Product Variety and Adjustment Costs - Evidence from the Light Truck Market

Alan Spearot*

University of California - Santa Cruz

February 22, 2017

Preliminary - comments welcome

Abstract

Varieties come in all shapes and sizes, and many firms produce a complex set of varieties within a single plant. This paper develops a framework to study adjustment costs in delivering product variety, and quantifies the model using data from the North American Light Truck Market. In a model in which demand arrives randomly and workers must adjust in real-time to produce different varieties, expected total costs at a plant are a function of (1) attributes of the varieties produced there, (2) the scale of production, and (3) an observable index of within-plant diversification. Using marginal cost estimates from a nested logit model of demand, a one standard deviation increase in expected adjustment costs increases variety-level marginal costs by $500. Within plants, theoretically and empirically, variety pairs with a small combined share of production have positively correlated costs, and variety pairs with a large combined share of production have negatively correlated costs. Finally, we utilize a novel constrained estimator to choose parameters to equalize expected marginal adjustment costs across plants. Some product characteristics (eg. liters in the engine) have little effect on adjustment, while others (eg. crew cab) have a relatively large effect. As reflected in adjustment cost parameters, inshore and offshore facilities are tooled to produce different types of varieties.

Key Words: Product variety, complexity, productivity, offshoring, inshoring, adjustment costs

*aspearot@ucsc.edu

1 Introduction

Since the time of Adam Smith, economists have been focused on the benefits of specialization, whether it is across tasks within a pin factory, or in the production of millions of aircraft parts across borders. Indeed, the recent growth of specialization has been astounding, where the modern economy exhibits a massive amount of specialization across firms that stands in stark contrast to the early 20th century examples of plants that did almost everything.[1] Firms trade specialized inputs across many borders, and the modern multinational is a complex organization that manages production across multiple locations, often with each focusing on a particular product or input that is traded to another affiliate or firm at arm's length.

However, despite this focus toward specialization and the associated segmentation of production across firms and borders, the growth in demand for variety has left the downstream firm responsible for much of the heavy lifting in organizing the production of many varieties with nuanced, but critical, differences in characteristics. Long gone are the days of the Fordist mantra of "you can have any car you want as long as it's black". Consumers demand significant choice in their consumption basket, and firms have responded with a plethora of brands, varieties, and features, even within narrowly defined products. In many cases, these different varieties and models are produced at the same location with the same workers and the same management team. While the benefits of offering variety to the consumer are clear, the costs of providing this variety have rarely been considered in a rigorous fashion. How do firms manage production across a potentially complex set of varieties within the same firm or even plant?

This paper presents a model of adjustment costs where firms may produce a number of distinct varieties within the same plant. In the model, expected adjustment costs are a function of the scale of production and an observable diversification index within the plant. We quantify the model using data from the North American market for light trucks, showing that varieties produced subject to

[1] The Ford Rouge facility is an example of this, where almost all parts of the car were made, including the steel used for the car. About the only thing it did not do was mine the iron ore for the steel.

higher marginal adjustment costs exhibit higher estimated marginal costs. Further marginal costs of varieties are linked according to their relative market-shares within the firm. We also develop a novel estimator that minimizes deviations from an equilibrium in which variety-level marginal costs are equalized across plants.

The novel feature of the model lies in the cost function that firms use for pricing and production, where the cost of each variety is a function of two factors: input costs and adjustment costs. Input costs will be treated in standard IO style - relating them to product characteristics. Adjustment costs are incurred if, in the process of production, the current variety is different from the last. In this case, we assume that there is an additional amount of labor required to find the new inputs or tools that correspond to the different variety.[2] Further, the additional amount of labor required depends on the number of different characteristics between the two varieties. With this simple adjustment process, the expected total cost for a given variety is the deterministic input cost and the expected adjustment cost. Assuming that demand arrives randomly and is memoryless, the probability that the last variety produced was some variety j is simply equal to variety j's within-plant production share. When aggregating to expected total plant-level costs under these assumptions, the expected total cost at a plant is a function of (1) attributes of varieties produced at that plant, (2) the scale of production, and (3) a diversification index of production concentration in the plant. Under a simplified version of this framework in which varieties are each defined by a single, unique characteristic, the diversification index is equal to one minus a Herfindahl index of production concentration in the plant.

Using this simplified version of the cost function, we derive the effects of own production and production of other varieties within the plant on variety-specific marginal costs. First, expected marginal costs are decreasing in own-quantity, which reflects the increased probability that no adjustment costs are incurred (since the variety has a larger probability of preceding itself during assembly). Second, the cost function yields a rich set of predictions on cross-variety complementar-

[2] There are a number of other interpretations for this which we discuss when outlining the model

ities in the same plant. Production of another variety may increase or decrease expected marginal costs of a given variety depending on the combined market share of the two and the overall concentration of production within the plant. As variety-specific market share and plant-level concentration indices are observable in the data, these cost complementarities can be tested once marginal cost at the variety level has been estimated.

To implement the model empirically, we use highly detailed data on light-truck production and sales over the period 1990-2000. The truck data is particularly useful in that it contains sales and plant of production for every permutation of the major characteristics that define a truck. To estimate marginal costs using this data, we utilize a nested-logit model of demand and invert the first-order conditions as in Berry (1994). To estimate the demand-side of the model, we use instrumental variables as suggested in Berry (1994) and similar to those used in Berry, Levinsohn, and Pakes (1995).

With estimated marginal costs in-hand, we begin the main empirical analysis by evaluating the novel predictions regarding variety linkages in marginal cost. In the typical setup, one would assume a constant unit cost that is a function of characteristics, or perhaps some variable marginal cost in overall production (eg. increasing returns). As described earlier, the model rationalizes the increasing returns assumption, but also provides a rich set of predictions in terms of cross-variety correlations in marginal costs (after accounting for variety characteristics). As the model predicts, for light-truck varieties produced in the same plant, estimated marginal costs (after controlling characteristics and trends) are more positively correlated when their combined market shares are low. In contrast, when two varieties are produced within the same firm but *not the same plant*, there is little correlation between their combined market shares and residual correlations in estimated marginal costs.

Next, we move to quantifying the role of expected marginal adjustment costs in marginal costs. Marginal costs are specified as an additive function of product characteristics and the expected marginal adjustment costs as specified by the model. Two measures of expected marginal adjustment costs are used: one that assumes any variety is defined by a unique characteristic, and another that assumes varieties are defined by a vector of characteristics, and the number of differences in characteristics measures the dissimilarity in varieties. As both measures are a function of observable market shares, we instrument for them using the number of other varieties produced at a given variety's plants, and motivated again by BLP, the sum of curbweight of these competing varieties within the plant. Using both instruments, higher expected marginal adjustment costs increase estimated marginal costs. In the preferred specification using the most general specification for adjustment costs, a one standard deviation increase in the costs of adjustment yield approximately a \$500 increase in the costs of the vehicle. Further in interacting the costs of adjustment with whether a variety was allocated to new production facilities both offshore and inshore, the estimated costs of adjustment are larger for those varieties that were allocated to both new offshore and inshore plants during the 90s.

To conclude the paper, we develop a novel estimator to study the allocation of varieties across plants, and in particular, the position of the same variety within the portfolio of multiple plants that produce it. The basic idea is the following. Unconstrained, firms will produce a given variety at the plant that minimizes marginal cost, and if produced at multiple plants, the marginal costs inclusive of delivery costs to the consumer should be equalized. In reality, capacity constraints and other factors are likely to get in the way of this, so relevant marginal costs will include the shadow cost of unobserved constraints. Thus, we adopt a simple assumption that firms wish to minimize deviations from marginal cost equilization for each variety, and we build the estimator around this. While the parameters of adjustment costs cannot be exactly identified, we adopt an intuitive normalization that classifies our estimator as a quadratic programming problem. Intuitively, the results indicate that some product characteristics (eg. liters in the engine) have little effect on adjustment, while others (eg. crew cab) have a relatively large effect. In terms of the international allocation of production, as reflected in the estimated adjustment cost parameters, inshore and offshore facilities are tooled to produce different types of varieties.

This paper is related to a number of literatures focusing on productivity and multinational production. At the paper's core is the issue of scope within the firm, and a number of papers acknowledge and evaluate the effects of scope at the plant level. Specific to the automotive industry, Van Biesebroeck (2007) evaluates the role of the number of different product types at the plant on the hours required per vehicle, as well as adoption of other technologies and outsourced inputs. The main differences in the current work is the micro-foundation of a precise adjustment cost, and evaluating how these costs may manifest in pricing and output at the level of detailed varieties. Outside of the auto industry, Arkolakis, Ganapati, and Muendler (2015) assumes that firms have a core competency in a given variety, and via an index of scope, higher scope reduces inefficiency. In our case, we do not assume any core competency of the firm, and any inefficiency of scope is endogenous through the mix of consumer demand. In terms of the precise index of complexity that we derive, it is actually similar (though with different micro-foundations) to the benchmark import to expenditure ratio from Helpman (1987), most recently used in Head and Mayer (2013). The paper is also related to a broader literature evaluating flexible production and the role of product scope; for example Eckel and Neary (2010).[3]

A number of papers exist evaluating the sourcing of brands across different automotive facilities. Using the same dataset as this paper, McCalman and Spearot (2013) evaluates the descriptive sorting of varieties across existing, offshore, and new inshore capacity. The results show that there is a significant selection of different varieties across borders, but issues of efficiency are not evaluated. Also using the same dataset, McCalman and Spearot (2015) evaluates the relaxation of an environmental policy that was specific to larger trucks. Sly and Soderbery (2014) uses a different automotive dataset to evaluate the role of wage bargaining in offshoring decisions. Two recent papers evaluate global sourcing of automotive products. Cosar, Grieco, Li, and Tintelnot (2015) evaluate how FDI can yield a kind of home market effect with consumers preferring domestically produced varieties, even if they are foreign owned. Finally, Head and Mayer (2015) quantifies a

[3]See also the seminal work in Milgrom and Roberts (1990).

number of frictions in selling automotive brands globally, and uses the model to simulate a variety of trade shocks, such as TTIP and Brexit.[4] Beyond the automotive industry, the role of production of "complex" tasks and varieties has been examined in Costinot, Oldenski, and Rauch (2011), Oldenski (2012), and Keller and Yeaple (2013).

The plan for the paper is as follows. First, in section two, we present the adjustment cost framework for multi-variety plants, and discuss its properties within and across varieties. Then, in section three, we integrate the adjustment cost framework within a discrete choice model of product differentiation to evaluate how implied marginal costs are related to the expected marginal costs of adjustment. Then, in section four, we propose the novel estimator based on marginal cost equalization across plants. In section five, we conclude.

2 Production with Adjustment Costs

The primary theoretical contribution of the paper is a simplified framework that can be used to quantify expected variety-level adjustment costs. Of course, realistic adjustment costs will include inventory and sourcing from suppliers, and these features are not in the model. However, in the model that follows, we hope to provide a base framework to study how workers produce many varieties within the same plant that differ in non-trivial dimensions.

The basic idea behind the theoretical framework is that while workers may have a set of tasks that are similar across varieties, the nuanced features of each variety require careful selection of tools, inputs, and installation techniques. As we will be focusing on the automobile industry in the empirical section, we start with a simple example of a worker on an assembly line installing a steering wheel. In most automotive plants, many similar varieties are produced on the same line,

[4] A number of other papers evaluate various aspects of the automobile industry. See Feenstra (1988) for the response of automotive firms to a voluntary export restraint, and Goldberg (1995) for a similar question using a nested logit estimator. Goldberg (1998) uses a similar approach in examining changes to the corporate average fuel economy program. Goldberg and Verboven (2005) test the "law of one price" in the European car market. Hellerstein and Villas-Boas (2010) evaluates the role of exchange rate pass through.

and varieties will differ in their precise characteristics. Some may differ in more broad characteristics like extended or crew cab (for trucks), or leather and cloth seats. In the steering wheel example, one can imagine that while the task of installing a steering wheel on a vehicle is pretty simple, a different variety of input is required depending on the features of the car. For example, while all steering wheels have an airbag (though this wasn't always the case), some have additional features like leather wrap, buttons for control of electronics in the vehicle, and some are also heated. Thus, depending on the exact order that is being processed on the assembly line at that time, the worker responsible for the steering wheel task must (1) properly select the input from inventory and (2) install the particular input correctly. Underlying the framework described below is that changing the nuanced nature of the task from one variety to the next variety, if they differ, will (potentially) increase the cost of completing the task. This cost may be a direct cost, such as additional labor at different points on the assembly line that correspond to different varieties, or more labor and quality evaluation at the end of the assembly line (especially if a variety that is rarely produced has a higher probability of mistakes in need of correction).

2.1 General adjustment costs

More formally, we assume that along with production costs that relate to product characteristics and pure inputs, a firm i faces adjustment costs when producing Q_i units during some period of time, which consists of different varieties v, with each variety being defined by a set of characteristics K. To begin, we will derive a general form of adjustment costs in which, for a given characteristic k, if variety v is different from some other variety w that was produced immediately before it, then r_k additional units of labor are used in the installation of characteristic k for variety v. Then, all adjustment costs are aggregated across $k \in K$ to calculate total adjustment costs. Finally, though we extend this in later sections for estimation, we begin by assuming that each firm i produces within a single plant.

Precisely, expected total costs for firm i are the following:

$$\mathbb{E}\left[C_i\right] = \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + \sum_{v=1}^{N_i} q_{iv} \left(\sum_{w=1}^{N_i} \Pr(w \to v) \sum_{k=1}^{K} r_k I_{vw}^k \right) \tag{1}$$

The first component in (1) is common to IO models, where $\sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv}$ measures the input costs for each variety v that firm i produces. In total, the firm produces N_i varieties, where ϵ_{iv} is the input cost for each variety v. Later, input costs will be written as a function of variety fixed effects and time-invariant characteristics (like vehicle weight).

The second component of (1) is the expected adjustment cost across all varieties v. For a given variety v, an adjustment cost is incurred for each product characteristic when the variety preceding production of v, variety w, is different. This is represented by the term $\Pr(w \to v) \sum_{k=1}^{K} r_k I_{vw}^k$, which first indicates the probability that w is before v, $\Pr(w \to v)$, and if so, tallies the adjustment costs incurred. For each variety k, r_k is a particular adjustment cost for that characteristics, and I_{vw}^k is an indicator function taking the value of one if variety v is different from w in dimension k.

In the data, I_{vw}^k will be observable, and r_k will be a parameter to be estimated under a variety of assumptions (usually that $r_k = r$ for all k). However, for now, the primary question is how to characterize the probability that a given variety v is preceded by w. In practice, this probability will be a function of some combination of inventory conditions and the degree of just-in-time manufacturing at a given plant. For the purpose of moving forward with the model in closed form, we adopt the assumption that arrival of varieties has a memoryless property.[5] Though a strong assumption, this facilitates the following simple characterization of the probability of a particular ordering of varieties on the assembly line before variety v.

$$\Pr(w \to v) = \tilde{s}_{iw}$$

[5]This can be derived from an assumption of exponentially distribution arrivals of demand for varieties, or random arrival of consumers with preferences described in section three.

where, $\tilde{s}_{iw} = \frac{q_{iw}}{Q_i}$ is the within firm market share. With this assumption, expected total cost for firm i is written as:

$$\mathbb{E}\left[C_i\right] = \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + \sum_{v=1}^{N_i} \sum_{w=1}^{N_i} q_{iv} \tilde{s}_{iw} \sum_{k=1}^{K} r_k I_{vw}^k \tag{2}$$

Taking a derivative of (2) with respect to q_{ij}, we get the expected marginal cost for variety j:

$$\frac{\partial \mathbb{E}\left[C_i\right]}{\partial q_{ij}} = \epsilon_{ij} + \sum_{v=1}^{N_i} \sum_{w=1}^{N_i} \tilde{s}_{iv} \tilde{s}_{iw} \sum_{k=1}^{K} r_k I_{vw}^k + 2\left(1 - 2\tilde{s}_{ij}\right) \sum_{w=1}^{N_i} \tilde{s}_{iw} \sum_{k=1}^{K} r_k I_{jw}^k \tag{3}$$

With the exception of ϵ_{iv} and r_k, everything in (3) is observable, and in particular, the second half of the equation can be used to construct a measure of expected marginal adjustment costs for variety j. These adjustment costs for variety j can be split into two components and have an intuitive interpretation. First, $\sum_{v=1}^{N_i} \sum_{w=1}^{N_i} \tilde{s}_{iv} \tilde{s}_{iw} \sum_{k=1}^{K} r_k I_{vw}^k$ is firm i specific, and simply measures the effect of variety j on total expected adjustment costs. The intuition for the second component, $2\left(1 - 2\tilde{s}_{ij}\right) \sum_{w=1}^{N_i} \tilde{s}_{iw} \sum_{k=1}^{K} r_k I_{jw}^k$, is more nuanced and specifically measures the effect of variety j production on overall production diversification within the plant. This could be positive of negative since increasing production of a small variety would increase diversification, where in contrast, increasing production of a large variety would decrease diversification.

In the empirics, we will use (3) to construct a measure of expected marginal adjustment costs, and motivate a set of instrumental variables to account for the fact that (3) is a function of endogenous outcomes (market shares). However, before doing so, we will adopt more restrictive assumptions, referred to as "simple adjustment", to study cost function and its properties in closed form.

2.2 Simple adjustment costs

Above, it is assumed that adjustments are incurred at the characteristic level, meaning that two varieties with more differences in characteristics are likely to incur more adjustment costs between them. A simplified version of this involves assuming that each variety, being a bundle of characteristics, has a unique, defining aggregate characteristic. Thus, for simple adjustment costs, we assume that a single and uniform adjustment cost is incurred if the current variety differs from the last.

To implement this assumption, we can restrict the above framework to require that $K = 1$, $r_k = r \; \forall \; k$, and $I^k_{vw} = 1 \; \forall \; v \neq w$. Precisely, under these assumptions, expected total costs for firm i can be written as

$$\mathbb{E}\left[C_i\right] \;\; = \;\; \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + \sum_{v=1}^{N_i} \cdot r q_{iv} \cdot (1 - \tilde{s}_{iv})$$

which can be simplified to:[6]

$$\mathbb{E}\left[C_i\right] = \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + r \cdot Q_i \cdot (1 - HHI_i) \tag{4}$$

In (4), HHI_i is the *production concentration* for firm i, where lower HHI_i implies more diversified production and higher expected retooling costs. Indeed, when there is full concentration of production and $HHI_i = 1$, there are no adjustment costs and production of each variety is solely a function of input costs. In contrast, as the firm produces a large number of varieties of equal

[6]Precisely,

$$\begin{aligned}
\mathbb{E}\left[C_i\right] &= \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + r \cdot \left(Q_i - \sum_{v=1}^{N_i} \frac{q_{iv}^2}{Q_i} \right) \\
&= \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + r \cdot Q_i \left(1 - \sum_{v=1}^{N_i} \frac{q_{iv}^2}{Q_i^2} \right) \\
&= \sum_{v=1}^{N_i} \epsilon_{iv} \cdot q_{iv} + r \cdot Q_i \cdot (1 - HHI_i)
\end{aligned}$$

quantity, $HHI_i \to 0$ and adjustment costs are incurred, in expectation, for every unit of output.

Using this formula, expected simple marginal costs for variety j can be written as:

$$\mathbb{E}\left[MC_{ij}\right] = \epsilon_{ij} + \underbrace{r \cdot (1 - HHI_i)}_{Scale\ Effect} - \underbrace{r \cdot Q_i \cdot \frac{\partial HHI_i}{\partial q_{ij}}}_{Concentration\ Effect}$$

As above, there are two new components that affect the marginal cost of producing variety j. The first is a scale effect, where increased production increases total expected changeovers across all varieties. Second, we have a concentration effect, where increased production of variety v changes the concentration of production, but the direction is ambiguous. Intuitively, if production of a small variety is increased, concentration will fall. However, production of a large variety is increased, concentration will rise.

Assuming that firms make pricing decisions based on expected costs (ie. they set an MSRP price at the beginning of each model year), expected marginal costs will be the relevant measure for pricing. Conveniently for the empirics (and the discussion of instruments), marginal costs for variety j can be decomposed into the importance of variety j within the firm and the production concentration of other varieties within the firm:

$$\mathbb{E}\left[MC_{ij}\right] \quad = \quad \epsilon_{ij} + r \underbrace{\left((1 - \tilde{s}_{ij})^2 + \sum_{v \neq j} \tilde{s}_{iv}^2 \right)}_{>0} \tag{5}$$

Noting that $1 - \tilde{s}_{iv} = \sum_{j \neq v} \tilde{s}_{ij}$, and simplifying we have:

$$\mathbb{E}\left[MC_{ij}\right] \quad = \quad \epsilon_{ij} + r \frac{\left(\sum_{v \neq j} q_{iv}\right)^2}{Q_i^2} \left(1 + \frac{\sum_{v \neq j} q_{iv}^2}{\left(\sum_{v \neq j} q_{iv}\right)^2} \right)$$

Defining $Q_{i,\neq j} = \sum_{v\neq j} q_{iv}$ and $HHI_{i,\neq j} = \frac{\sum_{v\neq j} q_{iv}^2}{\left(\sum_{v\neq j} q_{iv}\right)^2}$, we get:

$$\mathbb{E}\left[MC_{ij}\right] \;=\; \epsilon_{ij} + r\frac{Q_{i,\neq j}^2}{Q_i^2}\left(1 + HHI_{i,\neq j}\right)$$

Marginal cost is a function of inputs, ϵ_{ij}, total scale Q_i, scale of other varieties, $Q_{i,\neq j}$, and concentration within other varieties, $(1 + HHI_{i,\neq j})$. This formulation allows for a simple representation of the marginal cost function of variety j within firm i. That is, writing $Q_i = q_{ij} + Q_{i,\neq j}$, we have:

$$\mathbb{E}\left[MC_{ij}\right] \;=\; \epsilon_{ij} + \frac{rQ_{i,\neq j}^2}{\left(q_{ij} + Q_{i,\neq j}\right)^2}\left(1 + HHI_{i,\neq j}\right) \tag{6}$$

It is now immediate that,

$$\frac{\partial\mathbb{E}\left[MC_{ij}\right]}{\partial q_{ij}} < 0 \qquad\qquad \frac{\partial^2\mathbb{E}\left[MC_{ij}\right]}{\partial q_{ij}^2} > 0,$$

and,

$$\frac{\partial\mathbb{E}\left[MC_{ij}\right]}{\partial q_{ij}}(0) \;=\; \epsilon_{ij} + r\left(1 + HHI_{i,\neq j}\right)$$

$$\lim_{q_{ij}\to\infty}\frac{\partial\mathbb{E}\left[MC_{ij}\right]}{\partial q_{ij}} \;=\; \epsilon_{ij}$$

These properties are summarized in the following lemma.

Lemma 1 *Expected marginal costs exhibit increasing returns to scale, but at a diminishing rate. Formally,* $\frac{\partial\mathbb{E}[MC_{ij}]}{\partial q_{ij}} < 0$ *and* $\frac{\partial^2\mathbb{E}[MC_{ij}]}{\partial q_{ij}^2} > 0$

Thus, there is increasing returns within the cost function through specialization in a particular variety. Intuitively, increasing the scale of some variety decreases the probability that a different variety was produced immediately preceding it, thereby reducing expected adjustment costs.

Variety linkages through adjustment costs

Along with the link between own production and marginal costs, the cost function in (6) includes cross-effects between varieties. These effects are ambiguous in sign. On one hand, increasing production of other varieties increases the likelihood that adjustment costs will be incurred for the variety in question. On the other hand, increasing the share of another variety that has a small share to begin with will decrease concentration of the bundle of other varieties. Thus, it is a question of relative size of one variety and the next in terms of how they are linked through the cost of adjustment.

Conveniently, using the properties of the Herfindahl index and its relationship to market shares, it is straightforward to derive that,

$$\frac{\partial \mathbb{E}\left[MC_{ij}\right]}{\partial q_{il}} = \frac{2}{Q}\left(\tilde{s}_{il} + \tilde{s}_{ij} - HHI_i\right), \tag{7}$$

which leads to the following lemma summarizing the correlation of marginal costs across varieties.

Lemma 2 *Consider the expected marginal costs for variety j. For some $l \neq j$, if $\tilde{s}_{il} + \tilde{s}_{ij} > HHI_i$, then there is a negative correlation between $\mathbb{E}\left[MC_{ij}\right]$ and $\mathbb{E}\left[MC_{il}\right]$. Otherwise, there is a positive correlation.*

Interestingly, Lemma 2 indicates that there are necessarily complementarities between small varieties in that increasing the production of one improves the efficiency of producing another. In contrast, large varieties are more likely to have negative complementaries in production. Indeed, with only two varieties (each with positive production), the condition in Lemma 2 is always satisfied since HHI_i is less than one. Generally, as $\tilde{s}_{il}+\tilde{s}_{ij} > HHI_i$ is observable in the data, we will examine this condition and correlations in marginal costs after cost have been estimated using a discrete choice model.

2.3 Demand

As we will rarely have access to precise cost data by variety and plant, we need to work with observable sales or market shares to infer the role that adjustment costs play in firm-level decision making. While there are a number of utility systems that we can use to work toward this goal, we will use both logit and nested-logit frameworks to estimate mark-ups and recover marginal costs. After recovering marginal costs, we will correlate these costs with measures of expected marginal adjustment costs, and develop an instrumental variables strategy to quantify the impact of these costs. We will begin by deriving the standard logit setup for multi-product firms, and then extending to nested logit, with the ultimate goal of recovering marginal costs from the inverted set of first-order conditions.

2.3.1 Multinomial Logit

As above, suppose that firm i produces N_i varieties, with M firms in the market. We begin by using multinomial logit to represent demand. As is well known, for standard multinomial logit, the probability that some variety j is chosen is equal to,

$$\Pr(j\ chosen) = \frac{\exp(\delta_{ij})}{\sum_{i \in M} \sum_{v \in N_i} \exp(\delta_{iv})}, \tag{8}$$

where δ_{iv} is mean utility earned when consuming variety v produced by firm i:

$$\delta_{iv} = X_{iv}\theta - \alpha p_{iv} \tag{9}$$

Here, X_{iv} is a vector of product characteristics for variety v produced by firm i, θ is the vector utility values for these characteristics, p_{iv} is the price of variety v from firm i, and α is the associated coefficient on price.

In equilibrium these probabilities must equal market shares, $s_{iv}(X_{iv}, \theta, p_{iv})$. Assuming L consumers, firm i sets prices by maximizing the following profit function:

$$\Pi_i = \sum_{v \in N_i} p_{iv} L s_{iv}(X_{iv}, \theta, p_{iv}) - C(\mathbf{q}_i, \mathbf{r}, \mathbf{w}_i) \tag{10}$$

Here, $C(\mathbf{q}_i, \mathbf{r}, w)$ is the expected total cost function for the firm as described above (we henceforth remove expectations for brevity), with $\mathbf{q}_i$ the vector of quantities of each variety, $\mathbf{w}_i$, a vector of input prices for firm i, and $\mathbf{r}$ the vector of complexity costs parameters that may vary by characteristic.

For some variety j produced by firm i, the first order condition is written as follows:

$$\frac{d\Pi_i}{dp_{ij}} = Ls_{ij} + L \sum_{v \in N_i} p_{iv} L \frac{ds_{iv}(X_{iv}, \theta, p)}{dp_{ij}} - \frac{dC(\mathbf{q}_i, \mathbf{r}, \mathbf{w}_i)}{dq_v} L \frac{ds_{iv}(X_{iv}, \theta, p)}{dp_{ij}} = 0$$

Simplifying, we have:

$$s_{ij}(X_{ij}, \theta, p) + \sum_{v \in N_i} \left(p_{iv} - \frac{dC(\mathbf{q}_i, \mathbf{r}, \mathbf{w}_i)}{dq_{iv}} \right) \frac{ds_{iv}(X_{iv}, \theta, p)}{dp_{ij}} = 0 \tag{11}$$

One of the key innovations in Berry (1994) is noting that $\frac{ds_{ij}(X_{ij},\theta,p)}{dp_{ij}}$ can be written as a function of market shares. Within the multi-product firm context, we also need $\frac{ds_{iv}(X_{iv},\theta,p)}{dp_{ij}}$, $v \neq j$, which represents the cannibalization effect of one variety within the firm against another. By using (8), it is straightforward to show that:

$$\frac{ds_{ij}(X_{ij}, \theta, p)}{dp_{ij}} = -\alpha s_{ij}(1 - s_{ij}) \tag{12}$$

and

$$\frac{ds_{iv}(X_v, \theta, p)}{dp_{ij}} = \alpha s_{iv} s_{iv} \tag{13}$$

The signs of are intuitive. Raising the price of variety j within the firm increases demand for

$v \neq j$ and decreases demand for j. Within a nested-logit framework, which we will also use for the analysis, the share equations involve upper-tier market share probabilities, and hence equation is still tractable but more involved.

Substituting the price effects into (14), and simplifying, we have:

$$\left(p_{ij} - \frac{dC(\mathbf{q}_i, \mathbf{r}, \mathbf{w}_i)}{dq_{ij}}\right)(1 - s_{ij}) - \sum_{v \neq j,} \left(p_{iv} - \frac{dC(\mathbf{q}_i, \mathbf{r}, \mathbf{w}_i)}{dq_{iv}}\right) s_{iv} = \frac{1}{\alpha} \tag{14}$$

Arranging in matrix form using all varieties for firm i, and henceforth defining the market share of variety v sold by firm i as s_{iv} we have:

$$\underbrace{\begin{bmatrix} (1-s_{i1}) & -s_{i2} & -s_{i3} & \dots \\ -s_{i1} & (1-s_{i2}) & -s_{i3} & \dots \\ -s_{i1} & -s_{i2} & (1-s_{i3}) & \\ \vdots & \vdots & & \ddots \end{bmatrix}}_{\mathbf{S_i^{mnl}}} \underbrace{\begin{bmatrix} p_{i1} - \frac{dC(\mathbf{q}_i, r, \mathbf{w}_i)}{dq_1} \\ p_{i2} - \frac{dC(\mathbf{q}_i, r, \mathbf{w}_i)}{dq_2} \\ p_{i3} - \frac{dC(\mathbf{q}_i, r, \mathbf{w}_i)}{dq_3} \\ \vdots \end{bmatrix}}_{\mathbf{P_i - MC_i}} = \underbrace{\begin{bmatrix} \frac{1}{\alpha} \\ \frac{1}{\alpha} \\ \frac{1}{\alpha} \end{bmatrix}}_{\mathbf{a}}$$

Hence, for a given set of market shares for firm i's varieties, the vector of marginal costs varieties produced by firm i can be written as:

$$\mathbf{MC_i} = \mathbf{P_i} - \left(\mathbf{S_i^{mnl}}\right)^{-1} \mathbf{a} \tag{15}$$

In a moment, we will specify these variety-specific marginal costs as a function of variety-level attributes and expected marginal adjustment costs. However, to better capture patterns of substitution, we now derive the demand-side for multi-product firms under a nested-logit structure.

2.3.2 Nested Logit

For nested logit, (15) has the same form, but accounts for within "group" substitution that may be different from across groups.[7] Defining groups by $g \in G$, with some variety $j \in g$, the matrix $\mathbf{S_i^{nl}}$, with elements labeled as S^i_{jl}, is defined as follows

$$\begin{aligned} S^i_{jl} &= 1 - \sigma s_{ij/g} - (1-\sigma)s_{ij} \quad if \quad j = l \\ &= s_{il} \quad if \quad j \neq l \quad \& \quad h \in g \\ &= -s_{il} \quad if \quad j \neq l \quad \& \quad h \notin g \end{aligned}$$

Other than this alternate definition of the matrix of market-shares that determines mark-ups, the setup of nested logit is identical to standard logit.

With the systems of demand in place, and the method to recover mark-ups and hence marginal costs identical to Berry (1994), we now move to quantifying the role of attributes and adjustment costs in overall marginal costs, and testing the specific predictions of the adjustment cost model.

3 Quantifying Adjustment Costs

In the previous section, we derived a model of multi-product firms using a discrete choice model of demand. As is the case with logit-based demand models, one can explicitly invert the first-order conditions to solve for mark-ups, and relative to price, solve for marginal costs. We now describe our case-study that is used to estimate marginal costs and the role of adjustment cost.

The data we use to test the model is from *R. L. Polk* (Polk) for the North American Light truck

[7] Specifically, the utility of variety j that lies within group g is written as:

$$u_j = \delta_j + \zeta_g + (1-\sigma)\epsilon_j$$

where ϵ_j and ζ_g are both distributed extreme value. When $\sigma = 1$, individuals only care about group utility and view varieties within a group as perfectly substitutable.

market for model years 1990-2000. This data is matched to MSRP pricing from *Wards Automotive*. The advantage of the Polk data is that sales (in units) are broken down by permutations of the first 11-entries of a vehicle identification number. This can be linked back to product characteristics, as well as the plant of production.

It is these product characteristics that define varieties. Specifically, a variety is assumed to be defined by its unique permutation of model, weight class, engine type (litres, cylinders, fuel type), body style (extended cab, crew cab), drive type (2x4 or 4x4), brand, and heavy duty or long bed options. In our dataset, we have approximately 845 distinct varieties produced by Chrysler, Ford, and GM in an unbalanced panel over 1990-2000.

The data has been organized into definitions of broad vehicle type, called "Platforms", which represent a similar type and style that are refined into different models and then varieties. Importantly, automotive production is largely organized around these platforms, where plants may make many varieties, but are rarely equipped to make many platforms.[8] Below, varieties will be placed into three groups, the most important of which being those within offshored and inshored platforms, where the former were vehicle types that received new capacity in Mexico during the sample period, and the latter were vehicle types that received new US capacity. The final platform is the "no change" or "existing" group, in which there was no change in capacity over this period (though there may be multiple plants). Within these groups, we will identify varieties that were produced at different types of capacity, and any association with the marginal costs of production.

3.1 Demand Estimation

Through the lens of the discrete choice framework, once we estimate α (and σ if assuming a nested logit), we can back-out implied marginal costs and estimate the relationship between expected

[8] There are many reasons for this. First, since platforms share many common parts, there are economies of scale in inventories and management of a particular platform. Second, platforms may different substantially in size, so the human-factors design of plants - that there should be little wasted movement - would suggest that production is organized by platform.

adjustment cost and recovered marginal costs. Again, we need to use instruments to identify the effects adjustment costs on marginal costs, and since we are also in the discrete choice space, we will need to use instruments to identify the price coefficients that determine market shares. We begin by discussing the demand estimation and instrumental variable strategy used to identify the critical coefficients to recover marginal costs.

To estimate the price coefficients, we start from the following equation from Berry (1994) that is general enough for nested logit, but also includes standard logit as a special case:

$$\ln(s_{ijgt}) = \ln(s_{0t}) + \alpha p_{ijgt} + \sigma \ln(s_{ijgt/gt}) + \log(Curb_{ijt}) + \log(LXW_{ijt}) + l_{ij} + d_t + \epsilon_{ijgt} \quad (16)$$

Here, $\ln(s_{0t})$ is the market share of the outside good, which due to only having one market (North America), will be absorbed in a fixed effects strategy, p_{ijgt} is the price (in thousands) of variety j produced by firm i which is classified in some group g in year t, s_{ijgt} is its market share, and $s_{ijgt/gt}$ the market share within group g in year t. Of note, setting $\sigma = 0$ forces the model to be standard multinomial logit. The estimation is accomplished via classic panel regression, with l_{ij} representing variety fixed effects to control for the permutations of attributes that define product variety, and d_t year effects to control for common trends. To control for attributes of the variety that are time-varying, we include the log of the curb weight of the vehicle, $\log(Curb_{ijt})$ and the log of the footprint of the vehicle, $\log(LXW_{ijt})$.

Key to the estimation of (16) is finding instruments for prices and within group market shares. Following the literature, we will use the sum of product characteristics of rivals within each group in each year. For groups, we assume that firms choose broad product class first (compact van, full size fan, compact pick-up, full-size pick-up, compact suv, or full-size suv) and then choose amongst varieties across firms within the vehicle class. Thus, groups are defined by all permutations of vehicle type and size classification.

The estimates from this IV approach are presented in Table 1, where we use variety and year fixed effects and the instrumental variables strategy described above. Columns one and three show the typical problem with regressing quantities on price with OLS - positive coefficients due to the endogeneity problem. In columns two and four, we implement the IV using the rival, within-group product characteristics as instruments. Here, we find sensible estimates for the coefficient on price (where prices are defined in thousands to improve readability of the estimates). Further, the variable σ equals 0.628, which is within the feasible bounds of a nested logit framework.

Calculating markups using the nested logit formula and results from Table 1, we present the distribution of these mark-ups, pre and post NAFTA, in the top panel of Figure 1. Indeed, given the significant increase in the number of varieties available to consumers in this light-truck segment, the distribution of mark-ups shifted inward post-NAFTA. This occurs for two reasons: one intuitive and one mechanical. First, there is significant increase variety in the light truck market over this period which reduced market shares and thus mark-ups. Second, prices rose over this period, but this particular nested logit estimator does not produce wild variation in absolute mark-ups, so the percentage mark-up will fall naturally with prices rising faster than the price cost wedge.

Interestingly, in the bottom panel of Figure 1, we find that estimated costs rose and the spread of the distribution increased substantially. Again, there was a significant expansion in different varieties in certain segments of light truck - in particular very large trucks - and the distribution of estimated costs reflects this.

3.2 Variety Linkages through Marginal Costs

Before attempting to precisely quantify the role of adjustment costs in marginal costs, we return to the simple adjustment framework and the results from Lemma 2 to evaluate whether varieties are linked through the cost function. As a reminder, Lemma 2 predicted that if the combined within-firm market share of two varieties was greater than the Herfindahl Index of production with the firm, then production of one variety increases the marginal cost of the other variety. Precisely, if $\tilde{s}_{il} + \tilde{s}_{ij} > HHI_i$ for firm i and two varieties j and l, then $\frac{\partial \mathbb{E}[MC_{ij}]}{\partial q_{il}} > 0$. Since own marginal cost is decreasing in quantity, this suggests that if $\tilde{s}_{il} + \tilde{s}_{ij} - HHI_i > 0$ there is a negative correlation between marginal costs. In contrast, if $\tilde{s}_{il} + \tilde{s}_{ij} - HHI_i < 0$, then there is a positive correlation between marginal costs through production decisions.

To test these predictions, we construct a dataset of variety-to-variety correlations in marginal costs after accounting for variety-specific, time-invariant costs as well as aggregate trends in costs for different types of varieties. Precisely, the marginal costs we use to construct correlations are defined as the *residual* from the following regression:

$$MC_{ijt} = \beta_c \ln(curb_{ijt}) + \beta_s \ln(LXW_{ijt}) + l_{igt} + f_{ij} + \varepsilon_{ijt} \tag{17}$$

In (17) l_{igt} represents grouped firm-type-year fixed effects that are meant to capture cost trends in vehicle types at the firm-level. The variable f_{ij} represents a time-invariant variety-specific differences in costs for variety j produced by firm i, $\ln(curb_{ijt})$ is meant to capture how costs change with the overall mass (curb weight) of the vehicle, and $\ln(LxW_{ijt})$ is meant to capture any effects of size on marginal costs. Again, we use the residuals from this regression to evaluate correlations that are unrelated to attributes, size or trends (and therefore focused on costs not related to inputs).

Then, we construct pairs of varieties where we expect linkages to be present. To do this, we first calculate the correlation in residual costs for all pairs of varieties within the same firm that overlap in at least two years. We label this correlation as ρ_{jl} for varieties j and l. Then, we identify whether each within-firm pair j and l are ever produced at the same plant in the same year. If they are, then they are identified as "within plant" varieties. Finally, we construct the measures of market share to test Lemma 2. Since varieties are in many cases produced across multiple plants, we calculate the average plant-level market share for each variety, labeled $\tilde{\mu}_j$ and $\tilde{\mu}_l$, as well as the average Herfindahl index at all plants that produce either variety, HHI_{jl}.

To test for variety linkages, we run two regressions on two different samples. First, we test for the association between $\tilde{s}_{il} + \tilde{s}_{ij} - HHI_i$ and ρ_{jl}, but not accounting for whether the former is greater or less than zero:

$$\rho_{jt} \quad = \quad \beta_1 \left(\tilde{\mu}_j + \tilde{\mu}_l - HHI_{jl}\right) + \varepsilon_{ijt} \tag{18}$$

Second, we group variables together and test of a discrete impact exactly as indicated in Lemma 2,

$$\rho_{jt} \quad = \quad \beta_1 \mathbf{1} \left(\tilde{\mu}_j + \tilde{\mu}_l - HHI_{jl} > 0\right) + \varepsilon_{ijt} \tag{19}$$

We estimate both (18) and (19) using the within-plant sample, and also a within-firm but not within-plant sample. The latter is meant to be a falsification test, since the theory has no predictions regarding costs correlations of varieties that are not produced in the same plant. In both regressions and for both samples, we will also include manufacturer or platform fixed effects to account for broad correlations in residual costs. Finally, we use two-way clustering by each variety in the pair to adjust standard errors.

The results from estimating (18) are presented in Table 2. Here, we find strong and novel support for the relationship between combined within-plant market shares and residual cost correlations. In the first three columns, using the within-firm but not within-plant sample, we find virtually no relationship between within plant market shares and residual cost correlations. However, in columns four through six, we find a consistently significant and negative relationship between combined plant-level market shares and residual cost correlations, as the adjustment cost theory predicts.

Using (19), we next test the strict relationship from Lemma 2 in Table 3. Again, we find basically no relationship between the statistic in Lemma 2 and residual cost correlations when varieties are not produced in the same plant. In contrast, when using the within-plant sample, we find a negative residual cost correlation when the average combined plant-level market share is greater than the average plant-level Herfindahl index.

3.3 Marginal Costs

To estimate the role of adjustment costs at the variety level, we adopt a linear specification that is a function of expected adjustment costs, product attributes, and firm-group specific time trends:

$$MC_{ijt} \;\; = \;\; \beta\psi^{std}_{ijt} + \beta_{curb}\ln(curb_{ijt}) + \beta_{lw}\ln(LXW_{ijt}) + f_j + l_{igt} + \varepsilon_{ijt} \tag{20}$$

In 20, ψ^{std}_{ijt} represents a measure of expected marginal adjustment costs, standardized at the sample mean. Below, we discuss the construction of two measures of adjustment costs used for the analysis, and instruments for these measures. To account for product attributes, we include time varying attributes for the curbweight ($\ln(curb_{ijt})$) and footprint of the vehicle ($\ln(LXW_{ijt})$), as well as variety fixed effects, f_{ij} to account for the attributes that defined each variety and their effects on cost. Finally, we include firm-vehicle type-year controls, l_{igt}, to control for any correlated shocks across similar vehicle types within and across firms.

Constructing expected adjustment costs

We now develop a strategy to measure expected adjustment costs and then instrument for it within a two-stage regression model. In (3), we defined expected adjustment costs within the firm. However, since many varieties are produced across multiple plants, and pricing is by variety (not by variety-plant pair), we need to aggregate the measure of average adjustment costs to the variety level.

To begin, we define the "adjustment factor" as the measure of expected marginal costs for variety j in (3) without the characteristic-specific adjustment costs (the r's):

$$\psi_{ijpt} = \sum_{v\in N_{ipt}} \sum_{w\in N_{ipt}} \tilde{s}_{ivpt}\tilde{s}_{iwpt} \sum_{k=1}^{K} I^k_{vw} + 2\left(1 - 2\tilde{s}_{ijpt}\right) \sum_{w\in N_{ipt}} \tilde{s}_{iwpt} \sum_{k=1}^{K} I^k_{jw} \tag{21}$$

where $\tilde{s}_{ivpt}$ is the within-plant market share of variety v produced by firm i at plant p in year t, and N_{ipt} is the set of varieties that are produced by firm i at plant p in year t. From here, we average by weighting across production at plants that produce variety j in year t, which is defined by the set P_{ijt}.

$$Gadjust_{ijt} = \frac{\sum_{p \in P_{ijt}} \psi_{ijpt} q_{ijpt}}{\sum_{p \in P_{ijt}} q_{ijpt}} \tag{22}$$

We will refer to this as the general adjustment factor, which measures the average marginal adjustment costs in producing variety j.

As above, we will also simplify this measure by assuming that each variety is defined by a unique characteristic, so that an adjustment cost is incurred if one variety is different from the next (independent of how many differences, there are in characteristics, if any). Using (21), we set $K = 1$ and $I^k_{jw} = 1$ for all $j \neq w$ and 0 otherwise to get

$$\psi^s_{ijpt} = (1 - \tilde{s}_{ivpt})^2 (1 + HHI_{ipt,\neq j}) \tag{23}$$

where $HHI_{ipt,\neq j}$ is the Herfindahl of index of production for plant p in year t not including variety j. As with $Gadjust_{ijt}$, we weight this by plant-level production to get the simplified measure of complexity at the variety level:

$$Sadjust_{ijt} = \frac{\sum_{p \in P_{ijt}} \psi^s_{ijpt} q_{ijpt}}{\sum_{p \in P_{ijt}} q_{ijpt}} \tag{24}$$

Below, we use both $Sadjust_{ijt}$ and $Gadjust_{ijt}$ in all specifications that evaluate the role of adjustment costs in pricing. However, before we detail and run these regressions, we describe an instrumental variable strategy to address the endogeneity of $Sadjust_{ijt}$ and $Gadjust_{ijt}$ to output.

Instruments for Adjustment Factors

Clearly, both $Sadjust_{ijt}$ and $Gadjust_{ijt}$ are functions of market shares and structurally endogenous to the costs of production (and subsequent effects on pricing). Thus, a valid instrument must be found that affects market shares but is not directly affected by the unobserved shocks to production costs. To motivate these instruments, we focus on the simple adjustment factor, ψ^s_{ijpt}. In this factor, there are two components to consider - the within plant market share of variety j, and the concentration of other varieties within the plant. The former is clearly endogenous, and the latter will be endogenous unless cost shocks to j have a proportional effect on market shares of other varieties.

As in Berry, Levinsohn, and Pakes (1995), we assume that attributes of competing varieties, which are determined prior to production in a given year, are a good instrument that will shift market shares but away from the variety in question, but not be directly affected by costs since the attributes of competing varieties are set in advance. By analogy, we use the log of the sum of curbweight across all varieties within the plant not equal to variety j.[9] For the second component of ψ^s_{ijt}, the concentration index of other varieties, we use the number of varieties within the plant not equal to j. While it's possible that this could adjust during a given year, it is more likely that plants plan for the varieties that they must produce prior to production taking place, and the utilized instrument is motivated by this observation. For both instruments, we construct a weighted average of plant-level instruments using plant-level production for each variety.

Results

The results from estimating (20) are presented in Table 4. In this table, columns one and four run a standard OLS regression using simple and general adjustment costs respectively. Columns two and three use an IV strategy for simple adjustment, and five and six for general adjustment.

First, focus on columns one and four. In these columns there is a tiny, negative, and insignificant effect of expected marginal adjustment costs on the marginal costs of production. Indeed, there is a very severe endogeneity problem in these regressions, where any unobserved shock to marginal costs

[9] Since within plant attributes are highly correlated, we only use curbweight here since it provides the most variation.

will adjust the pattern of production and change the underlying measure of expected adjustment costs. To get around this, as described above, an instrumental variables strategy is used. In columns two and three, simple adjustment costs are instrumented as described above, and we find a significant, positive impact of expected marginal adjustment costs on marginal costs. When using firm-year fixed effects as opposed to the more rigorous firm-type-year fixed effects, the strength of the instruments are a bit weak, but closer to conventional levels when using firm-type-year fixed effects. In terms of quantifying these effects, using the more rigorous firm-type-year effects, we see that a one standard deviation increase in the simple adjustment factor is equivalent to a 0.31 log point increase in curbweight. Thus, this effect is fairly large relative to the effects of vehicle size.

The primary issue with using simple adjustment costs is that it is constructed assuming that varieties are each defined by a unique characteristic. In reality, some varieties, while different, only have subtle differences in characteristics like liters in the engine, rather than many large differences like liters, cylinders, cab types, and drive type. To capture this, the general adjustment factor accounts for the exact differences in varieties as determined by differences in characteristics. The results from using general adjustment and the described instrumental variables strategy are presented in columns five and six of Table 4. Here, we find decidedly smaller effects of the standardized general adjustment factor, but far more precise and far better in terms of the strength of the instrument. Precisely, when using firm-type-year fixed effects, a one standard deviation increase in general complexity increases marginal costs by about $500. This is about one seventh the effects of a log point increase in vehicle curb weight.

Offshoring and Inshoring

To extend the analysis in Table 4, we now exploit a characteristic of the light-truck market in the 1990s, which is that a number of new facilities were opened, both inshore and offshore, to produce certain platforms of truck. The most commonly known examples of these new facilities are in Mexico, where NAFTA reduced significantly the tariff applied to light trucks imported from Mexico.

However, also important during this period was that many new and refurbished (or previously shuttered) car facilities were opened in the US to meet the exploding demand for light trucks. Thus, this change after NAFTA provides a setting in which to at least correlate sourcing decisions, expected adjustment costs, and estimated marginal costs.

To do this, we essentially run the same type of specification as in (20), but with a full interaction with three indicator variables: $Both_{ijt}$, $Inshore_{ijt}$ and $Offshore_{ijt}$. Respectively, each variable identifies whether variety j in year t was produced at new facilities both inshore and offshore, only inshore, and only offshore. The other category that will be excluded are those varieties not produced at a new facility.

The results from this full interaction are presented in Table 5. All columns use the instrumental variable strategy described earlier, with the first three columns using simple adjustment and the second three columns using general adjustment costs. Columns one and four are the baseline estimates from Table 4 using the two measures of adjustment costs. First, focus on columns two and five, where the sourcing dummies have been added but no interaction with the adjustment factors. Interestingly, there is a clear ordering of the role of different sourcing options on costs. After controlling for variety fixed effects, firm-type-year fixed effects, time-varying attributes, and instrumented complexity factors, varieties produced at both offshore and inshore locations have a higher estimated marginal cost. Just below this effect are those varieties only produced at new inshore locations. In both cases, the results are significantly different from zero. For those varieties only produced offshore, there is no significant difference in costs compared to those produced at existing facilities in North America.

Finally, in columns three and six of Table 5, the sourcing dummy variables described above are interacted with the simple and general adjustment factors. Again, the results suggest an interesting ordering of interaction effects that are largest for those varieties produced at new facilities both inshore and offshore. Interestingly, in both the case of simply adjustment and general adjustment, the role of standardized adjustment costs for the excluded category is essentially identical between columns three and six. There is a significant increase in the effects of adjustment costs for those varieties produced both inshore and offshore.

4 Inferring Adjustment Costs through Allocations

In the final section of the paper, we exploit the first order conditions from a plant-level allocation problem to derive a novel constrained minimum distance estimator to evaluate the role of adjustment costs and different characteristics. One interesting feature of the data and the light truck market more generally is that the same variety is often produced across different plants. Focusing only on varieties that are produced across more than one plant, the observed allocation of production across plants can be exploited to infer the parameters of costs that determine this allocation. Indeed, if the cost of adjustment for one characteristic is relatively high at a particular plant, we should expect a lower share of production at that plant for varieties that have that characteristic.

To put more structure on this, consider a simple expansion of the expected marginal cost function from (3) to be defined by plant:

$$\begin{aligned}
\frac{\partial \mathbb{E}\left[C_i\right]}{\partial q_{ijp}} &= \epsilon_{ij} + d_p + \sum_{k=1}^{K} r_k^p \underbrace{\left(\sum_{v \in N_{ip}} \sum_{w \in N_{ip}} \tilde{s}_{ivp} \tilde{s}_{iwp} I_{vw}^k + 2\left(1 - 2\tilde{s}_{ij}\right) \sum_{w \in N_{ip}} \tilde{s}_{iwp} I_{jw}^k \right)}_{f_{ijpk}} \\
&= \epsilon_{ij} + d_p + \sum_{k=1}^{K} r_k^p f_{ijpk} \qquad (25)
\end{aligned}$$

Here, $\tilde{s}_{ivp}$ is the within-plant market share of variety v, N_{ip} is the set of varieties produced by firm i at plant p, and d_p is a plant-level cost shifter that is added to reflect that certain plants may be higher or lower cost, on average, due to distance from markets, age, or more nuanced factors like the shadow value of a capacity constraint.

Working with this marginal cost function presents a number of challenges. First and foremost, cost data by plant-variety-year does not exist (publicly, at least). Second, the specification includes fixed effects by plant as well as characteristic-specific adjustment costs, r_k^p. To deal with the first challenge, since we observe within-plant market shares, the pattern of production can be used under the assumption of efficient allocation across plants. That is, if the firm is allocating varieties efficiently in equilibrium, then variety-level marginal costs must be equalized across plants that produce the same variety. Formally, it must be the case that:

$$d_p + \sum_{k=1}^{K} r_k^p f_{ijpk} = d_{p'} + \sum_{k=1}^{K} r_k^{p'} f_{ijp'k} \quad \forall\ p, p' \ \in P_{ijt} \tag{26}$$

This motivates a measure of squared distance from the efficient allocation for variety j produced at plants p and p':

$$D_{jpp'} = \left(\left(\sum_{k=1}^{K} r_k^p f_{ijpk} - \sum_{k=1}^{K} r_k^{p'} f_{ijp'k} \right) + (d_p - d_{p'}) \right)^2 \tag{27}$$

One cannot estimate all r_k^p's and d_p's without restrictions. Obviously, one set of parameter estimates that sets $D_{pp'} = 0 \ \forall\ p, p' \in P_{ij}$ is setting every parameter to zero. To avoid this corner solution, we manipulate $D_{pp'}$ to form an intuitive normalization that also sets up the parameter estimation as a quadratic programming problem. Specifically, we divide all costs parameters by $r = \sum_{p \in P_{ij}} \sum_{k=1}^{K} r_k^p$, representing all new parameters with a tilde. Thus, when estimating, it must be the case that $\sum_{p \in P_{ij}} \sum_{k=1}^{K} \tilde{r}_k^p = 1$, which provides the normalization required to estimate relative adjustment costs across different plants.

Overall, to estimate the relative costs of adjustment at different plants, we solve the following quadratic programming problem:

$$\min_{\tilde{\mathbf{r}},\tilde{\mathbf{d}}} D = \sum_i \sum_j \sum_{(p,p')\in\tilde{P}_{ij}} \left(\left(\sum_{k=1}^{K} \tilde{r}_k^p f_{ijpkt} - \sum_{k=1}^{K} \tilde{r}_k^{p'} f_{ijp'kt} \right) + \left(\tilde{d}_p - \tilde{d}_{p'} \right) \right)^2 \quad (28)$$

$s.t.$

$$\sum_{p\in P_{ij}} \sum_{k=1}^{K} \tilde{r}_k^p = 1 \quad (29)$$

$$\tilde{r}_k^p \geq 0 \quad (30)$$

Here, we have extended the model to include a time dimension, but assume that all parameters are time invariant. Further, to save on notation, we have defined $\tilde{P}_{ijt}$ as the set of all unique plant pairs of firm i that produce variety j in year t.

The results from solving (28) under a variety of assumptions are presented in Tables 6 and 7. In Table 6, we do not distinguish between plant types, instead minimizing the within-variety-year differences in expected marginal adjustment costs across plants with respect to nine characteristic parameters. To reiterate, all estimates of these adjustment parameters must add to one in each table. In terms of inference, we run 500 bootstrap replications on the entire sample and generate 95% percentile intervals for each parameter using the empirical distribution from the bootstrap estimates.

Interestingly, in Table 6, there are four parameters that appear to have very little impact on expected marginal adjustment costs: the particular model name, liters in the engine, the presence of a heavy duty package, and the presence of an extended cab. In the case of the first parameter, this amounts to comparing different nameplates of similar platforms, which may amount to only changing the badge on the front of the vehicle and very few other things. Similarly, for liters in the engine, while noticeable in terms of vehicle performance, the defining characteristic of an engine (in terms of production) is usually it's size in terms of number of cylinders. It is unclear why heavy duty and extended cab trucks come in the way they do, but the results suggest that they are relatively unimportant in terms of adjustment costs.

In terms of those characteristics that have a large effect on expected adjustment costs, the number of cylinders, having a 4X4 or diesel engine, a long truck bed, and having a crew cab, all have a significant effect on adjustment costs that is above zero. Interestingly, these attributes tend to be associated with larger changes to the truck. For example, having a long-truck bed physically changes the dimensions of the vehicle, as does having a crew cab with different types of seats, additional doors, and other interior options (at least more so than extended cabs). Thus, it is intuitive that these types of characteristics associate with larger expected adjustment costs.

Finally, we solve (28) when assuming that the expected costs of adjustment may vary by plant type: existing, offshoring, and inshoring. These results are presented in Table 7. As a reminder, while all the estimates are lower than in Table 6, the sum still equals one across all 27 estimates in the table. The results show interesting differences in adjustment parameters across different plant types. Like before, the model of the vehicle and liters in the engine have little effect on overall adjustment costs. Further, for some attributes, like 4X4, offshore facilities face relatively higher adjustment costs compared with other facilities. In contrast, for attributes like crew cab and a heavy duty package, new inshore facilities seem to face higher adjustment costs.

5 Conclusion

This paper has presented a novel model of production for different varieties with potential adjustment costs. A variety incurs a larger adjustment cost if it is relatively small in demand, where extra labor or time is requires to finish a variety which is relatively infrequent. We test for these effects using two models of demand using a case study of light truck production in the US, and find broad support for the role of adjustment costs. Further, we show that these costs are higher for varieties that are produced jointly offshore and inshore. Finally, we develop an estimator to minimize deviations from marginal cost equalization across plants to recover attribute-specific adjustment costs.

The results suggest that certain attributes are far more costly than others to organize in production, and that inshore and offshore facilities are tooled for different types of varieties.

In terms of future work, there are two obvious areas to build on this model. In terms of the cost function itself, inventories and batch production are not present, and including inventories to meet demand would push the model more inline with the structure of many large production facilities.

Finally, within an international context, the model and empirical results suggest that different products and markets will be linked within the cost function. That is, a shock to a developed market in a high quality variety might affect the costs of producing for the developing market that demands a low quality variety. Further, some markets charge different tariffs within narrowly defined products. Thus, the adjustment cost framework may provide novel insight into trade shocks and the connections between different markets.

References

Arkolakis, C., S. Ganapati, and M.-A. Muendler (2015): "The extensive margin of exporting products: A firm-level analysis," Discussion paper, National Bureau of Economic Research.

Berry, S., J. Levinsohn, and A. Pakes (1995): "Automobile prices in market equilibrium," *Econometrica: Journal of the Econometric Society*, pp. 841–890.

Berry, S. T. (1994): "Estimating discrete-choice models of product differentiation," *The RAND Journal of Economics*, pp. 242–262.

Cosar, A. K., P. L. Grieco, S. Li, and F. Tintelnot (2015): "What Drives Home Market Advantage?," Discussion paper, National Bureau of Economic Research.

Costinot, A., L. Oldenski, and J. Rauch (2011): "Adaptation and the boundary of multinational firms," *The Review of Economics and Statistics*, 93(1), 298–308.

Eckel, C., and J. P. Neary (2010): "Multi-product firms and flexible manufacturing in the global economy," *The Review of Economic Studies*, 77(1), 188–217.

Feenstra, R. C. (1988): "Quality change under trade restraints in Japanese autos," *The Quarterly Journal of Economics*, 103(1), 131–146.

Goldberg, P. (1995): "Product differentiation and oligopoly in international markets: The case of the US automobile industry," *Econometrica*, pp. 891–951.

Goldberg, P., and F. Verboven (2005): "Market integration and convergence to the Law of One Price: evidence from the European car market," *Journal of International Economics*, 65(1), 49–73.

Goldberg, P. K. (1998): "The effects of the corporate average fuel efficiency standards in the US," *The Journal of Industrial Economics*, 46(1), 1–33.

Head, K., and T. Mayer (2013): "What separates us? Sources of resistance to globalization," *Canadian Journal of Economics/Revue canadienne d'économique*, 46(4), 1196–1231.

——— (2015): "Brands in Motion: How frictions shape multinational production," .

Hellerstein, R., and S. Villas-Boas (2010): "Outsourcing and pass-through," *Journal of International Economics*, 81(2), 170–183.

Helpman, E. (1987): "Imperfect competition and international trade: evidence from fourteen industrial countries," *Journal of the Japanese and international economies*, 1(1), 62–81.

Keller, W., and S. R. Yeaple (2013): "The gravity of knowledge," *The American Economic Review*, 103(4), 1414–1444.

McCalman, P., and A. Spearot (2013): "Why trucks jump: Offshoring and product characteristics," *Journal of International Economics*, 91(1), 82–95.

——— (2015): "Relaxing CAFE: Foreign Direct Investment, NAFTA, and Domestic Product Standards," *Canadian Journal of Economics*.

Milgrom, P., and J. Roberts (1990): "The economics of modern manufacturing: Technology, strategy, and organization," *The American Economic Review*, pp. 511–528.

Oldenski, L. (2012): "Export Versus FDI and the Communication of Complex Information," *Journal of International Economics*.

Sly, N., and A. Soderbery (2014): "Strategic sourcing and wage bargaining," *Journal of Development Economics*, 109, 172–187.

Van Biesebroeck, J. (2007): "Complementarities in automobile production," *Journal of Applied Econometrics*, 22(7), 1315–1345.

Table 1: Discrete Choice Demand

VARIABLES	(1) ln(s)	(2) ln(s)	(3) ln(s)	(4) ln(s)
$\ln(\sigma_{ijt/gt})$			0.953***	0.612***
			(0.006)	(0.041)
p_{ijt}	0.016	-0.313***	0.017***	-0.118***
	(0.011)	(0.073)	(0.003)	(0.034)
ln(Curb Weight)	-0.333	0.246	-0.258***	-0.049
	(0.240)	(0.313)	(0.065)	(0.136)
$\ln(LxW)$	0.377*	0.191	0.091	0.117
	(0.206)	(0.249)	(0.056)	(0.107)
Observations	3,015	2,871	3,015	2,871
Estimation	OLS	IV	OLS	IV
First Stage (alpha) F		9.811		9.811
First Stage (sigma) F				27.58

Unit of observation is Variety-Year. Prices in thousands

Variety and Year Fixed Effects included in all specifications

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 2: Variety Linkages - Correlations in Marginal Cost

VARIABLES	(1) ρ_{jl}	(2) ρ_{jl}	(3) ρ_{jl}	(4) ρ_{jl}	(5) ρ_{jl}	(6) ρ_{jl}
$\tilde{\mu}_j + \tilde{\mu}_l - HHI_{jl}$	-0.460	-0.209	-0.045	-1.273***	-1.166***	-1.276***
	(0.437)	(0.348)	(0.268)	(0.464)	(0.404)	(0.397)
Observations	14,139	14,139	14,139	8,213	8,213	8,213
Manu FE?	N	Y	N	N	Y	N
Platform FE?	N	N	Y	N	N	Y
Within Plant?	N	N	N	Y	Y	Y

Unit of observation is variety-pair. ρ is the correlation in marginal costs for each pair.
Least squares weighted by inverse of standard error of ρ
Robust standard errors in parentheses, two-level clustering by each variety
*** p<0.01, ** p<0.05, * p<0.1

Table 3: Variety Linkages - Correlations in Marginal Cost

VARIABLES	(1) ρ_{jl}	(2) ρ_{jl}	(3) ρ_{jl}	(4) ρ_{jl}	(5) ρ_{jl}	(6) ρ_{jl}
$\mathbf{I}\left(\tilde{\mu}_j + \tilde{\mu}_l - HHI_{jl} > 0\right)$	-0.107	0.001	0.047	-0.270*	-0.213*	-0.178
	(0.169)	(0.130)	(0.097)	(0.145)	(0.114)	(0.114)
Observations	14,139	14,139	14,139	8,213	8,213	8,213
Manu FE?	N	Y	N	N	Y	N
Platform FE?	N	N	Y	N	N	Y
Within Plant?	N	N	N	Y	Y	Y

Unit of observation is variety-pair. ρ is the correlation in marginal costs for each pair.
Least squares weighted by inverse of standard error of ρ
Robust standard errors in parentheses, two-level clustering by each variety
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Quantifying Adjustment Costs

VARIABLES	(1) mc	(2) mc	(3) mc	(4) mc	(5) mc	(6) mc
$Sadjust^{std}$	-32.7	1,129.2**	944.5**			
	(106.0)	(573.7)	(392.7)			
$Gadjust^{std}$				-55.6	389.4**	545.7***
				(105.8)	(175.6)	(203.9)
$\ln(curb)$	2,374.7***	2,274.9***	3,355.7***	2,374.7***	2,329.4***	3,714.6***
	(751.2)	(625.0)	(567.2)	(751.8)	(598.6)	(527.7)
$\ln(LxW)$	-29.4	168.5	-78.2	-35.5	69.8	-173.9
	(494.9)	(488.9)	(494.3)	(497.0)	(439.9)	(436.2)
Observations	2,999	2,854	2,854	3,007	2,854	2,854
Estimation	OLS	IV	IV	OLS	IV	IV
Firm-Year FE?	Y	Y	N	Y	Y	N
Firm-Type-Year FE?	N	N	Y	N	N	Y
Variety FE?	Y	Y	Y	Y	Y	Y
First Stage F		5.213	12.16		207.3	113.8

Unit of observation is Variety-Year

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 5: Quantifying Adjustment Costs - with Offshoring and Inshoring

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
$Sadjust^{std}$	944.5**	621.8*	574.3			
	(392.7)	(372.8)	(490.8)			
$Sadjust^{std}$ x Both?			1,022.5*			
			(562.2)			
$Sadjust^{std}$ x Inshore?			958.1*			
			(579.9)			
$Sadjust^{std}$ x Offshore?			-46.0			
			(417.9)			
$Gadjust^{std}$				545.7***	644.7***	519.6**
				(203.9)	(198.0)	(260.0)
$Gadjust^{std}$ x Both?						1,398.5**
						(624.6)
$Gadjust^{std}$ x Inshored?						-43.7
						(672.3)
$Gadjust^{std}$ x Offshored?						176.7
						(313.3)
Both?		1,612.1***	1,833.7***		1,606.3***	1,637.1***
		(349.3)	(417.2)		(344.5)	(385.5)
Offshore?		273.0	273.2		413.2	321.0
		(294.2)	(334.4)		(283.9)	(355.8)
Inshore?		1,209.7***	1,350.2***		1,255.6***	1,210.6***
		(193.0)	(251.9)		(199.9)	(233.7)
First Stage F	12.16	13.41	13.41	113.8	120.5	120.5

Unit of observation is Variety-Year. Firm-type-year and Variety fixed effects in all regressions.

Curb and LxW omitted from table for clarity.

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 6: Attribute-level Adjustment Parameters

model	0
	[0 , 0]
cyl	0.12
	[0.087 , 0.153]
ltr	0
	[0 , 0]
4X4	0.139
	[0.093 , 0.185]
diesel engine	0.381
	[0.283 , 0.452]
longbed	0.106
	[0.05 , 0.181]
heavyduty package	0
	[0 , 0]
extended cab	0.001
	[0 , 0.016]
crew cab	0.243
	[0.175 , 0.362]

Notes: Estimates are generated by solving (28) subject to (29) and (30), and restricting attribute parameters to be the same across all types of plant. 95% bootstrap percentile intervals from 500 replications in brackets.

Table 7: Attribute-level Adjustment Parameters by Plant Type

	Existing Facility	Offshoring	Inshoring
model	0	0	0.016
	[0 , 0.003]	[0 , 0]	[0.007 , 0.026]
cyl	0.032	0	0.027
	[0.026 , 0.038]	[0 , 0.008]	[0.013 , 0.04]
ltr	0.004	0	0
	[0 , 0.011]	[0 , 0.012]	[0 , 0.007]
4X4	0.026	0.14	0.077
	[0.021 , 0.033]	[0.103 , 0.193]	[0.059 , 0.101]
diesel engine	0.047	0.031	0
	[0.031 , 0.06]	[0.013 , 0.046]	[0 , 0.019]
longbed	0.066	0.117	0.112
	[0.051 , 0.084]	[0.093 , 0.149]	[0.075 , 0.158]
heavyduty package	0.012	0.047	0.088
	[0.005 , 0.02]	[0 , 0.14]	[0.062 , 0.119]
extended cab	0	0.045	0
	[0 , 0]	[0.018 , 0.083]	[0 , 0]
crew cab	0.007	0.023	0.063
	[0.002 , 0.014]	[0 , 0.046]	[0.047 , 0.077]

Notes: Estimates are generated by solving (28) subject to (29) and (30), and allowing attribute parameters to vary by existing plants, new inshore plants, and new offshore plants. 95% bootstrap percentile intervals from 500 replications in brackets.

Figure 1: Distribution of Mark-ups and Costs - Pre and Post NAFTA