental damages are not considered. One and two adult families with children face the largest burden under the tax scenario. While a lump-sum transfer and subsidies for public transportation reduce the tax incidence, the first instrument dominates regarding its distributional properties. In particular, one can see that for couples with children, subsidies for public transportation does not reduce the regressive effect of the tax as the lump-sum does. Consequently, when subsidies for public transportation are implemented, it should be considered that low income households might not profit from this policy as much as more affluent households. For instance low income households in retirement age are entitled to travel by free so this policy does not have any compensating effect for this household type. Lack of availability of public transportation, will make this policy regressive for low income and rural households.

Table 5: HEV relative to total expenditure (%)

	1st quartile	2nd quartile	3rd quartile	4th quartile
		Tax		
Single +65	-2.944	-2.163	-1.926	-2.150
Single with children	-3.832	-2.966	-2.130	-2.220
2 adults with children	-3.364	-2.956	-2.482	-1.843
		TaxRev		
Single +65	-1.267	-1.019	-0.982	-1.222
Single with children	-1.696	-1.500	-1.182	-1.278
2 adults with children	-1.594	-1.531	-1.413	-1.156
		TaxSub		
Single +65	-2.013	-1.578	-1.581	-1.876
Single with children	-2.720	-2.341	-1.823	-2.007
2 adults with children	-2.558	-2.418	-2.184	-1.703

Graph 1 shows welfare losses for rural and urban households. One can

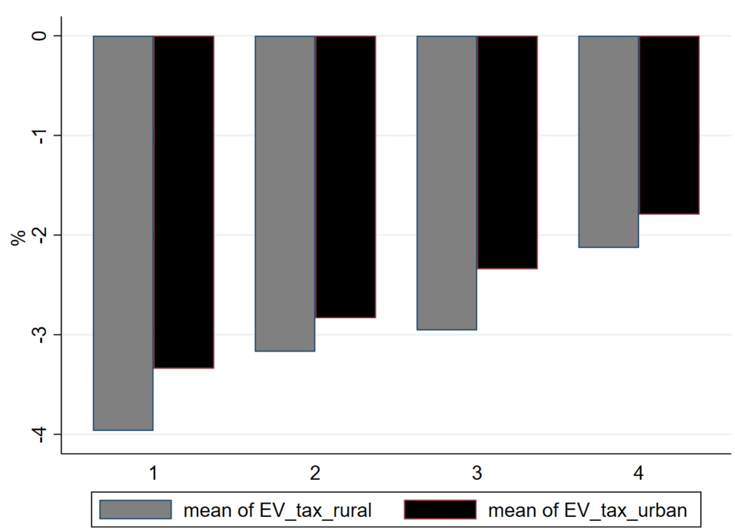

Figure 1: HEV relative to expenditure for rural and urban households

see the that carbon taxes impose a larger burden on rural households than urban ones. In the analyzed sample, while in rural Ireland the mean daily driven distance is 61 km, urban households drive around 45 km. Differences in the provision of public transportation in rural and urban areas has been identified as a barrier to transit towards a more sustainable transportation system in Ireland (see Browne et al., 2011).

Table 6 displays the estimates of Hicks equivalent variation relative to household expenditure estimated using the QUAIDS and the EASI demand systems. One can see that the Quadratic Ideal Demand System (QUAIDS) which assumes quadratic Engel curves (see Banks et al., 1997), slightly over estimate the incidence for low income households.

Table 6: HEV relative to total expenditure (%)

Expenditure deciles	EASI	QUAIDS
1	-3.584	-3.806
2	-3.180	-3.232
3	-2.845	-2.849
4	-2.847	-2.846
5	-2.592	-2.597
6	-2.464	-2.458
7	-2.246	-2.241
8	-2.076	-2.068
9	-1.954	-1.950
10	-1.599	-1.587

5.3 Welfare changes and the cost of pollution

Graph 2 displays the ratio of emissions per kilometer for diesel and petrol vehicles across expenditure levels. This shows that higher income levels have larger levels of pollution regarding vehicle use. Similarly, Tovar-Reanos (2020) found that large vehicles have larger CO_2 emissions compared to other vehicle types. If more affluent households have preferences for large vehicles that potentially have larger emissions ratios per km, carbon taxes on fuel prices need to be jointly designed by other policies such as motor and registration taxes. Currently in Ireland, the registration tax and motor tax was changed in July 2008 from engine size to carbon emissions. These taxes are based on vehicle emissions rather than emissions at the household level. This distinction becomes relevant when households own more than one vehicle.

Graph 3 shows the mean externality cost across expenditure levels. The values have been equivilised by household size. One can see that the cost increases for more affluent households. Graph 4 shows the incidence using the Hicks Equivalent Variation (HEV) when externality costs associated with driving are taken into account (e.g. $\frac{cost\ of\ pollution - |HEV|}{Total\ Expenditure}$). One can see that the incidence reduces significantly across all expenditure levels. The change in the incidence is particularly important for the first two deciles. Increases in fuel prices used in private transportation via carbon taxes is a policy instrument that can internalize the externalities associated with the vehicle usage. However, its implementation has shown not to be a trivial matter. Increasing the current carbon taxes above €26 per tonne has proven to be a

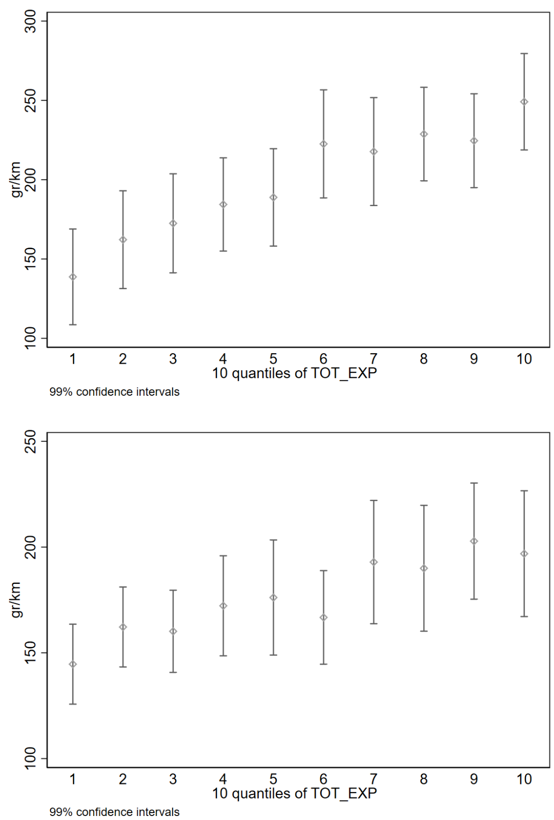

Figure 2: Household-emissions per km for diesel and petrol vehicles

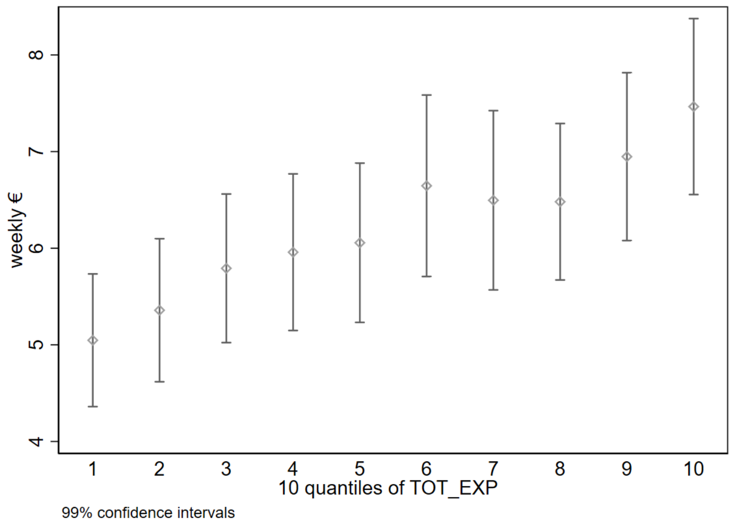

Figure 3: Externality cost

real challenge regarding public acceptance in Ireland. The results show that considering the externality cost associated with driving, can reduce the tax incidence of a carbon taxes on heating and transportation fuels that vehicle owners experience. Note that the externality cost associated with the use of fuels for heating is not considered and consequently, the incidence can be further reduced.

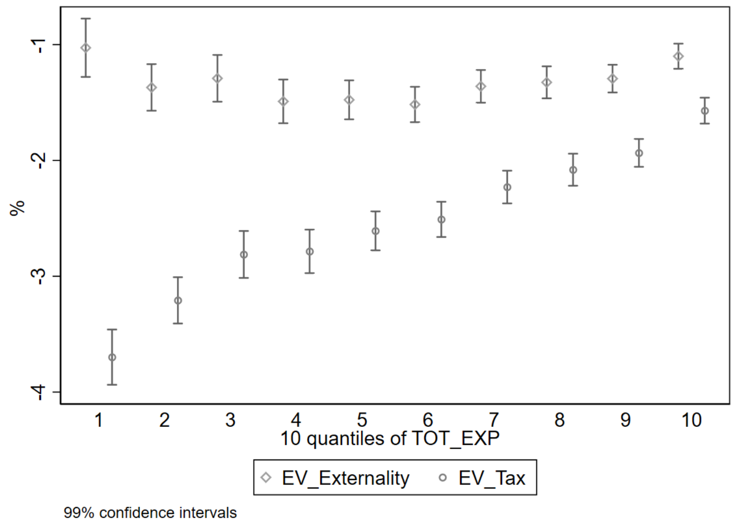

Figure 4: HEV including and excluding externality costs relative to expenditure.

5.4 Aggregate effects

The first row, in Table 7 displays the weekly emissions estimated for vehicle owners in 2016, the average daily driven kilometers and the revenue collected as a percentage of total expenditure. The following rows display the changes in these variables with respect to the base scenario. One can see that a carbon tax reduces emissions by 8% and increases inequality by 1%. The revenue-allocation scenario reduces the environmental benefits and the inequality caused by the tax. Under this scenario, 1% in emission reduction can be lost. Using subsidies for public transportation to reduce the incidence of the tax, reduces further emissions levels but increases inequality more than the revenue re-allocation scenario. When simulating the effects of subsidies for public transportation, the additional tax revues are not totally used. In this scenario, the rest of the tax revenues could be used to compensate low income households. The same pattern can be seen for the distance driven. One can see that subsidies for public transport increases the participation of the transport sector in the change in CO_2 emissions.

In order to analyse the robustness of my estimates, Table 8 provides the same metrics as Table 7 using the QUAIDS. While the same trends are found, changes in emissions and driving distance are slightly smaller at

Table 7: Changes in emissions, distance driven and revenue using the EASI demand system

Scenario	CO_2	Km	Revenue	Gini
Base	(Weekly 1000T) 97.146	(Daily mean Km) 51.280	(%)	0.245
Δ w.r.t to Base (%)				
Tax	-8.361	-3.761	1.908	1.226
TaxRev	-7.716	-3.068	0.000	0.860
TaxSub	-8.699	-4.117	1.091	0.953

aggregate level than the one estimated with the EASI demand system. It also over estimates the tax incidence.

Table 8: Changes in emissions, distance driven and revenue using the QUAIDS model

Scenario	CO_2	Km	Revenue	Gini
Base	(Weekly 1000T) 97.146	(Daily mean Km) 51.280	(%)	0.245
Δ w.r.t to Base (%)				
Tax	-8.253	-3.651	1.908	1.275
TaxRev	-7.600	-2.951	0.000	0.851
TaxSub	-8.575	-3.990	1.091	0.998

6 Policy implications

Carbon tax is a policy instrument that can internalize the externalities associated with vehicle usage. However, its implementation bring several challenges for policy makers. Setting the level of taxes according to the externality cost is the first challenge. In addition, carbon taxes need to be implemented alongside other policy instruments (i.e. subsidies for public transportation, working from home, taxes on motor taxes, congestion charges) to reduce emissions. It is important to design policies where drivers that are overcharged by carbon taxes can be compensated and higher taxes can be implemented for those that are undercharged. Addressing concerns about the distributional effects of the tax can increase public acceptance. This paper provides empirical evidence that when the externality cost associated with driving is included when computing the carbon-tax incidence, the regressive effect of the tax reduces sharply. It is also shown that while subsidies for public transportation can reduce emissions in the private transportation sector, it also increases inequality.

The paper provides evidence that the average emissions per kilometer are higher for high income households. Feebate schemes (e.g. the French 'bonus-malus' system) might help to achieve environmental goals by reducing the demand of heavy polluting vehicles. Under this scheme a rebate is paid to consumers purchasing a fuel-efficient vehicle and a penalty is imposed on those purchasing gas-guzzlers. However, this could induce increases in the vehicle stock. Another alternative is to make the purchase price of vehicles reflect their environmental damage. Hennessy and Tol (2011) show that in Ireland shifting vehicle registration (tax on purchases) and motor taxes (ownership tax) based on engine size to emissions has increased purchases of diesel vehicles which normally are larger vehicles. This has reduced the tax revenue on vehicle registration and ownership, shifting the tax burden from car ownership to car use. Given that current taxes in vehicle use do not charge for the driving externalities, the gap between the tax paid and the due tax increases for drivers of vehicles with high emissions factors. Offering grants for the purchase of electric vehicles are found to be regressive by Tovar-Reaños and Sommerfeld (2018). They found that these grants will increase income inequality as mainly high income households could afford to purchase them. In addition, for households that can afford more than one vehicle, grants could be indirectly subsidizing ownership of a second heavy polluting vehicle. Taxes based on the vehicle emissions need to be considered for the emissions at the household level and not only at vehicle level. This calls for a better design and combination of policy instruments to set the right tax addressing environmental damage and equity issues. A socially accepted policy must combine the ‘ability to pay ” and “polluters pay” principles.

7 Conclusions

By using Irish data and a highly flexible demand system, this paper provides the first empirical evidence that the carbon-tax burden reduces its regressive effect significantly when the externality cost associated with driving is taken into account.The estimated cross price elasticities for private and public transportation show that these commodities are complementary for low income households and are substitute for more affluent households. It is also found that affluent households have the largest average CO_2 emissions per kilometre which indicates preference for heavy polluting vehicles. In addition, subsidies for public transportation are found to be a good environmental policy but not an instrument for redistribution.

Acknowledgements

Tovar Reaños acknowledges funding from the ESRI's Energy Policy Research Centre. We are grateful to Ankita Gaur and Ciarán MacDomhnaill for assistance with data processing. All remaining errors or omissions are our own.

References

Baker, P., Blundell, R., and Micklewright, J. (1989). Modelling household energy expenditures using micro-data. *The Economic Journal*, 99(397):720–738.

Banks, J., Blundell, R., and Lewbel, A. (1997). Quadratic Engel curves and consumer demand. *The Review of Economics and Statistics*, 79(4):527–539.

Beaudoin, J. and Lin-Lawell, C.-Y. C. (2018). The effects of public transit supply on the demand for automobile travel. *Journal of Environmental Economics and Management*, 88:447 – 467.

Bento, A. M., Goulder, L. H., Jacobsen, M. R., and von Haefen, R. H. (2009). Distributional and efficiency impacts of increased us gasoline taxes. *American Economic Review*, 99(3):667–99.

Böhringer, C., Landis, F., and Tovar Reaños, M. A. (2017). Economic Impacts of Renewable Energy Production in Germany. *The Energy Journal*, 0(KAPSARC S).

Borger, B. D. and Rouwendal, J. (2014). Car user taxes, quality characteristics, and fuel efficiency: Household behaviour and market adjustment. *Journal of Transport Economics and Policy*, 48(3):345–366.

Börjesson, M., Eliasson, J., and Rubensson, I. (2020). Distributional effects of public transport subsidies. *Journal of Transport Geography*, 84:102674.

Browne, D., Caulfield, B., and O'Mahony, M. (2011). Barriers to sustainable transport in Ireland. *Environmental Protection Agency. CCRP Report.*

Bureau, B. (2011). Distributional effects of a carbon tax on car fuels in France. *Energy Economics*, 33(1):121 – 130.

Bureau, B. and Glachant, M. (2011). Distributional effects of public transport policies in the Paris region. *Transport Policy*, 18(5):745 – 754.

Clements, K. W., Wu, Y., and Zhang, J. (2006). Comparing international consumption patterns. *Empirical Economics*, 31(1):1–30.

Creedy, J. and Sleeman, C. (2006). Carbon taxation, prices and welfare in New Zealand. *Ecological Economics*, 57(3):333–345.

Deaton, A. and Muellbauer, J. (1980). An almost ideal demand system. *The American Economic Review*, 70(3):312–326.

Fullerton, D., Gan, L., and Hattori, M. (2015). A model to evaluate vehicle emission incentive policies in Japan. *Environmental Economics and Policy Studies*, 17(1):79–108.

Fullerton, D. and West, S. (2000). Tax and subsidy combinations for the control of car pollution. (7774).

Goodwin, P., Dargay, J., and Hanly, M. (2004). Elasticities of road traffic and fuel consumption with respect to price and income: A review. *Transport Reviews*, 24(3):275–292.

Graham, D. J. and Glaister, S. (2002). The demand for automobile fuel: A survey of elasticities. *Journal of Transport Economics and Policy*, 36(1):1–25.

Hennessy, H. and Tol, R. S. (2011). The impact of tax reform on new car purchases in Ireland. *Energy Policy*, 39(11):7059 – 7067. Asian Energy Security.

Jakob, M., Kübler, D., Steckel, J. C., and van Veldhuizen, R. (2017). Clean up your own mess: An experimental study of moral responsibility and efficiency. *Journal of Public Economics*, 155:138 – 146.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., and Stern, N. (2018). Making carbon pricing work for citizens. *Nature Climate Change*, 8(8):669–677.

Labandeira, X. and Labeaga, J. (1999). Combining input-output analysis and micro-simulation to assess the effects of carbon taxation on spanish households. *Fiscal Studies*, 20(3):305–320.

Labandeira, X., Labeaga, J., and Rodriguez, M. (2006). A residential energy demand system for Spain. *The Energy Journal*, Volume 27(Number 2):87–112.

Lewbel, A. (1989). Identification and Estimation of Equivalence Scales under Weak Separability. *Review of Economic Studies*, 56(2):311–316.

Lewbel, A. and Pendakur, K. (2009). Tricks with Hicks: The EASI Demand System. *American Economic Review*, 99(3):827–63.

Meier, H. and Rehdanz, K. (2010). Determinants of residential space heating expenditures in Great Britain. *Energy Economics*, 32(5):949 – 959.

Nikodinoska, D. and Schröder, C. (2016). On the emissions–inequality and emissions–welfare trade-offs in energy taxation: Evidence on the German car fuels tax. *Resource and Energy Economics*.

Parry, I. (2015). Designing fiscal policy to address the external costs of energy. *International Review of Environmental and Resource Economics*, 8(1):1–56.

Pashardes, P., Pashourtidou, N., and Zachariadis, T. (2014). Estimating welfare aspects of changes in energy prices from preference heterogeneity. *Energy Economics*, 42:58–66.

Poterba, J. M. (1991). Is the gasoline tax regressive? Volume 5:145–164.

Pothen, F. and Tovar Reaños, M. A. (2018). The distribution of material footprints in Germany. *Ecological Economics*, 153:237 – 251.

Sager, L. (2019). Income inequality and carbon consumption: Evidence from environmental Engel curves. *Energy Economics*, 84:104507. Eighth Atlantic Workshop on Energy and Environmental Economics.

Salotti, S., Montinari, L., Amores, A. F., and Rueda-Cantuche, J. M. (2015). Total expenditure elasticity of non-durable consumption of european households. In *JRC Technical Report EUR 27081 EN*, page 2015. European Union.

SEAI (2015). Sustainable energy authority of Ireland, energy-related emissions in ireland - february 2018. Available: http://www.seai.ie.

Sterner, T. (2012). Distributional effects of taxing transport fuel. *Energy Policy*, 41:75 – 83. Modeling Transport (Energy) Demand and Policies.

Tiezzi, S. and Verde, S. F. (2016). Differential demand response to gasoline taxes and gasoline prices in the U.S. *Resource and Energy Economics*, 44:71 – 91.

Tiezzi, S. and Verde, S. F. (2019). The signaling effect of gasoline taxes and its distributional implications. *The Journal of Economic Inequality*, 17:145–169.

Tovar-Reanos, M. A. (2020). Initial incidence of carbon taxes and environmental liability. a vehicle ownership approach. *Energy Policy*, 143:111579.

Tovar Reaños, M. A. and Wölfing, N. M. (2018). Household energy prices and inequality: Evidence from German microdata based on the easi demand system. *Energy Economics*, 70:84–97.

Tovar-Reaños, M. A. and Sommerfeld, K. (2018). Fuel for inequality: Distributional effects of environmental reforms on private transport. *Resource and Energy Economics*, 51:28 – 43.

van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., Brambilla, M., Fiorello, D., Fermi, F., Parolin, R., and Beyrouty, K. E. (2019). Handbook on the eexternal costs of transport. *Publications of CE Delft*.

Varian, H. (1992). Microeconomic theory. *W. W. Norton & Company, New York*.

West, S. E. (2004). Distributional effects of alternative vehicle pollution control policies. *Journal of Public Economics*, 88(3–4):735 – 757.

West, S. E. (2005). Equity Implications of Vehicle Emissions Taxes. *Journal of Transport Economics and Policy*, 39(1):1–24.

West, S. E. and Williams, R. C. (2007). Optimal taxation and cross-price effects on labor supply: Estimates of the optimal gas tax. *Journal of Public Economics*, 91(3):593 – 617.

Wijkander, H. (1985). Correcting externalities through taxes on/subsidies to related goods. *Journal of Public Economics*, 28(1):111 – 125.

Yang, J., Chen, S., Qin, P., Lu, F., and Liu, A. A. (2018). The effect of subway expansions on vehicle congestion: Evidence from Beijing. *Journal of Environmental Economics and Management*, 88:114 – 133.

Appendix: Tables

Table 9: Summary statistics

Variable	Mean	Std. Dev.	N
Budget shares:			
ws_food	0.217	0.108	
ws_housing	0.137	0.111	
ws_heating	0.041	0.027	
ws_pub. tran.	0.073	0.059	
ws_fuel	0.044	0.027	
ws_education	0.128	0.134	
Prices (logs):			
log(pfood)	4.236	0.258	
log(phousing)	3.318	0.476	
log(pheating)	3.774	0.387	
log(ppub. tran.)	4.01	0.389	
log(pfuel)	3.968	0.336	
log(peducation)	3.533	1.02	
Total expenditure	1242.8	1590.5	

Table 10: EASI demand system; linear 3 Stage Least Squares estimation, estimated from equation (4). Selected estimates from equation (4)

Regressor:	Dependent variable: budget share for ...					
	Food	Housing	Heating	Pub. Tran.	Fuel	Education
Polynomial coefficient:						
y1	0.231	0.149	-0.027	-0.007	0.008	-0.350
	(0.007)	(0.009)	(0.002)	(0.003)	(0.002)	(0.014)
y2	-0.115	-0.032	-0.013	-0.003	-0.010	0.116
	(0.003)	(0.003)	(0.001)	(0.001)	(0.001)	(0.006)
y3	0.018	-0.001	0.004	0.000	0.002	-0.010
	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)
y4	-0.001	0.000	-0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Interaction terms ($b_{i,j}$):						
ynp1	-0.040	0.004	0.004	0.004	-0.001	0.031
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
ynp2	0.004	-0.004	0.001	-0.003	0.002	-0.010
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ynp3	0.004	0.001	-0.007	-0.002	-0.001	0.002
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ynp4	0.004	-0.003	-0.002	-0.008	0.001	0.006
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ynp5	-0.001	0.002	-0.001	0.001	-0.005	0.003
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ynp6	0.031	-0.010	0.002	0.006	0.003	-0.058
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)
Price parameter ($a_{i,j,l}$)						
$a_{1,j,l}$	0.172	-0.040	-0.018	-0.038	-0.003	-0.072
	(0.001)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
$a_{2,j,l}$	-0.040	0.047	-0.008	0.016	-0.010	0.017
	(0.001)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
$a_{3,j,l}$	-0.018	-0.008	0.038	0.010	0.005	-0.010
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$a_{4,j,l}$	-0.038	0.016	0.010	0.036	-0.007	-0.009
	(0.001)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
$a_{5,j,l}$	-0.003	-0.010	0.005	-0.007	0.034	-0.009
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
$a_{6,j,l}$	-0.072	0.017	-0.010	-0.009	-0.009	0.124
	(0.001)	(0.001)	(0.000)	(0.001)	(0.000)	(0.005)
Inverse Mills Ratio	0.018	0.006	0.001	-0.003	-0.006	0.042
	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)
Constant	0.119	0.088	0.148	0.118	0.072	0.357
	(0.006)	(0.008)	(0.002)	(0.003)	(0.002)	(0.012)

$*p < 0.10, **p < 0.05, ***p < 0.01$