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Measuring global gasoline and diesel price and income elasticities ☆

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ABSTRACT

Price and income elasticities of transport fuel demand have numerous applications. They help forecast increases in fuel consumption as countries get richer, they help develop appropriate tax policies to curtail consumption, help determine how the transport fuel mix might evolve, and show the price response to a fuel disruption. Given their usefulness, it is understandable why hundreds of studies have focused on measuring such elasticities for gasoline and diesel fuel consumption. In this paper, I focus my attention on price and income elasticities in the existing studies to see what can be learned from them. I summarize the elasticities from these historical studies. I use statistical analysis to investigate whether income and price elasticities seem to be constant across countries with different incomes and prices. Although income and price elasticities for gasoline and diesel fuel are not found to be the same at high and low incomes and at high and low prices, patterns emerge that allow me to develop suggested price and income elasticities for gasoline and diesel demand for over one hundred countries. I adjust these elasticities for recent fuel mix policies, and suggest an agenda of future research topics.

1. Introduction

Global diesel and gasoline for road transport have consistently grown faster than total oil product consumption for the last four decades rising from about 30% of oil product consumption in 1971 to about 46% in 2007 as shown in Fig. 1. Diesel fuel's share, which has grown faster than gasoline, was only about 5% in 1971 but grew to about 19% in 2007, whereas gasoline's share, which was about 25% in 1971, grew by less than 2 percentage points. These fuels are often considered strategic and knowing how fast these fuels will grow in the future and how their mix will change in the coming decades has important implications on oil security, oil related carbon emissions, and refinery investment patterns. For these reasons considerable work has been done to estimate demand functions for these fuels. In this paper, I consider this heterogeneous work to see what it implies for price and income elasticities and challenge researchers to check these implications on well thought out research topics of homogenous design. I base my analysis on the demand for gasoline and diesel fuel using existing econometric estimates contained in two demand databases: Dahl Energy Demand Database for Gasoline (DEDD-G2010.xls) and Dahl Energy Demand Database for Diesel (DEDD-D2010.xls).[1] Papers in these historical databases will be referred to as historical studies throughout the paper. For these historical studies to be useful, it is necessary for energy consumption to follow predictable patterns as countries develop and prices change. In addition, these patterns relating to income and price must be discoverable and stable enough to provide insights on forecasting and policy analysis. It is these patterns, which I will seek to find in this paper. In particular, I will use historical studies to investigate whether the level of income and fuel price have affected the income and price elasticities in predictable ways.

The outline of this paper is as follows. Gasoline and diesel price elasticities are developed for 124 countries in Part 2. Gasoline and diesel income elasticities are developed for these same countries in Part 3. A summary, conclusions and suggestions for further work are given in Part 4.

2. Gasoline price elasticities

Gasoline and diesel prices vary considerably across countries. They are given in columns 2 and 3 of Table 1 along with income per capita (Y/Pop) and the income and price elasticities developed later in this paper. Income per capita is measured as gross domestic product divided by population converted to 1990 international dollars using purchasing power parities (PPP) (Maddison, 2008) and inflated to 2006 US dollars with the US consumer price index (US Bureau of Labor Statistics, 2010). According to GTZ (2007), 2006 prices in November for premium gasoline in 170 countries varied from a high of 719 US cents per gallon (¢/g) ($1.90 per liter) in Eritrea to a low of 8 ¢/g ($0.02 per liter) in Turkmenistan. (All prices reported by GTZ (2007) are in 2006 US ¢ converted with exchange rates.) Diesel prices varied from a high of 674 cents per gallon ($1.78 per liter) in Iceland to a low of 4 ¢/g ($0.01 per liter) in

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[1] These databases can be accessed online at http://dahl.mines.edu/courses/dahl/dedd/. All articles in the databases are referenced in Dahl (2010a).

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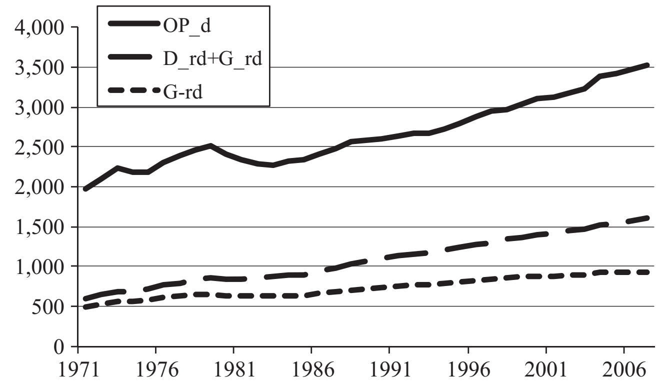

Fig. 1. Evolution of world consumption of oil products (Billions of tonnes of oil equivalents). *Notes:* OP_d = demand for total oil products, D_rd = diesel fuel used on roads, G-rd = gasoline used on roads.
Source: International Energy Agency, 2010a.

Turkmenistan. This diversity, shown in Figs. 2 and 3 for my sample of 124 countries, is largely the result of different taxation policies.

The mean and median gasoline price is about 370 US ¢/g. A rough estimate of cost of gasoline (C_g) at the pump excluding taxes is to take the November, 2006 Rotterdam price of gasoline adjusted to premium grade of 155.9 ¢/g, add a transportation, distribution, and retail sales margin of 60.4 ¢/g, to get 216.3 ¢/g, indicated by the dark vertical line in Fig. 2. (See Dahl and Anouti (2010) for development of gasoline and diesel margins.) More than 20 countries had gasoline prices below this amount in 2006 and were likely to be subsidizing gasoline.

The mean and median diesel price is about 320 ¢/g. Most countries have a lower price for diesel than for gasoline because of differences in taxation. A rough estimate of the cost of diesel (C_d) at the pump excluding taxes is to take the November 2006 Rotterdam price of 181 ¢/g add in a transportation, distribution, and retail sales margin of 58.3 ¢/g, to get 239.3 ¢/g, indicated by the dark vertical line in Fig. 3. (See Dahl and Anouti (2010) for development of gasoline and diesel margins.) More than 35 countries had diesel prices below this amount in 2006 and were likely to be subsidizing diesel fuel.

With this large heterogeneity of highway transport fuel prices, I am interested in determining whether the existing literature suggests that price elasticities are the same for low-price as for high-price countries. Another source of heterogeneity is the level of consumer's income. Fig. 4 shows a histogram of diversity of per capita incomes (Y/Pop) for the 124 countries in my sample, the actual values are shown in column 4 of Table 1. The energy ladder hypothesis suggests that as households get richer, they change their fuel mix in predictable ways towards more efficient fuels (Heltberg, 2004). They may also change their mix of desired goods that indirectly impacts transport fuel demand. To see whether the energy ladder hypothesis has relevance for transport fuel, I will also consider whether price elasticities and later income elasticities are influenced by the level of per capita income as well as by the price level.

I have found 240 gasoline demand studies for more than 70 countries (39 of these gasoline studies include cross sections (C) or cross section time series (CT) of countries) including over 2200 unique equations. I have found 60 diesel demand studies with over 300 unique equations for more than 55 countries (7 of these diesel studies include C or CT of countries). These studies are summarized in DEDD-G2010.xls and DEDD-D2010.xls. For more discussion of the database for gasoline and diesel demand elasticities, also see Dahl (2010a).

These elasticities are from both static equations and dynamic equations. Static equations include only non-lagged right hand side variables such as

$$Q_{g_t} = \alpha + \beta P_t + \chi Y_t + \delta X_t$$

where Q_g is the demand for gasoline, P is the price of gasoline, Y is a measure of income or economics activity, X represents other variables, greek letters are parameters to be estimated, and t indicates observation t.

Dynamic equations typically include non-lagged and lagged variables on the right hand side of the equation such as

$$Q_{g_t} = \alpha + \beta_0 P_t + \beta_1 P_{t-1} + \chi_0 Y_t + \chi_1 Y_{t-1} + \delta_0 X_t + \delta_1 X_{t-1} + \gamma Q_{g_{t-1}}$$

where $t-1$ represents time period $t-1$.

Studies which use dynamic models typically report both long and short run estimates. In earlier survey work (Dahl, 1995), I noted that elasticity estimates on static models are typically between the short run and long run estimates on dynamic models, and I labeled them as intermediate run.[2] However, more recent work suggests that in time series estimates, if the variables in the model are non-stationary unit roots, but are co-integrated, the elasticities from static models should be interpreted as long-run. I will follow this newer interpretation in this paper and focus my attention on elasticities estimated from static models. A caution should be noted with this interpretation. Only some more recent studies on a handful of countries have considered whether transport fuel demand equations are co-integrated. (For gasoline, they include Akinboade et al. (2008), Al Dossary (2008), Alves and Bueno (2003), Banfi et al. (2005), Bentzen (1994), Burnquist and Bacchi (2002), Cheung and Thomson (2004), Crôtte et al. (2009), Dahl and Kurtubi (2001), Eltony (2004), Eltony and Al-Mutairi (1995), Iooty et al. (2007), Manoel Antelo Gomez (2009), Polemis (2006), Ramanathan (1999), Ramanathan and Subramanian (2003), Rao and Gyaneshar (2008), Samimi (1995), Sohfi and Paknejad (2001), and Vasquez Cordano (2005). For diesel fuel, they include Al Dossary (2008), Christopoulos (2000), Dahl and Kurtubi (2001), De Vita et al. (2006), Eltony (2004), Iooty et al. (2007), Polemis (2006), and Vasquez Cordano (2005)).

Future work should seek to reconcile the difference in long-run estimates from static and dynamic models and check whether this long-run assumption holds by checking for co-integration in all time series estimates with non-stationary variables.[3]

Proceeding I limit my analysis and take only studies which include price elasticities from static models from DEDD-G2010.xls and DEDD-D2010.xls. For gasoline, there are about 140 articles with over 1000 estimated equations on about 70 countries. For diesel, there are 34 articles with about 120 estimated equations, on about 33 countries.[4] Figs. 5 and 6 summarize these price elasticity estimates from static models for gasoline and diesel fuel, respectively. The median price elasticities are −0.34 and −0.16 for gasoline and diesel, respectively.

In both cases, the price elasticities cluster around the medians with the distributions skewed to the right making the mean more elastic than the median. Although the range of estimates is wide, outliers are usually explainable and the removal of the most extreme explainable price elasticities puts the mean and median quite close to each other. Most of the positive elasticities for both fuels are not significantly different from zero with a 2 tailed test at

[2] This same result has been found in recent meta-analysis by Brons et al. (2008). They find average gasoline short run elasticities to be −0.34 and long-run elasticities to be −0.84 with average elasticity from static models of −0.50.

[3] The estimates on static models are equivalent to the first step in the Engel-Granger Two-Step Procedure. However, more recent work indicates that a two step procedure is typically not the most appropriate. See Amarawickrama and Hunt (2008) for a discussion and references on the two-step as well as other more recent procedures that might be more appropriate.

[4] These estimates are in the columns labeled Pstat in both the DEDD databases.

Table 1
Gasoline and diesel prices, income per capita, gasoline and diesel price, and income elasticities.
Sources: DEDD-G2010.xls, 2010; DEDD-D2010.xls, 2010. Gasoline and diesel prices: GTZ (2007). Income per capita: Maddison (2008). Income and price elasticities: developed by author from studies in DEDD-G2010.xls, 2010 and DEDD-D2010.xls, 2010.

Units	**¢/g**	**¢/g**	**$ (PPP)**	**P elasticities**		**Y elasticities**		**Fuel policy adjust.**		
Var	***Pg***	***Pd***	***Y/Pop***	ε_{gp}	ε_{dp}	ε_{gy}	ε_{dy}	ε_{gp}	ε_{gy}	ε_{dy}
Albania	545	488	2916	−0.26	−0.13	1.27	1.34			
Algeria	121	72	7177	**−0.30**	−0.22	**1.05**	**1.87**	−0.45	−0.59	
Angola	189	136	4954	−0.22	−0.22	1.27	1.34			
Argentina	235	182	12,745	**−0.05**	−0.22	**0.55**	1.34	−0.08	−1.09	
Australia	352	356	30,873	**−0.29**	**−0.65**	**0.55**	**0.69**			
Austria	500	477	30,496	**−0.54**	**−0.16**	**0.85**	**1.03**	−0.81	−0.79	1.79
Azerbaijan	174	155	1132	−0.22	−0.22	1.27	1.34			
Bahrain	79	49	24,551	**−0.50**	**−0.19**	**1.04**	1.34			
Bangladesh	299	170	4510	**−0.09**	−0.22	**2.06**	**1.66**			
Belarus	299	208	5660	−0.26	−0.22	1.27	1.34	−0.39	−0.37	
Belgium	617	507	29,461	**−0.34**	−0.38	**0.85**	**1.71**	−0.51	−0.79	1.79
Benin	307	307	1349	−0.26	−0.13	1.27	1.34			
Bolivia	204	178	3536	−0.22	−0.22	1.27	1.34			
Bos&Herz	507	469	7689	−0.26	−0.13	1.27	1.34			
Botswana	295	280	8493	−0.26	−0.13	1.27	1.34			
Brazil	477	318	7486	**−0.26**	**−0.32**	**0.84**	**0.90**	−0.39	1.37	
Brunei	129	79	18,943	−0.24	−0.27	0.99	1.34			
Bulgaria	397	409	8907	−0.26	−0.13	1.27	1.34	−0.39	0.74	
Cambodia	382	295	2482	−0.26	−0.13	1.27	1.34			
Cameroon	431	405	2728	−0.26	−0.13	1.27	1.34			
Canada	318	295	32,617	**−0.48**	**−0.74**	**0.72**	**1.26**			
Chile	413	326	11,377	**−0.25**	−0.13	**0.93**	**0.70**	−0.38	0.40	
China	261	231	4,076	−0.26	−0.22	**0.97**	**1.18**			
Colombia	371	216	4664	**−0.04**	−0.22	**0.91**	**0.83**	−0.06	−0.73	1.79
Congo, R.	363	254	2794	−0.26	−0.13	1.27	1.34			
Costa Rica	371	254	10,639	**−0.44**	−0.13	1.27	1.34			
Cote d'Iv.	454	401	2071	**−0.09**	**−0.46**	**0.57**	**1.19**	−0.14	−1.07	
Croatia	507	462	12,235	−0.32	−0.13	1.35	1.34	−0.48	0.82	1.79
Cuba	416	344	1609	−0.26	−0.13	1.27	1.34			
Cyprus	473	454	22,093	−0.33	−0.38	0.82	1.34			
Czech Rep.	492	488	19,131	−0.32	−0.38	0.98	1.34			
Denmark	598	549	30,628	**−0.40**	**−0.20**	**0.42**	**2.23**	−0.60	−0.11	1.79
Dom. Rep.	390	284	6038	**−0.29**	−0.13	**1.20**	1.34			
Ecuador	178	148	5512	**−0.18**	**−0.17**	**1.25**	**1.21**			
Egypt	114	45	4918	**−0.21**	−0.22	**1.36**	**0.86**			
El Salvador	310	303	4896	−0.26	−0.13	**1.95**	1.34			
Eritrea	719	307	706	−0.26	−0.13	1.27	1.34			
Estonia	466	462	16,706	−0.32	−0.38	1.11	1.34			
Ethiopia	352	235	904	−0.26	−0.22	1.27	1.34	−0.39	0.74	1.79
Finland	587	477	27,906	**−0.33**	**−0.05**	**1.09**	**1.35**	−0.50	0.56	
France	560	503	27,398	**−0.35**	**−0.24**	**0.87**	**1.78**	−0.53	−0.77	1.79
Gabon	242	148	7518	−0.22	−0.22	1.27	1.34			
Georgia	326	337	2634	−0.26	−0.13	1.27	1.34			
Germany	587	522	27,614	**−0.28**	−0.38	**1.21**	**1.29**	−0.42	0.68	1.79
Ghana	326	318	1609	−0.26	−0.13	1.27	1.34			
Greece	439	450	24,477	−0.33	**−0.44**	**1.29**	**1.18**			
Guatemala	295	242	3991	**−0.50**	**−0.22**	**1.43**	1.34			
Honduras	337	276	3336	**−0.30**	−0.13	1.27	1.34			
Hong Kong	379	379	33,098	**−0.12**	**−0.36**	**0.42**	**0.50**			
Hungary	492	496	15,809	−0.32	−0.38	1.16	1.34			
Iceland	704	674	33,050	−0.33	−0.38	0.62	1.34			
India	382	284	2,127	**−0.36**	−0.13	**1.37**	**1.12**			
Indonesia	216	167	2,840	**−0.20**	**−0.38**	**1.89**	**1.58**			
Iran	34	11	8,371	**−0.20**	**−0.15**	**1.11**	**1.68**			
Iraq − P05	11	4	2,513	**−0.09**	**−0.17**	**1.26**	**1.34**		0.63	
Ireland	507	511	37,371	**−0.30**	−0.38	**0.72**	**1.41**			
Israel	556	481	21,955	**−0.23**	**−0.19**	**1.20**	**0.46**			
Italy	590	564	24,612	**−0.38**	**−0.24**	**1.12**	**1.14**	−0.57	−0.52	1.79
Japan	413	341	27,523	**−0.15**	**−0.26**	**0.86**	**0.99**		1.39	
Jordan	326	170	3560	−0.26	−0.22	**0.85**	**1.05**			
Kazakhstan	265	170	8312	−0.26	−0.22	1.27	1.34			
Kenya	424	371	1655	−0.26	−0.13	**1.51**	1.34			
Korea, South	625	503	16,045	**−0.60**	−0.38	**1.67**	**1.33**	−0.90	1.14	0.88
Kuwait	83	79	45,879	**−0.09**	**−0.02**	**0.82**	**0.61**			
Latvia	454	435	13,184	−0.32	−0.13	1.30	1.34	−0.48		1.79
Lebanon	280	235	8,538	−0.26	−0.22	1.27	1.34		0.74	
Libya	49	49	10,117	**−0.09**	−0.22	**1.26**	**1.34**	−0.14	−0.38	
Lithuania	409	413	12,643	−0.32	−0.13	1.33	1.34	−0.48	0.80	1.79
Luxembourg	488	431	62,020	−0.33	−0.38	**0.67**	1.34	−0.50	0.14	
Maced. FYR	466	413	5033	−0.26	−0.13	1.27	1.34	−0.39	−0.37	
Malaysia	201	151	11,790	**−0.13**	−0.22	**0.95**	**1.61**			

Table 1 (*continued*)

Units	**¢/g**	**¢/g**	**$ (PPP)**	**P elasticities**		**Y elasticities**		**Fuel policy adjust.**		
Var	***Pg***	***Pd***	***Y/Pop***	ε_{gp}	ε_{dp}	ε_{gy}	ε_{dy}	ε_{gp}	ε_{gy}	ε_{dy}
Malta	522	477	14,274	−0.32	−0.13	1.24	1.34	−0.48	−0.40	
Mexico	280	197	11,195	**−0.31**	**−0.30**	**1.25**	**0.86**			
Moldova	367	326	1256	−0.26	−0.13	1.27	1.34			
Mongolia	333	329	2094	−0.26	−0.13	1.27	1.34			
Mozambique	435	401	675	−0.26	−0.13	1.27	1.34			
Myanmar	250	284	3322	−0.22	−0.13	1.27	1.34			
Namibia	329	329	30,925	−0.33	−0.38	**0.90**	**1.46**			
Nepal	356	276	1,503	−0.26	**−0.57**	1.27	1.34			
Netherlands	643	500	31,644	**−0.34**	**−0.01**	**0.60**	**1.31**			
New Zealand	371	265	23,595	**−0.10**	−0.38	**0.87**	1.34			1.79
Nicaragua	254	220	2320	−0.26	−0.22	1.27	1.34			
Nigeria	193	250	1314	−0.22	−0.22	**1.65**	1.34			
Norway	681	628	43,288	**−0.28**	**−0.07**	**1.00**	**2.08**	−0.42	−0.64	
Oman	117	148	18,175	**−0.52**	−0.27	**0.96**	1.34			
Pakistan	382	242	2004	**−0.41**	−0.22	**0.73**	**1.37**			
Paraguay	367	291	2245	**−0.22**	−0.13	**0.84**	1.34			
Peru	462	326	5852	**−0.37**	**−0.43**	**1.46**	**1.05**			
Philippines	288	254	2602	**−0.35**	−0.13	**0.57**	1.34			
Poland	492	492	12,627	−0.32	−0.13	1.33	1.34	−0.48	−0.31	
Portugal	590	416	18,002	**−0.25**	**−0.29**	**1.52**	**1.75**	−0.38	0.99	1.79
Qatar	72	72	44,704	**−0.08**	**−0.15**	0.62	1.34			
Romania	477	469	8812	−0.26	−0.13	1.27	1.34			
Russia	291	250	11,391	**−0.10**	−0.22	**0.23**	**1.11**			1.79
Saudi Arabia	61	26	16,831	**−0.09**	**−0.12**	**1.02**	**0.79**			
Senegal	496	413	1798	−0.26	−0.13	1.27	1.34			
Singapore	348	238	38,622	−0.33	**−0.12**	0.62	**0.68**			
Slovakia	511	541	15,248	−0.32	−0.38	1.19	1.34	−0.48	0.66	
Slovenia	466	458	21,442	−0.33	−0.38	0.85	1.34	−0.50	0.32	1.79
South Africa	322	318	6035	−0.26	**−0.13**	**0.54**	**1.20**			
Spain	435	416	25,841	**−0.24**	−0.38	**1.00**	**2.10**	−0.36	−0.64	1.79
Sri Lanka	333	208	4854	**−0.40**	**−0.17**	**1.02**	**1.04**			
Sudan	273	185	1521	−0.26	−0.22	1.27	1.34			
Sweden	553	545	30,468	**−0.32**	**−0.25**	**1.03**	**1.39**	−0.48	−0.61	
Switzerland	481	515	33,127	**−0.37**	**−0.43**	**1.48**	**1.18**			
Syria	227	49	3728	−0.22	−0.22	1.27	**1.34**			
Taiwan	314	269	24,181	**−0.69**	**−0.28**	**2.02**	**0.43**			
Tanzania	394	375	627	-0.26	-0.13	1.27	1.34			
Thailand	265	246	6422	**−0.16**	**−0.23**	**0.91**	**1.33**			
Togo	390	382	921	-0.26	−0.13	1.27	1.34			
Trin.&Tob.	163	91	20,720	−0.22	−0.27	0.89	1.34			
Tunisia	314	216	8570	**−0.22**	**−0.28**	**0.75**	**1.21**			
Turkey	712	613	9686	**−0.19**	−0.13	**1.10**	**2.27**	−0.29	0.57	
Ukraine	307	329	5319	−0.14	−0.17	0.84	1.34			
UAE	140	201	30,148	**−0.26**	**−0.13**	**1.27**	**1.34**		0.63	
UK	617	655	30,905	−0.33	−0.38	**1.41**	**1.60**	−0.50	−0.23	1.79
USA	238	261	37,846	**−0.30**	**−0.07**	**0.63**	**1.00**			
Uruguay	466	356	8410	−0.26	−0.13	**1.06**	1.34			
Uzbekistan	322	204	2642	−0.26	−0.22	1.27	1.34	−0.39	−0.37	
Venezuela	11	8	10,057	**−0.14**	**−0.17**	**0.70**	**1.65**			
Vietnam	254	201	2020	−0.26	−0.22	1.27	1.34			
Yemen	114	106	1966	−0.22	−0.22	1.27	**2.36**			
Zambia	496	462	1117	−0.26	−0.13	1.27	1.34			
Zimbabwe	231	246	2055	−0.22	−0.22	1.27	1.34			

Notes: All variables are measured in 2006 except prices in Zimbabwe, which are for 2005. ¢/g = US 2006 cents per gallon, PPP indicates income was converted using purchasing power parities. Bold elasticities are based on historical elasticities, non-bold elasticities are developed by this author from analysis of historical elasticities and historical data.

the 5% level suggesting that price is not influential or there is too much noise in the data to pick up the effect.

Next I stratify the available price elasticity survey work by country and combine with personal judgment to develop such elasticities for each of the fuels. From this analysis, I come up with gasoline and diesel demand price elasticities for 62 and 39 countries, respectively. These price and income elasticities are in bold in columns 5–8 above in Table 1. Next I look for patterns in the available price and income elasticities to develop the non-bold elasticities for all the remaining countries in Table 1.

Visual inspection and statistical pretesting of gasoline price elasticities showed some threshold effects for gasoline with lower-priced countries having a less elastic price response than higher-priced countries and lower-income countries having a less elastic price response than higher-income countries. Two alternative hypotheses might explain lower price response at lower income. In poorer countries, only the relatively rich may have personal vehicles, and they may be less responsive to price changes. Alternatively, poorer countries tend to have higher capital costs and anecdotal evidence suggests that they keep their vehicles longer. Thus, their vehicle stock turns over more slowly to newer more fuel efficient vehicles lowering their price responsiveness.

I jointly test the threshold effects for gasoline price elasticities with a two way analysis of variance to investigate whether there is any interaction between income and price that influences the price elasticities. I do find some evidence of interaction with statistically

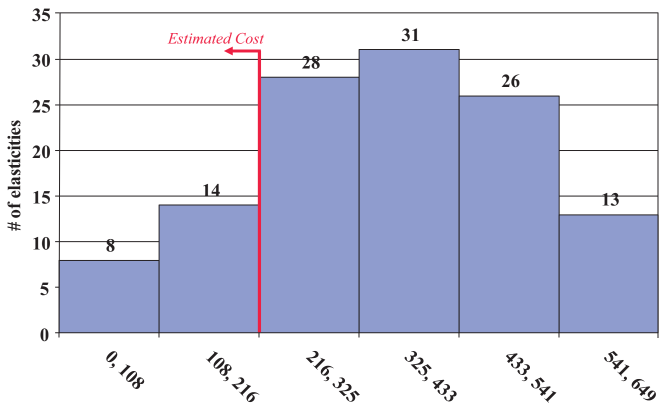

Fig. 2. Frequency of premium gasoline prices. *Notes*: Divide by 3.785 to get price per liter.
Source: Compiled from information in GTZ, 2007.

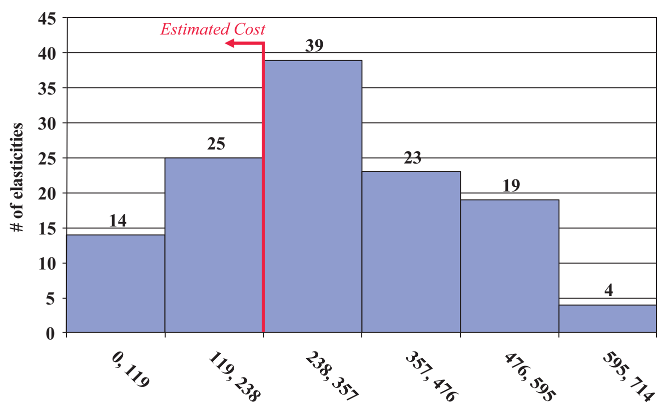

Fig. 3. Frequency of diesel prices. *Notes*: Divide by 3.785 to get price per liter.
Source: Compiled from data in GTZ, 2007.

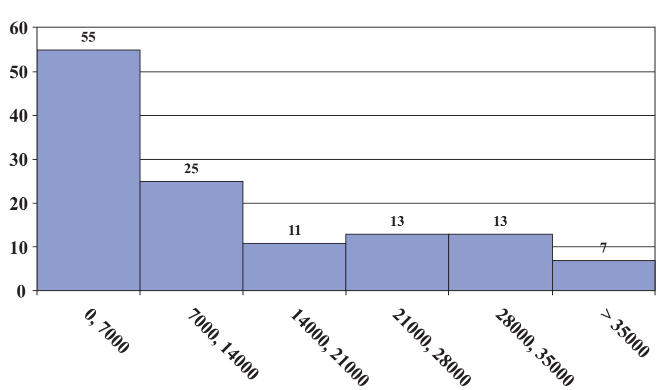

Fig. 4. Frequency of country income per capita, 2006.
Source: Created from data in US Energy Information Administration (EIA), 2009a.

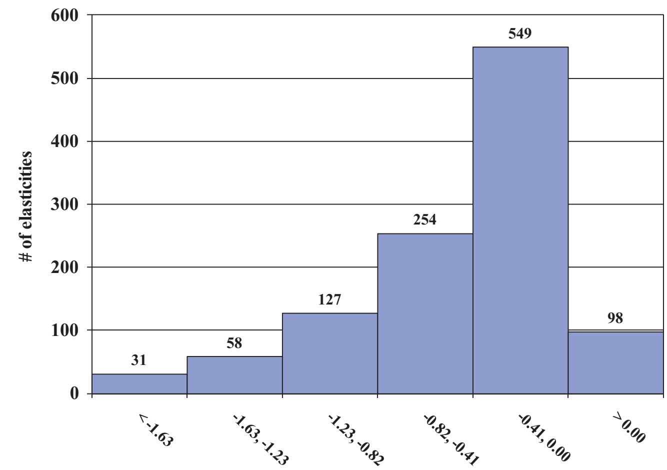

Fig. 5. Frequency of gasoline price elasticities from static models.
Source: DEDD-G2010.xls, 2010.

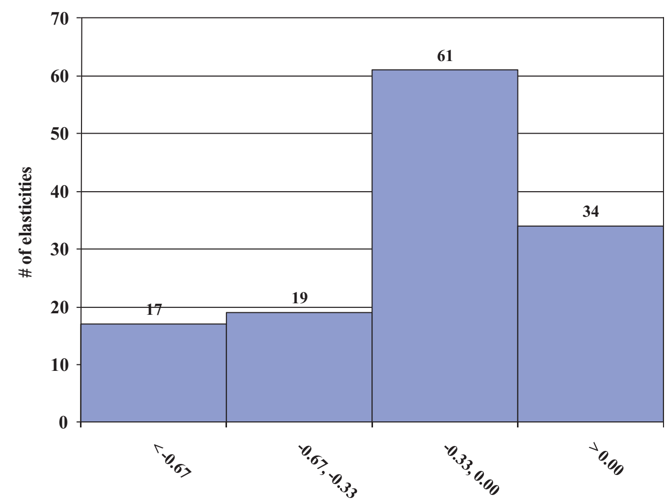

Fig. 6. Frequency of diesel price elasticities from static models.
Source: DEDD-D2010.xls, 2010.

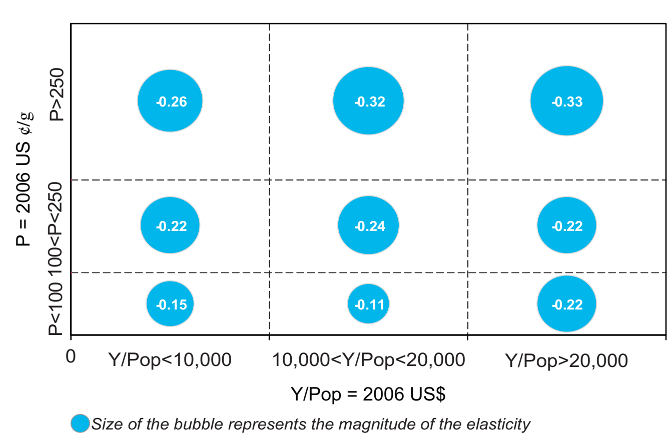

Fig. 7. Gasoline price elasticities across various price and income categories.
Source: Statistical analysis of studies in DEDD-G2010.xls, 2010.

preferred breaks for gasoline price elasticities at prices of 100 and 250 ¢/g and incomes of $10,000 and $20,000 (2006 US$) with the category means shown in Fig. 7. As price and income both increase, there is a tendency for price elasticities to increase. This interaction is highly significant with the *F* for the null hypothesis that the means are the same in all categories ($F(4,58)=22.35$) considerably above the critical value of 2.53.

With fewer observations, I find fewer threshold effects for diesel fuel price elasticities. The statistically preferred breaks for diesel price elasticities are at a price of 250 ¢/g and an income per capita

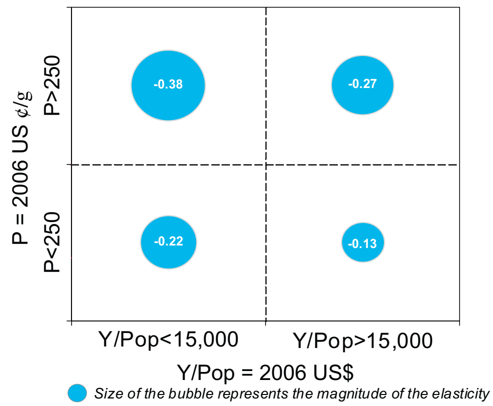

Fig. 8. Diesel price elasticities across various price and income categories.
Source: Statistical analysis of studies in DEDD-D2010.xls, 2010.

of $15,000 with the category means shown in Fig. 8. Again these differences are highly significant with the *F* for the null hypothesis that the means are the same in all categories ($F(4,35)=13.87$) considerably above the critical value of 2.64. These elasticities suggest that low-price, high-income countries show the least price response (-0.13) with more elastic response at higher price levels.[5]

I use the above elasticities in Figs. 7 and 8 along with price and per capita income to fill in for countries with missing price elasticities in Table 1. These elasticities are the non-bold elasticities under ε_{gp} and ε_{dp} in Table 1. (E.g. Singapore has a gasoline price of 348 ¢/g and an income per capita of $38,622, thus I assign a price elasticity of -0.33.)

In the last decade or so, there have been a number of countries that have had policies promoting fuel switching, either away from gasoline towards diesel fuel (e.g. many European countries and others) or away from petroleum based fuels towards bio-fuels (most notably Brazil). If these policies operate through increasing the own price of the fuel, the above price elasticities may still be fairly reliable. If the switching has been fairly small as is often the case for bio-fuels, the bias also is likely to be small.

However, consider some cases where the above price elasticities may not be good proxies and may require adjustments. Policies to promote other fuels may operate through the price of an alternative fuel. In such a case, a missing cross-price elasticity might be biasing the own-price elasticities. In consulting DEDD-G2010.xls, only 23 of the 240 gasoline demand studies have estimates of gasoline demand that include any cross-price elasticity. However, the median static own-price elasticities do not vary so much between the studies that include a cross price (median $\varepsilon_{gp}=-0.29$) and those that do not (median $\varepsilon_{gp}=-0.34$).

Historically the best substitute for gasoline has been diesel fuel with many European countries actively promoting a switch towards diesel engines in light duty vehicles. These policies, designed to promote fuel efficiency, often included lower taxes on both diesel fuel and on new diesel vehicles. Improved diesel performance in the 1990s including turbo-charged fuel injection engines that are quieter and cleaner along with other policies have dramatically increased the popularity of light duty diesel vehicles in Europe. By 2007, they comprised half of the new vehicle purchases in Western Europe (US Energy Information Administration (EIA), 2009a, 2009b). As a result of this fuel switching, gasoline consumption peaked in 1998 in W. Europe, but diesel consumption has continued to increase (International Energy Agency, 2010a).

Al Dossary (2008) is the study that most explicitly investigates substitution away from diesel fuels towards gasoline by specifically testing whether the cross-price elasticity of gasoline with respect to diesel fuel price is significant using a dynamic model on 23 separate countries (Australia, Belgium, Germany, France, Canada, Canada, Chile, India, Indonesia, Iran, Italy, Japan, South Korea, Mexico, Netherlands, Russia, Saudi Arabia, Spain, and Venezuela) on data through 2005. Somewhat to my surprise, he only finds a significant response to diesel price in Italy and Netherlands through 2005. There is little evidence that the insignificance of diesel price for the other countries results from collinearity between gasoline and diesel price, since I find the correlation between them for 1978–2007 to be less than 0.9 for all countries in his sample except for Germany and the USA. (International Energy Agency, 2010b). If I replicate his results on time series[6] for Italy and Netherlands as closely as possible with and without a diesel price, the long-run price elasticities change by less than 4% suggesting the omission of diesel fuel price in their case may not bias the own price elasticity very much.

Since the policies and technical changes in favor of diesel engines have been most important during the 1990s, Al Dossary also checked for structural breaks over his sample. Only for Spain did he find a structural break during the 1990s, but he did not find diesel price to be significant on his sample after the break. I further experimented with simple static demand models by country but did not find evidence of any consistent quantifiable effect of diesel fuel price on gasoline consumption. Nor did the omission of diesel fuel price consistently change the price elasticity.

Although Al Dossary (2008) did not find much evidence of breaks in the demand equation over the 1990s when the switch to diesel was occurring, I found a 50% more elastic price response on aggregate European data after the introduction of turbo-charged fuel injection diesel engines in Europe (1990–2007) compared to estimates over available data on years included in the surveyed articles, (1978–2005). This more elastic price response since 1990 was well outside of the confidence interval for the price elasticity over the longer sample. For this reason, I increased gasoline demand price elasticities by 50% for all those countries that have seen a strong switch towards diesel fuel with gasoline consumption decreasing. These adjusted price elasticities are in column 9 in Table 1. However, I would encourage more work to study policies by country to determine individual responses to policy.

Moving to the diesel side of the story, again Al Dossary (2008) is a recent study that most explicitly investigates substitution of gasoline towards diesel. He specifically tests whether the cross-price elasticity of highway diesel fuel demand with respect to gasoline price is significant. For the same 23 countries, he finds the price of gasoline significant for only four countries—Australia, Indonesia, Turkey, and the UK. However, the median long-run price elasticity from his dynamic models of these four countries (-0.33) was not so different from those where the price of gasoline was insignificant and omitted. Further checking for a discernible bias from the omission of the price of gasoline, I reran a static diesel demand model on time series for each of these four countries with own price and GDP excluding and including the price of gasoline for a sample as similar as possible to Al Dossary (2008) but only on data from 1990. For Australia, there was some evidence that gasoline substitutes for diesel on the sample from 1978 to 2005 but not on a more recent sample from 1990 to 2007. For Indonesia, there was no statistical evidence on the price coefficient that gasoline substitutes for diesel fuel on either a longer

[5] I experimented with meta-analysis and regression analysis but was not successful in finding a statistically significant functional relationship between price elasticity, price, and income.

[6] All my demand time series verification and estimation is done using from International Energy Agency (2010a, 2010b), Maddison (2008), and OPEC (2009).

(1980–2004) nor on a more recent sample from 1990 to 2007. Although Al Dossary found gasoline price significantly positive on Turkish data, he found evidence of a break in the demand equation in 1995 with no useable results on either pre- or post-1995 data. I was not any more successful on a static model over similar samples.

Since I was unable to find any evidence of systematic change in price elasticities for diesel demand for countries with policies favoring diesel, I did not adjust price elasticities from those suggested by historical data. Again further work might uncover variables to include that could better proxy the diesel policies.

3. Income effects on highway fuel demand

In the above analysis, I investigated how price elasticity varies over different price and income levels. In this section, I consider how income elasticity varies. Fig. 4 showed the income distribution for the 2006 database. The 50 or so low income countries ($Y/Pop<$7000 PPP USD) had around 70% of the world's population in 2006 and consume less than 20% of the world's gasoline and diesel fuel. As many of these economically emerging countries climb the economic ladder into higher per capita income categories, their fuel use will strongly influence global fuel consumption growth. Much of the econometric work favors constant elasticity functions suggesting that income elasticity at high incomes is the same as that at low incomes. However, Dargay et al. (2007) use an S shaped Gompertz function on a sample of 45 countries from 1960 to 2002 to estimate vehicle registration per 1000 population as a function of GDP per capita allowing for urbanization and population density. They find vehicle ownership grows more slowly at per capita incomes less than $4000, about twice as fast as income at per capita incomes of $4000—about $13,000 and then at about the rate of income until countries are saturated in vehicles. They allow saturation rates to vary across countries, but most are between 775 and 875 light duty vehicles per 1000 inhabitants with saturation typically occurring between $30,000–$40,000 per capita. If income elasticities increase and then decrease for vehicles, I would expect a somewhat similar function to occur for fuel demand. To check this out, I search the econometric estimates in DEDD-G2010.xls for patterns and check these patterns with 2006 data to see what they say about income elasticities and how they might change as income increases.

Fig. 9 shows a histogram of gasoline demand income elasticities from static models in DEDD-G2010.xls. The median income elasticity is 0.57 and 50% of the elasticities are between 0.25 and 0.99. About 10% of the elasticities are negative. More than 80% of these negative income elasticities are on stock models.

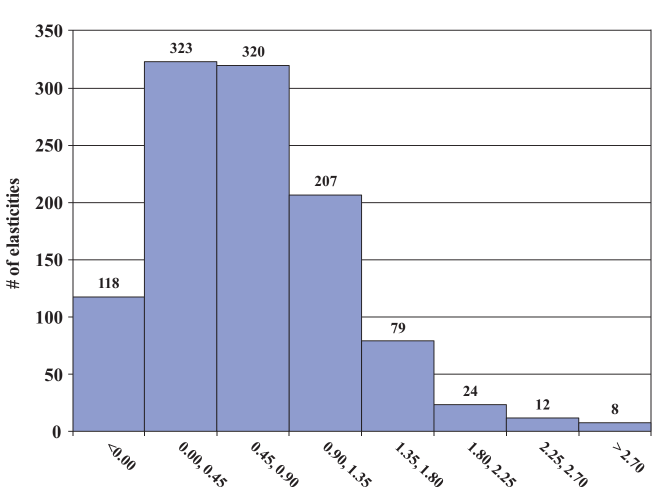

Fig. 9. Frequency of gasoline income elasticities from static models.
Source: Compiled from data in DEDD-G2010.xls, 2010.

For such stock models, if the stock of vehicles is held constant, fuel consumption falls as income increases suggesting that as countries get richer, they may own newer more efficient vehicles and they may use these vehicles less intensely. More generally, analysis of variance found a significant difference between the income elasticities on models that included some sort of vehicle stock variable (stock) and those that do not (non-stock) models as shown in Table 2. The income elasticities average 0.84 for non-stock models and 0.42 for stock models suggesting that about half of the adjustment to an income change comes from changing the use or efficiency of the fleet of vehicles, and the rest comes from changing the number of vehicles.

About half of the remaining negative income elasticities are on monthly data and they are usually not significantly different from zero at the 5% level. To further investigate the effect of data frequency, I do a second set of analysis of variance tests on non-stock models also shown in Table 2. I find that annual income elasticities are significantly different (mean=0.97) than income elasticities on monthly and quarterly data (mean=0.42) but there is no significant difference in the mean between estimates on monthly (mean=0.44) and quarterly data (mean=0.40). These means suggest that about 40% of an adjustment to a change in income happens within the first quarter of the change.

The above tests suggest that for single equation models, the non-stock models on annual data are the most appropriate elasticities for approximating a top-down look at total income elasticities by country. In the last set of tests, I consider whether income elasticities vary by income levels and whether they fall as consumers become saturated as suggested by Dargay et al. (2007) on vehicle ownership. For each estimate, I compute the average income for the country by averaging per capita income for the first and last year of their sample. Per capita income is taken from Maddison (2008), who reports historical income per capita by country converted to 1990 international dollars using purchasing power parities. I have inflated these to 2006 US$ using the US CPI.

To begin my investigation of the relationship between income elasticity and income per capita for gasoline, I present a scatter plot in Fig. 10. Although there is considerable noise in the data, the relationship appears to have a downward trend and a regression of income on elasticity on income per capita found a significant

Table 2
Analysis of variance tests on gasoline income elasticities.
Source: Computed from data in DEDD-G2010.xls, 2010.

	Non-stock	Stock
Mean G-Ystat	0.84	0.42
Count	635	480
***F*(1,1113)**	6.86	
***F* critical**	3.85	
***P* value**	0.00	
	Non-stock annual	Non-stock-*m*&*q*
Mean G-Ystat	0.97	0.42
Count	485	150
***F*(1,633)**	19.57	
***F* critical**	3.86	
***P* value**	0.00	
	Non-stock-*m*	Non-stock-*q*
Mean G-Ystat	0.44	0.40
Count	70	80
***F*(1,148)**	0.50	
***F* critical**	3.91	
***P* value**	0.48	

Notes: m=estimated on monthly data, non-stock=models that do not include some measure of vehicle stock, q=estimated on quarterly data, stock=models that include some measure of vehicle stock, G-Ystat=gasoline demand income elasticity.

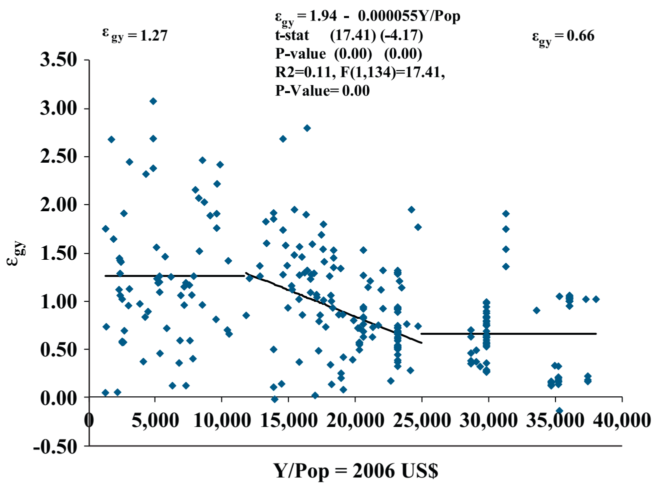

Fig. 10. Plot and estimates of gasoline income elasticities against income per capita. *Notes*: *Y/Pop* is GDP per capita. *t*-Stat below an estimated coefficient is the asymptotic *t* statistic for the null hypothesis that the coefficient is zero and the *p* value indicates the per cent of the time that the asymptotic t statistic in absolute value would be larger than the given value, if the null hypothesis were true. *Source*: Estimated from data in DEDD-G2010.xls, 2010.

downward slope. However closer perusal of the data suggested a more random pattern to income elasticity below \$11,800 and above \$26,000. Separate regressions and testing confirmed this suspicion. I could not reject a zero slope at per capital incomes below \$11,800 or reject a zero slope at incomes above \$26,000. The average of the income elasticities is 1.26 below income per capita of \$11,800 USD. Thus I assume a constant income elasticity of 1.26 for countries with income per capita less than \$11,800 USD. From \$11,800 to \$26,000 there is a perceived downward slope to the regression as indicated in the regression results included in Fig. 10.

Although the overall explanatory power of the equation is low at $R^2=0.11$, there is a highly significant downward slope of -0.000055. This slope indicates that the income elasticity falls 0.055 for every \$1000 increase in per capita income. At an income of \$10,800 the income elasticity is 1.29 and at an income of \$26,000 the income elasticity is 0.51. Since I could not reject the null hypothesis of a zero slope above 26,000, I took the mean of the income elasticities of 0.66.

The historical studies suggest that income elasticity is constant at a higher level for low incomes, and then gently slopes down as income increases until it levels out at 0.66. Neither of the two most popular demand functions for gasoline demand – log linear and linear – allow this kind of behavior. With the log linear function, income elasticity is constant as in the low and high income case. If demand is the linear function $Q=a+bY$, the income elasticity is

$$\varepsilon_y = \frac{dQ}{dY}\frac{Y}{Q} = b\frac{Y}{Q} = \frac{bY}{a+bY}$$

Note that for $a>0$ in this function as Y increases, the income elasticity increases, which is the opposite of what the database suggests for middle income countries. However, the function

$$\ln(Q) = \beta_1 + \beta_2 \ln(P) + \beta_3 \ln(Y) + \beta_4 Y \quad (1)$$

gives the price elasticity as

$$\frac{\partial Q}{\partial P}\frac{P}{Q} = \beta_2$$

and the income elasticity as

$$\frac{\partial Q}{\partial Y}\frac{Y}{Q} = \beta_3 + \beta_4 Y$$

If β_4 is negative, the income elasticity falls as per capita income rises. To check whether the equations suggested in the heterogeneous historical database (DEDD-G2010.xls) shown in Fig. 10 have any explanatory power for the present, I estimate a simple static demand equation on the cross-sectional database I have developed for this study for the three income ranges discovered above. I have a sample size of $T=74$ countries with income less than \$11,800 per capita. The pattern above suggests that the income elasticity is constant as income increases at about 1.26. The regression of gasoline consumption per capita (Q_g) on real gasoline price (P_g) and real per capital income (2006 PPP US\$) (Y/Pop) for countries with income $<$ \$11,800 for sample size T is

$$\ln\frac{Q_g}{Pop} = \cdots \underset{\substack{(-3.70)\\ [0.00]}}{-0.44} \ln P_g + \underset{\substack{(10.14)\\ [0.00]}}{1.16} \ln\frac{Y}{Pop}$$

$$R^2 = 0.656, \quad P \text{ value for equation} = 0.000, \quad T = 74 \quad (2)$$

The numbers in parenthesis under the estimated coefficients are estimated asymptotic t statistics for the coefficient and the numbers in square brackets are the P values. When a linear value of Y was also included as in Eq. (1), the coefficients on the logged price and income term remained strongly significant with P values of 0.00, but the coefficient on the linear income term was not (P value of 0.21).

A χ^2 test in Eq. (2) strongly rejects the null hypothesis that there is no significant difference between the linear and log linear formulation in favor of the log formulation with a constant elasticity for the above equation. The estimated Box–Cox chi squared statistic for sample size T is

$$\chi_1^2 = \frac{T}{2}\left|\ln\left(\frac{SSE_{lin}/\overline{Q}^2}{SSE_{ln}}\right)\right| = 144.35$$

With ln = the natural log, SSE_{lin} = the sum of squared errors for the regression on linear variables, and $\overline{Q}^2$ = the geometric mean of the dependent variable, SSE_{ln} = the sum of squared errors for the regression on logged variables. Since $\chi^2(1)=144.35$ is larger than the critical value, $\chi^2(1)=3.84$, and the denominator is smaller than the numerator, I reject the null hypothesis of no significance difference in fit between the linear and log formulation in favor of the log formulation. Eq. (2) supports the constant income elasticity suggested by the historical data and 1.16 is only about one standard deviation away from the mean income elasticity of 1.27 from the historical studies.

The historical data suggests that the gasoline income elasticity for per capita incomes between \$11,800 and \$26,000 equals

$$\varepsilon_Y = 1.94 - 0.000055Y$$

To check whether the newer cross-sectional data set confirms or contradicts this relationship, I ran a regression with Y/Pop added to Eq. (2) and got the following results:

$$\ln\frac{Q_g}{Pop} = \cdots \underset{\substack{(-3.84)\\ [0.00]}}{-0.51} \ln P + \underset{\substack{(0.51)\\ [0.61]}}{2.38} \ln\frac{Y}{Pop} - \underset{\substack{(-0.20)\\ [0.84]}}{0.000053}\frac{Y}{Pop}$$

$$R^2 = 0.48, \quad P \text{ value for equation} = 0.003, \quad T = 25 \quad (3)$$

The good news is that this equation gives us an income elasticity of $2.38-0.000053Y$ which shows a bit higher income elasticity but an almost identical downward trajectory as the historical data. The bad news is that the correlation coefficient between ln Y and Y over the sample is 0.99. Thus, multicollinearity is preventing the estimates from being very precise.

The last check is for the countries with income per capita above \$26,000. I find the fit quite poor when just price and income per capita are included ($R^2=0.22$ and the coefficient on income is small and insignificant with a P value of 0.74). Adding a population density variable (population/square kilometer), improves the fit and yields the following interesting result:

$$\ln\frac{Q_g}{Pop} = \ldots \underset{[0.00]}{\underset{(-4.21)}{-0.60}} \ln P + \underset{[0.17]}{\underset{(1.41)}{0.62}} \ln\frac{Y}{Pop} - \underset{[0.00]}{\underset{(-5.23)}{0.26}} \ln(PopDens)$$

$$R^2 = 0.62,\quad P \text{ value for equation} = 0.000,\quad T = 32 \tag{4}$$

Now the income elasticity is similar to that on the historical studies, but not so precise. The Box–Cox test strongly rejected the linear in favor of the log linear or constant income elasticity ($\chi^2(1)=19.43$, $\chi^2(1)_{critical}=3.84$). Thus, the three estimates (Eqs. (2)–(4)) provide some support for the income elasticity patterns from the historical data as shown in Fig. 10.

Population density is not the only variable that might influence fuel consumption across time and heterogeneous countries. Many other variables have been considered in the numerous studies that have been done including variables relating to urbanization, female labor force participation, industrial production, seasons, weather, family demographics, price of transit, price volatility, price or availability of public transit, speed limits, income distribution, and fuel efficiency standards. Future work could look for patterns in the historical databases relating to such variables as well as designing research programs to confirm any patterns found.

I was unable to reproduce any statistically significant results using binary variables for the different gasoline price ranges in each equation using the categories in Fig. 2. However, price elasticity becomes more responsive in the equations as countries get richer in Eqs. (2)–(4), repeating the earlier pattern. The demand price response in the three equations on strict cross-sectional data are more elastic than those suggested by the historical data, which are dominated by time series. In all three cases, the price elasticities tend to be more elastic than those in the last section. I see this same pattern in the whole DEDD-G2010.xls database. The median price elasticity (-1.02) from static non-stock models on strict cross-sectional data (98 elasticity estimates) is more elastic than median price elasticity (-0.30) on data from annual time series and cross-sectional time series (294 estimates). Since high price countries often have other policies to discourage gasoline consumption, I suspect that such policies might show up as higher price elasticities in strict cross-sectional data. Further work could be done to investigate this hypothesis. Although price level seems to influence the price elasticity as discussed above, I was unable to find any systematic pattern between the gasoline price level and income elasticity.

Based on the statistical testing above, I create the missing gasoline income elasticities by country shown in column 7 of Table 1. In each case, the bold numbers are derived from historical studies by country in DEDD-2010.xls. If no reasonably consistent historical estimates are available for a country, I apply the following prior from the equations shown in Fig. 10:

$$\varepsilon_Y = 1.26\ \forall\ Y/Pop < \$11{,}800$$
$$\varepsilon_Y = 1.94 - 0.000055Y/Pop\ \forall\ \$11{,}800 < Y/Pop < \$26{,}000, \text{ and}$$
$$\varepsilon = 0.66\ \forall\ Y/Pop > \$26{,}000 \tag{5}$$

A number of countries have had recent policies that favor an alternate fuel over gasoline that might not be reflected in the historical estimates in DEDD-G2010.xls. I identify countries where policies seem to have caused fuel shifting by examining historical highway transport fuel consumption data from International Energy Agency (2010a) since 1990. The countries identified with the most dramatic shifts away from gasoline are as follows: Algeria, Argentina, Austria, Belarus, Belgium, Colombia, Côte d'Ivoire, France, Italy, Latvia, Libya, Macedonia, Malta, Norway, Poland, Spain, Sweden, UK, and Uzbekistan. To determine how much to reduce these income elasticities, I experiment with simple regressions on time series using a static model and logged variables with gasoline consumption for road transport on GDP and price on data from 1990 to 2007. If diesel price is not available, the price of crude oil from BP (2010) is used. Price was only retained if the coefficient was negative. The results from these simple estimates compared to those derived from DEDD-2010D.xls suggested that the income elasticity on more recent data is smaller by a median difference of 1.64. Thus I reduced these countries gasoline income elasticities by 1.64 as shown in column 10 of Table 1. More often the switching for these countries is towards diesel fuel except for Algeria, Argentina, Belarus, and Uzbekistan where the switch appears to be towards natural gas. For Poland the switch seems to be towards diesel and natural gas. Countries with lesser switching away from gasoline are: Bulgaria, Chile, Croatia, Denmark, Ethiopia, Finland, Germany, South Korea, Lithuania, Luxembourg, Morocco, Portugal, Slovakia, Slovenia, and Turkey. The income elasticities from simple regression estimates on these countries compared to those derived from DEDD-2010 suggested that the income elasticity on more recent data is smaller by a median difference of 0.53. Thus, I reduced these countries gasoline income elasticities by 0.53, again shown in column 10 of Table 1. Again more of the countries appear to be switching towards diesel. Germany appears to be switching towards biodiesel, Bulgaria towards natural gas, while some countries are switching towards diesel along with natural gas and/or bio-fuels: South Korea, Lithuania, Portugal, and Slovakia. Brazil is an exception with a larger income elasticity for gasoline since 1990. Presumably this switch towards gasoline with its mandated 25% ethanol blend is reflecting this fuel policy in Brazil, and I increase its gasoline income elasticity by 0.53.

Next I consider income elasticities of diesel demand. There are far fewer estimates of income elasticity on static models for diesel demand than for gasoline. The histogram of the income elasticities are shown in Fig. 11. The median income elasticity is very near the mean at 1. Half of the income elasticities are between 0.85 and 1.31. There are very few estimates on stock models and on data with frequency less than a year, nor did the means and medians vary much between stock and non-stock models and between estimates on annual versus more frequent data so these estimates were not excluded from the statistical analysis.

I consolidated multiple estimates per study and per country and removed two implausible negative income elasticities leaving 23

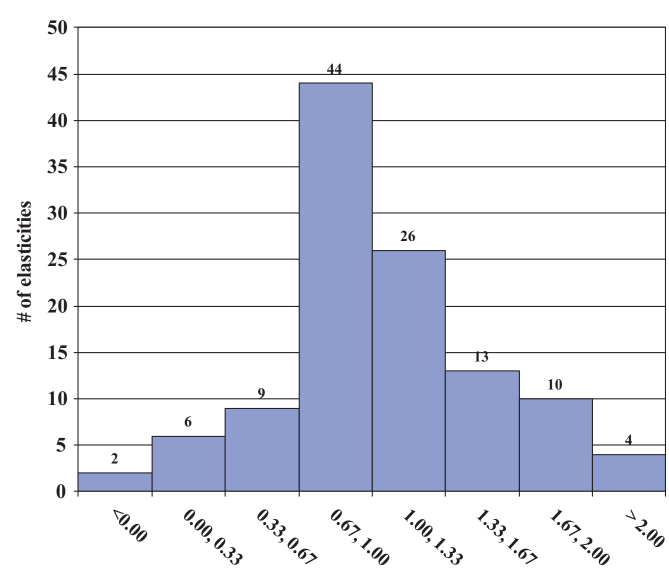

Fig. 11. Frequency of diesel income elasticities from static models.
Source: Compiled from data in DEDD-D2010.xls, 2010.

estimates. Regressing these 23 diesel demand income elasticities for 23 countries on income per capita (created by averaging income per capita for the first and last year of the sample for each estimate), I get the results in Eq. (6). I also plot these elasticities against 2006 income per capita in Fig. 12:

$$\varepsilon_y = \underset{(10.15)}{1.34} \underset{(-1.37)}{-0.000018} \ln \frac{Y}{Pop}$$

$$\quad [0.00] \quad [0.18]$$

$$R^2 = 0.08, \quad P \text{ value for equation} = 0.18, \quad T = 23 \tag{6}$$

The overall fit is imprecise for this small sample, but there is a faint suggestion that the income elasticity of diesel demand may fall as income increases. I do not see any leveling out of income elasticity at higher incomes, which may be because my highest income per capita is less than $24,000. The average income elasticity for the sample is 1.23. Unlike for gasoline, I was unable to provide any verification of this result on my 2006 strict cross-sectional data. On the strict cross section, I found an estimated income elasticity below 1 with no evidence it fell at higher income levels.

I proceeded to do my own estimates on recent time series on data for 1990–2007 by major world region using data from IEA (2010a, 2010b) and Maddison (2008). Many yielded surprisingly similar income elasticity point estimates to the intercept in Eq. (6). These income elasticities, which are all significant at less than a 1% level, are as follows: 1.36 for North America, 1.35 for Africa, 1.36 for the Middle East, 1.32 for non-OECD Asia excluding China, and 1.35 for non-OECD Europe plus non-Russian Former Soviet Union. Based on these new estimates and the low significance of the income elasticities in Eq. (6), I assume a constant income elasticity of 1.34 as the default value where no DEDD-2010.xls historical estimates are available.

In OECD Europe, the estimated income elasticity of demand for diesel fuel for 1990–2007 is 1.79. I believe this higher elasticity reflects the policy and technology shift in favor of diesel cars. To adjust, I change the income elasticity for diesel fuel to 1.79 for those European countries that appear to have policies that have noticeably shifted fuel consumption towards diesel fuel. Simple regressions also suggest that China, Russia, and New Zealand may have had higher diesel demand income elasticities and I adjust their

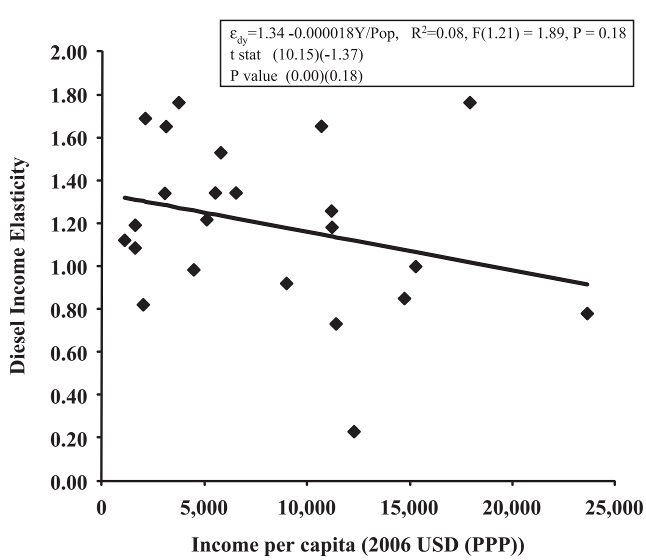

Fig. 12. Plot and estimate of diesel fuel income elasticities at different incomes. *Source*: Elasticity derived from data in DEDD-D2010.xls (2010) and Maddison (2008).

elasticities to this higher 1.79. All these adjusted diesel demand income elasticities are in column 11 of Table 1. The estimated income elasticity is slightly higher at 1.48 for Latin American. Two countries within this region appear to have policies that favor diesel, Colombia and Chile. I use the higher 1.79 for them but the 1.34 default for the rest. The only other regional diesel anomaly, estimated on the more recent time series diesel data, is an unusually low diesel demand income elasticity for the OECD Pacific of 0.88, again significant at less than a 1% level. This low income elasticity for diesel is considerably below that for other regions, which could be the result of Japan and Australia being islands and Korea being a peninsula with better access to coastal shipping. The perception that diesel engines are smelly and noisy along with more stringent emission regulations on hydrocarbons and NO_x from diesel engines in Japan than in Europe coupled with the popularity of hybrids may help explain this low diesel growth in Japan. (Daily Yomiuri Online, 2010) Historical income elasticities in DEDD-D2010.xls also reflect a smaller income elasticity for Japan as well as Australia and so no adjustment is made. Korea's higher income elasticity from the DEDD-D2010.xls is lowered to the more recent regional estimate regional average of 0.88.

One last caveat about all my developed price elasticities is that they are assumed to be symmetric to fuel price increases and decreases. A few studies have explicitly investigated whether such an assumption is supported empirically. The most common and comparable way to investigate such a hypothesis is some permutation of decomposing the price series into three series following Traill et al. (1978): the maximum historical price series – *Pmax*, the cumulating series of price cuts – *Pcut*, and the cumulating series of sub-maximum price recoveries – *Prec*. The expectation is that the response to price increases, particularly those above previous maximums will have a larger effect than price cuts.

I have found seven studies that have considered asymmetric price response for gasoline demand, diesel fuel demand, highway fuel demand or transport oil demand using variants of the above price decomposition. Unfortunately none are comparable to the static models I have chosen for my estimates. Two use oil price instead of gasoline or diesel price and most of the estimates from all the studies are on dynamic models.

Gately and Streifel (1997) include estimates for gasoline demand for 33 developing countries using the price of crude instead of the price of gasoline and an income variable. They consider a variety of models including models with asymmetric price response and pick a preferred model. They find an asymmetric model is preferred for only 5 of the 33 countries, all on lagged endogenous models that allow a different lag on price than income. For all five of these countries, the coefficient on *Pmax* is negative and significant but the coefficients on *Pcut* and *Prec* are not significant for four of the five. Only for one country are the *Pcut* and *Prec* coefficients significant, but they are unexpectedly more not less elastic than the coefficient on *Pmax*. Gately (1991, 1992) consider various combinations for the three price series on US gasoline data using the price of gasoline and income on dynamic models. The evidence is a bit mixed with no statistical testing but there is the suggestion that the *Pmax* elasticity is largest in absolute value (about 30% above that for a symmetric model), followed by the *Prec* elasticity (about 10% below the symmetric estimate) with the *Pcut* elasticity the lowest (about 55% of the symmetric estimate).

Only Gately and Streifel (1997) consider asymmetry of price response for diesel fuel. They find an asymmetric model preferred for only eight of their 33 developing countries using the price of crude oil instead of the price of diesel fuel. Their model of choice is static in price with demand adjusting to price within one period but constrains the income adjustment to follow a lagged endogenous process. Again the evidence is mixed. For one country, the coefficient on *Pmax* is negative and significant at a 5% level, while the coefficients on *Prec*, and *Pcut* are about 1/2 and1/4 as responsive. For two of the countries, the coefficient on *Pmax* is negative and significant but the coefficients on the other two series are not significant. For 5 of the countries, the coefficients on none of the series are significant.

A few studies aggregate highway fuels together and test for asymmetry. Dargay and Gately (1997) use a lagged endogenous model for the sum of highway gasoline, diesel, and Lpg with the price of gasoline and income. They specifically test but do not reject the null hypothesis that the elasticity on *Prec* and *Pcut* are equal for a cross section time series of 11 OECD countries/regions using a lagged endogenous variable. They find the long-run price elasticity of *Pmax* (-0.6) about four times as large as the elasticity on *Prec* and *Pcut* (-0.13).

To compare Dargay and Gately's to my price elasticity estimates, note the long-run price elasticities in dynamic models are typically about 60–100% larger than the price elasticities of static models. If I adjust the median static price elasticities for gasoline and diesel fuel in DEDD-G2010.xls and DEDD-D2010.xls with the median long run elasticities and take a global fuel weighted average, I get a price elasticity of -0.64, rather near the estimate in Dargay and Gately (1997).

Dargay (1990, 1992) aggregate highway gasoline and diesel fuel and uses a weighted average of their prices and income with an error correction model on data for France, Germany and the UK. She finds the elasticity of *Pmax* more often larger in absolute value than the elasticity for *Pcut*, but more often of similar magnitude to that for *Prec*. However, for the UK the elasticities of *Pcut* and *Prec* are similar. Gately (1993) finds mixed results on total transport oil demand for the US and Japan using a polynomial distributed lag on the real price of oil. He finds little short run price response for any of the series with *Prec* seeming to have the largest long run elasticity for the US, but *Pcut* having the largest long-run elasticity for Japan.

Although the evidence is mixed across these studies, and they are too non-comparable to make any adjustments to my price elasticities in Table 1, my hesitant overall impression is that *Pmax* is likely to have the highest elasticity, which is perhaps 10% more elastic but could be up to 30% more elastic than estimated symmetric elasticities. The elasticity for *Prec* is likely less elastic than that for *Pmax* and may be near or slightly below the symmetric elasticity. The elasticity for *Pcut* is likely the least elastic of all. Clearly more work could be done to try to better quantify any asymmetric effects in price response.

4. Summary, conclusions, and suggestions for further work

This paper builds upon the work of hundreds of researchers over the decades, whose challenge has been to estimate price and income elasticities for transport fuel. My contribution has been to search for patterns within this work, to develop price and income elasticities by country, and to indicate the topics that my investigation of this heterogeneous work suggests for future research.

I developed a 2006 database for over 100 countries that included prices, price elasticities, income per capita and income elasticities for gasoline and diesel fuel used for highway transport. Where I had historical estimates of price and income elasticity for individual countries, I used them. Where I did not, I used the priors developed from the historical studies. I found a number of interesting patterns to form my priors that I used to develop price and income elasticities. With statistical testing, I found that price elasticities were higher at high prices for both gasoline and diesel fuel, were higher at higher income per capita for gasoline but lower at higher income per capita for diesel. The gasoline price elasticities developed from historical studies, ranged between -0.11 and -0.33, while those for diesel fuel ranged between -0.13 and 0.38. I encourage more work to determine whether these same patterns hold on more recent data using homogeneous models.

Income elasticities seem to fall from lower to higher income per capita for gasoline. The developed income elasticities ranged between 1.26 and 0.66. Since comparisons with regressions on my 2006 data set generally supported these elasticity patterns, I used these patterns to develop income elasticities where existing historical estimates have not been found.

I suspect the same may be the case for diesel fuel, but the diesel studies were more limited and statistical evidence to support this conjecture weak. The historical studies suggested a rather high income elasticity of 1.34. Such a high elasticity was not supported by simple regressions on my 2006 cross section of data, but was generally supported by simple time series estimates on regional data from 1990 to 2007. I encourage more work using functional forms that allow a declining income elasticity with increased income per capita to tests these conjectures for both fuels on as large a database of countries as possible.

Technical changes along with numerous country policies have encouraged fuel switching, most often away from gasoline toward diesel fuel, but sometimes towards natural gas or biodiesel. These policies substantially changed demand patterns. I was not able to find consistent evidence of cross-price elasticities to measure the effect of these policies. I found some evidence that gasoline might be more price elastic and adjusted price elasticities accordingly, but I did not find a consistent effect on diesel price elasticities. The most consistent statistically measured fuel switching response to the policies tended to be through the income elasticity with gasoline income elasticities becoming low or even negative and diesel income elasticities increasing. Again I adjusted the elasticities to reflect the statistical evidence. Future work should be done to identify better proxies to reflect these policies as well as technical changes by country to quantify their effects by country.

Two important points that might be biasing the price adjustment down should be further investigated. First, I have assumed that the price elasticities from static models can be considered long-run, following the more recent time series interpretation. However, most of the historical work has not specifically tested for co-integration to support this conjecture. Further, the historical modeling that allows estimation of both long and short run typically finds a more elastic response. Median price elasticity estimates on non-stock models in DEDD-G2010.xls and DEDD-D2010.xls find long-run price estimates to be about 50% and 100% higher than those from static models for gasoline and diesel fuel, respectively. New work should be done to resolve this discrepancy and determine whether one model type or the other more accurately reveals long-run response.

The second issue is that of an asymmetric price response. If price increases are increasing to levels higher than previous maximums, the price response might be up to 30% greater than estimates on models assuming a symmetric response. Here again, more work might enlighten us as to whether a price elasticity adjustment should be made depending upon whether the price change is a cut, a recovery or an increase above any previous levels.

Work should also be done to look for other fuel consumption drivers including demographics, prices and availability of substitutes and complements, weather, technical change and fuel policies in the historical database as well as to verify any patterns revealed with well designed research projects.

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