# Oil and Petroleum Product Armington Elasticities: A new-geography-of-trade approach to estimation[*]

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**Abstract**

Exploiting the structural developments suggested by the geography-of-trade literature, we estimate the elasticity of substitution across regional varieties for six crude grades and seven refined products using fixed-effects gravity regressions. We use unique data, compiled by Al-Qahtani (2008), that include global coverage of bilateral trade and transport costs for the crude grades and refined products. We find that the point estimates of elasticities of substitution across import varieties exceed those commonly reported in the literature and those adopted in simulation analysis. Our estimates indicate that there may be far less hysteresis in the pattern of petroleum trade than previously forecast.

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# 1 Introduction

A critical parameter in the analysis of international petroleum markets, and energy policy in general, is the elasticity of substitution across differentiated regional commodities. While most theoretic and analytical models implicitly adopt values that are very high or infinite, empirical models find evidence for, and are dependent on, low values of inter-regional substitution. Motivated by recently developed structural theories, we estimate the cross-sectional spatial trade pattern in crude oil and petroleum products. Using a data set unique in its coverage of detailed goods and direct measures of trade costs, we find very high degrees of inter-regional substitution. We argue that these are the appropriate measures of response when long-run policy or structural shocks that affect relative import prices of energy commodities are under consideration.

From the perspective of traditional theory, most commodities are not differentiated by region. The elasticity of substitution is assumed infinite (or equivalently we say the goods are homogeneous or perfect substitutes). A commodity such as *crude oil* is treated as homogenous and once we net out transport costs, arbitrage ensures that the law of one price holds. This is a problematic empirical structure for thinking about multi-region trade, however, because it fails to explain observed intraindustry trade and also suggests an unrealistically unstable trade equilibrium. Multiregion homogeneous-goods models predict radical changes in the pattern of trade in reaction to even small transitory price changes. This problem is generally associated with a lack of convexity in the trade equilibrium, which results in *bang-bang* reactions (importers become exporters, exporters become importers, some observed high volume trade links might vanish, and unprecedented links suddenly appear).

In response to the problematic nature of having perfect substitutes, Armington (1969) proposes a model of regional differentiation. Commodities carry a regional index and prices can vary by source. Agents demand a composite (or aggregate) of the different regional commodities, which might have heterogeneous characteristics. These differences manifest themselves as preference, or technology, weights. For example, in the context of this study, we consider the possibility that North Sea light-sweet crude is not identical (from the perspective of an importing agent) to light-sweet crude sourced from Saudi Arabia. Price responses are limited by finite elasticities of substitution (often referred to as Armington elasticities). The resulting model is highly tractable. We can easily explain why a country both imports and exports a good (because the domestic and import goods contribute to the composite), and finite substitution elasticities add convexity to the trade equilibrium. In contrast to a homogeneous goods model, a finite elasticity indicates that small changes in the price vector result in relatively small (rather than radical) changes in the multi-regional trade pattern. Since the Armington structure accommodates homogeneous goods as a special case of very large elasticities, we empirically ask "how big is the Armington elasticity for oil and petroleum products?"

We approach the estimation of Armington elasticities from an economic geography perspective. Our six crude types and seven products are highly disaggregated. This suggest that we should find relatively high elasticities, and that the international pattern of demand will largely be driven by the heterogeneity introduced by geographical distance and the associated bilateral trade costs. In fact, this is what we find. Our simple structural gravity regressions perform well at explaining the pattern of trade and our elasticities are high relative to most estimates in the literature (on more aggregated products).

## 2 Literature

In parallel with the widespread adoption of the Armington structure, estimates of substitution elasticities appear in the empirical trade literature.[1] Most of these studies rely on

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[1] Many of the early studies on trade elasticities are found in the survey by Stern et al. (1976). Studies that directly measure the elasticity of substitution between US import and domestic goods at the industry

single-equation time-series specifications, and often report surprisingly low elasticity estimates (usually around one).[2] A very useful critique is offered by Erkel-Rousse and Mirza (2002). They explain that it is likely that the unit-value price proxies, that appear on the right-hand side of time-series import-demand studies, will be correlated with the errors. This generates a downward bias in the elasticity estimates. They suggest that economic geography (gravity-equation) approaches to elasticity estimation [e.g., Hummels (2001)] are likely more useful. Although our primary motivation for adopting an economic geography approach is that we feel it is an appropriate specification of trade in our disaggregated products, the econometric issues raised by Erkel-Rousse and Mirza (2002) provide additional arguments.

Following Erkel-Rousse and Mirza (2002), we highlight the fact that many of the low estimates that appear in the literature may suffer from traditional endogeneity/simultaneity problems. It is only under a restrictive set of assumptions that the Armington elasticity can be directly measured in a regression of relative quantities on relative prices. A good estimate of the substitution elasticity is obtained if it is reasonable to assume that the marginal rate of transformation is constant (horizontal supply), or if importing regions are small enough, such that prices are unaffected by demand. In contrast, gravity specifications are based on a reduced form of the expenditure system where market clearance is imposed. This allows for an estimation of the demand-side parameters while simultaneously controlling for supply. Of course, there are costs of adopting the gravity approach to identification. For example, we explain below that a key identifying assumption in the theory is one of homogeneous preferences and technologies. Clearly this may not be appropriate in a general

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level include Shiells et al. (1986), and Reinert and Roland-Holst (1992). Gallaway et al. (2003) utilize more advanced time-series techniques to distinguish between long and short-run elasticities.

[2] Brown (1987) and Balistreri and Markusen (2009) highlight, and criticize, the implication of low elasticities in the Armington structure, because they indicate high optimal tariffs, even for relatively small countries. Riedel (1988), Athukorala and Riedel (1991), and Panagariya et al. (2001) also challenge the low estimates and provide empirical evidence to the contrary, simply by focusing on the supply-side of trade (which is largely ignored in the literature). The survey paper by McDaniel and Balistreri (2003) also picks up the issue of our general mistrust of the time-series estimates.

set of situations. The pros and cons of the alternative approaches should be considered on a case by case basis.

In the context of our data we feel that the economic geography approach is the most appropriate. We would not want to rule out large-region effects or upward sloping supply. Our gravity specification utilizes source-specific fixed effects to control for the supply conditions, and we measure the trade pattern that emerges given the observed variation in relative trade costs (assuming that importing agents have identical preferences and technologies). This is designed to give us a good estimate of the long-run Armington elasticity between different import sources, while acknowledging that the data are being generated from an equilibrium where demand changes might affect price.

Since we focus on crude and petroleum products, we include in Table 1 some recent Armington elasticity estimates for related goods. The substitution elasticities are either measured on the domestic-import margin or on the more disaggregate import-import margin (across different import sources). Consistent with the Erkel-Rousse and Mirza (2002) critique, we see relatively small estimates from the traditional time-series studies, but the studies that take an economic-geography approach, Hillberry et al. (2005) and Hertel et al. (2007), measure relatively larger elasticities.[3] Notably the gravity based estimates in Hertel et al. (2007) are the preferred default elasticities in the most recent versions of the popular Global Trade Analysis Project (GTAP) computable general equilibrium model.[4] We focus our measurement efforts on the import-import elasticity to provide additional gravity based estimates for crude oil and petroleum products at a more detailed level of aggregation.

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[3] Hillberry et al. (2005) do not estimate a gravity equation, but they use the same cross-sectional variation in trade flows across geography to identify a best fit elasticity. Their criteria for fit is to minimize the influence of an idiosyncratic taste-bias parameter in calibrating the Armington technology.

[4] For more information visit the GTAP web page, www.gtap.org. GTAP versions 6 and later adopt the Hertel et al. (2007) elasticities (see Hertel et al. (2008)).

Table 1: Petroleum-related Armington Elasticities from the Literature

| | **Sample** | **Economic** | | **Elasticity** | |
|---|---|---|---|---|---|
| **Author(s)** | **Type** | **Geography** | **Commodity** | Domestic-Import | Import-Import |
| Reinert and Roland-Holst (1992) | Time-series | No | Crude Oil and Nat.Gas | 0.31 | |
| Gallaway et al. (2003) | Time-series | No | Petroleum Products | 0.85 | |
| Hillberry et al. (2005) | Cross-section | Yes | Crude Oil | | 15.0 |
| | | | Petroleum and Coal Products | | 13.8 |
| Welsch (2006) | Time-series | No | Fuel and Power Products | 0.11 | |
| Hertel et al. (2007) | Cross-section | Yes | Crude Oil | | 10.4 |
| | | | Petroleum and Coal Products | | 4.2 |
| Németh et al. (2008) | Panel | No | Coal, Crude Oil, and Nat.Gas | 0.85 | 2.0 |
| Welsch (2008) | Time-series | No | Fuel and Power Products | 0.01 | |

# 3 Theory

Following Anderson and van Wincoop (2004) we describe nominal trade by a generalized gravity equation derived from a constant-elasticity-of-substitution (CES) expenditure system.[5] Let $x_{ij}^k$ be the value of trade in a particular good $k$ from region $i$ to region $j$, and denote the source price $p_i^k$ and bilateral trade cost factor $t_{ij}^k$ such that we have the import quantity $q_{ij}^k = x_{ij}^k/(p_i^k t_{ij}^k)$. The unit cost function for the composite commodity consumed in region $j$ is given by

$$P_j^k \equiv \min \left\{ \sum_i x_{ij}^k \quad \text{s.t.} \quad \left[ \sum_i \left( \frac{q_{ij}^k}{\psi_i^k} \right)^{\rho_k} \right]^{1/\rho_k} = 1 \right\}. \tag{1}$$

The $\psi_i^k$ parameters indicate the technology weighting of the varieties across the source regions, and $\rho_k \equiv (\sigma_k - 1)/\sigma_k$ indicates response, where $\sigma_k$ is the elasticity of substitution. Solving (1) yields

$$P_j^k = \left[ \sum_i \left( \psi_i^k p_i^k t_{ij}^k \right)^{1-\sigma_k} \right]^{1/(1-\sigma_k)}. \tag{2}$$

Given total region-$j$ expenditures on $k$ of $E_j^k$, the nominal demand functions are given by

$$x_{ij}^k = \left( \frac{\psi_i^k p_i^k t_{ij}^k}{P_j^k} \right)^{1-\sigma_k} E_j^k. \tag{3}$$

We continue with the derivation of *gravity* by imposing market clearance, $Y_i^k = \sum_j x_{ij}^k$, where $Y_i^k$ is the nominal value of production of commodity $k$ in region $i$. Substituting (3) into market clearance and isolating the source specific terms, we have

$$\frac{Y_i^k}{(\psi_i^k p_i^k)^{1-\sigma_k}} = \sum_j \left( t_{ij}^k / P_j^k \right)^{1-\sigma_k} E_j^k. \tag{4}$$

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[5] See also Anderson and van Wincoop (2003) or Baldwin and Taglioni (2006).

Defining output and expenditure shares ($\theta_i^k \equiv Y_i^k / \sum_j Y_j^k$ and $\phi_i^k \equiv E_i^k / \sum_j Y_j^k$), and with some manipulation we have the Anderson and van Wincoop (2004) index of (source-specific) outward trade resistance:

$$\Pi_i^k \equiv \frac{(\theta_i^k)^{1/(1-\sigma_k)}}{\psi_i^k p_i^k} = \left( \sum_j \left( t_{ij}^k / P_j^k \right)^{1-\sigma_k} \phi_j^k \right)^{1/(1-\sigma_k)} . \tag{5}$$

Destination-specific inward resistance is summarized by the unit expenditure index, which can be simplified using (5) to

$$P_j^k = \left( \sum_i \left( t_{ij}^k / \Pi_i^k \right)^{1-\sigma_k} \theta_i^k \right)^{1/(1-\sigma_k)} . \tag{6}$$

Finally, we can again use (5) to give us the Anderson and van Wincoop (2004) theoretic gravity equation:

$$x_{ij}^k = \frac{E_j^k Y_i^k}{Y^k} \left( \frac{t_{ij}^k}{P_j^k \Pi_i^k} \right)^{(1-\sigma_k)} , \tag{7}$$

where $Y^k$ (without a subscript) is the value of total world output of good $k$.

The generality of (7) is worth noting. There are no restrictions on the technologies or resources upstream of regional output of $k$, and there are no restrictions on the downstream determinants of regional expenditures on $k$. The key assumptions are simply market clearance and a CES aggregation of varieties. Market clearance is hardly controversial and the CES form is, at a minimum, locally reasonable.

We highlight one caveat, however, concerning our assumption that preferences and technologies are identical across regions. This assumption is essential to our approach as it allows us to interpret the spatial equilibrium independent of idiosyncratic bilateral technology weights. The only bilateral terms in (7) are trade flows and trade costs. The CES weights for goods sourced from region $i$ are identical in each of the region $j$ aggregations; the $\psi_i^k$ do not include a $j$ index. In the context of this study, we are assuming that all importers (refiners) have the same technology weights on product sourced from a specific region. Consistent with contemporary gravity studies, we do not consider the possibility that the weights might be inherently bilateral. At a higher level of aggregation this may be problematic, as identical technologies are not supported [see Welsch (2008)]. Our use of highly disaggregated data is critical to exploiting the geographic pattern to infer substitution elasticities, but we must acknowledge that a refiner in region $j$ may have a unique technology for dealing with the special characteristics of crude from some source region $i$. If the pattern of these potential unique technologies is correlated with our measure of transport costs the elasticity estimates contain a potential bias.

The critical difference between equation (7) and many early gravity-model applications is the appearance of the aggregate indexes $P_j^k$ and $\Pi_i^k$, or so-called "multilateral resistance indexes." Anderson and van Wincoop (2003) emphasize the need to consider these indexes (which depend on trade barriers with *all* trading partners) in an empirical estimation of (7). The most popular contemporary method for dealing with multilateral resistance is to subsume these terms in measured coefficients on source and destination fixed effects. One of the first examples of a theory-based fixed-effects gravity specification of trade is from an early version of Hummels (2001). Many researchers followed, including the textbook treatment by Feenstra (2004), p 161, which is derived directly from a version of equation (7).[6] A clear presentation of the method, theoretic justification, and empirical pitfalls is given by Baldwin and Taglioni (2006). The theory-based log-linear fixed-effects empirical gravity specification

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[6] Other prominent studies that use the fixed-effects approach to control for multilateral trade resistance include Redding and Venables (2000), Rose and van Wincoop (2001), Hertel et al. (2007), and Baier and Bergstrand (2009). In fact, Anderson and van Wincoop (2003) use a fixed-effects method in one of their sensitivity analyses, although they use a non-linear constrained-least-squares technique in their central estimation. Anderson and van Wincoop conclude that the alternative techniques have little impact on the coefficients of interest. They do, however, point out that the fixed-effect regression identifies a potential problem with the non-linear method, because the non-linear method requires a highly uncertain measure of internal regional distances. The vast majority of authors that have followed after Anderson and van Wincoop (2003) have opted for the fixed-effects method to control for multilateral resistance. Our study falls within that literature.

is given by:

$$\ln x_{ij}^k = \alpha_i^k + \beta_j^k + \gamma^k \ln t_{ij}^k + \epsilon_{ij}^k. \tag{8}$$

The $\alpha_i^k$ are source fixed effects that control for the $Y_i^k/(\Pi_i^k)^{1-\sigma_k}$ terms; and $\beta_j^k$ are destination fixed effects that control for the $E_j^k/(P_j^k)^{1-\sigma_k}$ terms. We run the regressions with an intercept, so one source and one destination dummy are omitted and the intercept is interpreted as including these omitted coefficients and the aggregate output term ($Y^k$) from equation (7). The coefficient on the ad valorem transport margin, $\gamma^k$, measures $(1-\sigma_k)$, where $\sigma_k$ is the Armington elasticity from equation (2). If we assume $\epsilon_{ij}^k$ is a well behaved stochastic error, and we have measures of $x_{ij}^k$ and $t_{ij}^k$, we can estimate (8) using ordinary least squares (OLS).

## 4 Empirical Results

Our data are unique in that they consist of a full bilateral trade matrix (in quantities, values, and transport costs) for each of the crude grades and refined products on a cross-section from 2004.[7] The trade data are compiled from various sources including the International Energy Agency (IEA), Energy Information Administration (EIA), Organization of Petroleum Exporting Countries (OPEC), Blackwell Energy Research, Ente Nazionale Idrocarburi (ENI), and Energy Intelligence Research. The transportation costs were compiled using two major sources: Worldscale Association (NYC) Inc. and Platts Energy Information. For more details on the data construction see Al-Qahtani (2008) pages 35 through 44. The bilateral matrix covers the following 29 regions, 6 crude types, and 7 petroleum products:

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[7] Methods for estimating the gravity equation using panel data are available and commonly employed [see Baldwin and Taglioni (2006)]. Unfortunately, these data are not currently available, and would be costly to construct at our level of aggregation.

**Regions**

- Canada
- Mexico
- US East
- US West
- Brazil
- Venezuela
- Rest of America
- Norway
- UK
- EU OECD North
- EU OECD South
- Rest of Europe
- Russia
- Rest of Eurasia
- Iran
- Iraq
- Saudi Arabia
- Other Gulf OPEC
- Rest of MidEast
- N.Afr. OPEC
- W.Afr. OPEC
- Rest of Africa
- China
- Indonesia
- India
- Japan
- South Korea
- Singapore
- Rest of Asia

**Crude Types**

- Light Sweet
- Heavy Sweet
- Light Sour
- Medium-1 Sour
- Medium-2 Sour
- Heavy Sour

**Refined Products**

- Liquefied Petroleum Gas (LPG)
- Naphtha
- Gasoline
- Jet Fuel and Kerosene
- Diesel and Fuel Oil
- Residual Fuel Oil
- Other

The trade quantities are reported in barrels per day for 2004. The value of trade is constructed by taking the product of the trade quantity and the gross price paid by the importer ($x_{ij}^k = (p_i^k + \tau_{ij}^k) q_{ij}^k$), where $\tau_{ij}^k$ is the transport cost given in dollars per barrel. The ad valorem transport cost index is calculated as the ratio of the gross to the net price [$t_{ij}^k = (p_i^k + \tau_{ij}^k)/p_i^k$], where $t_{ij}^k$ is the trade cost factor that enters the right-hand side of the regression equation (8). Consistent with our goal of estimating a pure import-source substitution elasticity, we eliminate domestic use ($x_{ii}^k$) observations from the sample.[8]

Table 2 reports the fixed-effects regression results. In the first column we report the value of trade in millions of dollars per day to offer some context for the importance of each commodity. The elasticities measured are very big relative to the existing literature. The point estimates vary between 15 and 39. In contrast, most of the literature estimates in Table 1 are much smaller. The largest estimate in the literature, reported by Hillberry et al. (2005) for their crude oil aggregate, is at our smallest point estimate of 15 for Light sour. Our relatively higher estimates are explained in two ways. First, we use the cross-sectional gravity approach which may eliminate the downward biases suggested by Erkel-Rousse and

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[8] We also drop any observations that report zero trade ($x_{ij}^k = 0$). The basic Armington theory with identical CES weights cannot accommodate zero demand for a regional variety. The gross import price must approach infinity in order to explain a zero import quantity. Theories that explain and predict zero flows in manufacturing trade have been developed [e.g., Helpman et al. (2008)], but these are based on a love-of-variety aggregator. Love-of-variety is not a very attractive assumption in the context of crude and petroleum products.

Table 2: Log Trade Flows Regressed on Log Trade Costs and Fixed Effects

| **Commodity ($k$)** | **Trade Vol.** ($\sum_i \sum_j x_{ij}^k$) | **Coefficient** ($\gamma^k$) | **S.E.** | **Obs.** | $R^2$ | **Elasticity** ($\sigma_k = 1 - \gamma^k$) |
|---|---|---|---|---|---|---|
| Crude Types | | | | | | |
| Light Sweet | 828 | -31.11** | 6.14 | 211 | 0.67 | **32** |
| Heavy Sweet | 20 | -16.44* | 6.30 | 88 | 0.72 | **17** |
| Light Sour | 118 | -13.67 | 9.00 | 64 | 0.86 | **15** |
| Med-1 Sour | 563 | -22.66** | 5.96 | 128 | 0.75 | **24** |
| Med-2 Sour | 66 | -18.40** | 6.66 | 92 | 0.70 | **19** |
| Heavy Sour | 171 | -35.97** | 8.47 | 121 | 0.57 | **37** |
| Refined Products | | | | | | |
| LPG | 67 | -15.74* | 6.72 | 187 | 0.68 | **17** |
| Naphtha | 85 | -24.06** | 6.74 | 162 | 0.64 | **25** |
| Gasoline | 123 | -37.82** | 7.81 | 200 | 0.48 | **39** |
| Jet Fuel and Kerosene | 58 | -14.31 | 7.65 | 183 | 0.39 | **15** |
| Diesel and Fuel Oil | 171 | -32.46** | 6.14 | 220 | 0.39 | **33** |
| Residual Fuel Oil | 96 | -19.51** | 4.69 | 212 | 0.47 | **21** |
| Other | 115 | -26.48** | 4.78 | 287 | 0.59 | **27** |

Notes: Trade volumes are reported in $M per day, and do not include own trade ($i \neq j$).
* Significant at 0.05 level;
** Significant at 0.01 level.

Mirza (2002). Second, we are looking at far more disaggregate commodities relative to the previous literature. As we disaggregate we move closer to a classification of homogeneous goods. All of our estimates are statistically significant at the 5% level except for Light Sour Crude and Jet Fuel and Kerosene.

In addition to the central results, we examine sensitivities to geographic fixed effects for aggregate regions. These results are presented in the appendix. For example, in one of the specifications we impose a fixed effect for all trade flows within Europe, in addition to the normal source and destination effects. We find that the elasticity estimates are not very sensitive to additional geographic fixed effects. In fact, in none of these sensitivity runs do the point estimates for $\gamma^k$ fall beyond one standard error of the central point estimates presented in Table 2.

Given that most modeling efforts do not consider disaggregation beyond crude oil, we also explore potential elasticities for the crude aggregate. We expect the aggregate elasticity for crude to be lower, because heterogeneity across the crude grades limits substitution. As a reference the weighted average elasticity across crude types is 28. This is probably unrealistically high. If we simply regress the logged aggregate value of crude trade flows on the logged weighted average crude trade cost factor, we estimate an elasticity of 26. Simply aggregating trade flows across crude types, however, is only consistent with theory if the substitution elasticity between crude types is infinite. An alternative assumption is to consider a common Armington elasticity for each of the subaggregates. This suggests a pooled regression, where each trade flow is maintained as an observation and there is a fixed effect for each crude type. In that case we estimate an elasticity of about 23.[9] This is probably a reasonable parameterization of the elasticity in crude trade when long-run shocks are considered, and this puts in question the much lower estimates commonly adopted.[10]

# 5 Conclusion

In this study we adopt a gravity (or new-geography-of-trade) approach to estimating Armington substitution elasticities for six crude oil types and seven refined petroleum products. The gravity approach measures elasticities far in excess of most that appear in the literature. We attribute this difference to two innovations. First, we adopt an economic geography approach to estimation. Second, we examine highly disaggregated commodities. As one moves from classifications of crude oil to disaggregates that fall within a range of specific gravities and sulfur content (e.g., Light Sweet Crude), the closer we are to classifying a homogeneous good.

We do not present our elasticities as values that should be adopted in every situation. In

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[9] The coefficient estimate is $-22.21$ with a standard error of 3.05.

[10] It is important to point out that aggregation bias may still be a concern in most trade models. We tested, and rejected at less than the 0.05 significance level, the null hypothesis that the $\gamma$ coefficients across the crude grades is the same. This indicates that aggregation to a level that views *crude* as an individual commodity could be problematic.

fact, if one attributes our high estimates primarily to our high level of disaggregation then they are most appropriate in a model that exhibits a similar level of disaggregation.[11] In addition, we are estimating on variations in the spatial trade pattern that have developed over decades (or longer). Our estimates should be interpreted as very long-run elasticities. If one is modeling near-term trade responses then our elasticities may not be appropriate. In general, elasticities must be chosen to fit the specific model and the specific purpose.

Our results have significant implications for modeling efforts in energy and energy policy. Consider the debate over energy-supply security. Simulation models that adopt low import-source elasticities would suggest considerable dependence on specific bilateral trade relationships. In contrast, our results suggest that it is relatively easy to switch to alternative source regions in the long run.

We argue that when modeling significant long-run policy or structural shocks it is important to consider the full response in the trade equilibrium. Our large estimated substitution elasticities for crude and petroleum products indicate that transportation costs are a dominant component in determining the trade equilibrium. The evidence and market outcomes are consistent with the stance of many modelers. A refiner can easily switch from North Sea light-sweet crude to light-sweet crude sourced from Saudi Arabia in response to a small relative price change. The cross-sectional trade pattern observed is consistent with high degrees of substitution, once we control for source and destination fixed effects, which include the theoretically motivated multilateral trade resistance terms. In the long run, high degrees of substitution indicate that policies permanently affecting delivered costs will significantly change the pattern of trade. Standard applications that adopt very low elasticities may overlook this fact.

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[11] Our exploration of specifications aimed at finding an Armington elasticities for the crude aggregate suggests that disaggregation is not the primary explanation for our high estimates. We estimate an elasticity of 26 on the crude aggregate, and 23 when we maintain the individual trade flows and add a crude-type fixed effect. Both of these estimates are well above the values commonly adopted for crude trade in policy simulation models.

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# A Appendix: Sensitivity Results

In Table 3 we explore alternative specifications that included fixed effects for bilateral trade within aggregates of the regions. In the first sensitivity case we include an additional fixed effect for trade between the two US regions (US-US), and in the second case we include an additional fixed effect for trade between Canada, the US regions, and Mexico (NAFTA). In the Americas run we add a fixed effect for Western-hemisphere trade. The final specification includes a Europe fixed effect. In none of the sensitivity runs do the point estimates fall beyond one standard error of the central estimates, and in most cases the estimates are very close to the central estimates.

Table 3: Estimates of $\gamma^k$ under alternative specifications

| **Commodity** | **Central Specification** | **US-US Dummy** | **NAFTA Dummy** | **Americas Dummy** | **Europe Dummy** |
|---|---|---|---|---|---|
| Crude Types | | | | | |
| Light Sweet | -31.11 | -31.96 | -28.12 | -23.48 | -29.64 |
| | (6.14) | (6.12) | (6.18) | (6.20) | (6.24) |
| Heavy Sweet | -16.44 | NA | NA | -11.50 | -16.79 |
| | (6.30) | | | (6.90) | (6.35) |
| Light Sour | -13.67 | NA | NA | NA | -13.85 |
| | (9.00) | | | | (9.05) |
| Med-1 Sour | -22.66 | -24.63 | -20.60 | -16.69 | -22.54 |
| | (5.96) | (5.90) | (6.17) | (5.92) | (6.00) |
| Med-2 Sour | -18.40 | NA | NA | -14.21 | NA |
| | (6.66) | | | 6.91 | |
| Heavy Sour | -35.97 | -38.59 | -33.17 | -27.18 | -31.32 |
| | (8.47) | (8.54) | (8.68) | (8.66) | (9.09) |
| Refined Products | | | | | |
| LPG | -15.74 | NA | -16.11 | -14.28 | -9.97 |
| | (6.72) | | (6.81) | (6.65) | (6.90) |
| Naphtha | -24.06 | NA | -22.19 | -20.02 | -19.95 |
| | (6.74) | | (6.34) | (6.23) | (7.17) |
| Gasoline | -37.82 | NA | -37.20 | -36.22 | -28.28 |
| | (7.81) | | (7.78) | (7.73) | (7.86) |
| Jet Fuel and Kerosene | -14.31 | NA | -13.76 | -12.32 | -10.89 |
| | (7.65) | | (7.72) | (7.73) | (7.87) |
| Diesel and Fuel Oil | -32.46 | NA | -31.10 | -30.22 | -24.73 |
| | (6.14) | | (6.20) | (6.16) | (6.17) |
| Residual Fuel Oil | -19.51 | NA | -18.67 | -15.94 | -16.94 |
| | (4.69) | | (4.72) | (4.62) | (4.64) |
| Other | -26.48 | NA | -25.88 | -25.41 | -20.70 |
| | (4.78) | | (4.83) | (4.85) | (4.81) |

Notes: "NA" indicates a collinearity between the added dummy and the regional fixed effects. Standard errors in parentheses.