Refining the Evidence: British Columbia's Carbon Tax and Household Gasoline Consumption

Chad Lawley and Vincent Thivierge***

ABSTRACT

The impact of carbon prices on consumer behavior is a central element in current policy debates dealing with mitigation of greenhouse gas emissions. We examine the impact of British Columbia's carbon tax on private automobile gasoline use. We control for several factors that influenced gasoline demand during our study period, including local public transit improvements and increased cross-border shopping. Our results suggest that a 5 cent per litre carbon tax reduced gasoline consumption by 8%. We find that households residing in Vancouver and other cities responded to the carbon tax, whereas households in small towns and rural areas did not respond. We perform several sensitivity analyses. Even our most conservative lower bound estimate suggests that a 5 cent per litre carbon tax reduced gasoline consumption by 5%.

Keywords: Carbon tax; gasoline consumption; price elasticity of gasoline demand; heterogeneous responses; carbon leakage

https://doi.org/10.5547/01956574.39.2.claw

1. INTRODUCTION

Several North American jurisdictions currently have in place or are contemplating policies that put a price on carbon—either through a carbon tax or a cap and trade program—in an attempt to reduce greenhouse gas emissions. A common concern is that a price on carbon will impose significant costs on households but will not substantially reduce consumption of inelastically demanded emission-intensive goods such as vehicle and home heating fuels.[1] There is some empirical support for this concern. Hughes, Knittel, and Sperling (2008) find that the price elasticity of gasoline demand has become increasingly inelastic over time. While carbon pricing is increasingly being considered as an important policy tool by governments around the world, there is little direct empirical evidence of its effectiveness (Rivers and Schaufele 2015). The impact of carbon prices on consumer behavior is therefore a central element in current policy debates about their role in reducing greenhouse gas emissions.

1. For example, in the 2015 Canadian Federal election, Prime Minister Stephen Harper defended his governments regulatory approach to reducing greenhouse gas emissions rather than "carbon tax schemes, principally because carbon taxes are not about reducing emissions; carbon taxes are about raising revenue for the government" (Macleans 2015). http://www.macleans.ca/politics/ottawa/tale-of-the-tape-transcript-of-the-globe-debate-on-the-economy/

* Corresponding author. Associate Professor, Department of Agribusiness and Agricultural Economics, University of Manitoba, 377-66 Dafoe Road, Winnipeg, MB R3T 2N2; (204) 474-9397; chad.lawley@umanitoba.ca.

** Ph.D. Student, Bren School of Environmental Science and Management, University of California, Santa Barbara, 3031 Bren Hall, Santa Barbara, CA 93106; vthivierge@bren.ucsb.ca

 Copyright © 2018 by the IAEE. All rights reserved.

In this article, we investigate the impact of a carbon tax enacted in the Canadian province of British Columbia (BC) on July 1, 2008. The carbon tax applies to fuels used within the province and is determined on the basis of the carbon content of the fuels (Murray and Rivers 2015). With respect to gasoline, the BC carbon tax started at CAD$0.024 per litre of gasoline in 2008 and increased annually for the first five years reaching $0.067 per litre in 2012.[2] The tax was introduced as a revenue-neutral tax; as of 2012, the BC carbon tax raised revenue of approximately $2.5 billion and paid out $3 billion in rebates and cuts to income and corporate taxes (Antweiler and Gulati 2012). Previous studies examining the aggregate impact of BCs carbon tax have attributed substantial declines in gasoline consumption to the carbon tax (Rivers and Schaufele 2015; Elgie and McClay 2013; Antweiler and Gulati 2016). We build on these previous studies using a national household-level survey documenting annual automobile fuel expenditures in BC and in other Canadian provinces, both before and after the introduction of the BC carbon tax. Our study is the first to use household-level data, which enables us to estimate the impact of the carbon tax and the retail price of gasoline on private vehicle fuel consumption, accounting for several confounding factors that have potentially biased previous estimates.

Recent research has examined the impact of fuel excise taxes and carbon taxes on private vehicle fuel use (Davis and Killian 2011; Li, Lin, and Muehlegger 2014; Rivers and Schaufele 2015; Antweiler and Gulati 2016). Rivers and Schaufele (2015) examine the impact of BCs carbon tax on consumer behavior using a 2000–2011 monthly panel of Canadian province-level gasoline consumption. As opposed to the prior literature examining carbon taxes in Europe, Rivers and Schaufele (2015) examine consumer responses to a *new* stand-alone carbon tax applied uniformly within the province of BC. They find that the carbon tax had a substantial short-run impact on fuel consumption: a five cent increase in the carbon tax reduced fuel consumption by 8.4%. This is four times larger than the impact of a five cent increase in the carbon tax-exclusive price (retail price plus provincial and federal excise taxes and city-specific public transit taxes) of gasoline, which reduced vehicle fuel consumption by 2.1%.

A related study by Antweiler and Gulati (2016) examines the short-run impact of all fuel taxes—carbon taxes, provincial and municipal excise taxes, and sales taxes—on both gasoline consumption and automotive purchases. Antweiler and Gulati (2016) control for cross-border trips to account for potential carbon leakage associated with the favourable Canada-US exchange rate that prevailed in 2010–2014. Similar to Rivers and Schaufele (2015), they use a monthly panel of province-level gasoline consumption from 2001 to 2014 and estimate that removal of the BC carbon tax would increase gasoline consumption in BC by 7%.

We build on Rivers and Schaufele (2015) and Antweiler and Gulati (2016) in several important respects. First, our use of household-level expenditure data allows us to account for two potential confounding factors in previous studies. For instance, major public transit improvements, such as the 2009 Canada Line in Vancouver, could explain part of the decrease in private vehicle gasoline consumption that is currently attributed to the carbon tax. We use information about the physical location of households to more precisely assign local improvements in public transit to each household. An additional potential confounding factor is carbon leakage across the BC-Washington border due to an increase in cross-border trips. Our use of *total* household expenditure data (purchases both within and outside of BC), as opposed to strictly within-BC gasoline expenditures, allows us to account more directly for potential increases in cross border shopping.

Second, we view the BC carbon tax as a unique North American policy experiment in a province with a diverse mix of urban and rural households. The tax was not universally popular with

2. Monetary terms are expressed as Canadian dollars throughout.

All rights reserved. Copyright © 2018 by the IAEE.

voters and local governments; it faced little opposition in Vancouver and the Lower Mainland but was met with substantial resistance in northern and rural BC (Peet and Harrison 2012).[3] Part of the resistance in rural and northern BC was due to a perceived inability to adjust gasoline consumption in response to the tax.[4] This is consistent with recent research that suggests opposition to low carbon policies is strongest among those households that are least able to adapt to increased vehicle fuel prices (Holian and Kahn 2015).

Two recent studies present conflicting results on this topic. Spiller, Stephens, and Chen (2017) find that rural and suburban households are more responsive to gasoline prices, whereas Wadud, Graham, and Noland (2010) find that gasoline demand is less price elastic for rural households than it is for urban households. Gillingham and Munk-Nielsen (2016) present evidence supporting the importance of public transit. They show that Danish commuters in the tails of the work-distance distribution are most responsive to changes in the price of driving, such that those with very short commutes and those with the longest commutes have a price elasticity of driving close to –0.6 compared to their mean medium-run estimate of –0.3. Danes have near universal access to public transit, which allows households with the longest commutes to switch. We present new evidence specific to the BC carbon tax that separately identifies the adjustments made by households in less densely populated rural and northern regions of BC (with very little access to public and alternative modes of transit) from those in the more densely populated Greater Vancouver metropolitan area.

Our results indicate that households responded to the BC carbon tax by reducing gasoline consumption. We estimate an average medium (or intermediate)-run carbon tax semi-elasticity of approximately –0.016, which suggests that a one cent per litre increase in the gasoline tax reduced gasoline consumption by 1.6%. Our estimates of the price semi-elasticities of gasoline demand range from –0.004 in Alberta to –0.008 in Quebec. Our baseline results suggest that a 5 cent per litre carbon tax reduced gasoline consumption by 8%, on average, which is 2.9 times the response to an equivalent change in the price of gasoline. These aggregate results are estimated from yearly carbon tax adjustments and price changes and are within the range of the short-run results estimated from monthly data as presented in Rivers and Shaufele (2015) and Antweiler and Gulati (2016). Importantly, our results are robust to adjustments accounting for potential carbon leakage and incomplete pass-through of the carbon tax to the retail price of gasoline. Our most conservative lower bound estimate indicates that the carbon tax semi-elasticity is –0.01 when accounting for cross-border shopping and incomplete pass-through. Although the literature on this topic is still in its early stages, the combined evidence to date suggests that the BC carbon tax reduced gasoline consumption and that consumers responded more to the carbon tax than to equivalent gasoline price changes.

Our investigation of heterogeneous responses to the BC carbon tax are consistent with the sources of public opposition to the carbon tax. Households in more densely populated urban centres, including Vancouver and smaller BC cities, are more responsive to the carbon tax than households in rural and northern areas of BC, which appear to have not responded to the carbon tax. Specifically, we estimate that a 5 cent per litre carbon tax reduces gasoline consumption by 12% in

3. Goel and Nelson (1999) present a model of the political motivations for gasoline taxes. Among several results, they find that gasoline taxes tend to increase in times of low gasoline prices, perhaps because it is less politically costly to increase gasoline taxes when prices are low. Hammar, Lofgren, and Sterner (2004) present similar results with respect to the relationship between gasoline prices and gasoline taxes.

4. The concern that households in rural regions have greater difficulty adjusting to increased gasoline taxes is longstanding. Knittel (2014) documents such concerns in the Ford and Carter administrations in the U.S. Difficulty adjusting to gasoline prices has also been connected with household income; Kayser (2000) finds that lower income households do not respond as much to gasoline prices relative to wealthier households.

Copyright © 2018 by the IAEE. All rights reserved.

Vancouver and 10% in smaller cities in BC such as Victoria, Kelowna, and Abbotsford. We find no evidence that households in rural and northern areas responded to the carbon tax. Our results therefore suggest that the BC carbon tax is an effective means of reducing gasoline consumption in more densely populated areas, but is not effective in less densely populated locations where households have fewer transportation options and are therefore more dependent on private vehicles. This result is in line with the intent of carbon taxes, which is to encourage those who can adapt at least cost to reduce their consumption.

The remainder of the paper proceeds as follows. We present the empirical framework and data in the following section. This includes a detailed discussion of the data sources, the identification strategy and robustness tests, and the choice of variables for the econometric model. Section three presents the econometric results and the final section provides concluding remarks.

2. EMPIRICAL FRAMEWORK

Our primary objective is to estimate the effect of BCs carbon tax on private vehicle gasoline use in BC. We follow the approaches of Li, Linn, and Muehlegger (2014) and Rivers and Schaufele (2015) and estimate separate gasoline price and carbon tax semi-elasticities of gasoline demand. Specifically, we estimate semi-elasticity parameters from the following two models. The first is the log-linear model used in Rivers and Schaufele (2015):

$$\ln\left(q_{hgt}\right) = \alpha_1 \tau_{gt}^{BC} + \beta_{1r} p_{gt} * D_r + X_{ht}\delta_1 + \mu_g + \varphi_t + \varepsilon_{hgt} \quad (1)$$

The second is a regional adaptation of the log-log specification used in Li, Linn, and Muehlegger (2014):

$$\ln\left(q_{hgt}\right) = \alpha_2 \ln\left(1 + \frac{\tau_{gt}^{BC}}{p_{gt}}\right) + \beta_{2r} \ln\left(p_{gt}\right) * D_r + X_{ht}\delta_2 + \mu_g + \varphi_t + \omega_{hgt} \quad (2)$$

where q_{hgt} is the quantity of gasoline consumed in litres by household h residing in census division g in year t; τ_{gt}^{BC} is the per litre BC carbon tax if the household resides in BC; p_{gt} is the carbon tax-exclusive per litre price of gasoline in census division g; D_r is a set of dummy variables for each region r in Canada; X_{ht} is a vector of household demographics and dwelling characteristics; μ_g and φ_t are census division and year fixed effects, respectively; and ε_{hgt} and ω_{hgt} are error terms clustered by census divisions in all regressions.

We account for two levels of geography in equations (1) and (2). Prices are measured at the census division level, denoted g. There are 293 census divisions in Canada, as displayed in Figure 1. As indicated in equations (1) and (2), we allow the coefficients on gasoline price to vary by region, denoted r, including the Atlantic provinces (Newfoundland, Nova Scotia, and New Brunswick), Quebec, Ontario, Manitoba-Saskatchewan, Alberta, and BC. We allow the price elasticities to vary regionally to reflect regional differences in demand elasticity factors, due to variation in population density, population centrality, jobs-housing imbalance, and public transit infrastructure, all of which have been shown to influence transportation choices (Bento et al. 2005).

We are primarily interested in the BC semi-elasticity estimates on the carbon tax and the carbon tax-exclusive gasoline price. The semi-elasticities for BC are obtained directly from the parameters α_1 and β_{1BC} estimated in the log-linear model presented in equation (1). Semi-elasticities for the BC carbon tax and prices are obtained from coefficient estimates from the log-log model in equation (2) as $\alpha_2\left(\frac{1}{p+\tau}\right)$ and $\left(\frac{1}{p}\right)\left\{\beta_{2BC} - \alpha_2\left(\frac{\tau}{p+\tau}\right)\right\}$, respectively, where p and τ are evaluated

All rights reserved. Copyright © 2018 by the IAEE.

Figure 1: Canadian census divisions

at their mean values. The price semi-elasticities and elasticities for regions outside of BC are obtained directly from equations (1) and (2), respectively. Note that our analysis is restricted to the BC carbon tax and as a consequence we do not estimate a carbon tax semi-elasticity for the other Canadian regions.[5] In addition to the baseline estimates, we also estimate price and carbon tax semi-elasticities for households residing in different metropolitan areas through a series of interaction models. Specifically, we estimate separate semi-elasticities for households residing in 1) Vancouver, 2) the smaller cities of Victoria, Kelowna, and Abbotsford, and 3) small towns and rural areas.

As highlighted in the introduction, our analysis builds on previous studies of the BC carbon tax in several key ways. First, Rivers and Schaufele (2015) and Antweiler and Gulati (2016) use province-level data capturing gasoline consumption within each province. This data will incorrectly measure household consumption by residents in provinces where there is substantial cross-border purchases of gasoline. The extent of mismeasurement is potentially substantial for BC since the Vancouver metropolitan area is in close proximity to the Canada-US border and increases in cross border shopping coincided with introduction of the BC carbon tax. While Rivers and Schaufele (2015) point out that a favorable Canada-US exchange rate dramatically increased cross-border shopping starting in 2010, they do not empirically account for it. Antweiler and Gulati (2016) control for cross-border carbon leakage with cross-border trips and an instrumental variables approach. Our use of expenditure data captures fuel expenditures both within BC and outside of BC and allows

5. Quebec has a small carbon tax applied to gasoline purchases within the province. The size of the carbon tax is small and it varies little over the time frame of this analysis. We include this small carbon tax in the carbon tax-exclusive price for Quebec households.

Copyright © 2018 by the IAEE. All rights reserved.

us to use the location of households to directly estimate the potential importance of cross-border purchases. We are therefore able to bound our estimate of the impact of the carbon tax.

Second, public transit access in the city of Vancouver increased in 2009 due to the Canada Line expansion, which is a rapid transit line linking Vancouver, Richmond, and the Vancouver International Airport. Rivers and Schaufele (2015) account for this in robustness checks with a Canada Line dummy that takes on a value of one in BC from 2010 onwards and is zero otherwise. They find that inclusion of the Canada Line dummy eliminates the statistical significance of the carbon tax semi-elasticity, which is potentially due to the high level of province-level correlation between the carbon tax and the Canada Line dummy. One interpretation of this result is that the carbon tax semi-elasticity is not cleanly identified using province-level BC consumption data. Antweiler and Gulati (2016) do not control for public transit improvements. Using household-level data, we use a spatially explicit dummy variable for those metropolitan areas that have greatest access to the Canada Line and would be more likely to reduce gasoline consumption due to its opening, irrespective of the carbon tax.

Finally, the use of province-level data in Rivers and Schaufele (2015) and Antweiler and Gulati (2016) masks heterogeneous responses to the carbon tax. This heterogeneity is potentially important in BC, which is composed of the densely populated Vancouver metropolitan area on one extreme, and the less densely populated rural and northern areas at the other extreme. We expect carbon taxes to have greater influence on consumer behavior in more densely populated areas with greater access to alternative forms of transportation. If this is correct, a province-level estimate of the impact of carbon taxes will underestimate the impact of the tax in densely populated metropolitan areas and will overestimate the impact of the tax in less densely populated areas. Once again, we take advantage of the household data to estimate carbon tax semi-elasticities of gasoline demand that vary by household location.

3. DATA AND VARIABLE SELECTION

Our primary data source is Statistics Canada's Survey of Household Spending (SHS). The SHS is produced annually and represents the primary household expenditure survey in Canada.[6] We obtained access to the confidential SHS micro-datasets for 2001 through 2012 through an agreement with Statistics Canada's Research Data Centres program. Merging the annual data files creates a repeated cross-sectional dataset (or a quasi-panel) with over 100,000 observations. While these are not the same households throughout the dataset, the sample collected each year is representative of 98% of the Canadian population.[7] We include households in nine of the ten Canadian provinces; households in Prince Edward Island are dropped because gasoline excise rates vary monthly and our price and consumption data is annual. The average sampling rate of the SHS from 2001 through to 2012 is 68.5%, with a maximum sampling rate of 76% in 2001 and a minimum of 63.4% in 2008. Statistics Canada calculates survey weights to make the sample nationally representative and we report survey weighted results following the requirements of our agreement with Statistics Canada's Research Data Centres program.

6. Data from the SHS has been used in several previous empirical studies on topics in health, environment, and econometric analyses of consumer demand systems (for example Gruber, Sen, and Stabile 2003; Chang and Serletis 2014; Beck et al. 2015).

7. The SHS excludes official representatives of foreign countries living in Canada, individuals representing Canada abroad, residents of institutions, hotels, rooming houses, religious orders, and members of the Canadian Forces living in camps (Barrett, Levell, and Milligan 2013).

All rights reserved. Copyright © 2018 by the IAEE.

Households were dropped from the sample if 1) the household does not own or lease a personal vehicle and 2) the household did not spend money on gasoline. Dropping these households removes 21,554 observations, accounting for 16% of the total sample.[8] Our results should therefore be interpreted as conditional on the household both owning or leasing a car and having positive expenditure on gasoline within the sample year. Restricting the sample to those households with vehicles is consistent with the approach taken in Li, Linn, and Muehlegger (2014), who study the impact of gasoline taxes on household vehicle miles travelled. Li, Linn, and Muehlegger (2014) use the vehicle file of the U.S. National Household Travel Survey, which details household vehicle driving behavior through odometer readings of the household's vehicle stock, and restrict their sample to those households that own or lease at least one vehicle. An alternative approach is to estimate a selection model that accounts for zero gasoline expenditures in a first stage. As reported in the Appendix, correcting for potential selection effects does not substantially influence the elasticity estimates. Further, we cannot reject the hypothesis that the two equations in the selection model are independent.

The demographic variables include household income, number and ages of household members, labor status, and household characteristics such as the number of vehicles owned or leased and the dwelling type. The demographic characteristics are annual variables. The confidential SHS provides disaggregated geographic identifiers of household locations at the economic region, census division, and census subdivision levels.[9] Important for this study, expenditure variables include private vehicle fuel expenditures.

The SHS underwent a redesign in 2010, in which the survey methodology transitioned from a one-year recall survey to a continuous data collection model in an effort to reduce respondent burden and to better align with methodologies used internationally (Tremblay et al, 2010). The one-year recall survey used prior to 2010 was conducted in January, February, and March for the previous twelve month period from January 1 to December 31. The recall survey data was collected through a face-to-face interview in which respondents consult with source documents including credit card statements (Barrett, Levell, and Milligan 2014). The continuous data collection method adopted since 2010 involves a two-week diary of all frequent purchases such as food and gasoline, backed up by an audit of receipts from that two-week period. The two-week estimates are scaled by a factor of 26 to construct annual gasoline expenditure. Note that we include household-level dummy variables controlling for the period the two-week diary was collected for 2010 through 2012.

In 2008 Statistics Canada conducted the SHS using both methods in an effort to evaluate differences between the two survey designs. They found that the variance for frequent expenditures, such as gasoline, are not substantially influenced by the new method (Tremblay, Lynch and Dubreuil 2010). Furthermore, studies confirm that frequency of purchase rather than survey collection methodology is the most important determinant of data quality. Barrett, Levell, and Milligan (2014) construct "coverage ratios" that measure the ratio of surveyed expenditures to expenditures reported in the national accounts for Australia, Canada, the UK, and the U.S. In addition to aggregate coverage ratios, they are able to compare the coverage ratios between countries for a frequently purchased good such as "food at home." The Canadian SHS used a recall method during the period of their

8. There are two reasons a household is dropped from the sample. First, 18,291 are dropped if the household does not own a vehicle and has zero gasoline expenditure. Second, 3,263 are dropped if the household has positive gasoline expenditure but does not own a vehicle (this might include households that have rented a vehicle or that use gasoline in other machines).

9. Economic regions, census divisions and census subdivision are standard geographic areas defined by Statistics Canada. Based on the 2011 Census, Statistics Canada defined 76 economic regions, 293 census division and 5253 census subdivisions (Statistics Canada 2011).

Copyright © 2018 by the IAEE. All rights reserved.

study (up to and including 2009), whereas Australia, the UK, and the U.S. used a two-week diary. This allows Barrett, Levell, and Milligan (2014) to assess the importance of methodology in determination of the coverage ratio.

They find several interesting results. First, the coverage ratio of the Canadian SHS is close to one through to 2009 suggesting strong correspondence between the SHS and the national accounts. Second, Barrett, Levell, and Milligan (2014) find that for the frequently consumed good, "food at home," there is little difference in the coverage ratios across the four countries suggesting that an expenditure survey is not vulnerable to the different collection methods for food—a frequently purchased good. We expect that this result carries over for other frequently purchased goods such as gasoline. Further, our inclusion of year fixed effects will control for any systematic biases due to the change in the survey design. Additionally, we find that our results are robust to specifications that include province-level survey redesign dummies.

3.1 Gasoline Prices and Taxation

The SHS is an expenditure based survey and therefore does not provide gasoline prices nor the quantity of gasoline consumed. We merge the SHS data with gasoline price and taxation data for 37 Canadian cities from 2001 through 2012 retrieved from Kent Marketing Services Limited.[10] We assign annual average price and taxation data to each economic region in our study area. Gasoline price and tax data is directly available in the most populous regions of Canada, for a total of 37 out of 70 economic regions. Price and tax rates in the nearest economic region are assigned to the 33 less populated economic regions that remain.[11]

Table 1 present's summary statistics for BC and the rest of Canada in the 2001–2007 period (pre-BC carbon tax) and the 2008–2012 period (post-BC carbon tax). Gasoline prices tended to be higher in BC than the rest of Canada, and were also higher in all provinces in the 2008 to 2012 period. Figure 2 plots province-level annual average gas prices, federal and provincial excise taxes, municipal-level transit taxes for Vancouver and Victoria, and the BC carbon tax from 2001–2012. Note that there is little variation in the federal and provincial excise taxes during the time frame of our study. Also note that gasoline prices in BC and the rest of Canada tend to follow similar paths due to the importance of national and global macroeconomic forces in gasoline markets. Compared to excise taxes, there is more variation in the metropolitan transit taxes and the BC carbon tax. Our focus in this study is to identify the effect of the BC carbon tax, controlling for variation in gasoline prices and other taxes.

3.2 Household and Dwelling Characteristics

We control for a rich set of household demographic characteristics, including household income, the number of individuals in the household partitioned into five age groups (0–3, 4–14, 15–24, 25–65, and >65 years), the number of full time workers, the number of part time workers, and the major source of household income. We expect that households with higher incomes consume more gasoline. The summary statistics presented in Table 1 indicate that real incomes in BC

10. This price data has been used in previous studies of Canadian gasoline markets (Rivers and Schaufele 2015; Mann 2016). Collection of the price data is funded through support from Natural Resources Canada and is available at http://kentreports.com/wpps.aspx.

11. Second nearest assignment and random assignment within a province were performed to check the robustness of results. We find that results are robust to these alternative assignments.

All rights reserved. Copyright © 2018 by the IAEE.

Table 1: Summary statistics

	BC				Rest of Canada			
	2001–2007		2008–2012		2001–2007		2008–2012	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Gasoline expenditure (CAD $)	2184	1900	2858	2599	2334	1890	3067	2485
Quantity of gasoline (litres)	2502	2099	2459	2261	2806	2258	2777	2272
Price of gasoline (CAD $/litre)	0.88	0.15	1.17	0.11	0.84	0.13	1.12	0.14
Number of household vehicles:								
1	0.5	0.5	0.48	0.5	0.51	0.5	0.48	0.5
2	0.37	0.48	0.37	0.48	0.37	0.48	0.39	0.49
>=3	0.13	0.33	0.15	0.36	0.12	0.32	0.13	0.34
Number of household persons:								
0–3	0.13	0.41	0.12	0.4	0.14	0.44	0.13	0.42
4–14	0.33	0.72	0.31	0.72	0.35	0.74	0.33	0.74
15–24	0.36	0.74	0.35	0.73	0.37	0.74	0.37	0.74
25–64	1.5	0.91	1.5	0.91	1.5	0.86	1.5	0.89
>=65	0.33	0.65	0.36	0.65	0.31	0.63	0.32	0.64
Number full-time members	0.85	0.82	0.83	0.84	0.93	0.83	0.91	0.83
Number part-time members	0.7	0.87	0.76	0.89	0.67	0.85	0.69	0.84
Major income source:								
Self-employed (0,1)	0.11	0.31	0.075	0.26	0.073	0.26	0.052	0.22
Investment (0,1)	0.026	0.16	0.027	0.16	0.015	0.12	0.017	0.13
Government transfers (0,1)	0.15	0.36	0.16	0.37	0.15	0.36	0.16	0.36
Other (0,1)	0.082	0.27	0.095	0.29	0.08	0.27	0.088	0.28
Real income (CAD $)	66864	56358	77588	82744	69556	60443	75684	66408
Dwelling type:								
Semi-detached (0,1)	0.16	0.37	0.17	0.38	0.14	0.35	0.15	0.36
Apartment (0,1)	0.19	0.39	0.21	0.41	0.19	0.4	0.19	0.39
Other (0,1)	0.043	0.2	0.035	0.19	0.016	0.13	0.015	0.12
Number of observations	9096		6275		57225		40581	

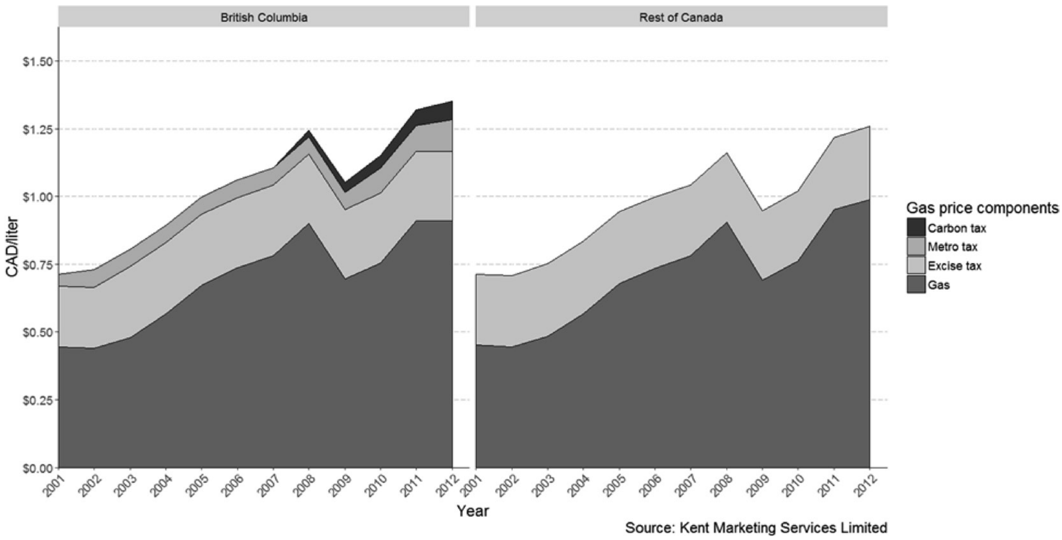
are lower than in the rest of Canada in the pre-2008 period, but higher in the post-2008 period. Households with more individuals—particularly those with more members under the age of 65—likely drive more often and consume more gasoline. The total number of household members is approximately 2.7 and, on average, 1.5 of those members are between the ages of 24 and 65. Our sample suggests that household age composition is very comparable across time and across BC and the rest of Canada.

We suspect that households with more full-time and part-time workers commute to work and are therefore likely to consume more gasoline. Consistent with the household age composition, on average the households in our sample have 1.6 members employed in full time or part time work. We also include a series of dummy variables that capture the primary source of income for each household, categorized into 1) paid employment income, 2) self-employment income, 3) investment income, 4) government transfers, and 5) other sources. Relative to households in the rest of Canada, households in BC are more likely to be self-employed and to have investment income as their primary source of income, both in the pre and post-carbon tax periods.

We also include variables that capture characteristics of the household that influence driving behavior. We control for the total number of vehicles with a set of dummy variables for: 1)

Copyright © 2018 by the IAEE. All rights reserved.

Figure 2: Nominal components of retail gasoline price (2001–2012)



households that own or lease one vehicle, 2) two vehicles, or 3) three or more vehicles. Households with more vehicles drive more often and so, on average, should use more gasoline. In our sample approximately 50% of households own or lease one vehicle, 38% own two, and 12% own three or more. Finally, we control for dwelling type with a series of categorical variables for 1) single-detached, 2) semi-detached, townhouse, or duplex, 3) apartment, and 4) hotel, mobile home, or other moveable dwelling. We expect that households living in single-detached dwellings live in less densely populated areas and as a consequence are more reliant on private vehicles relative to semi-detached and apartment dwellers.

3.3 Local Public Transit Improvements

Time varying improvements to local public transit lines are potentially important determinants of private vehicle gasoline use. In the short run, greater access to public transit reduces the number of trips by private vehicle, which in turn reduces congestion and trip time for remaining private vehicle trips.[12] We include a series of major public transit improvement dummy variables that are assigned to households based on the year of the improvement and the census subdivision the household resides in. Perhaps the most important among these variables are the dummy variables within BC: the Millennium Line was completed in 2002 and the Canada Line was completed in 2009. Similar major public transit expansions occurred in several cities across Canada over our sample period. We include dummy variables for transit line improvements or expansions for Montreal in 2007, Toronto in 2002, Calgary in 2001, and Edmonton in 2006.

4. RESULTS

We present and discuss the results of several specifications in log-linear and log-log form as follows. All econometric specifications include census division and year fixed effects. We first

12. In the long run, the road space freed by increased public transit supply can make road use more appealing to drivers and lead to increased driving (Duranton and Turner 2011).

All rights reserved. Copyright © 2018 by the IAEE.

present baseline results from two regressions that estimate the regional price elasticities of gasoline demand and the carbon tax elasticity for BC. Next, we present results from regressions that allow the carbon tax elasticities to vary by metropolitan type, defined as Vancouver, smaller cities, and small towns and rural areas. We take steps to assess the robustness of our results. We assess the potential impact of cross-border gasoline purchases on our estimates, with a focus on estimates that vary by metropolitan type. Finally, it is possible that the carbon tax was not fully passed through to the final retail price. We use estimates of gasoline tax pass through from the literature to place bounds on our estimates of the carbon tax semi-elasticity.

4.1 Baseline Carbon Tax and Gasoline Price Response

Table 2 presents results from two regressions focusing on the price elasticity and semi-elasticity of gasoline demand, where the gasoline price is the final retail price of gasoline paid by the consumer at the pump. In the case of BC households, the carbon tax is deducted from the final retail price. We find that the carbon tax semi-elasticity of gasoline demand is –0.016. This suggests that a 5 cent per litre carbon tax reduced the quantity of gasoline demanded by 8%.[13]

Our application is most comparable with Rivers and Schaufele (2015), who find similar results; a 5 cent per litre carbon tax generated a 8.4% reduction in gasoline demand. A couple of points related to Rivers and Schaufele (2015) are worth noting. First, there are reasons to expect our elasticity estimates to be smaller than those in Rivers and Schaufele (2015). The province-level control for the Canada Line expansion in Rivers and Schaufele (2015) is highly correlated with the timing of the BC carbon tax. We are able to control for the Canada Line expansion at the census subdivision-level, which should reduce our estimate of the carbon tax semi-elasticity relative to the baseline result presented in Rivers and Schaufele (2015). Also, we use total gasoline expenditure of BC households (including cross-border purchases), whereas Rivers and Schaufele (2015) use expenditures within BC. If carbon leakage in response to the carbon tax is a significant concern, then our use of total expenditure data should generate smaller carbon tax elasticity estimates. As a first pass, the fact that our results are so close to Rivers and Schaufele (2015) should provide confidence in their estimates.

Second, in another respect our research design might generate larger elasticity estimates than those in Rivers and Shaufele (2015), which are derived from monthly province-level panel data and interpreted as short-run estimates. We use an annual household-level repeated cross section and identify the impact of the carbon tax based on inter-household variation over several years, including five years after introduction of the BC carbon tax. Utilizing inter-household variation over many years implies that we are capturing some longer run household adjustments to the carbon tax, including changes in the types of vehicles and residential and employment turnover (Wadud, Graham, and Noland 2010). Further, using a dataset documenting daily gasoline purchases and prices, Levin, Lewis, and Wolak (2017) present evidence that the use of aggregate data tends to underestimate price responsiveness of gasoline demand.[14] To the extent that our estimates are medium (or

13. We also tried a specification that included region-specific survey redesign dummy variables to allow for the potential that the survey redesign affected regions reported gasoline expenditures differently. Including region-specific survey redesign dummies increases the magnitude of the carbon tax semi-elasticity to –0.02.

14. Levin, Lewis, and Wolak (2017) show that in the very short-run (within 4 to 5 days for example) gasoline demand is highly elastic. They present evidence based on their disaggregated data that estimates of short-run demand (defined over months or several years) based on aggregated data—for instance national time series data—will substantially underestimate the price elasticity of gasoline demand. Data aggregated at the state and month level reduces biases due to aggregation (compared to national time series) but still tends to underestimate price elasticity of demand.

Copyright © 2018 by the IAEE. All rights reserved.

Table 2: Baseline estimates of gasoline price and carbon tax semi-elasticities

	Log-linear model		Log-log model	
Variable	Coefficient	Std. Error	Coefficient	Std. Error
Carbon tax	–0.016**	0.007	–0.015*	0.008
Price:				
Maritimes	–0.006***	0.002	–0.007***	0.002
Quebec	–0.008***	0.002	–0.009***	0.002
Ontario	–0.007***	0.002	–0.008***	0.002
Manitoba-Saskatchewan	–0.005**	0.002	–0.005**	0.002
Alberta	–0.004**	0.002	–0.005***	0.002
BC	–0.005***	0.002	–0.006***	0.002
Number of household vehicles:				
2	0.587***	0.021	0.586***	0.021
3	0.697***	0.018	0.697***	0.018
Number of household persons:				
0–3	0.012	0.008	0.012	0.008
4–14	0.063***	0.004	0.063***	0.004
15–24	0.054***	0.006	0.054***	0.006
25–64	0.101***	0.007	0.101***	0.007
>65	0.066***	0.010	0.066***	0.010
Number full-time members	0.056***	0.009	0.056***	0.009
Number part-time members	0.035***	0.008	0.035***	0.008
Major income source:				
Self-employed	–0.133***	0.013	–0.133***	0.013
Investment	–0.113***	0.021	–0.113***	0.021
Government transfers	–0.197***	0.011	–0.197***	0.011
Other	–0.059***	0.012	–0.059***	0.012
Real income	0.017***	0.002	0.0166***	0.002
(Real income)^2	–6.04xE^{-5}***	0.000	–6.04xE^{-5}***	0.000
Dwelling type:				
Semi-detached	–0.068***	0.009	–0.068***	0.009
Apartment	–0.127***	0.013	–0.127***	0.013
Other	0.024	0.022	0.024	0.022
Number of observations	113,177		113,177	
R^2	0.345		0.345	

Notes: All specifications include year fixed effects, census division fixed effects, transit expansion dummy variables, and collection month dummy variables for 2010–2012. Standard errors are adjusted for census division clusters. Coefficients on dummy variables are adjusted following Kennedy (1981). The coefficient estimates for the carbon tax and price in the log-log model are calculated from $\alpha_2\left(\frac{1}{p+\tau}\right)$ and $\left(\frac{1}{p}\right)\left\{\beta_{2BC}-\alpha_2\left(\frac{\tau}{p+\tau}\right)\right\}$, respectively. Real income is included in \$10,000 increments.
* Significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

intermediate)-run, we expect that our carbon tax elasticity estimates should be larger than the short run estimates reported in Rivers and Schaufele (2015).[15]

With respect to gasoline price, our results suggest that the gasoline price semi-elasticities of demand are statistically different across Canadian regions, ranging from a low of –0.004 in Alberta to –0.008 in Quebec. These results imply, for example, that a one cent per litre increase in the price of gasoline reduces demand by 0.4% in Alberta and by 0.8% in Quebec. Overall, we find that

15. Coglianese et al. (2016) show that anticipation of gasoline tax changes can bias estimates of the price elasticity of gasoline demand. For instance, households might be able to store gasoline for short periods of time in anticipation of a gasoline tax increase. Studies that rely on monthly data need to account for potential anticipation effects. We use annual expenditure data and so it is not possible to separately identify potential anticipation effects associated with the BC carbon tax.

All rights reserved. Copyright © 2018 by the IAEE.

households in the more densely populated provinces of Quebec and Ontario are most responsive to gasoline price changes while households in the less densely populated provinces of Alberta, Saskatchewan, and Manitoba are least responsive.

It is useful to compare these price elasticity estimates to other results in the literature. Brons et al. (2008) perform a meta-analysis of price elasticity of gasoline demand. Their data collection reveals substantial variation in previous price elasticity estimates, which can range from elastic to highly inelastic in both the short and long-run. They estimate that the mean short-run price elasticity of gasoline demand is approximately –0.35 and the mean long-run price elasticity is approximately –0.83.[16] Using household-level cross-sectional data, Spiller, Stephens, and Chen (2017) account for geographic heterogeneity in elasticity estimates and report mean and median short-run elasticity estimates of –0.52 and –0.74, respectively. After converting the semi-elasticities reported in Table 2 to elasticities, our medium-run estimates range from approximately –0.36 (–0.45) in Alberta to –0.84 (–0.95) in Quebec in the log-lin (log-log) specifications. In BC, the elasticity estimates range from –0.5 to –0.6 in the log-lin and log-log specifications. Our mean estimate of the price elasticity of gasoline demand is –0.58.

Similar to the prior literature examining the impact of the BC carbon tax, our results suggest that the response to the carbon tax exceeds the response to the gasoline price. Specifically, we find that the carbon tax semi-elasticity is approximately 2.9 times the price semi-elasticity. Rivers and Schaufele (2015) find that consumers are 4 times more responsive to the carbon tax and suggest that the response to the carbon tax is higher due to the salience of carbon taxes. Antweiler and Gulati (2016) suggest the response is due the permanence of the carbon tax relative to the impermanence of retail gasoline prices, which can fluctuate significantly. While these papers propose alternative explanations, the differences between carbon tax and retail price responses that they estimate are similar in magnitude and our estimates fall within the same range.

Countering these interpretations, Levin, Lewis, and Wolak (2017) provide evidence that tax elasticity estimates from aggregate data are subject to less bias relative to price elasticities using the same data. One implication of their result is that the price elasticities reported in prior studies are underestimated while the more elastic tax elasticities are estimated with less bias. This is an alternative partial explanation for the substantial differences in elasticity estimates found in carbon tax studies. As discussed above, the results in Levin, Lewis, and Wolak (2017) also suggest that the price elasticity estimates in this paper are subject to less bias. The fact that the estimated ratio of the carbon tax semi-elasticity to the gasoline price elasticity reported in this article is lower than in Rivers and Schaufele (2015) is also consistent with Levin, Lewis, and Wolak (2017).

4.2 Baseline Covariate Results

Table 2 presents the estimated coefficients for the covariates included in the regressions as controls. These results are largely consistent with our expectations. We find that households with more private vehicles use more gasoline. For instance, a household with two vehicles uses 59% more gasoline than a household with one vehicle, and a household with three or more vehicles uses 70% more gasoline than a household with one vehicle.

With the exception of children three years old or younger, an additional member in the household increases gasoline consumption. The effect is most pronounced for additional house-

16. These estimates are averaged across several different types of studies, including time series and cross-sectional. Brons et al. (2008) also examine the impact of different modelling approaches on elasticity estimates and find that estimates of the price elasticity of demand tend to be higher in cross-sectional studies.

Copyright © 2018 by the IAEE. All rights reserved.

hold members between the ages of 25 and 64; an additional member of the household in this age category increases gasoline consumption by 10%. An additional household member with full time employment increases gasoline consumption by 5.6%, while an additional member with part-time employment increases gasoline consumption by 3.5%. We also find that source of employment matters. Those households whose major source of income is paid employment appear to purchase more gasoline than households obtaining income from all other sources of income including self-employment income, investment income, and government transfer payments. This is consistent with the notion that households with paid employment income travel to work, whereas members of households earning other sources of income may not need to commute.

As expected, we find that household income tends to have a positive relationship with gasoline consumption. At a household income of $70,000, our results suggest that an increase in household income of $10,000 will increase gasoline consumption by 1.7%. This effect diminishes as income increases. For example, at a household income of $500,000, a $10,000 increase in household income increases gasoline consumption by 1.4%. We also find that households that reside in single detached homes use more gasoline than all other types of dwellings aside from those households residing in hotels, lodging houses, and mobile homes.

Although not reported directly in Table 2, we include several geography-specific indicators that vary at the census subdivision-level, which take on a value of one after major expansions of public transit lines. Individually, each of these indicators suggests that gasoline expenditures fell following the public transit expansion. In Vancouver, the public transit dummies indicate that expansions of Vancouver public transit are associated with reduced private vehicle gasoline consumption. In the following section we report the results of a series of robustness checks on our baseline specification, including the impact of excluding the public transit expansion dummies on the estimated carbon tax and price semi-elasticities.

4.3 Robustness to Excluded Covariates

In this section we assess the robustness of our results to the exclusion of a set of time-varying post-treatment controls that may be influenced by the carbon tax, sometimes referred to as “bad” controls (Angrist and Pinske 2009). Gelman and Hill (2007) discuss several issues associated with controlling for post-treatment variables. The results of these robustness checks are reported in Table 3. We begin with a robustness check that excludes the variables controlling for the households’ number of vehicles. It is possible that households reduced the number of vehicles owned or leased in response to the carbon tax, which led to a reduction in gasoline expenditure.[17] As reported in column (1) of Table 3, we find that dropping the number of vehicles has little impact on the price and carbon tax semi-elasticities of gasoline demand; the carbon tax semi-elasticity estimated in the log-log model increases slightly to –1.6%. Next, we exclude employment status out of a concern that the carbon tax reduced household gasoline expenditure through changes in BCs economic activity rather than through the price of gasoline. Once again, as presented in column (2) of Table 3, we find little evidence that excluding this covariate substantially changes the impact of the carbon tax.

Finally, we assess the robustness of our results to exclusion of the dummy variables for public transit expansions, presented in column (3) of Table 3. We find that exclusion of the public transit dummies does not influence the carbon tax semi-elasticity estimates. Further, exclusion of

17. Espey (1996) shows that vehicle ownership is an important determinate of gasoline demand. More recently, Small and Van Dender (2007) and Frondel and Vance (2013) emphasize the importance of vehicle ownership in studies of gasoline demand related to the rebound effect.

All rights reserved. Copyright © 2018 by the IAEE.

Table 3: Robustness to exclusion of covariates

	(1)		(2)		(3)	
	Number of vehicles dropped		Employment status dropped		Public transit expansion dummies dropped	
Variable	Log-linear model	Log-log model	Log-linear model	Log-log model	Log-linear model	Log-log model
BC Carbon tax:	–0.016**	–0.016**	–0.016**	–0.016*	–0.016**	–0.016*
	(0.007)	(0.007)	(0.008)	(0.010)	(0.008)	(0.010)
Price:						
Maritimes	–0.007***	–0.007***	–0.005***	–0.006***	–0.005***	–0.006***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Quebec	–0.008***	–0.010***	–0.007***	–0.008***	–0.007***	–0.008***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Ontario	–0.008***	–0.010***	–0.007***	–0.008***	–0.007***	–0.008***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Manitoba-Saskatchewan	–0.005**	–0.006***	–0.004*	–0.005**	–0.004*	–0.005**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Alberta	–0.005**	–0.006***	–0.005**	–0.006***	–0.005**	–0.006***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
BC	–0.006***	–0.007***	–0.005***	–0.005***	–0.005***	–0.005***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number of observations	113,177	113,177	113,177	113,177	113,177	113,177
R^2	0.280	0.280	0.336	0.336	0.344	0.344

Notes: Specifications include the full suite of controls included in the baseline regressions, plus year fixed effects, census division fixed effects, transit expansion dummy variables, and collection month dummy variables for 2010–2012. Standard errors are adjusted for census division clusters. The coefficient estimates for the carbon tax and price in the log-log model are calculated from $\alpha_2\left(\frac{1}{p+\tau}\right)$ and $\left(\frac{1}{p}\right)\left\{\beta_{2BC}-\alpha_2\left(\frac{\tau}{p+\tau}\right)\right\}$, respectively.

* Significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Copyright © 2018 by the IAEE. All rights reserved.

these dummies has little influence on estimates of the price semi-elasticities of gasoline demand. These result suggests that the public transit expansion dummy variables are not important controls for the purpose of identifying the impact of the carbon tax on gasoline demand.

4.4 Heterogeneous Responses to the Carbon Tax

In this section we describe results from a series of regressions that allow the carbon tax semi-elasticity to vary by the type of metropolitan area the household resides in. We divide the sample into three metropolitan area types: 1) large cities; 2) smaller urban centres classified by Statistics Canada as census metropolitan areas; and 3) all other areas including small towns and rural areas. We find little difference in the magnitudes of the retail price semi-elasticity estimates across census metropolitan types within a region, and the differences are not statistically significant. As such, Table 3 reports results from a regression that estimates one price semi-elasticity for each region (as in the baseline specification), but estimates carbon tax semi-elasticities that vary by metropolitan type within BC.

We find that households in Vancouver respond most to the carbon tax, followed by households in the smaller cities of Victoria, Kelowna, and Abbotsford. We find that a one cent increase in the carbon tax results in a 2.4% decrease in the quantity of gasoline demanded in Vancouver and a 2% decrease in the quantity demanded in smaller cities. This suggests that a 5 cent per litre carbon tax reduced gasoline consumption in Vancouver by 12% and in smaller centres such as Victoria by 10%. We find no evidence that households in small towns and rural BC respond to the carbon tax.

These results are consistent with the notion that households in Vancouver, and perhaps also in smaller cities, live in more densely populated communities and have better access to public transit and other transportation alternatives, relative to their small town and rural counterparts. Several studies show that households in more densely populated areas tend to consume less gasoline for personal transportation (Brownstone and Golob 2009; Cao, Mokhtarian, and Handy 2009). Bento et al. (2005) examine the impact of alternative measures of density on private vehicle use. They show that an increase in population centrality (a spatial GINI coefficient) and decrease in jobs-housing imbalance (which captures the availability of employment relative to housing) both reduce private vehicle use. They suggest this is due to greater availability of alternative transportation infrastructure and the fact that households endogenously sort into communities based in part on their preferences for private vehicle versus alternative transportation. Our results are consistent with the notion that households in more urban locations have better access to alternative transportation and are more likely to use those alternatives. Our results are also consistent with the significant public opposition to the carbon tax in rural and northern communities in BC—as highlighted by Peet and Harrison (2012)—who have apparently not adjusted gasoline demand in response to the carbon tax.

4.5 Assessing the Importance of Carbon Leakage

Antweiler and Gulati (2016) stress the potential importance of carbon leakage in response to the carbon tax. Their contention is that the timing of the carbon tax coincided with a favourable US-Canada exchange rate that provided BC residents with increased incentives to cross-border shop for U.S. goods and services, including gasoline. Antweiler and Gulati (2016) document the dramatic increase in cross border trips beginning in 2010 and present evidence that fuel taxes and the carbon tax increased cross-border trips between BC and Washington State. They also find that increased border crossings lead to lower per capita gasoline consumption in BC.

All rights reserved. Copyright © 2018 by the IAEE.

Table 4: Census metropolitan area carbon tax semi-elasticities

	Log-linear model		Log-log model	
Variable	Coefficient	Std. Error	Coefficient	Std. Error
BC Carbon tax:				
Vancouver	–0.024***	0.004	–0.027***	0.004
Smaller cities	–0.020**	0.010	–0.022**	0.010
Small town and rural	–0.002	0.012	0.0002	0.013
Price				
Maritimes	–0.005**	0.002	–0.006***	0.002
Quebec	–0.007***	0.002	–0.008***	0.002
Ontario	–0.007***	0.002	–0.007***	0.002
Manitoba-Saskatchewan	–0.004	0.002	–0.004*	0.002
Alberta	–0.003	0.002	–0.004*	0.002
BC	–0.004**	–0.002	–0.004**	–0.002
Number of observations	113,177		113,177	
R^2	0.345		0.345	

Notes: Specifications include the full suite of controls included in the baseline regressions, plus year fixed effects, census division fixed effects, transit expansion dummy variables, and collection month dummy variables for 2010–2012. Standard errors are adjusted for census division clusters. The coefficient estimates for the carbon tax and price in the log-log model are calculated from $\alpha_2\left(\frac{1}{p+\tau}\right)$ and $\left(\frac{1}{p}\right)\left\{\beta_{2BC}-\alpha_2\left(\frac{\tau}{p+\tau}\right)\right\}$, respectively.
* Significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Rivers and Schaufele (2015) and Antweiler and Gulati (2016) use provincial gasoline sales, a quantity that is particularly sensitive to cross-border shopping. If cross border shopping is substantial, this will bias estimates of the response to the carbon tax upwards. We use household-level expenditures, which in the case of BC, document gasoline expenditures by BC households both within BC and outside of BC. Thus, cross-border expenditures are included in our expenditure variable. That said, it is possible that our estimates are biased upwards because our dependent variable is gasoline expenditure divided by the full retail gasoline price. If retail gasoline prices in the U.S. are lower than in BC, then use of the BC retail gasoline price will understate the quantity of gasoline purchased in the presence of cross-border shopping. Assuming U.S. gasoline prices along the U.S.-Canada border do not respond to the BC carbon tax, the introduction of the carbon tax will further understate the quantity of gasoline purchased (relative to the situation prior to the carbon tax) and will lead to an upward bias in the estimated carbon tax semi-elasticity of gasoline demand.

The following provides details of our method of accounting for potential carbon leakage and bounding our estimates. Our calculation of the extent of cross-border shopping is outlined in Table 4. We begin by estimating the potential importance of cross border shopping based on annual data documenting the number of same day, overnight, and two or more day trips of returning Canadian automobiles between BC and Washington State. We assume that each trip involves a gas tank fill and that the average gasoline tank size is 68 litres. We use annual information on the number of trips combined with our assumptions about tank size to estimate the upper-bound of total quantity of gasoline purchased by British Columbia households in Washington State in each year. Then, using SHS data on the average annual household expenditure on gasoline, data on the total number of households in BC per year from BC Stats, and retail BC gasoline prices we are able to estimate the annual total household gasoline consumption in BC. The potential importance of cross-border shopping is then assessed as the estimated share of gasoline purchases in Washington State over

Copyright © 2018 by the IAEE. All rights reserved.

total household gasoline consumption. Our calculations suggest that between 2001 and 2009, 5 to 8% of gasoline consumption by BC households was in the U.S. Consistent with increases in border crossings, between 2010 and 2012 we find that this share roughly doubled to between 10 and 16%.

Next, we adjust the quantity of gasoline consumed by combining our estimates of the share of cross-border shopping in total gasoline expenditures with the Washington State gasoline price. We adjust the dependent variable for households in Vancouver and in select census subdivisions that are in close physical proximity to major roadways connecting BC to the U.S. For example, if we estimate that 7% of gasoline purchases occur in Washington State, then we assume 7% of gasoline was purchased at the Washington State price and 93% at the BC price in that year for those households in close proximity to the U.S. border. Since the quantity of gasoline purchased is obtained by the total gasoline expenditure divided by price, assigning the lower Washington State price for a share of expenditures will increase our estimate of the quantity consumed.

We run a series of regressions that impose different assumptions about the extent of cross-border shopping by those households in close proximity to Washington State. We use the estimates presented in Table 4 to guide the sensitivity analysis. Our first scenario assigns the estimated share of purchases in Washington State exactly as they are reported in Table 4. Our second scenario accounts for the fact that roughly half of the BC population resides in close proximity to the U.S. border. If we assume that this part of the population is responsible for virtually all of the cross border trips then the share of purchases in Washington should roughly double. We therefore multiply the estimated shares by two for the second scenario. This implies that *every* household in close proximity to the U.S. border bought approximately 12% of their total gasoline purchases in Washington State pre-2010, and approximately 26% in the 2010 to 2012 period. We want to stress that these estimates of the share of purchases in Washington State are large and should certainly be viewed as upper bound estimates of the true share.

We present the results from both scenarios in a series of regressions in Table 5. As expected the estimated carbon tax semi-elasticity falls if we account for cross-border shopping. For instance, in the baseline model as reported in Table 2 we estimate semi-elasticities of –0.016 and –0.015 from the log-linear and log-log models, respectively. As reported in models (1) and (3) of Table 5, both of these semi-elasticities fall to –0.013 when accounting for cross border shopping. In scenario (2), which doubles the assumed importance of cross-border shopping, the semi-elasticity falls to –0.011 in model (5) and is statistically insignificant in model (7).

When allowing for heterogeneous responses, as expected we find that the carbon tax semi-elasticity for Vancouver is most sensitive to the cross border shopping adjustments. For example, in the log-linear model (2), the carbon tax semi-elasticity for Vancouver falls from –0.024 to –0.019, whereas the carbon tax semi-elasticity for smaller cities is essentially unchanged at –0.020. In our second cross-border shopping scenario, which assumes that more than one-quarter of gasoline purchases in Vancouver and the surrounding area are in the US, the semi-elasticity falls to –0.014 in the log-linear specification and to –0.015 in the log-log specification. Finally, the carbon tax semi-elasticity remains statistically insignificant for small towns and rural areas, irrespective of the cross border shopping adjustment. These results are consistent with the fact that there would be very little cross border effects for smaller cities, small towns, and rural areas that are not adjacent to the BC-Washington State border. Most importantly, the magnitudes and significance of our provincial and Vancouver specific carbon tax elasticities seem to withstand this conservative cross-border sensitivity exercise.

All rights reserved. Copyright © 2018 by the IAEE.

Table 5: Importance of cross-border shopping for gasoline

	Annual BC household expenditure ($)	Number of BC households (100,000)	BC tax-inclusive gasoline price ($/litre)	Total quantity gasoline consumed (100,000 litres)	Number of trips to U.S. (100,000)	Quantity of gasoline purchased in U.S. (100,000 litres)	Share of total gasoline purchased in U.S.
Year	A	B	C	D=(A*B)/C	E	F=68*E	G=100*F/D
2001	1,368	15.9	0.71	30,561	32.7	2,224	7%
2002	1,533	16.1	0.70	35,094	28.0	1,907	5%
2003	1,488	16.2	0.78	31,115	28.7	1,949	6%
2004	1,769	16.4	0.86	33,889	30.4	2,067	6%
2005	2,115	16.6	0.97	36,080	31.5	2,142	6%
2006	2,254	16.8	1.03	36,604	31.0	2,109	6%
2007	2,066	17.0	1.08	32,626	32.2	2,189	7%
2008	2,176	17.3	1.21	31,231	34.6	2,354	8%
2009	2,103	17.6	1.00	36,835	33.1	2,250	6%
2010	2,094	17.9	1.08	34,636	48.7	3,310	10%
2011	2,245	18.0	1.25	32,368	63.9	4,344	13%
2012	2,169	18.3	1.27	31,368	71.6	4,868	16%

Notes: We use annual average BC gasoline prices. We assume the average tank size is 68 litres and that each trip to the U.S. involves one complete tank fill in the U.S. We use total trips to the US, which includes same day, overnight, and two or more day stays. One day trips account for the majority of total trips. Annual household expenditure is obtained from the SHS; number of BC households from BC Stats (2016); number of trips to U.S. obtained from Statistics Canada (2016).

Copyright © 2018 by the IAEE. All rights reserved.

4.6 Carbon Tax Pass Through

Previous research into BCs carbon tax has assumed that the carbon tax is fully passed through to the retail price of gasoline. This is supported by recent evidence from the U.S. that suggests taxes are quickly and fully passed through to the retail price of gasoline, including studies by Marion and Muehlegger (2011) and Li, Linn, and Muehlegger (2014). However, Chouinard and Perloff (2004) find evidence that excise taxes are not fully passed through to consumers. They present evidence that a 1 cent increase in the U.S. federal specific tax increased tax inclusive retail gasoline prices by 0.47 cents. This implies that the tax exclusive price decreased by 0.53 cents in response to the tax. [18] Chouinard and Perloff (2004) also find that U.S. State specific taxes are fully passed through to the retail price.

In a separate set of regressions not reported in this article we estimate the pass through of the BC carbon tax to retail prices using city-level monthly retail gasoline price data. Our point estimates suggest that the carbon tax was not fully passed through to the retail price of gasoline, but the precision of our estimates is weak and we cannot conclude that the pass through was less than one. Since the confidence intervals on our estimates using Canadian data suggest those estimates are unreliable, we use the pass through rate of –0.53 from Chouinard and Perloff (2004) to assess the sensitivity of our results to a *highly* conservative assumption about carbon tax pass-though.

We calculate a conservative lower bound estimate of the carbon tax semi-elasticity based on the unadjusted carbon tax semi-elasticity estimate of –0.013 accounting for carbon leakage as reported in Table 6. The pass-through adjustment is the multiple of the pass-through rate of –0.53 and the gasoline price semi-elasticity of –0.005.[19] Our most conservative lower bound estimate of the carbon tax semi-elasticity is therefore –0.01, which suggests that gasoline consumption falls by 1% for every one cent increase in the carbon tax. Once again, even this conservative lower bound estimate suggests that the BC carbon tax reduced gasoline consumption. It is important to note that all of the recent evidence suggests complete pass-through of gasoline taxes applied by smaller geographic regions, such as U.S.states. We have no evidence that this is different in the case of the BC carbon tax. The estimate of the pass through rate we use in this sensitivity exercise is derived from the U.S. Federal excise tax and is therefore unlikely to apply to the BC case.

5. SUMMARY AND CONCLUDING REMARKS

In this article, we examine the impact of the BC carbon tax on private vehicle gasoline use. Our baseline results suggest that, on average, a one cent carbon tax reduces gasoline consumption by 1.6%. This implies that a five cent per litre carbon tax on gasoline reduced the quantity of gasoline demanded by 8%. Whereas previous studies of the BC carbon tax have used province-level data, our use of household-level data allows us to investigate heterogeneous responses to the carbon tax. We do so according to the type of metropolitan area the household resides in, including Vancouver,

18. The retail price is the sum of the tax exclusive price p and the specific tax t^s : $p^{Retail} = p + t^s$. The change in the retail price in response to the specific tax is: $\frac{dp^{Retail}}{dt^s} = \frac{dp}{dt^s} + 1$. From Chouinard and Perloff (2004), if the change in the tax inclusive price is a 0.47 cent increase in response to a one cent increase in the specific tax, then the tax exclusive price must decrease by 0.53 cents: $\frac{dp}{dt^s} + 1 = 0.47 \Rightarrow \frac{dp}{dt^s} = -0.53$.

19. The pass-through adjustment is calculated by $\frac{dlnq}{d\tau} = \alpha\left(\frac{1}{p+\tau}\right) + \frac{dp}{d\tau}\frac{dlnq}{dp}$. At an unadjusted carbon tax semi-elasticity of –0.013, a pass through rate of –0.53, and a price semi-elasticity of –0.005, this works out to an adjusted carbon tax semi-elasticity of –0.01.

All rights reserved. Copyright © 2018 by the IAEE.

Table 6: Accounting for carbon leakage

	Cross-border shopping scenario (1)				Cross-border shopping scenario (2)			
	Log-linear model		Log-log model		Log-linear model		Log-log model	
Variable	Baseline	CMA	Baseline	CMA	Baseline	CMA	Baseline	CMA
BC Carbon tax:								
Aggregate	–0.013**		–0.013*		–0.011*		–0.010	
	(0.007)		(0.007)		(0.006)		(0.007)	
Vancouver		–0.019***		–0.021***		–0.014***		–0.015***
		(0.004)		(0.004)		(0.004)		(0.005)
Smaller cities		–0.020**		–0.020**		–0.020**		–0.021**
		(0.010)		(0.010)		(0.010)		(0.010)
Small town and rural		–0.002		0.0002		–0.002		0.000
		(0.012)		(0.013)		(0.012)		(0.013)
Number of observations	113,177	113,177	113,177	113,177	113,177	113,177	113,177	113,177
R^2	0.345	0.345	0.345	0.345	0.345	0.345	0.345	0.345

Notes: All specifications include the full suite of controls included in the baseline regressions, plus year fixed effects, census division fixed effects, transit expansion dummy variables, collection month dummy variables for 2010–2012, and gasoline price by region. Standard errors in brackets are adjusted for census division clusters. The coefficient estimates for the carbon tax in the log-log models are calculated from $\alpha_2\left(\frac{1}{p+\tau}\right)$.

* Significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Copyright © 2018 by the IAEE. All rights reserved.

smaller cities, and small towns and rural areas. We find that households in Vancouver and in smaller cities respond the most to the carbon tax whereas households in small towns and rural areas do not respond to the carbon tax. This result is consistent with the fact that households in small towns and rural areas have fewer options to adjust their driving behavior. It is also consistent with the vocal opposition to the carbon tax, which originated in small towns and rural areas who argued they would not be able to adjust to the new tax.

We also shed light on the potential importance of cross-border shopping through the use of household expenditure data. Our adjustment is conservative and we argue that it is an upper bound estimate of the true impact of cross border shopping. While our baseline results estimate a carbon tax semi-elasticity of –0.016, our adjustment for cross border shopping reduces the semi-elasticity estimate to –0.013. A conservative adjustment for potential carbon tax pass through reduces the carbon tax semi-elasticity further to –0.010. Together, these adjustments can be considered lower bound estimates; they reduce but do not eliminate the impact of BCs carbon tax on gasoline consumption.

Our results clearly demonstrate that households respond to a price on carbon. Perhaps most importantly, our results suggest that the location of the household matters. Households in cities are better able to respond to an increased carbon tax than households in rural or northern locations. This is consistent with greater population densities and access to a wider variety of transit and commuting options in urban centres and metropolitan areas. One implication of this result is that the aggregate response in a diverse province such as BC cannot be transferred to less densely populated regions with few urban centres. A second implication is that the BC carbon tax operated as intended; those that can adapt at lower cost are, in fact, more likely to adapt.

ACKNOWLEDGMENTS

We thank seminar participants at the University of Ottawa Institute of the Environment, Climate Economics Chair at the Paris Dauphine University, and the 2015 Association of Environmental and Resource Economists Annual Meeting (San Diego) for several helpful comments and suggestions. Thivierge was a Research Associate with the Smart Prosperity Institute, University of Ottawa when the majority of this research was conducted. This research was supported by funds to the Canadian Research Data Centre Network (CRDCN) from the Social Sciences and Humanities Research Council (SSHRC), the Canadian Institute for Health Research (CIHR), the Canadian Foundation for Innovation (CFI), and Statistics Canada. Although the research and analysis are based on data from Statistics Canada, the opinions expressed do not represent the views of Statistics Canada.

REFERENCES

Angrist, J.D. and J.S. Pischke (2009). *Mostly harmless econometrics: An empiricist's companion.* Princeton, NJ, USA: Princeton University Press.

Antweiler, W. and S. Gulati (2012). "Policy forum: Reducing the environmental impact of transportation—British Columbia's tax policy initiatives." *Canadian Tax Journal*, 60(4): 869–879.

Antweiler, W. and S. Gulati (2016). "Frugal Cars or Frugal Drivers? How carbon and fuel taxes influence the choice and use of cars." SSRN Working Paper 2778868, May 2016. https://doi.org/10.2139/ssrn.2778868.

Barrett, G., Levell, P. and K. Milligan (2014). A Comparison of Micro and Macro Expenditure Measures across Countries Using Differing Survey Methods. *NBER Chapters*, 263–286.

Beck, M., Rivers, N., Wigle, R., and H. Yonezawa (2015). "Carbon tax and revenue recycling: Impacts on households in British Columbia." *Resource and Energy Economics,* 41, 40–69. https://doi.org/10.1016/j.reseneeco.2015.04.005.

All rights reserved. Copyright © 2018 by the IAEE.

Bento, A.M., Cropper, M.L., Mobarak, A.M. and K. Vinha (2005). "The effects of urban spatial structure on travel demand in the United States." *Review of Economics and Statistics*, 87(3): 466–478. https://doi.org/10.1162/0034653054638292.

BC Stats. 2016, May 12. Household estimates and projections. (http://www.bcstats.gov.bc.ca/StatisticsBySubject/Demography/Households.aspx)

Brons, Martijn, Peter Nijkamp, Eric Pels, and Piet Rietveld (2008). "A meta-analysis of the price elasticity of gasoline demand: A SUR approach." *Energy Economics*, 30(5): 2105–2122. https://doi.org/10.1016/j.eneco.2007.08.004.

Brownstone, D. and T.F. Golob (2009). "The impact of residential density on vehicle usage and energy consumption." *Journal of Urban Economics*, 65(1): 91–98. https://doi.org/10.1016/j.jue.2008.09.002.

Cao, X., Mokhtarian, P.L. and Handy, S.L. (2009). "Examining the impacts of residential self-selection on travel behaviour: a focus on empirical findings." *Transport Reviews*, 29(3): 359–395. https://doi.org/10.1080/01441640802539195.

Chang, D., and A. Serletis (2014). "The demand for gasoline: evidence from household survey data." *Journal of Applied Econometrics,* 29(2): 291–313. https://doi.org/10.1002/jae.2312.

Chouinard, Hayley and Jeffrey Perloff (2004). "Incidence of federal and state gasoline taxes." *Economics Letters*, 83(1): 55–60. https://doi.org/10.1016/j.econlet.2003.10.004.

Coglianese, J., Davis, L.W., Kilian, L. and J.H. Stock (2016). "Anticipation, tax avoidance, and the price elasticity of gasoline demand." Forthcoming, *Journal of Applied Econometrics*.

Davis, Lucas W. and Lutz Kilian (2011). "Estimating the effect of a gasoline tax on carbon emissions." *Journal of Applied Econometrics*, 26(7): 1187–1214. https://doi.org/10.1002/jae.1156.

Duranton, G., and M. Turner (2011). "The Fundamental law of road congestion: Evidence from US cities." *The American Economic Review*, 101: 2616–2652. https://doi.org/10.1257/aer.101.6.2616.

Elgie, Stewart and Jessica McMlay (2013). "BC's carbon tax shift is working well after four years." *Canadian Public Policy*, 39(s2): 1–10. https://doi.org/10.3138/CPP.39.Supplement2.S1.

Espey, M. (1996). "Explaining the Variation in Elasticity Estimates of Gasoline Demand in the United States: A Meta-Analysis." *The Energy Journal,* 17(3): 49–60. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol17-No3-4.

Frondel, M. and C. Vance (2013). "Re-identifying the rebound: what about asymmetry?." *The Energy Journal*, 34(4): 43–55. https://doi.org/10.5547/01956574.34.4.3.

Gelman, A. and J. Hill (2007). *Data analysis using regression and multilevel/hierarchical models* (Vol. 1). New York, NY, USA: Cambridge University Press.

Gillingham, K. and A. Munk-Nielsen (2016). *A Tale of Two Tails: Commuting and the Fuel Price Response in Driving* (No. w22937). National Bureau of Economic Research. https://doi.org/10.3386/w22937.

Goel, R.K. and M.A. Nelson (1999). "The political economy of motor-fuel taxation." *The Energy Journal*, 20(1): 43–59. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol20-No1-3.

Gruber, J., Sen, A., and M. Stabile (2003). "Estimating price elasticities when there is smuggling: the sensitivity of smoking to price in Canada." *Journal of Health Economics*, 22 (5): 821–842. https://doi.org/10.1016/S0167-6296(03)00058-4.

Hammar, H., Löfgren, Å. and T. Sterner (2004). "Political economy obstacles to fuel taxation." *The Energy Journal*, 25(3):1–17. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol25-No3-1.

Holian, Matthew J. and Matthew E. Kahn (2015). "Household Demand for Low Carbon Policies: Evidence from California." *Journal of the Association of Environmental and Resource Economists*, 2(2): 205–235. https://doi.org/10.1086/680663.

Hughes, Jonathan E., Christopher R. Knittel, and Daniel Sperling (2008). "Evidence of a shift in the short-run price elasticity of gasoline demand." *The Energy Journal*, 29(1): 113–134. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol29-No1-9.

Kayser, H.A. (2000). "Gasoline demand and car choice: estimating gasoline demand using household information." *Energy Economics*, 22(3): 331–348. https://doi.org/10.1016/S0140-9883(99)00043-2.

Knittel, C.R. (2014). "The Political Economy of Gasoline Taxes: Lessons from the Oil Embargo." *Tax Policy and the Economy*, 28(1): 97–131. https://doi.org/10.1086/675589.

Levin, L., Lewis, M.S. and F.A. Wolak (2017). "High frequency evidence on the demand for gasoline." *American Economic Journal: Economic Policy*, 9(3): 314–347. https://doi.org/10.1257/pol.20140093.

Li, Shanjun, Joshua Linn, and Erich Muehlegger (2014). "Gasoline taxes and consumer behavior." *American Economic Journal: Economic Policy*, 6(4): 302–342. https://doi.org/10.1257/pol.6.4.302.

Mann, Janelle (2016). "Rockets and feathers meet markup margins: Applications to the oil and gasoline industry." *Canadian Journal of Economics*, 49(2): 772–788. https://doi.org/10.1111/caje.12213.

Marion, Justin and Erich Muehlegger (2011). "Fuel tax incidence and supply conditions." *Journal of Public Economics*, 95(9): 1201–1212. https://doi.org/10.3386/w16863.

Murray, B. and N. Rivers (2015). "British Columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy." *Energy Policy*, 86: 674–683. https://doi.org/10.1016/j.enpol.2015.08.011.

Copyright © 2018 by the IAEE. All rights reserved.

Peet, Chelsea, and Kathryn Harrison (2012). "Historical legacies and policy reform: Diverse regional reactions to British Columbia's carbon tax." *BC Studies*, 173(2012): 95–120.
Rivers, Nicholas and Brandon Schaufele (2015). "Salience of carbon taxes in the gasoline market." *Journal of Environmental Economics and Management*, 74: 23–26. https://doi.org/10.1016/j.jeem.2015.07.002.
Small, K.A. and K. Van Dender (2007). "Fuel efficiency and motor vehicle travel: the declining rebound effect." *The Energy Journal*, 28(1): 25–51. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol28-No1-2.
Spiller, Elisheba, Heather M. Stephens, and Yong Chen (2017). "Understanding the heterogeneouse effects of gasoline taxes across income and location." *Resource and Energy Economics*, 50(2017): 74–90. https://doi.org/10.1016/j.reseneeco.2017.07.002.
Statistics Canada (2011). Geographic Attribute File, Reference Guide. (http://www.statcan.gc.ca/pub/92-151-g/92-151-g2011001-eng.pdf)
Statistics Canada (2016). May 12. CANSIM Table 427-0001: Number of international travellers entering or returning to Canada, by type of transport. (http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=4270001)
Tremblay, J. Lynch, J., and G. Dubreuil (2010). "Pilot survey results from the Canadian Survey of Household Spending Redesign." Paper presented at the Joint Statistical Meetings 2010, Section on Survey Research Methods.
Wadud, Zia, Daniel J. Graham, and Robert Noland (2010). "Gasoline demand with heterogeneity in household responses." *The Energy Journal*, 31(1): 47–74. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol31-No1-3.
West, S. E. and R.C. Williams (2004). "Estimates from a consumer demand system: Implications for the incidence of environmental taxes." *Journal of Environmental Economics and Management,* 47(3): 535–558. https://doi.org/10.1016/j.jeem.2003.11.004.

APPENDIX: SAMPLE SELECTION MODEL RESULTS

We estimate the parameters from a full information maximum likelihood (FIML) selection correction model that accounts for those households with zero gasoline expenditure. West and Williams (2004) take a similar approach to estimating gasoline price elasticity of demand using a similar national survey dataset from the U.S. The dependent variable in the selection equation is a dummy variable that takes on a value of zero if the household had zero expenditure on gasoline and a value of one if the household had positive gasoline expenditure. We include the province-level Consumer Price Index for new vehicles and the Consumer Price Index for leased vehicles as exclusion restrictions in the selection equation. Similar to Kayser (2000), we expect that these variables influence the choice to purchase or lease a vehicle but should not directly influence expenditures on gasoline once the vehicle is purchased or leased. The FIML estimation allows for the use of survey weights and for cluster-robust standard errors (as in the baseline regressions reported in the manuscript).

Our full sample is comprised of 134,731 households. Of the total households in the sample, 18,291 do not consume gasoline and are considered censored observations in the selection correction model. An additional 3,263 households consume gasoline but do not own a vehicle. These households are included as uncensored observations in the selection correction model, but are excluded in the regressions reported in the article. Inclusion of the 3,263 households with positive gasoline consumption but no car in the selection correction model provides a robustness check on the results excluding them as presented in the article.

The results of the sample selection model are reported in Table A1 below. Similar to results presented in the article, the results in Table A1 suggest that a one cent increase in the carbon tax educed gasoline expenditures by between 1.7% and 1.8%. This is only slightly higher than the baseline results presented in Table 2. The coefficients on the regional prices suggest that the price semi-elasticity of gasoline demand ranges from –0.04 in BC to -0.08 in Quebec, once again similar to results in the baseline models. Note also that several of the price semi-elasticities of gasoline demand are less precisely estimated in the sample selection models. Finally, we find that $\hat{\rho} = -0.007$, with a standard error of -0.02, which suggests that the correlation between the errors of the two

All rights reserved. Copyright © 2018 by the IAEE.

equations are not statistically different from zero. This implies that we cannot reject the hypothesis that the two equations are independent.

Table A1: Estimates of gasoline price and carbon tax semi-elasticities from full information maximum likelihood (FIML) sample selection model

	Log-linear model		Log-log model	
Variable	Coefficient	Std. Error	Coefficient	Std. Error
Carbon tax	-0.017***	0.006	-0.018**	0.007
Price:				
Maritimes	-0.004*	0.002	-0.005**	0.002
Quebec	-0.007***	0.002	-0.008***	0.002
Ontario	-0.006**	0.002	-0.007***	0.002
Manitoba-Saskatchewan	-0.003	0.003	-0.004*	0.002
Alberta	-0.002	0.003	-0.003	0.003
BC	-0.004	0.002	-0.004*	0.002
Number of household persons:				
0-3	0.026**	0.011	0.026**	0.011
4-14	0.061***	0.007	0.061***	0.007
15-24	0.089***	0.006	0.089***	0.006
25-64	0.190***	0.009	0.191***	0.009
>65	0.166***	0.009	0.166***	0.009
Number full-time members	0.119***	0.011	0.119***	0.011
Number part-time members	0.081***	0.009	0.081***	0.008
Major income source:				
Self-employed	-0.148***	0.018	-0.148***	0.013
Investment	-0.060*	0.031	-0.060*	0.031
Government transfers	-0.236***	0.022	-0.236***	0.022
Other	-0.029*	0.016	-0.030*	0.016
Real income	0.027***	0.003	0.027***	0.003
(Real income)^2	-9.84xE^{-5}***	0.000	-9.84xE^{-5}***	0.000
Dwelling type:				
Semi-detached	-0.158***	0.012	-0.158***	0.011
Apartment	-0.312***	0.020	-0.312***	0.019
Other	0.012	0.023	0.012	0.023
Rho $(\hat{\rho})$	-0.007	0.020	-0.007	0.020
Number of observations	134,731		134,731	
Censored observations	18,291		18,291	
Uncensored observations	116,440		116,440	
Log pseudolikelihood	-1.99 xE^8		-1.99 xE^8	

Notes: All specifications include year fixed effects, census division fixed effects, transit expansion dummy variables, and collection month dummy variables for 2010-2012. Standard errors are adjusted for census division clusters. Coefficients on dummy variables are adjusted following Kennedy (1981). The coefficient estimates for the carbon tax and price in the log-log model are calculated from $\alpha_2\left(\frac{1}{p+\tau}\right)$ and $\left(\frac{1}{p}\right)\left\{\beta_{2BC}-\alpha_2\left(\frac{\tau}{p+\tau}\right)\right\}$, respectively. Real income is included in \$10,000 increments.

***Statistical significance at 1%; ** Statistical significance at 5%; * Statistical significance at 10%.

Copyright © 2018 by the IAEE. All rights reserved.

Connect with
IAEE
on facebook