

HOW FAST WILL JET FUEL CONSUMPTION RISE?

By

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ABSTRACT

Jet fuel consumption accounts for a growing amount of greenhouse gas emissions and continues to rise with globalization. Due to its increasing share of greenhouse gas emissions, aviation has been thrust into the spotlight as an industry with the potential to abate carbon emissions. Despite collaborative intentions, many countries cannot come to an agreement for aviation standards and greenhouse gas reduction targets. In projecting jet fuel consumption levels in 2030 and 2050, I hope to create the basis upon which discussions for setting jet fuel consumption policy can begin.

I use data on oil prices, income per capita, and population to create a model to estimate expected jet fuel consumption while accounting for various stages in economic development. I find that income elasticities for jet fuel consumption are highest in the poorest countries, with the most inelastic demand occurring in the 7,000 to 15,000 GDP per capita range. My research predicts jet fuel consumption levels in 2030 and 2050 will be 39.65% and 95.06% greater than 2013 jet fuel consumption levels, respectively.

KEYWORDS: Jet fuel consumption, Greenhouse gas emissions, Aviation, Forecasting

THE TRANSPORTATION SECTOR has been one of the fastest growing sectors of greenhouse gas emission contributors in the United States, comprising of around 27% of all U.S. greenhouse gas emissions in 2015 (EPA, Sources of Greenhouse Gas Emissions). The emissions derive from burning fossil fuels to power vehicles such as cars, trucks, ships, trains, and airplanes, and more than 90% of these fuels are derived from petroleum (EPA, Sources of Greenhouse Gas Emissions). Within the transportation sector, the majority of greenhouse gas emissions come from passenger cars and light-duty trucks, however, jet fuel consumption has

dramatically increased its share of the pie. In 2016, jet fuel consumption by aircraft was responsible for 12% of all U.S. transportation greenhouse gas emissions and 3% of total U.S. greenhouse gas emissions across all sectors (EPA, Regulations for Greenhouse Gas Emissions from Aircraft).

With increasing globalization, the demand for aviation continues to rise to meet needs for passenger travel and international trade through air cargo. With declines in the real cost of air fares and increasing non-stop flights, the demand for passenger travel has risen dramatically (IATA, Annual Review 2016). However, increased flying and jet fuel consumption comes at a cost. The University of Reading warns of the potential for increased turbulence by as much as 170% by the end of the century and 40% stronger turbulence, due to instability in the jet stream¹ due to climate change (Williams 2017). This would result in longer journeys, increased jet fuel consumption, and thus higher ticket prices. In terms of its carbon dioxide contribution, approximately 3 kilograms of CO₂ are produced per kilogram of jet fuel burned directly (Barrett 2013). Since these emissions are occurring at a high altitude, there may be even more complex impacts on the environment (Barrett 2013).

Aviation regulation also plays a significant role in jet fuel consumption. Along with safety regulations, there are environmental standards that focus on the negative externalities associated with flying, such as noise, air quality, and climate impacts. The U.S. House of Representatives passed the American Clean Energy and Security Act of 2009, which is predicted to curtail jet fuel consumption emissions between 2012 and 2050 (Winchester et al. 2013). Internationally, countries initially agreed to reduce carbon dioxide emissions under the Kyoto

¹ Jet streams are narrow, high-altitude bands of strong wind in the atmosphere. The winds blow west to east and the streams stay within boundaries of hot and cold air. The strongest winds in jet streams are close to the core of the jet stream, similar to a river (National Weather Service, The Jet Stream).

Protocol in 1997 for implementation in 2005 (UN Framework Convention on Climate Change, Kyoto Protocol 2013). The 2016 Paris Agreement, similarly to the Kyoto Protocol, supported the efforts of ICAO as the means to push international aviation carbon dioxide emission abatement (UN Framework Convention on Climate Change, The Paris Agreement 2017). In this agreement, the countries would collaborate through the International Civil Aviation Organization (ICAO) to determine an international regulation for jet fuel consumption emissions (Meltzer 2013). The International Civil Aviation Organization (ICAO) is a United Nations specialized agency that works with 191 member states to determine civil aviation Standards and Recommended Practices (SARPs) (ICAO, About ICAO 2014). 102 of ICAO's member states have submitted an action plan for reducing aviation carbon dioxide emissions (ICAO, Climate Change: Action Plans and Assistance 2017), however ICAO has been largely unsuccessful in implementing an international standard.

Due to the lack of efficacy in ICAO, the European Union included carbon dioxide emissions from aviation in the EU's emissions trading system (ETS) in 2012 (Meltzer 2013; European Commission: Climate Action, Reducing Emissions from Aviation 2017). This regulation had been limited to the European Economic Area (EEA) prior to 2016, but now extends to the entire European Union (European Commission: Climate Action, Reducing Emissions from Aviation 2017).

The efforts to reduce carbon dioxide emissions from aviation could result in a decreased demand for jet fuel. New technology, such as more efficient or cleaner jet fuel, would lead to a reduction of petroleum-based jet fuel consumption demand. While there is research being

devoted to discover new drop-in² jet fuels that are more environmentally friendly through other fossil sources and biomass, there are many barriers to both invention and implementation (Barrett 2013). In terms of invention, jet fuels must meet thermal stability and freezing point thresholds to avoid thermal deposit build-ups in the hot parts of the aircraft and avoid freezing at the high altitude during flight (Barrett 2013). With implementation, the new jet fuel alternatives may require other technological changes or updates in the aircrafts or fueling stations. With an average service lifespan of 30 years, aircraft fleets are slow to adopt new technology (Barrett 2013).

With the discussions regarding climate change policy and the inclusion of aviation in the carbon emission reduction targets, it is critical to understand the projected global jet fuel consumption demand as a basis for setting future policy. The intention of this research is to create a model that can predict the jet fuel consumption for a country to 2030 and 2050. I hope that this research can be helpful in setting policy on a country to country basis and act as an encouragement in investments to appropriately control fossil fuel consumption. This paper does not intend to recommend jet fuel consumption reduction policies for any countries within the dataset nor an international standard.

I utilize a model of projecting jet fuel consumption per capita through income per capita and oil prices, serving as a proxy for jet fuel prices. In my research, I consider the population of countries as a means to weight the importance of observations and create five income per capita levels to further identify trends within the data. Jet fuel consumption by country was pulled from the U.S. Energy Information Agency (EIA), while GDP per capita and population numbers used

² Drop-in jet fuels are fuels that can function in the current aircrafts and fueling infrastructure in operation. Drop-in jet fuels typically must meet Jet A fuel type specifications. Essentially, drop-in jet fuels are the most readily adoptable form of jet fuel alternatives (Barrett 2013).

were from the World Bank World Development Indicators (WDI) and supplemented with data available from the United Nations Conference on Trade and Development (UNCTAD) Statistics Data Center.

I find that very poor countries experience high income elasticity for jet fuel consumption and the elasticity falls with increasing GDP per capita after the 15,000 GDP per capita mark. Given that developing economies have the most inelastic demand for jet fuel consumption, it would be helpful to consider the usage breakdown for jet fuel consumption and the country's GDP per capita level in order to fairly implement regulations for greenhouse gas reductions.

The goal of this research is to create a prediction model for jet fuel consumption levels per capita per country to 2030 and 2050, as a precursor to discussions for aviation regulation regarding greenhouse gas emission reduction. I find that global jet fuel consumption will increase by 39.65% and 95.06% in 2030 and 2050 over 2013 jet fuel consumption levels.

I. RELATED LITERATURE

There has been much research investigating the relationship between GDP growth and energy usage. In Medlock and Soligo (2001), they use 28 countries to determine energy use by end-use sector at various levels of development. The study mentions consumer activity rising with per capita income increases, specifying consumer durables such as housing appliances and transportation, up to a certain saturation point. However, the only transportation that the study focuses on is automobiles.

Further research has been conducted investigating the relationship between the growth of GDP per capita and car ownership, inclusive of observable factors such as the saturation of a country, the population density, and the level of urbanization. Dargay, Gately, and Sommer

(2007) discuss a model they have constructed to predict vehicle ownership levels in each country. The premise behind the study is that poorer countries today will follow a similar pattern of economic growth and vehicle ownership levels as richer countries, which have already grown through the stages that are currently being experienced by poorer countries. While this research is not specific to jet fuel, it highlights the relationship between income growth and discretionary spending, which is the basis for my research model.

There has been a lot of research conducted on transportation and airline energy demand in the United States. While investigating the U.S. transport sector's demand for energy, Uri (1982) discusses a rapid growth in jet fuel consumption since 1965 due to increased air travel. Jet fuel expenditures accounted for 2% of the U.S. transport sector's energy expenditures in 1965 and grew to 6% by 1975 (Uri 1982). Uri (1982) estimates the U.S. demand for jet fuel through a model including per capita income, the price of jet fuel, and an exponential trend variable to account for the dramatic increase in jet fuel demand. The study finds that jet fuel consumption demand is related to energy prices and overall economic activity. A limit to this study includes the time series of the data being only 14 years between 1964 and 1978. Cigliano (1982) models jet fuel demand by domestic trunk airlines or passenger airlines within the United States through jet fuel price, proportion of output³ generated by second generation jet transports⁴ in the airline's fleet, and the average flight length in miles for all aircraft types in a certain airline's fleet. Jet fuel demand by U.S. trunk airlines was found to be relatively price inelastic (Cigliano 1982). Using

³ Output was defined as total production available in ton-miles generated by the airline in all of its domestic route markets.

⁴ Jet transports provide the take-off thrust for airplanes. This variable is an explanatory variable that helps to account for the technological change in the 1950's that resulted in the invention of the high bypass turbofan engine. The high bypass turbofan engine resulted in the creation of the second generation of commercial jet transports, which had twice the take-off thrust as the first generation of commercial jet transports. The technology was largely implemented between 1971 and 1979, and so this variable helps to explain the transition to a more efficient commercial jet transport.

passenger miles per person, fleet efficiency, air ticket prices, and gross national product growth, Gately (1988) shows still increasing jet fuel demand in the United States.

In terms of technology that could be implemented by countries, there has already been research on renewable jet fuel. Jet fuels are hydrocarbon blends and have the potential to be synthetically made as current research suggests alkanes can be constructed in a laboratory. In fact, the possibility of renewable jet fuels is growing the most rapidly out of all of the potential renewable fossil fuels (Kallio, Pásztor, Akhtar, and Jones 2014). Subsequent research on climate policies and its impact on jet fuel consumption, such as using biofuels has been conducted, however the impacts of using biofuels as a substitution or partial substitution for jet fuel are not certain (Hochman, Rajagopal, and Zilberman 2011).

One might expect that current developing countries may also benefit from technological change, such as jet fuel alternatives, that is available today but was not in the past. With this technological change, developing countries have access to technology that allows for more efficient energy levels per capita than developed countries had access to during the same economic growth period in the past. While research on this has not been conducted specifically on jet fuel consumption, this study concludes that developing countries do not jump to a lower-carbon economy in the energy sector on a macro level even with access to technological advancements (van Benthem 2014).

There has also been research conducted on the impact of climate change policy on aviation. The U.S. House of Representatives passed the American Clean Energy and Security Act of 2009, which is predicted to curtail jet fuel consumption emissions to a 103% to 123% increase versus a 130% increase without the climate policy between 2012 and 2050 (Winchester et al. 2013). However, Winchester et al. (2013) also finds that due to the high costs of abatement

in the aviation sector, it is more efficient for the airlines to fund abatement in other sectors than to reduce emissions themselves.

This paper aims to further the literature from Uri (1982) through the application of a longer time frame and implementation of weighted observations and analysis of subsets of the data by five bands of different income per capita levels. Following the premise of Dargay et al. (2007), this research will utilize historical observations of jet fuel consumption of developed countries today as a means of projecting future jet fuel consumption demand for current developing countries.

II. METHODOLOGY AND DATA

I followed a similar means of data analysis as Dargay, Gately, and Sommer (2007) in their paper “Vehicle Ownership and income Growth, Worldwide: 1960 – 2030”. Dargay et al.’s model (2007) predicted the long-run equilibrium level of vehicle ownership as a function of GDP, through per capital income, a country’s saturation levels and income elasticity. The premise behind the study is that poorer countries today will follow a similar pattern of growth and therefore pattern of vehicle ownership levels as richer countries, which have already grown through the stages that are currently being experienced by poorer countries.

I constructed a model based on observable country characteristics such as GDP per capita and population in order to predict jet fuel consumption per capita. GDP per capita influences jet fuel consumption as an item for discretionary spending. Population also provides the means to control for jet fuel consumption levels by calculating it on an income growth per person basis. By regressing GDP per capita on jet fuel consumption per capita, I estimate the elasticity at which jet fuel is demanded at various levels on income. Jet fuel prices should also be included in

the analysis, as the cost of a discretionary good will influence the amount of a good consumed.

With an increase in jet fuel price or the cost of any discretionary good, there should be a decrease in the demand for the good. Since taxes and subsidies have various influences on jet fuel prices globally and jet fuel prices may vary regionally, I use oil price as a proxy for jet fuel prices. Oil prices serve as a good proxy for jet fuel prices, as jet fuel is a petroleum product and therefore is refined from crude oil. As the raw material base for jet fuel, crude oil prices should follow similar fluctuations as jet fuel prices.

As my research is focused on jet fuel consumption per capita in countries and not on the number of airplanes demanded or fleet count per country, I did not include data such as urbanization, population density, number of airports, or passengers per aircraft in my analysis. This research is focused on jet fuel consumption from an energy perspective, not an industry angle.

The impact of technology should be considered, since the aim of the study is to project out jet fuel demand in around 15 to 35 years and technological change can aid in reducing jet fuel demand through the use of biofuels and hybrid jet fuels and increase energy efficiency. However, while there have been breakthroughs in aviation technology that have increased the aerodynamics of aircraft, none have made a dramatic enough impact on jet fuel consumption to offset the increasing demand.

GDP per capita at purchasing power parity in constant 2011 international dollars was pulled from the World Bank World Development Indicators (WDI), which covers 1960 to 2016. I used purchasing power parity numbers as they are the standard form of GDP per capita, and they control for how prices for certain goods vary across countries. Therefore, the basket of goods will be different. While GDP per capita at purchasing power parity does have challenges

such as determining the basket size and goods, it still provides a means of better international comparisons (van Benthem 2014). A limitation to using the GDP per capita at purchasing power parity was that the purchasing power parity data had missing values for all countries until 1990, whereas GDP per capita not at purchasing power parity had data values intermittently for many countries starting in 1960.

Population numbers for each country were pulled from the United Nations Conference on Trade and Development (UNCTAD) Statistics Data Center and offer data from 1950 and projects out to 2050. This data was augmented by the World Bank World Development Indicators population numbers, in order to obtain population numbers for territories and small islands.

As a proxy for jet fuel prices, I used the historical oil prices from the BP Statistical Review of World Energy 2016, which date back to 1861 and provides annual prices to 2015. I converted the prices to 2011 US dollars to match the year of the data used for GDP per capita.

I used jet fuel consumption data per country (`jet_fuel`) from the U.S. Energy Information Administration International Energy Statistics. The data is available from 1980 up until 2014 and is in thousand barrels per day units.

I divided jet fuel consumption numbers by population numbers in order to derive jet fuel per capita data (`jet_fuel_cap`). Since jet fuel per capita was in 1000 barrels per day units, I scaled the jet fuel consumption per capita data up by 1000. I utilized time fixed effects to allow for trends, such as technological change, to be accounted for in subsequent observations.

In order to account for the various sizes of countries, I created a term to weight countries by their population (`pop_wt`). The variable `pop_wt` was created by determining the mean

population of each country and using that as the weight for all the observations for that country. This allows countries to influence the regression based on their size rather than equally, which could result in smaller countries potentially skewing the regression.

Additionally, certain countries were also relatively small in population, but had extremely high GDP, resulting in a large GDP per capita. These small but wealthy countries were also typically landlocked, which skewed the regression towards a lower jet fuel consumption than what would be expected. In order to avoid this, very poor and very rich countries were removed from the data set by eliminating observations less than the first percentile and greater than the 99th percentile in the GDP per capita distribution to avoid skewing by the extremities.

I also created dummy variables of income bands of approximately equal size in number of observations to allow countries to exhibit different jet fuel consumption patterns at various levels of development as defined by GDP per capita levels. I created five income bands of GDP per capita levels of zero to 2,000 international 2011 dollars (`inc_band_0_2`), GDP per capita between 2,000 to 7,000 (`inc_band_2_7`), between 7,000 and 15,000 (`inc_band_7_15`), 15,000 to 30,000 (`inc_band_15_30`), and finally GDP per capita above 30,000 (`inc_band_30_above`). I also used these dummy variables to create income banded logarithmic transformations of GDP per capita by multiplying each income band by the log of GDP per capita (`log_gdp_cap`). This allowed me to create variables that could indicate various slopes for observations within the given income band. The smallest GDP per capita income band (`inc_band_0_2`) multiplied by the log of GDP per capita became `log_gdp_cap_ib1`. Each income band progressed as such until `log_gdp_cap_ib5`, for the dummy variable `inc_band_30_above` multiplied by `log_gdp_cap`.

III. ESTIMATION STRATEGY AND RESULTS

Before running regressions, I created scatterplots of jet fuel consumption per capita versus GDP per capita in order to see if there appeared to be any relationship. First, I created the graphs by mapping each country by their jet fuel consumption and their GDP per capita. Figure 1 displays all of the countries that had data available in the categories that I collected, GDP per capita, jet fuel consumption, and population. The countries overall are sloping upwards in a linear fashion, indicating that as GDP per capita increases, the consumption of jet fuel increases, as well. The green data points above 750 thousand barrels per day of jet fuel consumption are data points of the United States. The United States consistently exhibited the most jet fuel consumption per year, at levels sometimes with jet fuel consumption over 1000% greater than the next highest jet fuel consuming country. The lowest this discrepancy in jet fuel consumption has ever been was in 1988, when the United States was using 146% more jet fuel than Russia. Most recently in 2013, China has been steadily increasing their jet fuel consumption levels to become the second highest consumer of jet fuel. Figure 2 shows the same graph as Figure 1, but focuses on a few key countries. Again, we can see a still upwards sloping trend as GDP per capita at PPP rises.

The United States consumes an enormous amount of jet fuel relative to the rest of the world. However, the U.S. jet fuel consumption numbers do not include consumption by the US military and air force. This is due to the US government being blanket exempt from all international climate agreements and thus is not required to publish any data on military greenhouse gas emissions (Lawrence 2014). Therefore, the jet fuel consumption numbers are likely even higher than the ones used in this study.

Figure 1: Log GDP per capita at PPP vs. Log Jet Fuel Consumption

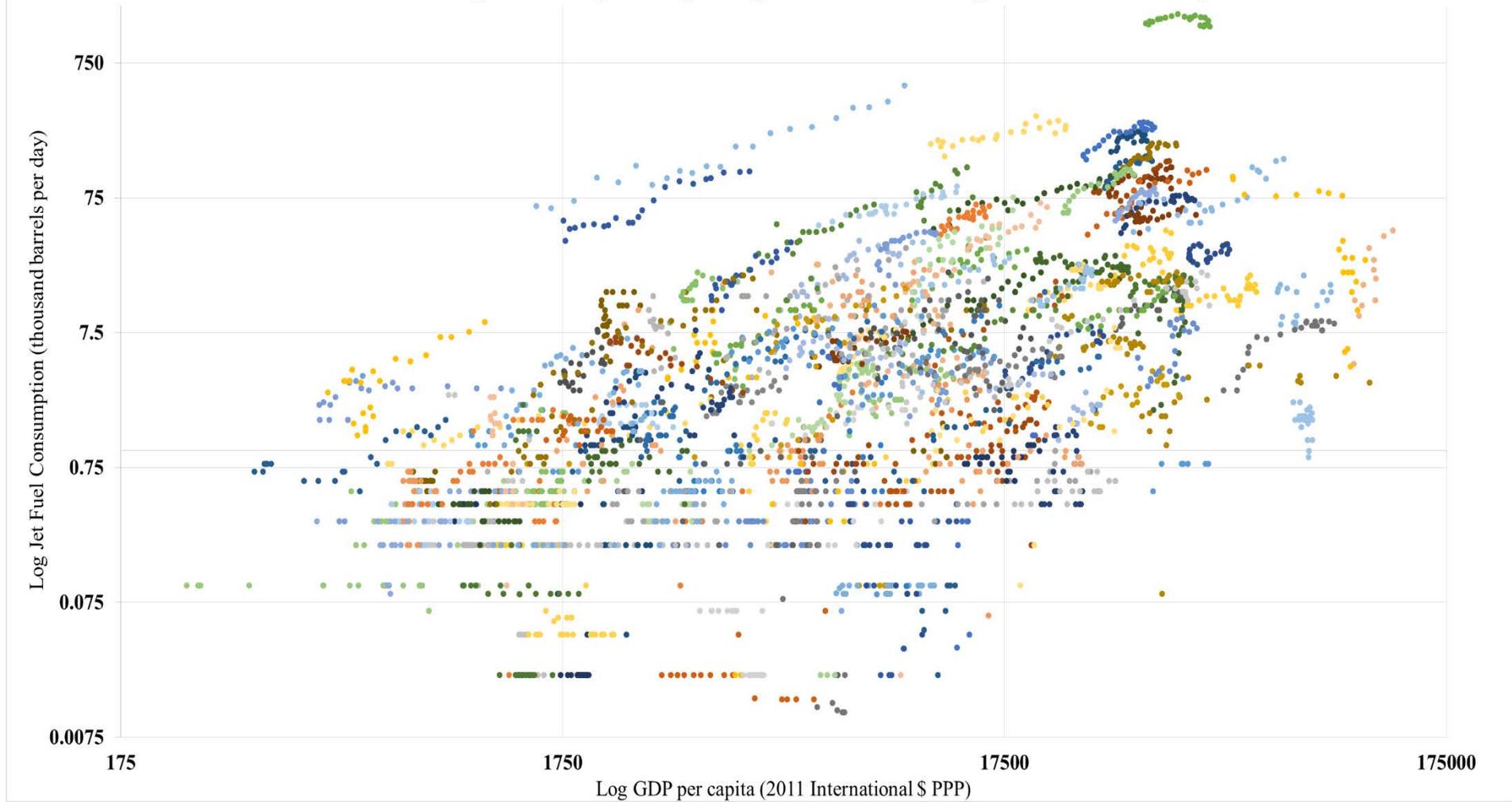
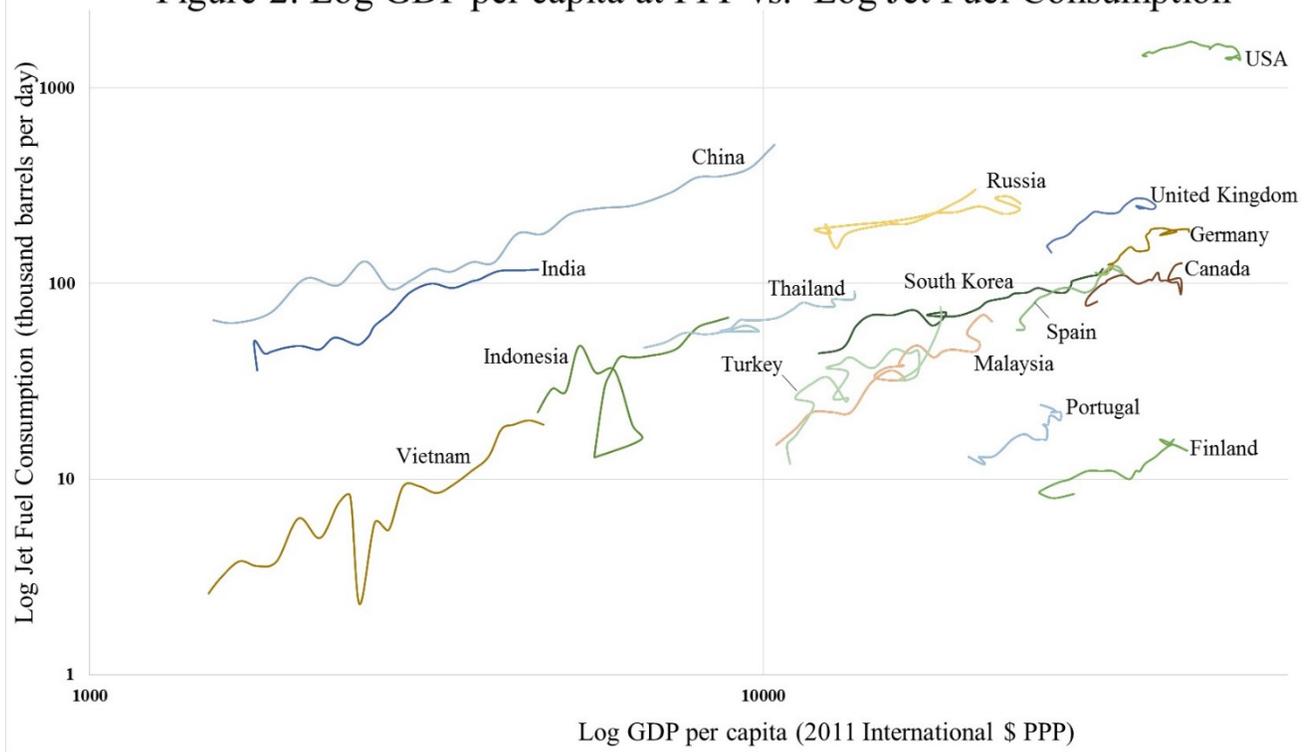
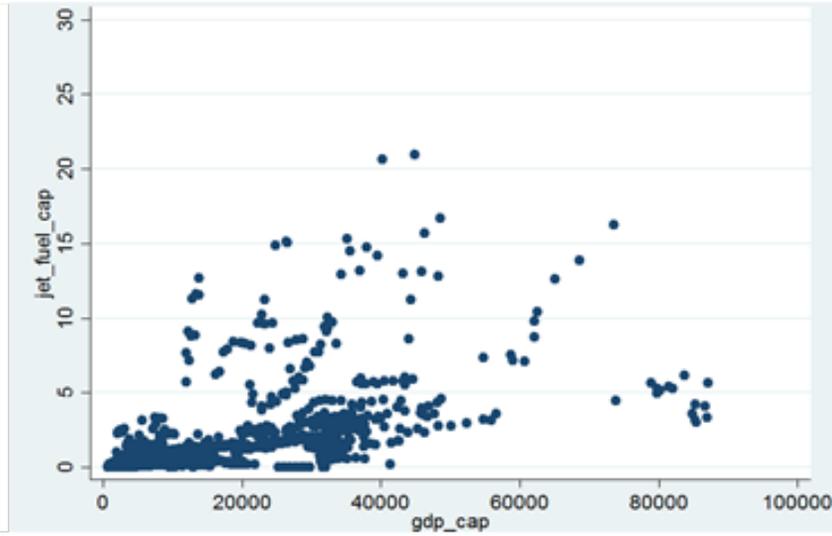


Figure 2: Log GDP per capita at PPP vs. Log Jet Fuel Consumption

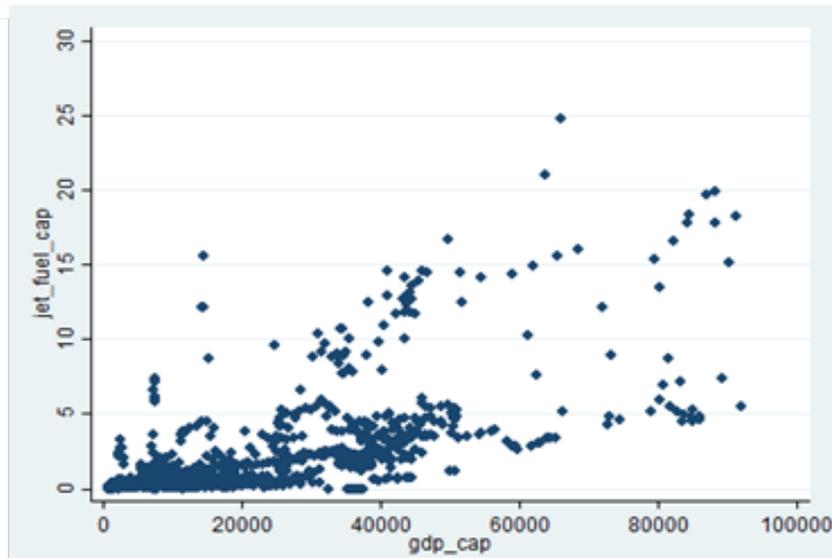


After I was satisfied with the data, I utilized the logarithmic transformed variables in my regressions to facilitate interpretation of the results. Transformed variables allow for a percentage to percentage change in interpretation if there is a relationship between the variables. The first regression was a basic regression that regressed GDP per capita and oil price on jet fuel consumption. It included time fixed effects allow for global annual trends such as aircraft efficiency technology. In the first regression, we see that GDP per capita and jet fuel consumption per capita have a statistically significant relationship, with a 1% increase in GDP per capita resulting in a 0.69% increase in jet fuel consumption per capita. While the regression establishes that there is a relationship, it is not a very precise model, since it fits the data to a linear equation. However, while it is trending upwards as seen in Figure 2 and Figure 4, jet fuel

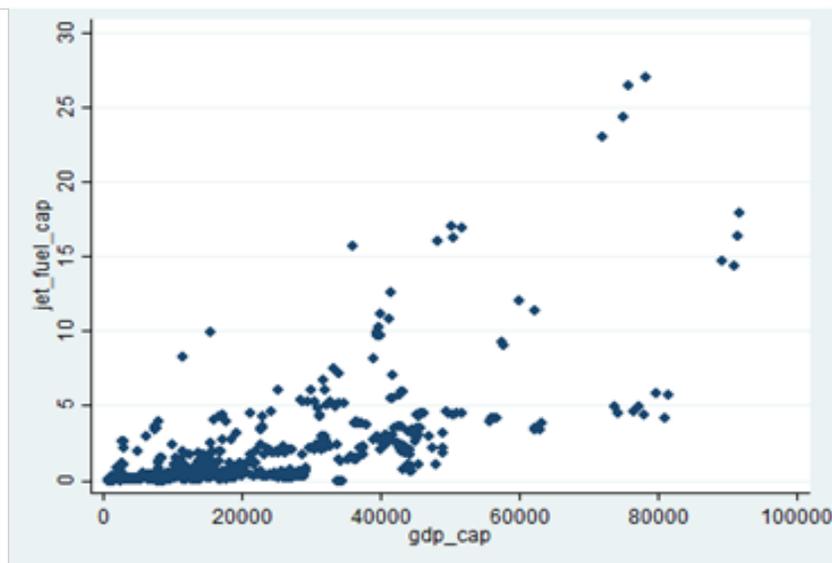
Figure 3A: Jet Fuel Consumption per Capita vs. GDP per Capita in 1990's



B: Jet Fuel Consumption per Capita vs. GDP per Capita in 2000's

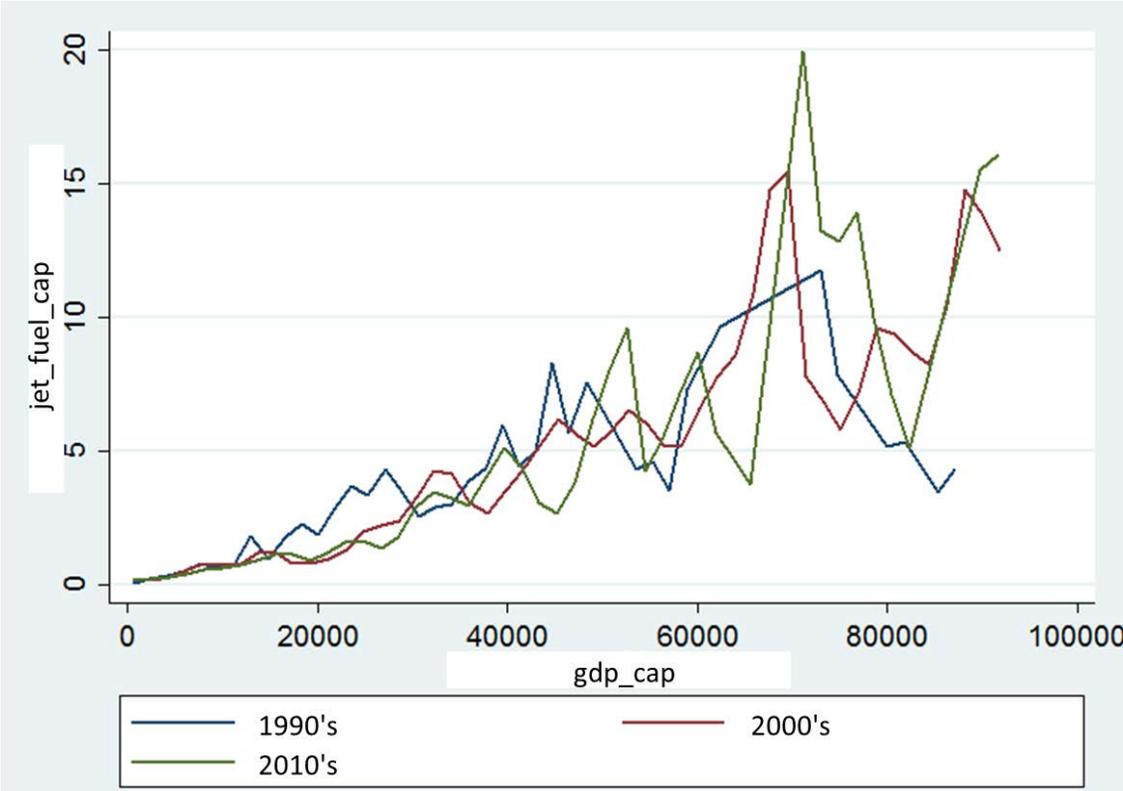


C: Jet Fuel Consumption per Capita vs. GDP per Capita in 2010's



consumption may not be best predicted by a linear regression. Oil price had a negative coefficient, which is expected as an increase in price should deter spending and thus lower jet fuel consumption per capita. However, this relationship was not statistically significant, indicating a weak relationship.

Figure 4: Jet fuel per capita vs. GDP per capita at PPP by decades



Having established a relationship between jet fuel consumption per capita and GDP per capita, I wanted to see if jet fuel consumption could be fitted to a quadratic curve, still accounting for time fixed effects. Thus, I added a squared term of the log of GDP per capita in the second regression in order to test this. The squared term would indicate whether the relationship between per capita GDP and jet fuel consumption was increasing or decreasing. The

Table 1: Regression Results

	log(jfcc)					
	1	2	3	4	5	6
coefficient	-6.90**	-3.63	-14.23	-7.45	-10.80**	-6.51
	(1.38)	(3.55)	(7.82)	(14.51)	(2.22)	(5.44)
log_gdp_cap	0.69**	-0.05	2.52	0.56		
	(0.20)	(0.75)	(1.97)	(2.83)		
log_oilprice	-0.05	-0.09	-0.07	-0.21	-0.02	-0.07
	(0.12)	(0.13)	(0.23)	(0.13)	(0.06)	(0.07)
sq_log_gdp_cap		0.04	-0.12	0.03		
		(0.04)	(0.12)	(0.14)		
inc_band_0_2					4.12	-3.77
					(2.65)	(6.06)
inc_band_2_7					6.82**	-2.59
					(2.54)	(5.63)
inc_band_7_15					6.61**	-4.44
					(3.12)	(5.56)
inc_band_15_30					3.27	-1.03
					(2.83)	(5.30)
inc_band_30_above					Omitted	Omitted
log_gdp_cap_ib1					0.64**	1.05**
					(0.28)	(0.33)
log_gdp_cap_ib2					0.32**	0.88**
					(0.21)	(0.11)
log_gdp_cap_ib3					0.36**	1.10**
					(0.30)	(0.21)
log_gdp_cap_ib4					0.72**	0.74**
					(0.27)	(0.20)
log_gdp_cap_ib5					1.04**	0.66
					(0.24)	(0.54)
number of obs	3,646	3,646	1,940	1,706	3,646	3,646
absorb(country)	175	175	115	96	175	175
cluster(country)	175	175	115	96	175	175
pop_wt						1.40E+08
year	X	X	X	X		
gdp_cap <10,000			X			
gdp_cap >10,000				X		

Note: ** p < .05

Standard errors are clustered at the country-sector level in parentheses.

Dependent variable log(jfcc). "X" denotes time fixed effects and subdividing the data by the specified GDP per capita level.

results of the second regression indicated no statistically significant relationships. GDP per capita actually had a slightly negative coefficient, along with oil price. The squared GDP per capita term was slightly positive, indicating an upwards slope.

In order to better fit the countries in the data, I decided to split the data regression into two parts, less than 10,000 GDP per capita at PPP in international 2011 international dollars and greater than 10,000 GDP per capita. In regression three, I ran the same regression as the second regression, with the time fixed effects and squared GDP per capita term, but with only the observations with GDP per capita less than 10,000 GDP per capita. There were no statistically significant variables, however, GDP per capita was a positive coefficient and oil price was unsurprisingly a negative coefficient. The squared GDP per capita term was actually negative, however, indicating that the slope for countries with GDP per capita of less than 10,000 was downwards sloping. Regression four was essentially the same regression as regression three, however it focused only on the subset of countries that had GDP per capita greater or equal to 10,000. Similarly, the GDP per capita had a positive coefficient although at much more elastic rate than in equation three. Oil price was negative, however the squared GDP per capita term was slightly positive. While none of the coefficients in regression four were statistically significant, there is an indication that after a certain GDP per capita threshold, such as 10,000, the responsiveness of jet fuel consumption per capita to GDP per capita will increase. Regressions three and four indicate that there are differing elasticities of jet fuel consumption at various levels of GDP per capita, and therefore increased flexibility in GDP per capita would be helpful in creating the regression.

In order to allow for increased flexibility at various GDP per capita levels, I created five income bands of nearly equal size in number of observations that included observations with

GDP per capita within the specified income levels. I used these variables in regression five and six.

In regression five, all of the income banded log of GDP per capita variables were statistically significant. At the lowest income level, between 0 to 2,000 GDP per capita, the income elasticity is fairly inelastic with a 1% increase in GDP per capita resulting in a 0.64% increase in jet fuel consumption demand. As GDP per capita grows to between 2,000 and 15,000 international 2011 dollars, the demand for jet fuel consumption becomes fairly elastic with a 1% increase in GDP per capita resulting in a 0.32% and 0.36% increase in jet fuel consumption at the second (2,000 to 7,000) and third (7,000 to 15,000) income bands, respectively. In the highest two income bands, jet fuel consumption becomes fairly inelastic. At above a GDP per capita of 30,000, a 1% increase in GDP actually results in a 1.04% increase in demand for jet fuel per capita. The curve is a moderate “N” shape, indicating increasing demand at the extremities of very poor and very rich countries. This is fairly surprising, since it indicates there is no saturation of jet fuel consumption in richer countries, contrary to other discretionary consumer goods. In fact, even in very rich countries, as income per capita increases, people want to fly more.

For regression six, I ran the same regression as regression five with the various income bands, however, I added the population weighting term (pop_wt). All of the income banded GDP per capita variables except the highest income band (log_gdp_cap_ib5) were statistically significant. When weighted by population, the most inelastic income bands were income bands 1 and 3. Regression six tells an almost opposite story to regression five, with relatively inelastic jet fuel consumption resulting in a 1.05% and 1.10% increase in demand with a 1% increase in GDP per capita within the bands of 0 to 2,000 and 7,000 to 15,000, respectively. At the highest income

band, income elasticity is relatively elastic compared to the other income bands, indicating that demand peters off in richer countries, although this coefficient was not statistically significant.

Weighting the regression by population also led to a substantial jump in jet fuel consumption demand in the poorest three income bands, but particularly the middle income banded GDP per capita between 7,000 to 15,000 international 2011 dollars. This implies that the countries in the middle range of GDP per capita have a fairly inelastic demand for jet fuel consumption in their development. The subsequent decrease in inelasticity at higher income levels implies that there is a certain saturation rate for richer countries where richer countries demand less jet fuel consumption than when they were developing.

The implication for the regression is that jet fuel consumption per capita is demanded the most when countries are growing between 7,000 and 15,000 in GDP per capita at PPP in international 2011 dollars. Jet fuel consumption is also relatively inelastic in very poor countries, and demanded the least in the richest countries above 30,000 GDP per capita.

This is contrary to previous studies on energy per capita, which finds relatively low or elastic income in poor countries, increasing inelasticity between 5,000 to 10,000 GDP per capita, and then a subsequent slowing with increasing income. This creates a sort of S-curve. Jet fuel consumption per capita weighted by population, on the other hand, is relatively inelastic in poor countries up until 15,000 GDP per capita and then drops and becomes increasingly elastic with rising GDP per capita.

This may be due to the globalization trends mentioned earlier. Jet fuel consumption is representative of both passenger travel and cargo flights. Poorer countries are still developing their trade agreements, relying on exports and gradually increasing passenger travel. Countries

with GDP per capita between 7,000 and 15,000 may experience the highest income elasticity (inelastic demand) because these countries are reaching the apex of cargo flights. After the apex, the number of cargo flights levels off and the subsequent demand in jet fuel consumption at GDP per capita greater than 15,000 is due to passenger travel increasing. Many of the countries within the 7,000 to 15,000 GDP per capita range are also islands, resulting in cargo planes representing a critical means of transporting exports and imports.

IV. FORECAST AND IMPLICATIONS

I wanted to forecast global jet fuel demand in order to create a basis upon which climate change policy can be discussed for implementation. I used the last regression (regression 6) to estimate each country's annual jet fuel consumption demand. I used the assumption that oil prices were constant in the long run used Equation 1 to project jet fuel consumption based on GDP per capita. While UNCTAD population numbers are already projected out to 2050, the GDP per capita at PPP numbers from the World Bank WDI only extended to 2015. I projected out GDP per capita for each country using the same income bands that I created in my regression. For the poorest countries, or those with a GDP per capita below 2,000 international 2011 dollars, I applied the highest annual growth rate at 6%. For each subsequent higher income band, I applied a 1% drop in annual growth, as shown in Table 2. The decreasing growth rates with increasing GDP per capita accounted for the stabilization of growth for countries as they exit the high economic growth development stage and become a developed country. As projected GDP per capita increased, the growth rate applied to GDP per capita would fluctuate depending on the income band that the GDP per capita fell in for the given year. In order to find the growth rate of jet fuel consumption per year, the GDP per capita growth rate was multiplied by the beta for associated income band. This was the growth rate for jet fuel consumption in the given year t ,

and so the jet fuel consumption level of the previous year, in year t-1, was multiplied by one plus the multiplied beta to find the jet fuel consumption in year t. In Equation 1, JF_t is the jet fuel

Table 2: Betas and Growth Rates by Income per Capita

	B	GDP min	GDP max	g
log_gdp_cap_ib1	1.05		2,000.00	0.06
log_gdp_cap_ib2	0.88	2,000.00	7,000.00	0.05
log_gdp_cap_ib3	1.10	7,000.00	15,000.00	0.04
log_gdp_cap_ib4	0.74	15,000.00	30,000.00	0.03
log_gdp_cap_ib5	0.66	30,000.00		0.02

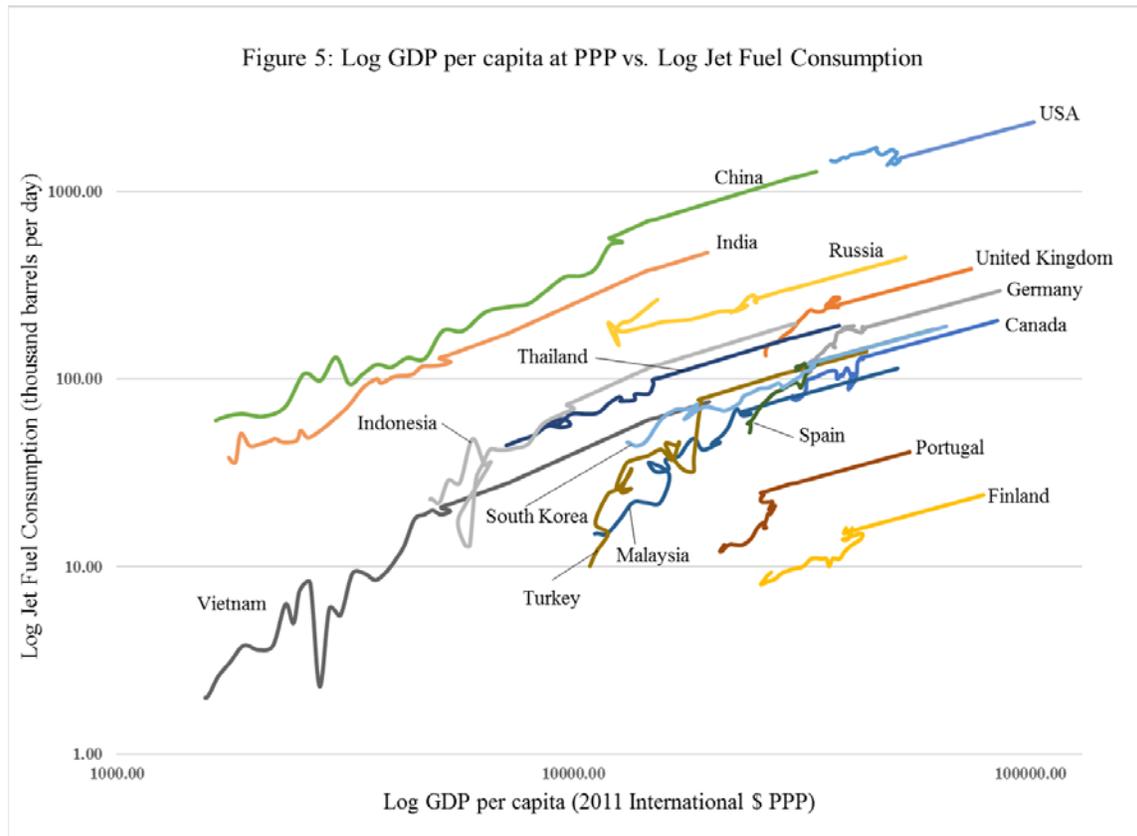
consumed in time t, $B_{\log_inc_band_X_Y,t}$ is the income banded GDP per capita beta associated with the GDP per capita at time t within the income band range of X and Y. The beta is multiplied by $g_{GDP,t}$ or the growth rate associated with the GDP per capita at time t. JF_{t-1} indicates the jet fuel consumption level of the previous year. After determining the annual jet fuel consumption level

$$JF_t = (1 + (B_{\log_inc_band_X_Y,t}) * g_{GDP,t}) * JF_{t-1} \quad (1)$$

for each country, I aggregated the results to determine the world jet fuel consumption demand.

I found that by 2030, jet fuel consumption will rise by 39.65% over 2013 levels, which is the last published jet fuel consumption level without any of my estimations. By 2050, global jet fuel consumption levels are expected to rise to 95.06% of 2013 levels. In terms of income per capita growth, my model has aggregate GDP per capita in 2030 rising 46.86% over 2013 aggregate GDP per capita. By 2050, my model predicts aggregate GDP per capita will be 132.81% greater than 2013 levels. While jet fuel consumption is rising rapidly and keeping pace

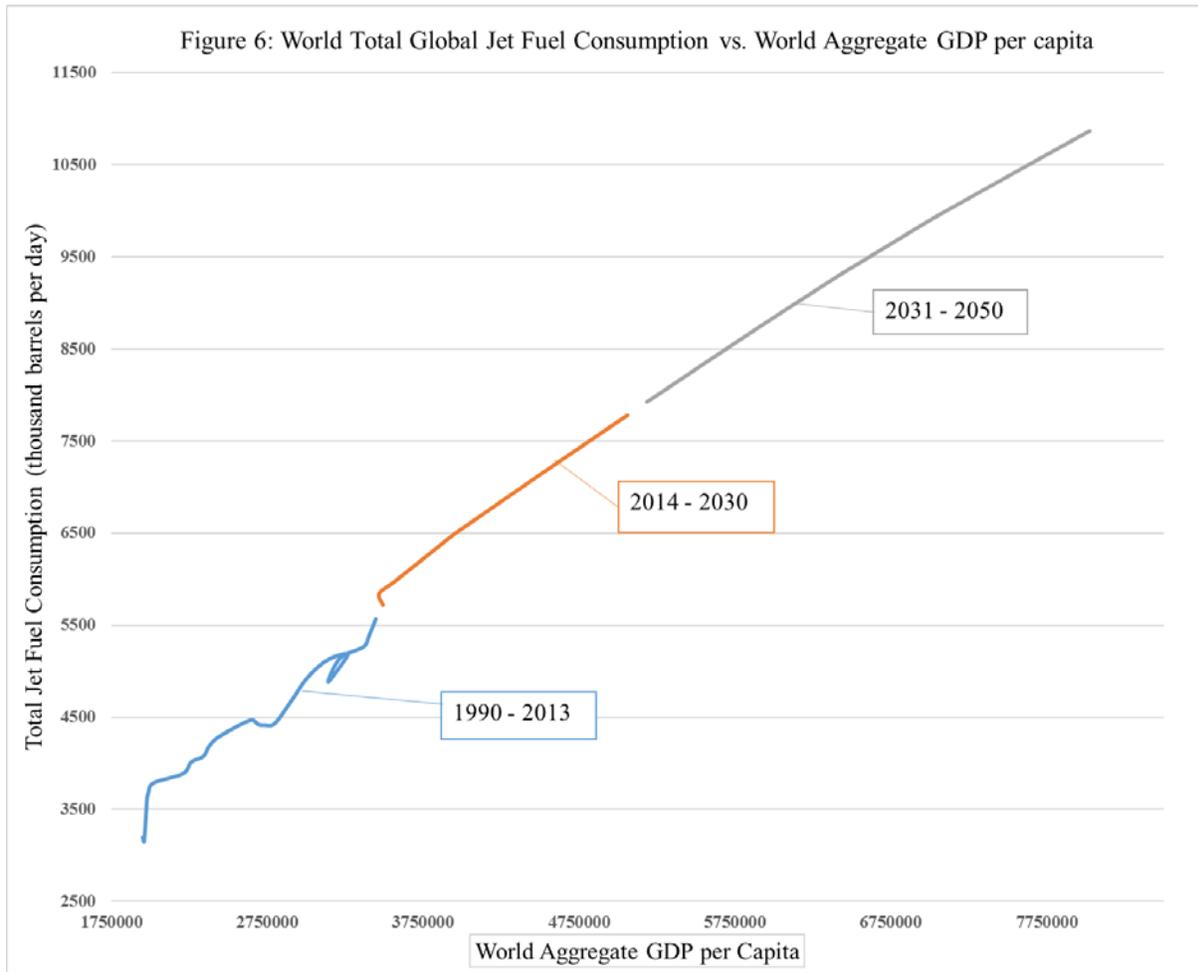
with the growth in GDP per capita, it is not outstripping economic growth. The high income



elasticity for developing countries likely contributes to this high growth. As seen in Figure 5, jet fuel consumption is increasing and marginally begins to become more elastic in the later years of the projection. India, Vietnam, Indonesia, and Thailand have identifiable kinks in the projected jet fuel consumption curve, indicating the country has passed the 7,000 to 15,000 GDP per capita threshold and experience a drop in income elasticity for jet fuel consumption.

It is interesting to note that a 39.65% growth rate of jet fuel consumption levels to 2030 over 2013 levels is a slightly higher rate than the 38.67% increase in jet fuel consumption experienced over the same time period in 1996 to 2013. Between those years, global jet fuel consumption rose by 38.67%. This indicates that a growth rate in the high thirties is not outrageous, and actually quite reasonable, particularly when compared to projected GDP per

capita growth levels. This high growth will likely be sustained by the many developing countries



as they mature into more stable economies. Figure 6 shows the increasing jet fuel consumption on a global level. The increasing demand starts to slow very slightly near 2050, but is still upwards and had yet to reach a true saturation point.

V. CONCLUSION

Jet fuel consumption has risen steadily and continues to capture an increasing percentage of transportation greenhouse gas emissions. Many previous energy per capita studies have focused on the relationship between energy consumption per capita and income per capita. Initial data scatterplots appeared to indicate a relationship between GDP per capita at PPP, with increasing jet fuel consumption with rising per capita GDP.

To further investigate this relationship, I ran regressions that divided up the data into subsets by GDP per capita levels. First, I ran a linear regression that indicated that there was a relationship between GDP per capita and jet fuel consumption. To try to find a better fit, I applied a quadratic function to the data, and subsequently split the data to two subsets of less than 10,000 GDP per capita and greater than 10,000 GDP per capita. I applied a quadratic function to both subsets, and in all three cases of applying a quadratic function to the data, there was no statistical significance.

In order to allow for increased flexibility at different stages of economic development, I created five income bands of equal size. These bands allowed for countries to experience different elasticities at five different economic development levels, rather than at one sweeping rate. This resulted in statistically significant elasticities that indicated fairly inelastic demand for jet fuel in very poor countries and very rich countries. However, when the observations were weighted by population, it indicated that less developed countries experienced the highest income elasticity or inelastic demand for jet fuel consumption with increasing GDP per capita. The highest elasticity occurred at the 7,000 to 15,000 GDP per capita income band with a 1% increase in GDP per capita resulting in a 1.10% increase in jet fuel consumption per capita demanded. When weighted by population, income elasticity fell in richer countries, indicating a saturation level.

The higher elasticity in poor countries could be attributable to a differing need for jet fuel in poor versus rich countries. In very poor countries, the economy could be very dependent on exports and likely relies minimally if at all, on tourism. Therefore the majority of jet fuel consumption demand is likely attributable to cargo flights and less to passenger travel. As countries become richer, passenger travel and tourism increases along with increased

globalization and trade. Globalization becomes extremely dependent on jet fuel and aviation if the country is an island, where the only options for trade are by air or by sea. Many of the countries in the 7,000 to 15,000 GDP per capita income band were islands and this income band also had the highest income elasticity, when weighted by population. As countries become developed economies, there could possibly be a saturation rate at which the marginal cargo flight does very little to increase GDP per capita. At this point, beyond 15,000 GDP per capita at PPP, increased demand in jet fuel consumption comes primarily through increased tourism and passenger travel.

Projected global jet fuel consumption levels are expected to be 39.65% and 95.06% higher than 2013 jet fuel consumption levels in 2030 and 2050, respectively. These are reasonable growth rates that track a steady pace of increasing global jet fuel consumption demand, with global GDP per capita expected to rise at a higher rate. While they could be refined further, these growth rates can be used to determine a projected impact on greenhouse gas emissions and climate change. In a future study, I believe it would be interesting to breakdown jet fuel consumption by end use to determine the factors that are driving the increase jet fuel consumption demand and their direct impact on increasing GDP per capita in order to identify jet fuel usage that is more critical to a country's economic growth.

Limitations to my study include GDP at PPP data only extending to 1990 despite jet fuel consumption numbers extending beyond and international jet fuel consumption numbers derived from the EIA's Independent Statistics & Analysis Beta version. However, these numbers were consistent with jet fuel consumption numbers published previously by the U.S. EIA. Additionally, the jet fuel numbers were not segregated by usage, such as passenger, cargo, or military. There is also a lack of available information on military jet fuel consumption,

particularly by the United State military and Air Force. Further studies should investigate the impact of military size and operation, such as whether a country has an air force as another driver of jet fuel consumption demand.

VI. Appendices

Appendix 1: Summary of Data

Statistic	Description	Units	N	Mean	St. Dev	Min	Max
year	Year		13,757	1,982.50	20.37	1,861.00	2,016.00
country	Country						
jet_fuel	Jet Fuel Consumption	1000 bbl/d					
jet_fuel_cap	Jet Fuel Consumption per Capita	x1000 bbl/d/person	5,175	25.90	124.46	0.00	1,725.00
gdp_cap	GDP per Capita, PPP	2011 International \$	5,103	2.18	4.72	0.00	77.03
pop	Population	'000s	4,185	14,922.95	16,458.38	610.89	91,864.52
oilprice	Oil Price	2011 US\$	4,185	37,069.30	136,276.70	100.23	1,376,409.00
log_jet_fuel_cap			13,757	39.02	28.43	9.30	111.92
log_gdp_cap			5,103	-0.79	2.11	-10.56	4.34
sq_log_gdp_cap			7,426	8.23	1.53	4.75	11.65
log_oilprice			7,426	70.02	25.56	22.55	135.79
log_pop			13,757	3.40	0.72	2.23	4.72
			4,185	8.90	1.79	4.61	14.13

Appendix 2: Regressions

- 1 xi: areg log_jet_fuel_cap log_gdp_cap log_oilprice i.year, absorb(country) cluster(country)
- 2 xi: areg log_jet_fuel_cap log_gdp_cap log_oilprice sq_log_gdp_cap i.year, absorb(country) cluster(country)
- 3 xi: areg log_jet_fuel_cap log_gdp_cap log_oilprice sq_log_gdp_cap i.year if gdp_cap < 10000, absorb(country) cluster(country)
- 4 xi: areg log_jet_fuel_cap log_gdp_cap log_oilprice sq_log_gdp_cap i.year if gdp_cap >= 10000, absorb(country) cluster(country)
- 5 xi: areg log_jet_fuel_cap log_oilprice log_gdp_cap_ib1 inc_band_0_2 log_gdp_cap_ib2 inc_band_2_7 log_gdp_cap_ib3 inc_band_7_15 log_gdp_cap_ib4 inc_band_15_30 log_gdp_cap_ib5 inc_band_30_above, absorb(country) cluster(country)
- 6 xi: areg log_jet_fuel_cap log_oilprice log_gdp_cap_ib1 inc_band_0_2 log_gdp_cap_ib2 inc_band_2_7 log_gdp_cap_ib3 inc_band_7_15 log_gdp_cap_ib4 inc_band_15_30 log_gdp_cap_ib5 inc_band_30_above [aweight = pop], absorb(country) cluster(country)

Appendix 3: Stata Commands

Clean Up Data:

```
sort country year  
  
replace gdp_cap=. if gdp_cap ==0  
  
replace jet_fuel=. if jet_fuel ==0  
  
replace pop=. if pop ==0  
  
drop if year ==.
```

Create Variables:

```
gen jet_fuel_cap = jet_fuel/pop  
  
replace jet_fuel_cap = jet_fuel_cap*1000
```

Generate Log Variables:

```
gen log_gdp_cap = log(gdp_cap)  
  
gen sq_log_gdp_cap = log_gdp_cap^2  
  
gen log_jet_fuel_cap = log(jet_fuel_cap)  
  
gen log_oilprice = log(oilprice)  
  
gen sq_log_gdp_cap = log_gdp_cap^2
```

Population Weights:

```
bysort country: egen pop_wt = mean(pop)
```

Income Bands:

Create Income Bands and Income Banded GDP per capita:

```
gen inc_band_0_2 = (gdp_cap < 2000)
gen inc_band_2_7 = (gdp_cap >=2000 & gdp_cap< 7000)
gen inc_band_7_15 = (gdp_cap >=7000 & gdp_cap< 15000)
gen inc_band_15_30 = (gdp_cap >=15000 & gdp_cap< 30000)
gen inc_band_30_above = (gdp_cap >=30000)
gen log_gdp_cap_ib1 = log_gdp_cap * inc_band_0_2
gen log_gdp_cap_ib2 = log_gdp_cap * inc_band_2_7
gen log_gdp_cap_ib3 = log_gdp_cap * inc_band_7_15
gen log_gdp_cap_ib4 = log_gdp_cap * inc_band_15_30
gen log_gdp_cap_ib5 = log_gdp_cap * inc_band_30_above
```

Create Stata Graphs:

```
gen decade1 = 1 if inrange(year,1990,1999)
gen decade2 =1 if inrange(year,2000,2009)
gen decade3 =1 if inrange(year,2010,2019)
tway (lpoly jet_fuel_cap gdp_cap if decade1==1) (lpoly jet_fuel_cap gdp_cap if decade2
==1) (lpoly jet_fuel_cap gdp_cap if decade3==1)
```

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