Innovation and Pricing Frictions*

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Abstract

This paper studies how pricing frictions over the product life cycle shape innovation and growth. Using detailed product and firm panel data, we show that the average nominal prices of incumbent products exhibit little systematic growth over the life cycle, while new products enter at substantial price premia. We develop and estimate an endogenous growth model with trend inflation and pricing frictions. Anticipating limited price adjustment over a product's life, firms set elevated introductory prices. Product introduction provides an additional opportunity to reset prices, changing both firms' incentives to innovate and the nature of the products they introduce. Pricing frictions shift innovation toward products that facilitate price adjustment but generate smaller quality improvements, which is further verified empirically. Consequently, they can increase total product introduction while reducing aggregate growth and welfare.

JEL Classification: E31, E52, L11, O31, O41

Keywords: Innovation, economic growth, pricing frictions, product life cycle, product introduction, price adjustment.

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1 Introduction

How do pricing frictions shape firms' innovation decisions and, ultimately, economic growth? Standard macroeconomic models typically treat nominal rigidities as short lived and therefore irrelevant for long run outcomes.[1] Because firms are thought to reset prices frequently enough, such frictions are assumed not to influence long-run decisions such as innovation or creative destruction. In this paper, we revisit this view using rich product and firm longitudinal data and show that pricing frictions operate over much longer horizons, as reflected in the evolution of prices over the product life cycle, with significant consequences for the pricing of new products and firms' innovation incentives.

We combine detailed product and firm longitudinal data with a quantitative model of innovation and price adjustment. We document that the average nominal prices of incumbent products exhibit little systematic growth over their life cycle, despite ongoing inflation, while new products enter at substantial price premia. We refer to this limited cumulative adjustment of incumbent prices as *long run pricing frictions*. The entry premium is larger in sectors with greater pricing frictions, and tariff induced cost increases pass-through to the prices of new products but have little effect on incumbent prices. These findings suggest that firms use product introduction as an important margin of price adjustment. We then develop and estimate an endogenous growth model in which pricing frictions shape both the incentives to innovate and the nature of innovation. To the best of our knowledge, this is the first endogenous growth model to incorporate product introduction as an alternative margin of price adjustment and study its implications for innovation and growth. Beyond the expected future profits generated by a new product, long run pricing frictions create an additional incentive to innovate by making product introduction a margin of price adjustment. They also change the nature of innovation by shifting product introduction toward products that facilitate price adjustment but contribute relatively little to economic growth. As a result, pricing frictions can increase total product introduction while reducing aggregate growth and welfare.

We begin the empirical analysis using consumer goods scanner data from 2006 to 2022, with products identified by their barcodes. First, we document that new products enter the market with substantial price premia relative to existing products. We compute average log prices by product cohort and follow their evolution over time, accounting for differences across product sectors and calendar periods. Each successive cohort enters at higher prices than earlier cohorts, with new products priced between 10 and 20 percent above the prevailing price level in their sector. Related evidence from consumer durables shows similar qualitative patterns with new models entering at higher prices than continuing models (Bils, 2009). Our observed premium is

[1] See, for example, Friedman (1968); Woodford (2003); Galí (2015).

pervasive across products introduced by new and incumbent firms, across product categories, and, importantly, across products with different degrees of measured quality improvement, as captured by the novelty of their features relative to those already available in the market. Although higher quality can account for part of the entry premium, even products that introduce relatively few new features enter at substantially higher prices.[2]

Second, we study how the prices of incumbent products evolve over the product life cycle. We follow the same products over several years and estimate age profiles of log prices while controlling for sector, cohort, and calendar time. The resulting profiles summarize the average relationship between prices and product age, around which individual price trajectories can vary. We find that the average nominal price of incumbent products exhibits little systematic growth as products age. Once sector level price trends are absorbed, their relative prices decline by approximately 2 to 3 percent per year over the first five years. The results are robust across specifications and samples and hold when prices are measured for each barcode nationally or at the store level. Prices change frequently in our data, consistent with the evidence in prior work (Bils and Klenow, 2004; Klenow and Kryvtsov, 2008; Nakamura and Steinsson, 2008), but the frequency of these changes does not reveal whether they accumulate into systematic price growth over the product life cycle.

This distinction between price changes and cumulative adjustment in the average life cycle profile is central to our interpretation of long run pricing frictions. By long run, we mean adjustment over the life of a product rather than the response of posted prices over weeks or months. For our analysis, the relevant object is whether price changes cumulatively realign the average nominal price of a continuing product with the aggregate price trend over its life cycle. Because firms can set a new price when they introduce a product, this cumulative adjustment shapes the value of product introduction and, therefore, firms' incentives to innovate. Importantly, the term does not imply that all products follow the same price trajectory or that no products experience substantial price increases. The estimated profiles characterize average price dynamics rather than the price path of every individual product. Moreover, We use the term to characterize this empirical pattern without taking a stand on why the average price of incumbent products exhibits limited cumulative adjustment relative to the aggregate price trend.

Our third empirical finding is that the entry price premium is systematically connected to the degree of price adjustment among incumbent products. We document this relationship using variation across product sectors and across firms within sectors. Across sectors, we

[2] Feature-based estimates for comparable barcode products imply quality improvements smaller than the average entry premia we document (e.g., Cafarella, Ehrlich, Gao, Haltiwanger, Shapiro and Zhao, 2023; Argente, Lee and Moreira, 2024).

construct measures of price rigidity using both the frequency of weekly price changes and the life cycle slope of incumbent prices. These measures capture complementary dimensions of price adjustment. The frequency of price changes measures how often firms adjust posted prices over short horizons, while the life cycle slope measures whether these changes accumulate into systematic price adjustment as products age. We find that sectors with less frequent price changes and more limited cumulative adjustment over the product life cycle exhibit systematically larger entry premia. These relationships are robust to various controls and hold across both measures of pricing frictions. The evidence suggests that when firms adjust the prices of continuing products less systematically, product introduction becomes a more important margin through which they update the price level of their portfolios.

We complement this evidence by exploiting variation across firms within sectors in their exposure to import tariffs. Tariff changes generate cost shocks for firms that sell a larger share of imported products, allowing us to compare how these shocks pass through to incumbent and newly introduced products. We find a pronounced asymmetry. Tariff exposure has little detectable effect on the prices of incumbent products but significantly increases the relative prices of products introduced in subsequent years. This effect is especially large in sectors with greater price rigidity. These findings strengthen the interpretation that firms use product introduction as a margin of price adjustment when the prices of continuing products exhibit limited cumulative adjustment.

Recognizing product introduction as a margin of price adjustment makes it important to distinguish between two forms of innovation (Garcia-Macia et al., 2019; Akcigit and Kerr, 2018). Firms can introduce products that are similar to those already in their portfolios, or they can expand their portfolios by introducing products with new features. We refer to these margins as replacement and expansion innovation. We measure them using the similarity between the features of a new product and those of the firm's incumbent products. A new product is classified as replacement innovation when its features are similar to those already represented in the firm's portfolio, and as expansion innovation when it introduces features that are new to the firm.[3] Both forms allow the firm to set a new price, but they play different economic roles. Replacement innovation is more likely to cannibalize the firm's existing products and provides a way to correct price misalignment for a particular product line, while expansion innovation is more likely to steal business from competitors and fix prices on the product portfolio level.

Motivated by these facts, we develop an endogenous growth model with trend inflation and long run pricing frictions. The framework builds on models of endogenous technological

[3]Replacement innovation includes cases in which the primary change is package size. These cases relate to the literature on shrinkflation, which studies firms' use of product downsizing to raise unit prices without comparable increases in posted package prices (Çakır and Balagtas, 2014; Kim, 2024; Janssen and Kasinger, 2026).

change (Romer, 1990; Aghion and Howitt, 1992; Grossman and Helpman, 1991) and incorporates firm innovation dynamics in the spirit of Klette and Kortum (2004). The model includes both replacement and expansion innovation as endogenous margins. Firms choose their investment in each margin and the introductory price of every newly launched product. After introduction, firms face frictions in adjusting incumbent prices, so inflation gradually erodes their relative prices and markups. We first quantify this baseline environment without idiosyncratic product-level shocks. We then extend the model to allow idiosyncratic productivity shocks and two-sided price adjustment, which accommodates price changes in both directions.

Anticipating that inflation will gradually erode the real price and markup of a product, firms optimally set an introductory markup above the static optimum. A higher initial price keeps the effective markup closer to the desired level over the expected duration of the price spell and raises the value of the product. We refer to this behavior as *price overshooting*. This mechanism is related to the role of inflation expectations in standard New Keynesian models (Werning, 2022). Forward looking firms choose current prices in anticipation of future changes in marginal costs and the aggregate price level. In our setting, this logic applies to the introductory price of a product and generates the entry premia observed in the data.

Long run pricing frictions affect the level of innovation through two opposing forces. First, they reduce product values by limiting firms' ability to maintain desired real markups, lowering profit flows and thus weakening incentives to expand into new product lines. Second, product introduction allows firms to reset prices, making it more valuable as a margin of price adjustment when the price of an existing product is misaligned. The net effect of pricing frictions on the level of innovation must therefore be determined quantitatively. Replacement and expansion innovation also differ in how they affect firm value and generate different quality improvements. Pricing frictions can therefore affect the composition of innovation as well. Importantly, the model allows total product introduction and aggregate growth to move in opposite directions when pricing frictions shift innovation toward replacement innovation that generates smaller quality improvements but cheaper and can be used in price adjustment.

Pricing frictions also generate an endogenous distribution of markups over the product life cycle. New products enter with elevated introductory markups. Inflation then erodes their real prices, while occasional price adjustment and product replacement return products to the reset price. The resulting dispersion creates misallocation because households consume too little of products with elevated markups and too much of products whose markups have been eroded. Innovation affects this distribution by increasing product turnover and returning product lines to their reset prices. This creates a link between innovation, price adjustment, and allocative efficiency that is absent from standard endogenous growth models.

We estimate the baseline model using seven moments capturing replacement and expansion innovation, aggregate growth, the contribution of expansion to growth, expected product duration, price overshooting, and the upper tail of positive price adjustments. We subsequently estimate an extension with idiosyncratic productivity shocks using the age profiles of positive and negative cumulative price changes. Together, these moments discipline the level and composition of innovation, its contribution to growth, and its interaction with price adjustment. This degree of joint empirical discipline is unusual in quantitative studies of innovation. The model closely matches the targeted moments and also reproduces the survival profile of identical products, which is not directly targeted. The estimates imply that persistent realignment of prices within continuing products is rare.

Our results show that innovation accounts for approximately 54.4 percent of these effective price resets, confirming that product introduction is quantitatively important as a margin of price adjustment. The estimated model also reveals substantial differences between the two innovation margins. Replacement innovation raises product quality by approximately 5.7 percent, while expansion innovation raises quality by approximately 21.5 percent. Expansion accounts for about 43 percent of innovation events but approximately 79 percent of aggregate growth. Replacement innovation is therefore comparatively incremental and inexpensive, while expansion innovation is more costly but produces a much larger contribution to growth. These estimates quantify the dual role of product replacement: a new product both improves quality and permits the firm to choose a new price. Earlier measurement studies document large price discontinuities and quality changes at product turnover (Bils, 2009; Nakamura and Steinsson, 2012). We make the replacement decision endogenous and show that the repricing opportunity changes the composition of innovation.

We use the estimated model to quantify how long run pricing frictions affect innovation, growth, and welfare. Moving to frictionless pricing reduces replacement innovation from 6.56 to 5.09 percent and raises expansion innovation from 4.91 to 5.47 percent. Although total innovation falls, aggregate growth rises from 2.04 to 2.13 percent because innovation shifts toward the margin with the larger quality improvement. Pricing frictions also generate meaningful misallocation through the dispersion of markups over the product life cycle. Allocative efficiency is 97.76 percent in the baseline, implying an efficiency loss of approximately 2.24 percent. This loss is of the same order of magnitude as existing estimates of misallocation caused by markup dispersion.[4] Together, improved allocative efficiency and faster growth raise consumption

[4]The mechanisms and counterfactuals differ across these studies, but their estimates provide a useful comparison of magnitudes. Peters (2020) finds that markup dispersion reduces aggregate productivity by approximately 1 percent, while Blanco et al. (2024) estimate productivity losses of 1.3 percent from inefficient price dispersion. Edmond et al. (2022) report value added productivity losses between 2 and 6 percent from markup dispersion. Relatedly, Burstein et al. (2026) estimate that eliminating markup dispersion across buyers of the same intermediate

equivalent welfare by 5.3 percent. Comparative statics deliver the same conclusion. Stronger pricing frictions increase price overshooting and replacement innovation, reduce expansion innovation, and lower growth. More frequent opportunities to reset prices instead compress markup dispersion and shift innovation toward expansion.

In the last part of the paper, we then evaluate these model implications in the data using variation in inflation and pricing frictions across product sectors. Price overshooting rises with inflation, especially in sectors where prices adjust less frequently. Replacement innovation also rises with inflation, while expansion innovation declines. Both relationships are stronger in sectors with greater pricing frictions. These patterns are consistent with the model's central mechanism: when inflation erodes incumbent markups and persistent price adjustment is limited, firms rely more heavily on product replacement and shift away from expansion into new product lines.

Related Literature. This paper contributes to several strands of literature. First, it relates to models of firm innovation and dynamics in general equilibrium (Klette and Kortum, 2004; Acemoglu et al., 2018; Akcigit and Kerr, 2018). Our contribution is to incorporate empirically motivated long run pricing frictions into this framework and to distinguish between replacement and expansion innovation. Pricing frictions change the value of each innovation margin differently because replacement also resets the price of an existing product line. This mechanism connects price adjustment to the composition of innovation and shows that more product introduction need not imply faster growth.

Second, the paper connects to the macroeconomic literature on nominal rigidities. Traditional models emphasize price adjustment at business cycle frequencies and its implications for monetary transmission (e.g., Calvo, 1983; Woodford, 2003; Bils and Klenow, 2004; Klenow and Kryvtsov, 2008; Nakamura and Steinsson, 2008). The reference price literature shows that frequent transaction price changes can coexist with much greater persistence in the price levels around which those changes occur (Eichenbaum et al., 2011; Kehoe and Midrigan, 2015). We document an analogous distinction over the product life cycle and study its implications for innovation and growth. Our analysis also relates to Argente and Yeh (2022), who show that young products adjust prices more frequently because of demand learning, and to Adam and Weber (2023), who document declining relative prices over product age and study their implications for optimal inflation. We instead focus on how life cycle pricing patterns affect firms' product introduction decisions and the composition of innovation.

Our paper is also related to work studying how monetary policy and aggregate economic conditions affect R&D and technology adoption (Moran and Queralto, 2018; Anzoategui et al.,

input raises aggregate productivity by 0.17 to 0.48 percent, or 2.4 to 6.8 percent when normalized by the share of sales affected.

2019; Ma and Zimmermann, 2023). This literature emphasizes how aggregate demand, financial conditions, and the profitability of R&D affect innovation. We study a distinct mechanism through which frictions in adjusting product prices directly shape firms' product introduction decisions and the composition of innovation.

Several mechanisms may contribute to the limited cumulative price adjustment that we document. In particular, Rebelo et al. (2025) show that firms may maintain stable prices to avoid inducing consumers to reconsider their purchasing decisions. Such behavioral forces may also help explain why firms find it easier to change prices when they introduce products with different attributes. Reference prices, customer relationships, organizational practices, and other forces may generate similar life cycle patterns. Our analysis complements this work by taking the observed patterns as an empirical input and quantifying their consequences for innovation and growth.

Third, the paper is closely connected to work on product turnover and the measurement of prices. Bils (2009) documents a sharp contrast between the declining prices of matched durable models and the higher prices observed when new models replace old ones. Using changes in market shares and the persistence of price differences over the model cycle, he concludes that much of the new-model price increase reflects quality growth. Nakamura and Steinsson (2012) show that price indexes following identical products can miss adjustment occurring at product replacement, while Cavallo et al. (2014) show that international relative-price differences arise primarily when products are introduced rather than through subsequent adjustment of identical products. Recent work uses barcode-level transactions data and detailed product information to incorporate product turnover, quality changes, and consumer substitution into price indexes (Cafarella et al., 2023; Ehrlich et al., 2023). We start from the same empirical distinction between price adjustment within continuing products and price setting at product introduction, but emphasize an additional component of the price change at turnover. When the price of an incumbent product has not kept pace with the desired price, introducing a new product allows the firm to reset the accumulated price gap. Quality upgrading and price resetting are therefore not mutually exclusive. We provide evidence for the reset component by showing that entry premia are systematically larger where incumbent prices adjust less and that tariff-induced cost increases pass through to new products but not to continuing products. Rather than constructing a price index, we endogenize product introduction and study how the repricing opportunity changes the level and composition of innovation.

Fourth, the paper contributes to the literature on markups, misallocation, and aggregate growth. Existing work studies how heterogeneous markups across firms distort allocations and affect aggregate outcomes (Peters, 2020; Edmond et al., 2022; Blanco et al., 2024). We introduce a dynamic source of markup dispersion that arises from trend inflation and long run pricing

frictions, even among products with identical underlying productivity. This dispersion evolves with product age and is affected by both conventional price adjustment and innovation. The framework therefore provides a unified way to study how pricing frictions influence product turnover, misallocation, and growth.

Finally, the paper contributes to the literature using tariff shocks to study cost pass through (e.g., Fajgelbaum et al., 2020; Cavallo et al., 2021). Existing work primarily examines average prices, markups, and import patterns. We document a new asymmetry between continuing and newly introduced products. Tariff induced cost increases are reflected in the prices of products introduced in subsequent years but have little detectable effect on incumbent prices. This evidence links trade shocks to product introduction and supports the interpretation of innovation as a margin of price adjustment.

2 Data

In our analysis, we use product-level data to document the life-cycle behavior of prices for incumbent products and to quantify the relative pricing of newly introduced products. We then exploit tariff information to construct measures of firm- and module-level cost shocks, which we use to evaluate how these shocks transmit into the prices of incumbents and new products.

2.1 Product-level data

We primarily use scanner data from the NielsenIQ Retail Measurement Services (RMS), provided by the Kilts–Nielsen Data Center at the University of Chicago Booth School of Business. The RMS records weekly, store-level sales and quantities for every UPC sold through point-of-sale systems in participating retail outlets. The data cover roughly 30% of total U.S. expenditures on food and beverages and about 2% of total household consumption (Beraja et al., 2019). The main strength of this dataset is its breadth and depth, both in the number of products and in the consistency of coverage over time (Argente et al., 2024). Our analysis spans 2006–2022, allowing us to track product prices over a very long horizon.

The dataset includes a wide variety of goods, ranging from food items to semi-durable non-food products. It contains over 1.7 million distinct UPCs, each classified into a hierarchical structure: 1,066 product modules, aggregated into 115 product groups, and then into 10 major departments.[5]

To link products to their producers, we use data from GS1 US, which provides information on the parent companies associated with each barcode prefix. Because GS1 US maintains the

[5]The structure of the source data changed in 2020. Appendix X documents how we harmonize the classification to ensure consistency over the full 2006–2022 period.

universe of company prefixes issued in the United States, we merge these prefixes with the UPCs observed in the RMS. This linkage allows us to map each product to its parent firm and, in turn, to characterize the full product portfolio of every firm represented in our sample.

Our baseline dataset aggregates information for each product across all stores in the sample at a quarterly frequency (or annually for product–year analyses). For every UPC, we observe prices, quantities, and sales, along with detailed product classifications (module, group, department), longitudinal characteristics (age and cohort), and firm-level attributes.

For each product u in period t, we define total sales Y_{ut} as the sum of sales across all stores and weeks in that period. Total quantity sold, y_{ut}, is defined analogously. The nominal price p_{ut} is constructed as the ratio of total sales to total quantity, which corresponds to the quantity-weighted average price.

Throughout the empirical analysis, a firm refers to the manufacturer identified through the GS1 company prefix. NielsenIQ reports transaction prices paid by consumers rather than manufacturer wholesale prices, so we do not directly observe the prices set by manufacturers. Evidence using matched wholesale and retail prices, however, indicates substantial transmission of wholesale-price changes into consumer prices. Besanko et al. (2005) find own-product pass-through exceeding 60 percent in most of the grocery categories they study; Nakamura and Zerom (2010) find that delayed cost pass-through in the coffee industry occurs primarily at the wholesale rather than the retail stage; and Eichenbaum et al. (2011) document a close relationship between retailers' acquisition costs and their reference prices. Because our baseline measure also averages prices across retailers, thereby reducing retailer-specific variation from sales and other temporary pricing decisions, this evidence gives us confidence that changes in average consumer prices reflect, to an important extent, manufacturers' pricing decisions.

To construct longitudinal variables, we infer product age and cohort from the timing of a product's first observed transaction. We define entry as the period in which a product first appears in the data and exit as the first period following its last observed sale. Products already present at the beginning of the sample are classified as left-censored, as their true entry dates cannot be identified. Similarly, products with transactions in the final period of the sample are classified as right-censored, since their exit cannot be observed.

At the firm level, we focus primarily on distinguishing new and incumbent firms and constructing measures of firm size, including the number of products offered and total firm sales.

Our baseline data include all participating stores and exclude private-label products. Table 1 reports descriptive statistics for this sample. To address potential concerns regarding the measurement of product entry and exit, we construct robustness samples that restrict attention to a balanced set of stores and drop products that do not record at least one transaction per

Table 1: Summary Statistics of Products by Censoring

	All	By Censoring Type			
		Not Censored	Right	Left	Right & Left
Total # of products	1,789,738	937,647	372,172	395,179	84,740
Duration (quarters)					
average	21	15	22	25	68
less than 4	22	28	18	14	0
above 20	37	26	39	48	100
above 28	26	15	30	35	100
Revenue (quarterly, $1,000)					
mean	51	23	105	23	207
25th percentile	0.2	0.1	0.7	0	2.1
median	1.6	1.2	5.6	0.5	14
75th percentile	14	9.4	45	5	95
90th percentile	79	44	217	35	444
95th percentile	199	98	478	92	930
Price (quarterly)					
mean	0.097	0.14	0.17	-0.059	0.022
25th percentile	-0.36	-0.34	-0.25	-0.51	-0.36
median	0.13	0.18	0.18	-0.0014	0.015
75th percentile	0.62	0.69	0.64	0.43	0.42
90th percentile	1.1	1.2	1.1	0.9	0.85
95th percentile	1.4	1.5	1.4	1.2	1.1

Notes: The table presents the summary statistics for the products included in the baseline sample for 2006q1–2022q4. Products already active in 2006q1–2006q2 are left-censored; products with sales in 2022q3–2022q4 are right-censored. "Not Censored" includes products observed from entry to exit. "Right Censored" indicates products still sold at the end of the sample. "Left Censored" refers to products already on the market at the start of the sample. "Right & Left" includes products with both entry and exit censored. Duration is in quarters. Revenue and price are quarterly. Revenue is in thousands of dollars. Prices are differenced from the sector×quarter median price.

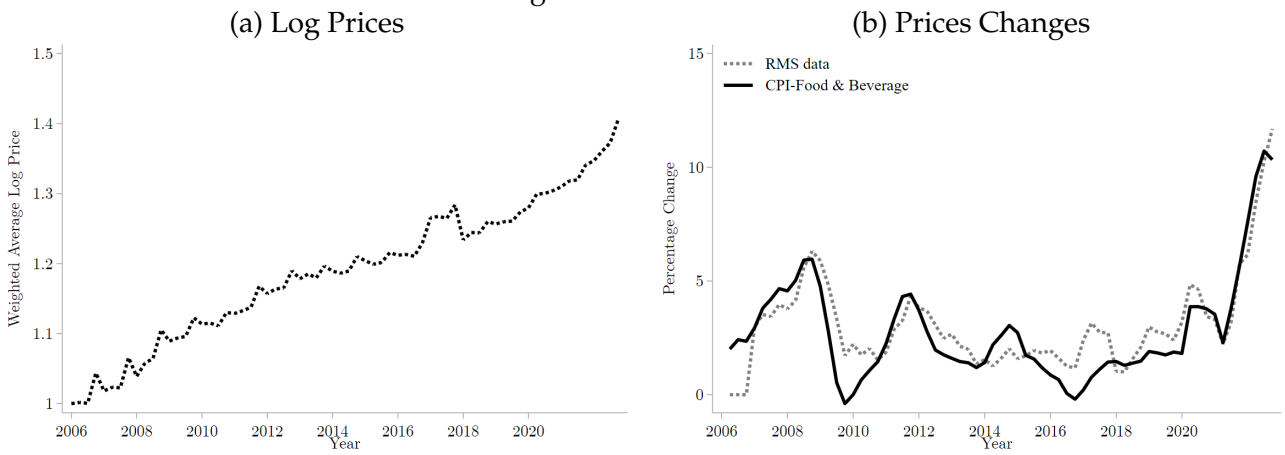
quarter after entry. These samples also exclude private-label items and departments that are less representative. Appendix B reports the results based on these robustness specifications.

Our analysis further draws on product×store–level datasets, following Campbell and Eden (2014). Using the weekly RMS microdata, we construct measures of the frequency and size of price changes, aggregated to the product–store–year level. Appendix C provides details on these constructions.

Matching Aggregate Price Indexes– We evaluate how the average prices in our dataset relate to the Consumer Price Index (CPI) for Urban Consumers, specifically the Food and Beverages category. Using the product-quarter dataset, we compute the average prices and price changes at the sector-quarter level (here defined as RMS's product modules). To obtain a measure of the aggregate price index, we use the following formula:

$$\Delta_t = \sum_j^J \omega_j \Delta_{j,t}, \quad \Delta_{j,t} = \frac{P_{j,t} - P_{j,t-4}}{P_{j,t-4}} \times 100 \tag{1}$$

Figure 1: Price Indexes



Notes: Figure (a) shows the weighted average log price using the Nielsen RMS data at the quarterly-level, computed as $\log\bar{p}_t = \sum_m^M \omega_m \log \bar{p}_{m,t}$, where $\log \bar{p}_{m,t}$ is the average (log) prices of products in product module m at time t and ω_m represents the average sales weights of module m. The weighted average Log price is normalized to 1 at 2006q1. Figure (b) shows the quarterly price changes computed as in equation (1) and the one implied from CPI for all urban consumers: food-at-home.

where ω_m represents the average sales weights, and $\Delta_{j,t}$ denotes the sector-specific price changes. Figure1(a) presents the sales-weighted log prices, while Figure1(b) illustrates Δ_t alongside the CPI index. The plot indicates that the average prices in our dataset broadly approximate the official inflation patterns, that was on average 3% annual in the period 2006-2022. The ability of RMS to approximate official inflation indexes is consistent with Argente and Lee (2020), who compare the Nielsen data using a Laspeyres price index and demonstrate that it closely matches the overall patterns of the CPI index.

2.2 Tariff-exposure

We construct a firm's measure of exposure to international tariffs and estimate its relationship with firm outcomes. Our approach integrates detailed tariff schedules, barcode-level country of origin information, and annual product-level data from NielsenIQ.

We begin by assembling a comprehensive dataset on product-level tariffs. Our primary source is the UNCTAD TRAINS database accessed through WITS, which provides tariff information at the exporter-country $\times$ HS code level. Specifically, we use the *Effectively Applied Tariff*—a weighted-average tariff that incorporates both MFN rates and preferential tariffs arising from trade agreements. Because tariffs are defined at the HS8 level, we aggregate to HS6 using import-weighted averages. This measure excludes additive tariffs (e.g., fixed dollar amounts per kilogram). Using Bai and Stumpner (2019), we employ concordance tables to map HS codes into NielsenIQ module codes. For each country of origin, we generate country $\times$ module $\times$ year tariff series that can be matched to firm products.

The second component of the exposure measure is product-level country of origin (COO). We rely on LabelInsights, which provides country of origin for consumer goods products based

on products' package. The data does not cover all products and some products do not report contry of origin in its package. Bai et al. (2025) combine related NielsenIQ and barcode-level country-of-origin data with the tariff changes associated with the 2018–2019 U.S.–China trade war. Our measure instead uses TRAINS effective applied tariffs over 2010–2022 and aggregates exposure to the firm–module–year level.

Product information comes from the NielsenIQ annual UPC-level data from 2010–2022. For each barcode, we construct a panel of firm identifiers, quantities sold, and revenues. This dataset forms the base structure onto which country of origin and tariff information are merged. We merge the UPC-level product data with COO information and subsequently with tariffs using the country-of-origin $\times$ module combination. Products that cannot be matched to country of origin or tariffs are retained to measure coverage and selection patterns.

For each firm i, module j, and year t, we construct as measures of tariff exposure:

$$T_{ijt}^{(1)} = \sum_{u \in j} w_{uijt} T_{uijt}, \qquad w_{uijt} = \frac{q_{uijt}}{\sum_{u \in j} q_{uijt}}. \tag{2}$$

All weights are computed using only products with tariff information. Alternative time-invariant weights will be estimated as robustness checks. Appendix X provides more details and summary statistics of the measures.

3 Prices of New and Incumbent Products

3.1 Stylized facts

This section establishes three facts that connect the pricing of new products to the evolution of incumbent prices. We use NielsenIQ Retail Measurement Services scanner data from 2006 through 2022, with products identified by their barcodes. This unit of observation allows us to follow the same product over several years and to distinguish price adjustment within a continuing product from the price chosen when a new product is introduced. We first document that new products enter at sizable price premia. We then estimate how the average prices of incumbent products evolve over the product life cycle. Finally, we examine whether the entry premium is systematically related to the degree of price adjustment among incumbent products.

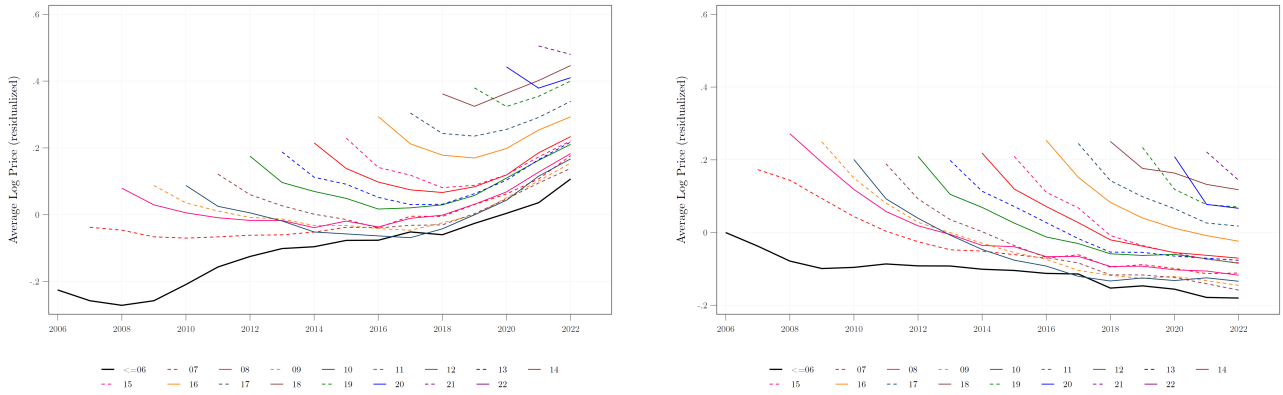
Fact 1: New Products Enter with Price Premia

We begin by comparing the prices of new and incumbent products. We define a product's cohort as the year in which its barcode first appears in the data. Using the product by year panel, we regress log prices on sector fixed effects and compute average residual prices by cohort and calendar year. Panel (a) of Figure 2 presents these cohort profiles. Products that were already

Figure 2: Prices by Product Cohort

(a) Sector Controls

(b) Sector and Time Controls



Notes: The figure reports average residual log prices by product cohort and calendar year using the baseline annual sample. In panel (a), log prices are residualized using sector fixed effects. In panel (b), log prices are residualized using sector by year fixed effects. Products active at the beginning of 2006 are grouped into the initial cohort. Cohort averages are unconditional on subsequent survival.

active when the sample begins are grouped into a single cohort because their exact entry dates are not observed. Each remaining line represents the average price of a cohort introduced during the sample period.

Panel (a) shows that successive cohorts enter at progressively higher nominal prices. The differences are visible at entry and remain persistent over the periods in which the cohorts are observed. Because aggregate prices also increase over time, panel (b) absorbs sector by year fixed effects. The resulting profiles compare each cohort with the average price of products sold in the same sector and year. Even relative to this contemporaneous benchmark, newly introduced products enter at substantially higher prices. Across specifications and cohorts, the entry premium is approximately 10 to 20 percent.

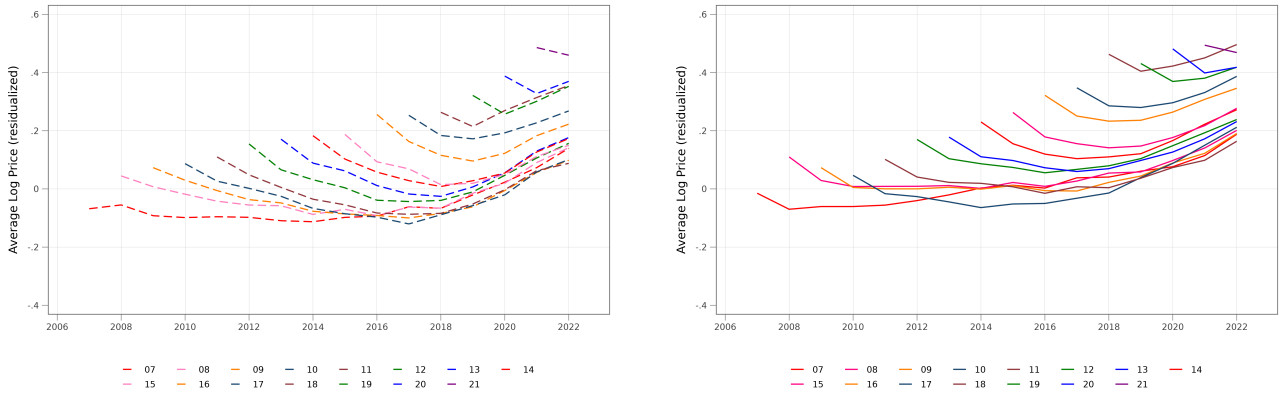
Some premium is expected if new products offer higher quality or greater consumer appeal. We therefore examine whether the pattern is concentrated among products that introduce new observable attributes. We distinguish between two forms of product introduction that will also play different roles in the model (Garcia-Macia et al., 2019; Akcigit and Kerr, 2018). NielsenIQ reports a set of attributes specific to each product category. For carbonated soft drinks, for example, these attributes include brand, manufacturer, flavor, package size, container, type of drink, formula, and whether the product is a private label. Each product is represented by the specific values taken by these attributes. Related work has used this information to measure the novelty of product attributes and combinations of attributes (Argente et al., 2024; Granja and Moreira, 2023).

We compare the attribute values of a new product with those represented in the firm's incumbent portfolio. A new product is classified as *replacement innovation* when its attribute values are similar to those of products the firm already offers. It is classified as *expansion*

Figure 3: Entry Price Premia for Expansion and Replacement Products

(a) Expansion Products

(b) Replacement Products



Notes: The figure reports average residual log prices by product cohort and calendar year separately for expansion and replacement products. Log prices are residualized using sector fixed effects. Expansion products introduce characteristics or combinations of characteristics that are new to the firm's portfolio. Replacement products have characteristics similar to those of products already in the firm's portfolio.

innovation when it introduces attribute values, or combinations of attribute values, that are new to the firm.[6] Replacement innovation includes introductions for which the main observable change is package size. These introductions connect to the literature on shrinkflation, which studies product downsizing as a margin of unit price adjustment (Çakır and Balagtas, 2014; Kim, 2024; Janssen and Kasinger, 2026). The Data Appendix provides additional examples and further details on the construction of the measure.

Our classification is necessarily based on the attributes observed in the NielsenIQ data and may miss product differences that are not captured by these attributes. The interpretation does not require the data to capture every dimension of product quality. It requires only that omitted differences do not systematically reverse the ranking implied by the observed attributes, so that products classified as expansion are, on average, more distinct from the firm's incumbent products than products classified as replacement.

Figure 3 shows that both forms of product introduction exhibit sizable entry premia. The premium for expansion products is only slightly larger than the premium for replacement products. Thus, higher entry prices are not concentrated among products that are more distinct from the firm's incumbent portfolio based on their observable attributes. In particular, replacement products also enter at prices substantially above those of incumbent products. Higher quality may therefore account for part of the entry premium, but it does not appear to account for the entire pattern. Our findings relate to those of Cafarella et al. (2023). Using NielsenIQ scanner data, they apply machine learning to extract information about product

[6] Although we refer to these attribute values as new to the firm, the measure also has a consumer interpretation. Because firm and brand identity are included among the attributes, a bundle that is new to the firm's portfolio also represents a new product offering to consumers, even when some of its physical attribute values have appeared in products sold by other firms.

attributes from product descriptions and construct hedonic price indexes that incorporate quality improvement associated with product entry and exit. Their estimates imply meaningful quality upgrading through product turnover, while also showing sizable price adjustment at product entry and exit after accounting for quality differences. Although their exercise concerns aggregate price measurement rather than the entry premium of individual new products, their findings support our interpretation that product turnover reflects both quality improvement and an important margin of price adjustment.

The Appendix shows that the entry premium is also present for products introduced by new and incumbent firms and for food and nonfood categories. These exercises establish that the aggregate pattern is not driven by a particular type of firm or product category. In the main text, we focus on replacement and expansion because this distinction is directly related to whether a new product primarily updates the firm's existing portfolio or extends that portfolio through new features.

Related work documents similar entry-pricing patterns in durable-goods markets. Bils (2009) shows that new models enter at higher prices than continuing models; Copeland and Shapiro (2016) document high introductory prices followed by rapid declines for personal computers; and Abe et al. (2016) find that price increases at product turnover in Japanese durable goods exceed those justified by observed quality improvements. Our evidence extends these patterns to a broad set of nondurable and semi-durable consumer goods.

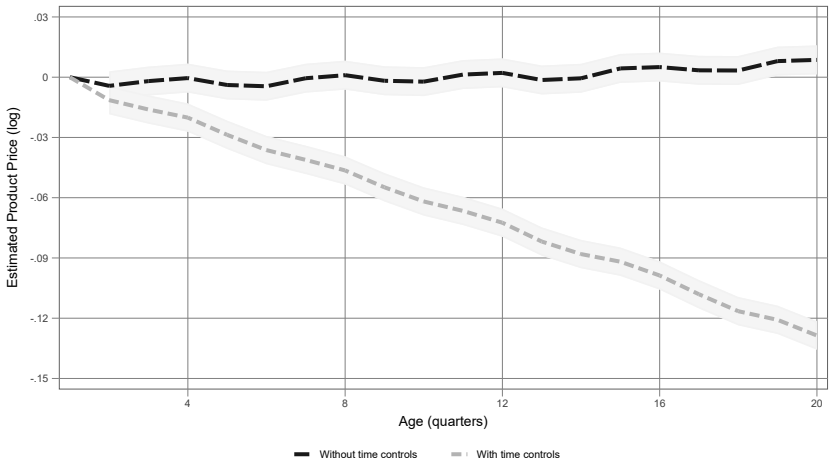
Fact 2: Incumbent Prices Exhibit Limited Adjustment Over the Product Life Cycle

We next study how the prices of incumbent products evolve after introduction. The cohort profiles above are useful for comparing the price levels of successive generations of products, but they are unconditional on survival. As products exit, changes in the average price of a cohort may reflect both changes in the prices of continuing products and changes in the composition of products that remain active. To isolate price evolution over the product life cycle, we follow the same barcodes over several years and estimate average price profiles as a function of product age. These profiles summarize the net evolution generated by all price changes as products age, rather than the frequency or size of individual price changes.

Let P_{ut} denote the price of product u in period t, $a(u,t)$ its age, $c(u)$ its entry cohort, and $j(u)$ its sector. Let S_u be an indicator equal to one for products whose age profile we estimate. We estimate two versions of the following specification:

$$\ln P_{ut} = \alpha + \sum_{a=2}^{A} \beta_a \mathbf{1}\{a(u,t) = a\} S_u + \eta(1 - S_u) + \theta_{c(u)} + \Gamma_{j(u),t} + \varepsilon_{ut}. \tag{3}$$

Figure 4: Prices Over the Product Life Cycle



Notes: The figure reports the estimated age coefficients from equation 3. The nominal price profile includes sector and cohort controls. The relative price profile additionally absorbs sector by time effects. The estimation uses all products to identify the controls and reports age effects for products introduced from 2006q3 through 2016q3 that remain active for at least 20 quarters. The shaded areas indicate 95 percent confidence intervals.

The coefficients β_a trace the average price at each age, relative to the first full period of activity, for products with $S_u = 1$. Products with $S_u = 0$ do not contribute to the age coefficients but remain in the estimation to help identify the sector, cohort, and calendar time controls. Using the broader product sample for these controls ensures that the sector by time effects capture the overall price trend in the sector rather than the trend among the selected products alone. In the specification without calendar time controls, $\Gamma_{j(u),t}$ includes sector fixed effects only. This specification traces the evolution of average nominal prices. In the specification with calendar time controls, $\Gamma_{j(u),t}$ includes sector by time fixed effects, which absorb changes common to products in the same sector, including sector inflation. This specification traces how the price of a continuing product evolves relative to the contemporaneous price trend in its sector.[7]

In the baseline specification, $S_u = 1$ for products that remain active for at least 20 quarters. The purpose of this restriction is to estimate every point of the five year age profile using the same set of barcodes. Without it, later age coefficients would place increasing weight on products that survive longer, and the estimated profile could reflect selective product exit rather than the evolution of prices for continuing products. The baseline therefore provides a transparent estimate of price evolution for long lived products. Because it conditions on realized survival, the Appendix examines less restrictive samples that allow products to exit at different ages and estimates separate profiles by realized product duration.

[7] Age, cohort, and calendar time are linearly related. We follow Deaton (1997) and impose the standard normalization on cohort effects. The Appendix shows that the results are robust to alternative treatments of cohort and time effects.

Figure 4 presents the baseline profiles with and without sector by time controls. The average nominal price of incumbent products exhibits little systematic growth as products age. Over the first five years, the nominal price profile remains close to its initial level even though aggregate prices are increasing. Once sector by time effects are absorbed, relative prices decline by approximately 2 to 3 percent per year. Thus, a continuing product becomes progressively less expensive relative to other products in its sector. Similar patterns have been documented in other sectors, including consumer durables and personal computers (Bils, 2009; Copeland and Shapiro, 2016; Abe et al., 2016).

These estimates characterize an average life cycle profile and do not imply that every product follows the same path. The result in Figure 4 is that, after averaging across individual trajectories, the sequence of price changes does not produce systematic nominal price growth with product age. The Appendix complements this average profile by reporting the distribution of product level price changes over the full 20 quarter window for all products used to estimate the age effects. The distribution includes substantial price increases and declines, but also a large mass around zero, illustrating both the heterogeneity in individual price trajectories and the limited net adjustment of many products. Beyond documenting this heterogeneity, the distribution provides additional moments that we later use to discipline price adjustment in the quantitative model. This is a different object from the frequency or magnitude of individual price changes measured over shorter intervals.

Because product exit can affect estimated age profiles, the Appendix first examines several samples that differ in how they address selection. The baseline uses a balanced sample of products that remain active for at least 20 quarters. We compare it with a partially balanced sample that includes cohorts observable for at least five years but allows individual products to exit earlier, and with an unrestricted sample that includes products regardless of cohort coverage or realized duration. Figure A1 shows that the profiles are quantitatively similar across these samples, particularly after sector by time effects are included. Without time controls, samples that allow exit display somewhat greater declines in nominal prices. We also estimate profiles conditional on realized durations ranging from 2 to 28 quarters. Figure A2 shows that the relative prices of both short lived and long lived products decline over their life cycles.

The Appendix next varies the controls and the sample used to identify them. In the baseline, products outside the balanced sample remain in the estimation to help identify sector, cohort, and time effects. Figure A3 shows that estimating the specification using only products in the balanced sample produces qualitatively similar profiles. We also vary the treatment of cohort effects and include firm by sector by time effects to absorb changes specific to firms within sectors. Figures A4 and A5 show that these alternatives do not materially affect the main result.

We next examine whether changes in the set of stores selling a product can account for the national profiles. Our baseline price is a quantity weighted average across stores, and substantial price dispersion across retailers may cause changes in store composition to affect this average (Kaplan and Menzio, 2015). We therefore estimate the price profile of the same barcode within individual stores, defining age from the first period in which the barcode is sold in that store. Figure C.1 in the Appendix shows that store barcode prices also exhibit little systematic growth as products age.

Finally, we examine whether the price profiles reflect changes in the composition of households purchasing a product. One possibility is that new products are initially purchased disproportionately by higher income households and subsequently diffuse toward lower income households. If purchases by higher income households are associated with higher markups, this change in buyer composition could generate a decline in average prices as products age even without changes in pricing within income groups. Using NielsenIQ Homescan data, we find little systematic change in the income composition of purchasing households over the product life cycle. The share of purchasing households in the highest income group is only negligibly higher at entry. We also estimate life cycle price profiles separately by household income group and find that the prices paid by all income groups exhibit patterns similar to the aggregate profile in Figure 4. The aggregate price profile therefore does not appear to be driven by products diffusing from higher income toward lower income households as they age. Overall, the results are robust across specifications, samples, and both national barcode and store barcode level data.

These price profiles do not by themselves identify how markups evolve because scanner data do not report product-level marginal costs.[8] We therefore interpret the decline in relative prices as suggestive of markup erosion rather than as a separately identified markup profile.

We refer to the limited adjustment of average incumbent prices relative to the aggregate price trend as *long run pricing frictions*. By long run, we mean adjustment over the product life cycle rather than the response of posted prices over weeks or months. We use the term to characterize this empirical pattern without taking a stand on why incumbent prices, on average, exhibit limited adjustment relative to the aggregate price trend. This average life cycle path is the relevant object for our analysis because it determines how price misalignment evolves while

[8] Argente et al. (2024) use the same NielsenIQ data and the structural decomposition developed by Hottman et al. (2016) to infer product-level marginal costs. Their model-based estimates imply that nominal marginal costs increase with product age, while marginal costs relative to the sector trend decline only modestly. Because this decomposition relies on static pricing optimality conditions, however, the estimates should be viewed as suggestive in our setting, in which observed prices may be persistently misaligned. Relatedly, using plant-level prices and quantities for both outputs and inputs, Eslava et al. (2024) show that residual marginal-cost measures combine technical efficiency, input prices, and residual wedges. They find that technical efficiency is approximately flat over the plant life cycle, although their unit of observation is the plant rather than the individual product.

a product remains active and, therefore, how pricing frictions affect the value of introducing a product at a newly chosen price.

Fact 3: Entry Premia Are Larger When Incumbent Prices Are More Rigid

Facts 1 and 2 together suggest a possible connection between product introduction and price adjustment. New products enter at high relative prices, while the prices of incumbent products do not, on average, keep pace with the sector price trend. One interpretation is that firms choose elevated introductory prices in anticipation that inflation will erode their real prices before substantial cumulative adjustment occurs. We use the term *price overshooting* for the component of the entry premium associated with this forward looking pricing motive. Observable quality differences can still account for part of the premium. The question in this subsection is whether the entry premium is systematically larger when incumbent prices adjust less.

Cross Sectional Evidence. We first use variation across consumer product sectors. For each sector, we construct two complementary measures of pricing frictions. The first is the average frequency of weekly price changes, computed from store by barcode scanner data, following the metrics in Nakamura and Steinsson (2008). This measure captures how often the prices of incumbent products change. The second is the slope of the relative price profile over the product life cycle, estimated separately for each sector using equation 3. This measure captures whether price changes accumulate into systematic adjustment relative to the sector price trend. The first measure concerns the incidence of price changes over short intervals and provides a useful proxy for pricing frictions if the forces that discourage frequent price adjustment also limit the realignment of incumbent prices over longer horizons. The second measure directly captures the cumulative outcome of price changes over the product life cycle.

We relate these measures to the average price premium of new products in each sector and quarter. Table 2 reports the results. Columns (1) through (3) use the frequency of price changes. Sectors in which prices change more frequently exhibit smaller entry premia. Columns (4) through (6) use the estimated life cycle slope. Sectors in which the relative prices of incumbent products decline more rapidly exhibit larger entry premia. Both relationships remain statistically and economically significant after controlling for calendar time and for fixed differences across broader product groups.

The two measures need not capture identical pricing behavior. In particular, frequent price changes can include sales and other adjustments that have little effect on the cumulative price profile. Their agreement is therefore informative. Sectors in which incumbent prices change less frequently, or in which those changes generate less cumulative adjustment relative to the sector trend, are also the sectors in which firms set higher relative prices when introducing new

Table 2: Entry Price Premia and Measures of Pricing Frictions

	Entry Price Premium of New Products					
	(1)	(2)	(3)	(4)	(5)	(6)
Frequency of price changes	-0.269^{***}	-0.268^{***}	-0.212^{***}			
	(0.017)	(0.017)	(0.034)			
Life cycle slope				-2.438^{***}	-4.893^{***}	-2.636^{***}
				(0.094)	(0.078)	(0.125)
Observations	58,207	58,207	58,207	58,207	58,207	58,207
R^2	0.004	0.021	0.160	0.011	0.079	0.166
Time fixed effects	No	Yes	Yes	No	Yes	Yes
Product group fixed effects	No	No	Yes	No	No	Yes

Notes: The table relates the entry price premium of new products to two sector measures of pricing frictions using module by quarter observations from 2007q1 through 2022q4. The frequency of price changes is computed from weekly store by barcode data. The life cycle slope is the annualized change in relative prices over the product life cycle, estimated separately for each module using equation 3. The dependent variable is $\widetilde{P}_{mt} = (P^{\text{new}}_{mt} / P^{\text{inc}}_{mt}) - 1$. Observations are weighted by revenue. The Appendix reports unweighted estimates and alternative measures. Standard errors are reported in parentheses. *** denotes significance at the 1 percent level.

products. This evidence is consistent with product introduction becoming a more important pricing margin when the prices of continuing products adjust less systematically.

Tariff Induced Cost Variation. Cross sectional differences in pricing behavior may be correlated with other characteristics of products and markets. We therefore complement this evidence using variation across firms within consumer product sectors in their exposure to import tariffs. Firms selling a larger share of imported products experience greater cost increases when tariffs rise. Conditional on sector by year and firm by sector fixed effects, this variation allows us to compare how similar cost changes are reflected in the prices of incumbent and newly introduced products.

We construct tariff exposure for firm i in consumer product sector j and year t as described in equation 2.2. The measure combines tariff changes across countries and products using the firm's product composition. We then estimate local projections of the form

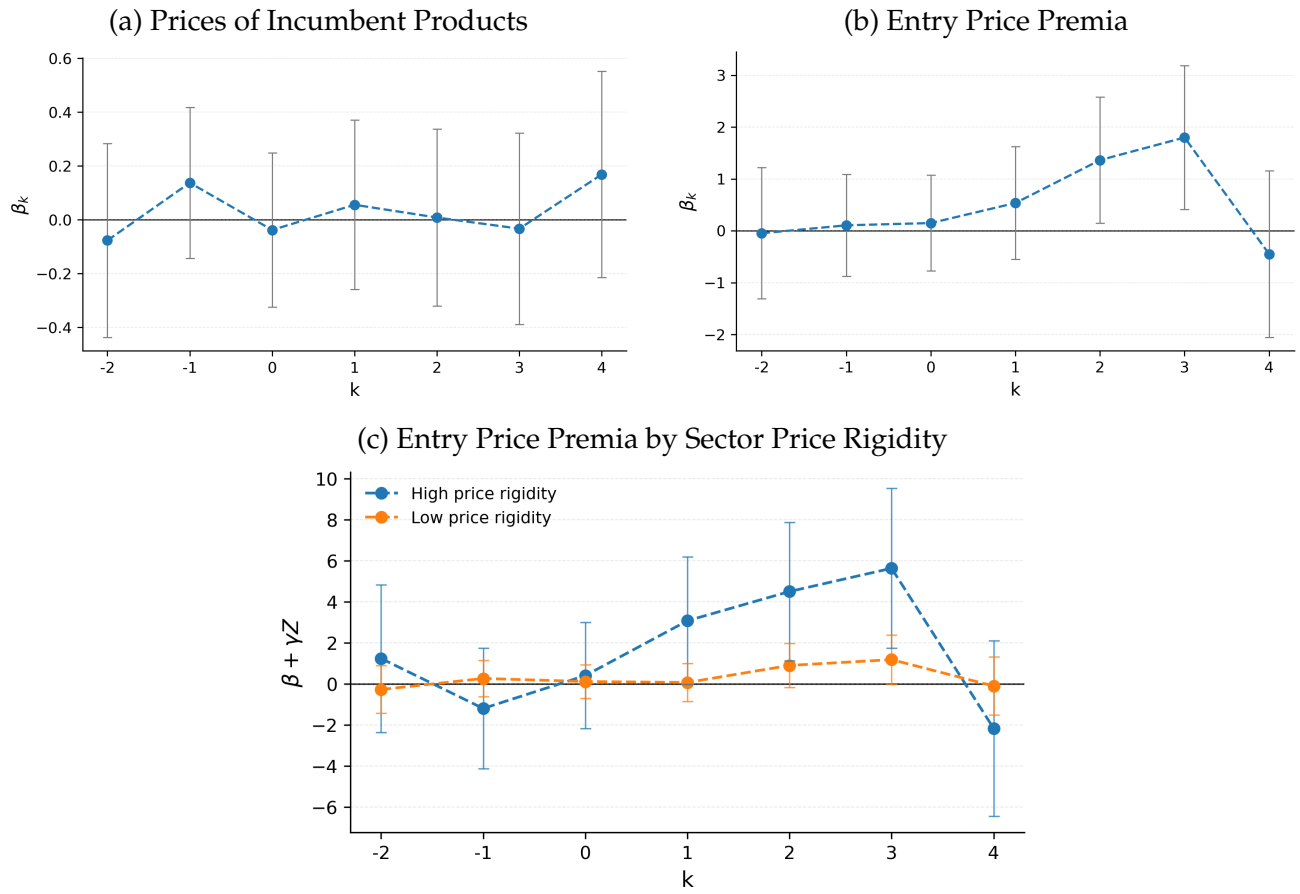
$$y_{ij,t+k} = \beta_k T_{ijt} + \omega_{j,t+k} + \phi_{ij} + X'_{ij,t+k}\delta_k + \varepsilon_{ij,t+k}, \qquad k = -2, \ldots, 4, \tag{4}$$

where T_{ijt} is firm tariff exposure, $\omega_{j,t+k}$ denotes sector by year fixed effects, and ϕ_{ij} denotes firm by sector fixed effects. We consider two outcomes. The first is the average log price of the firm's incumbent products. The second is the price of its newly introduced products relative to its incumbent products in the same sector. The controls $X_{ij,t+k}$ include the share of the firm's sales for which tariff information is available.

Panels (a) and (b) of Figure 5 reveal a pronounced asymmetry. Tariff exposure has little detectable effect on the prices of incumbent products.[9] By contrast, it increases the relative

[9]Studies using customs and import-price data generally find substantial or nearly complete pass-through of recent U.S. tariffs into the duty-inclusive prices paid by importers (Amiti et al., 2019; Fajgelbaum et al., 2020; Cavallo et al., 2021). These estimates concern border prices rather than the retail prices of continuing products. At retail,

Figure 5: Tariff Exposure and the Prices of Incumbent and New Products



Notes: Panels (a) and (b) report the coefficients β_k from equation 4. The outcome in panel (a) is the average log price of incumbent products. The outcome in panel (b) is the price of new products relative to incumbent products. Panel (c) adds an interaction between tariff exposure and the standardized sector frequency of price changes and reports the implied effects for sectors one standard deviation below and above the mean frequency. A lower frequency corresponds to greater price rigidity. Vertical bands indicate 95 percent confidence intervals.

prices of products introduced in subsequent years. The response emerges gradually and is largest approximately two years after the change in exposure. A 10 percentage point increase in tariff exposure is associated with an increase of approximately 0.14 percentage points in the relative price of new products after two years. The timing is consistent with the fact that firms can incorporate the cost change into introductory prices only when they launch new products.

Panel (c) examines whether this response depends on the degree of price rigidity among incumbent products. We interact tariff exposure with the sector frequency of price changes and report the implied effects for sectors with high and low rigidity. Tariff exposure produces a substantially larger increase in the relative price of new products in sectors where incumbent

Cavallo et al. (2021) estimate a small response for individual products that is statistically indistinguishable from zero. Most closely related, Bai et al. (2025) find a tariff elasticity of 0.10–0.14 within continuing barcodes, compared with 0.44 for unit values that incorporate product turnover. Our confidence intervals do not rule out modest within-product pass-through of this magnitude. In addition, tariff variation is more limited among the consumer goods represented in scanner data and is further smoothed by our annual firm–module exposure measure, reducing the precision with which small incumbent-price responses can be estimated.

prices change less frequently. The estimates show no systematic differences before the tariff change, and the difference between high and low rigidity sectors declines after the initial response.

The Appendix reports the corresponding coefficient estimates, specifications using changes rather than levels of tariff exposure, alternative controls, and results based on log price differences. Across these specifications, tariff exposure increases the future relative price of new products but has little detectable effect on the prices of incumbent products. The sector by year fixed effects absorb cost and demand changes common to firms in the same market, while the firm by sector fixed effects absorb persistent differences in firm sourcing and pricing. Together with the absence of pretrends, these results support an interpretation in which tariff-induced cost increases pass through disproportionately through products introduced after the cost change. This evidence complements existing work on the incidence and price effects of recent tariff changes (Amiti et al., 2019; Fajgelbaum et al., 2020; Cavallo et al., 2021; Bai et al., 2025).

Taken together, the cross sectional and tariff evidence connect the entry price premium to the adjustment of incumbent prices. Firms set higher relative prices for new products in sectors with greater pricing frictions, and firm specific cost increases pass through to new products rather than incumbent products, especially when incumbent prices are more rigid. These findings support the interpretation that product introduction provides firms with a margin of price adjustment.

3.2 Discussion

Frequent price changes and cumulative adjustment. Our finding of limited cumulative adjustment is not inconsistent with the extensive evidence that retail prices change frequently. Bils and Klenow (2004) use the microdata underlying the Consumer Price Index to measure the duration of individual price spells. Klenow and Kryvtsov (2008) use the same type of price records to study how the frequency and size of individual changes contribute to inflation, while Nakamura and Steinsson (2008) distinguish regular price changes from temporary sales and document substantial heterogeneity across sectors. These papers focus primarily on whether and when a posted price changes over relatively short intervals. We instead follow the same barcode over several years and estimate whether the sequence of changes produces cumulative nominal price growth as the product ages. Prices can therefore change frequently even when the average life cycle profile exhibits little cumulative adjustment.

This distinction is closely related to the literature on reference and regular prices. Using weekly scanner data, Eichenbaum et al. (2011) define the reference price as the most common price within a quarter. They find that weekly prices change approximately every two weeks, while reference prices have an average duration of about one year. Kehoe and Midrigan (2015)

show that frequent temporary price changes can coexist with substantial rigidity in regular prices and with sizable real effects of monetary shocks. We extend this distinction to a longer horizon. Our estimates do not require every observed price change to be temporary, nor do they imply that every product has a stable price. They show that the collection of changes observed over a product's life does not generate systematic cumulative growth in the average nominal price. This slow moving component is the relevant one for innovation because it determines how the value of an incumbent product changes relative to the value of introducing a product at a new price.

Related work also studies how pricing behavior varies with product age. Using weekly store by UPC data, Argente and Yeh (2022) estimate age profiles for the frequency and absolute size of individual price changes, focusing primarily on the first year after introduction. They show that young products change prices more frequently and by larger amounts, consistent with firms learning about demand. Adam and Weber (2023) document systematic trends in relative prices over product age and use those trends to study the optimal inflation target. Our analysis instead asks whether individual price changes accumulate into systematic growth of average nominal prices over a much longer horizon and how limited cumulative adjustment affects the pricing and introduction of new products.

Product turnover, quality adjustment, and price resetting. Our results are closely related to work studying prices when products turn over. Bils (2009) documents that prices of continuing durable models decline while new models enter at higher prices. Using changes in market shares and the persistence of price differences over the model cycle, he concludes that most of the price increase at replacement reflects quality growth. Nakamura and Steinsson (2012) show that price indexes following identical products can miss adjustment that occurs when one product replaces another, while Cavallo et al. (2014) find that international relative-price differences are established largely when products are introduced rather than through subsequent adjustment of identical products.

These studies highlight the difficulty of separating quality improvement from price adjustment at product turnover. Our interpretation adds a price-reset component associated with the limited adjustment of incumbent prices. Quality improvement and price resetting are not mutually exclusive: a new product may gain market share because its quality improves while the firm simultaneously uses its introduction to correct an accumulated price gap. Moreover, such a reset can remain persistent over the product's life cycle. Evidence based on market shares and persistence can therefore establish the importance of quality improvement without ruling out a simultaneous price-reset component.

Barcode data are particularly useful in this setting because they distinguish price changes within an identical product from prices chosen when a new product is introduced. Recent

work combines these data with detailed product characteristics and demand information to account for product turnover and quality change in price indexes (Cafarella et al., 2023; Ehrlich et al., 2023). We use these advantages for a different purpose. Observable product features show that entry premia remain sizable among relatively incremental introductions, while the cross-sectional and tariff evidence connects these premia to the limited adjustment of incumbent prices. Rather than constructing a price index, we treat product introduction as a firm decision and study how the opportunity to choose a new price shapes innovation incentives.

Interpretation of long run pricing frictions. Our use of the term friction describes the observed persistence of the average price component rather than a particular mechanism generating it. Standard explanations for price rigidity include direct costs of changing prices, infrequent opportunities to adjust, imperfect information, contractual arrangements, and organizational decision costs. These mechanisms can delay adjustment following a shock, but many are designed to operate over relatively short horizons and do not by themselves explain limited cumulative adjustment over several years. Mechanisms that make firms reluctant to change the price of an otherwise unchanged product may be more relevant over the product life cycle. For example, Rebelo et al. (2025) develop a model in which price changes can lead consumers to reconsider their purchasing decisions, generating endogenous price inertia. Their mechanism suggests one possible reason why firms may find it easier to choose a new price when they also change product attributes, as consumers evaluate a new product offering rather than a pure price increase for an unchanged product. Reference prices and customer relationships may provide related explanations. We do not distinguish among these mechanisms. Instead, we take the average life cycle price pattern as an empirical input and study its consequences for product introduction and innovation.

The three empirical facts provide a consistent picture. Incumbent products exhibit limited cumulative price adjustment, new products enter at sizable premia even when they introduce few new features, and the entry premium is larger when incumbent prices are more rigid. Tariff induced cost changes display the same asymmetry, passing through to products introduced subsequently but not to continuing products. These findings motivate a framework in which product introduction affects firm value through both quality improvement and price adjustment.

4 Model

Motivated by our empirical findings on the nominal prices of incumbent products and the price premia of new products, we develop a continuous-time monetary general equilibrium

model of endogenous growth with long-run pricing frictions. Our goal is to understand how these frictions, which are typically absent from standard growth frameworks, shape product values, innovation incentives, and aggregate growth.

The real side of the model builds on canonical frameworks of innovation-driven growth featuring creative destruction and quality improvement (Aghion and Howitt, 1992; Klette and Kortum, 2004). The monetary side features money in the household's utility function and trend growth in the money supply. Product prices are chosen at introduction. Thereafter, firms can reset them either upon receiving a random adjustment opportunity, as in Calvo (1983), or by paying an adjustment cost, as in Golosov and Lucas (2007). Together, these features imply that firms do not continuously reoptimize product prices to maintain their desired markups. Between price resets, inflation erodes a product's relative price and markup, making its value depend on its current markup. Anticipating this erosion, firms optimally set the reset markup above the static profit-maximizing markup, a behavior we refer to as price overshooting. The economy admits a balanced growth path with stationary normalized allocations and an endogenous stationary distribution of markups across products.

The central mechanism of the model is that product introduction allows firms to choose a new price and therefore provides an additional margin of price adjustment. We represent firms' innovation choices along two margins. Firms can update product lines they already operate or innovate in product lines operated by competitors, thereby expanding their portfolios. We refer to these activities as replacement and expansion innovation, respectively. Both margins result in the introduction of a new product and can increase the quality of the affected product line. We allow the magnitude of the quality improvement and the cost of innovation to differ across the two margins and discipline both through estimation. Because replacement displaces a product already owned by the firm, whereas expansion adds a new line to its portfolio, the pricing benefit enters the returns to the two margins differently. This distinction allows the model to capture how pricing frictions shape the nature of innovation.

4.1 Household and Monetary Environment

We adopt a continuous-time monetary environment with money in the utility function, following Golosov and Lucas (2007), together with preferences consistent with balanced growth. A representative household consumes the final good C_t, supplies labor L_t, holds nominal money balances M_t, and owns nominal interest-bearing assets B_t, which include claims to firms and government bonds and yield the nominal return R_t. The household solves

$$\max_{\{C_t, L_t, M_t, B_t\}_{t\geq 0}} \mathbb{E}_0 \int_0^\infty e^{-\rho t} \left[\ln C_t - L_t + \chi \ln \left(\frac{M_t}{\widehat{P}_t} \right) \right] dt, \tag{5}$$

subject to

$$\dot{B}_t + \dot{M}_t = W_t L_t + R_t B_t + T_t - \widehat{P}_t C_t, \tag{6}$$

where B_t denotes nominal interest-bearing assets, T_t denotes lump-sum nominal transfers, $\rho > 0$ is the discount rate, $\chi > 0$ governs the utility from real money balances, and $\widehat{P}_t$ is the quality-adjusted price index defined below.

The household's first-order conditions imply

$$\widehat{P}_t C_t = W_t, \qquad \widehat{P}_t C_t = \frac{R_t}{\chi} M_t, \qquad \frac{\dot{C}_t}{C_t} = R_t - \frac{\dot{\widehat{P}}_t}{\widehat{P}_t} - \rho. \tag{7}$$

The first condition determines labor supply, the second is the demand for money, and the third is the consumption Euler equation. The consumption-based real interest rate is

$$r_t \equiv R_t - \frac{\dot{\widehat{P}}_t}{\widehat{P}_t}.$$

We assume that the nominal money supply grows at the constant rate

$$\frac{\dot{M}_t}{M_t} = \bar{\pi}.$$

New money is injected through lump-sum transfers, so that $T_t = \dot{M}_t$ in the aggregate. Along a balanced growth path, $R_t = R$ is constant. Taking growth rates of the money-demand condition and combining it with the consumption Euler equation yields the following result.

Proposition 1. *Along the balanced growth path,*

$$R = \rho + \bar{\pi}, \qquad W_t = \frac{R}{\chi} M_t, \qquad \widehat{P}_t C_t = \frac{R}{\chi} M_t. \tag{8}$$

Because R/χ is constant along the balanced growth path, nominal wages and nominal consumption expenditures are proportional to the money supply and therefore grow at rate $\bar{\pi}$. The parameter χ affects real money balances but not the remaining real allocations. With log utility over consumption and linear disutility from labor, the income and substitution effects on labor supply offset. Labor is therefore constant along the balanced growth path, although its level can differ across stationary equilibria, as shown in Section 4.9.

4.2 Production, Product Lines, and Demand

There is a unit measure of product lines, indexed by $i \in [0, 1]$. At each date, one product is active in each product line. When a new product is introduced in a line, the product previously

operating in that line exits.[10] The final good is a CES aggregate of the products operating in these lines:

$$Y_t = \left[\int_0^1 (q_{it} y_{it})^{\frac{\sigma-1}{\sigma}} di \right]^{\frac{\sigma}{\sigma-1}}, \tag{9}$$

where $\sigma > 1$ is the elasticity of substitution, q_{it} denotes the quality of the product in line i, and y_{it} is its quantity.

Let p_{it} denote the nominal price of product i. Cost minimization by the final-good producer yields

$$y_{it} = q_{it}^{\sigma-1} \left(\frac{p_{it}}{\widehat{P}_t} \right)^{-\sigma} Y_t, \tag{10}$$

where

$$\widehat{P}_t = \left[\int_0^1 \left(\frac{p_{it}}{q_{it}} \right)^{1-\sigma} di \right]^{\frac{1}{1-\sigma}} \tag{11}$$

is the quality-adjusted price index.

Intermediate goods are produced one-for-one with labor,

$$y_{it} = \ell_{it}, \tag{12}$$

where ℓ_{it} is labor employed in product line i.[11]

To separate aggregate quality from differences in quality across product lines, define

$$Q_t \equiv \left(\int_0^1 q_{it}^{\sigma-1} di \right)^{\frac{1}{\sigma-1}} \tag{13}$$

and relative quality

$$\widehat{q}_{it} \equiv \frac{q_{it}}{Q_t}.$$

By construction,

$$\int_0^1 \widehat{q}_{it}^{\sigma-1} di = 1.$$

The evolution of Q_t will summarize the contribution of innovation to aggregate growth.

[10] The single-product restriction can be implemented by assigning each product line a single operating slot. An intermediary receiving an ε share of operating profits allocates the slot to the profit-maximizing product. The intermediary has no pricing role, and taking $\varepsilon \to 0$ makes the device affect product selection without affecting equilibrium prices or payoffs.

[11] Section 5.3 extends the production technology to $y_{it} = Z_{it} \ell_{it}$, allowing desired prices to move in both directions.

4.3 Pricing, Markups, and Profits

Because production is linear in labor, nominal marginal cost is common across product lines and equal to W_t. We define the product-level markup μ_{it} by

$$p_{it} = \mu_{it} W_t. \tag{14}$$

We define the aggregate markup m_t as[12]

$$m_t \equiv \frac{\widehat{P}_t Q_t}{W_t} = \left(\mathbb{E}_{\widehat{q},t} \left[\mu_{it}^{1-\sigma} \right] \right)^{\frac{1}{1-\sigma}}. \tag{16}$$

Combining product demand with the production technology and imposing labor-market clearing yields

$$Y_t = v_t Q_t L_t, \qquad v_t \equiv \frac{m_t^{-\sigma}}{\mathbb{E}_{\widehat{q},t} \left[\mu_{it}^{-\sigma} \right]} \leq 1. \tag{17}$$

The term v_t measures allocative efficiency, while $1 - v_t$ is the efficiency loss generated by markup dispersion. Allocative efficiency equals one when all products carry the same markup. When markups differ, demand is tilted toward low-markup products and away from high-markup products, lowering aggregate output for a given amount of labor and product quality.

The labor share satisfies

$$\frac{W_t L_t}{\widehat{P}_t Y_t} = (v_t m_t)^{-1} = \frac{\mathbb{E}_{\widehat{q},t} \left[\mu_{it}^{-\sigma} \right]}{\mathbb{E}_{\widehat{q},t} \left[\mu_{it}^{1-\sigma} \right]}. \tag{18}$$

Equivalently,

$$\frac{\widehat{P}_t Y_t}{W_t L_t} = v_t m_t$$

is the sales-weighted harmonic mean of product-level markups, consistent with Edmond et al. (2022).

The real profit flow of product i, measured in units of the final good, is

$$\pi_{it} = \frac{(p_{it} - W_t) y_{it}}{\widehat{P}_t} = m_t^{\sigma-1} Y_t \widehat{q}_{it}^{\sigma-1} (\mu_{it} - 1) \mu_{it}^{-\sigma}. \tag{19}$$

[12] To aggregate across product lines, we use the quality weights $\widehat{q}_{it}^{\sigma-1}$. Because these weights integrate to one. For any product-level variable g_{it}, we define its quality-weighted average as

$$\mathbb{E}_{\widehat{q},t}[g_{it}] \equiv \int_0^1 g_{it} \widehat{q}_{it}^{\sigma-1} \, di. \tag{15}$$

Profits are proportional to market size and relative product quality. As a function of the product's own markup, profits are hump-shaped and attain their static maximum at

$$\mu^* = \frac{\sigma}{\sigma - 1}.$$

With the pricing frictions introduced below, firms choose markups dynamically, trading off current profits against future markup erosion.

4.4 Markup Dynamics and Price Adjustment

Between price adjustments, a product's nominal price remains fixed. Because $p_{it} = \mu_{it} W_t$, its markup evolves according to

$$\frac{\dot{\mu}_{it}}{\mu_{it}} = -\frac{\dot{W}_t}{W_t}. \tag{20}$$

By Proposition 1, the nominal wage grows at the constant money-growth rate $\bar{\pi}$. Therefore,

$$\frac{\dot{\mu}_{it}}{\mu_{it}} = -\bar{\pi}. \tag{21}$$

Thus, in the absence of a price adjustment, trend nominal growth gradually erodes a product's markup.

Firms can choose a new price through three channels. First, a product receives a costless price-adjustment opportunity at Poisson rate γ, as in Calvo (1983). Second, the firm can adjust at any time by paying the real menu cost $\kappa Y_t \widehat{q}_{it}^{\sigma-1}$, as in Golosov and Lucas (2007). These two channels adjust the price of a continuing product. Third, successful innovation introduces a new product and allows the innovating firm to choose its initial price.

We define $\mu_t^u(\widehat{q})$ as the optimal reset markup for a product of relative quality $\widehat{q}$. This is a dynamic object and therefore generally differs from the static profit-maximizing markup $\mu^* = \sigma/(\sigma - 1)$. We also define $\mu_t^\ell(\widehat{q})$ as the lower adjustment threshold, with

$$\mu_t^\ell(\widehat{q}) < \mu_t^u(\widehat{q}). \tag{22}$$

The firm leaves the nominal price unchanged while the markup remains above $\mu_t^\ell(\widehat{q})$. If the markup reaches this threshold, the firm pays the menu cost and resets its price to attain $\mu_t^u(\widehat{q})$. A Calvo opportunity arriving before the threshold is reached also returns the product to its optimal reset markup. Similarly, a newly introduced product begins at the reset markup corresponding to its post-innovation quality.

We show below that the homogeneity of the firm's problem makes the reset markup and the adjustment threshold independent of relative quality. We can therefore write them as μ_t^u and

μ_t^ℓ. Moreover, because firms anticipate that markups will subsequently erode, the optimal reset markup exceeds the static optimum, generating price overshooting.

4.5 Innovation

Firms innovate along two margins. Replacement innovation targets a product line already operated by the firm. Upon success, the firm introduces a new product in that line, while the size of its portfolio remains unchanged. Expansion innovation targets a product line operated by another firm. Upon success, the innovator introduces a new product, acquires the line, and displaces its previous owner. Expansion therefore increases the innovator's portfolio by one line and reduces the portfolio of the displaced firm by one line, capturing creative destruction as in Aghion and Howitt (1992). A firm exits when it loses its last product line.

Following Klette and Kortum (2004), innovation builds on the firm's knowledge capital, which we proxy by the number of product lines in its portfolio. Let M_{ft} denote the number of lines operated by firm f. A firm with M_{ft} lines conducts M_{ft} R&D programs in parallel, so its innovation opportunities and R&D expenditures scale with its portfolio. We therefore formulate innovation decisions in per-line terms and aggregate them across the firm's product lines.

For a product line of relative quality $\widehat{q}$, the incumbent chooses an intensity $n^I \geq 0$ for replacement innovation. The associated real flow cost is

$$c_t^I(n^I, \widehat{q}) = \xi^I \left(n^I\right)^{\frac{1}{1-\alpha}} \widehat{q}^{\sigma-1} Y_t, \tag{23}$$

where $\xi^I > 0$ is a cost shifter and $\alpha \in (0,1)$ governs the curvature of R&D costs. Upon success, the firm introduces a new product whose quality satisfies

$$q' = \lambda^I q, \qquad \lambda^I > 1, \tag{24}$$

and chooses its price.

Expansion innovation is untargeted. Each innovation attempt draws a product line uniformly from the unit mass of lines, independently of its quality. The firm chooses a per-line expansion intensity $n^E \geq 0$. Conditional on drawing a line of relative quality $\widehat{q}$, the real flow cost is

$$c_t^E(n^E, \widehat{q}) = \xi^E \left(n^E\right)^{\frac{1}{1-\alpha}} \widehat{q}^{\sigma-1} Y_t. \tag{25}$$

Upon success, the innovator acquires the selected line and introduces a new product whose quality satisfies

$$q' = \lambda^E q, \qquad \lambda^E > 1. \tag{26}$$

The innovator then chooses the price of the new product. We allow the quality improvement and the cost shifter to differ across the two innovation margins and discipline these parameters through estimation.

In addition to endogenous creative destruction, each active product is displaced by an exogenous shock at rate ψ. Following this shock, a new firm enters the corresponding product line, introduces a product of the same quality as the displaced product, and chooses its price. These shocks therefore generate product turnover and price setting without contributing directly to quality growth. Because every displaced product is immediately replaced, the total measure of product lines remains equal to one.

At an innovation event, the price choice applies to the newly introduced product; the prices of the firm's other products remain unchanged. Because replacement displaces a product already owned by the innovator, whereas expansion adds a product line to its portfolio, the pricing opportunity enters the returns to the two innovation margins differently.

4.6 Firm's Problem

Let

$$\Omega_{ft} = \left\{ \left(\mu_{jt}, \widehat{q}_{jt} \right) \right\}_{j=1}^{M_{ft}} \tag{27}$$

denote the set of markups and relative qualities of the product lines operated by firm f. Because operating profits and innovation technologies are additive across product lines, the firm's value can be written as

$$\mathcal{V}_t(\Omega_{ft}) = \sum_{j=1}^{M_{ft}} V_t \left(\mu_{jt}, \widehat{q}_{jt} \right), \tag{28}$$

where $\mathcal{V}_t$ and $V_t(\mu, \widehat{q})$ are real values. The latter denotes the value of operating a product line with markup μ and relative quality $\widehat{q}$. We use $\mathcal{V}_t$ for firm value to distinguish it from the nominal wage W_t.

For later use, define the growth rates

$$g_t^Y \equiv \frac{\dot{Y}_t}{Y_t}, \qquad g_t^Q \equiv \frac{\dot{Q}_t}{Q_t}, \tag{29}$$

and let F_t denote the real flow fixed operating cost per product line.

Define the continuation operator

$$\begin{aligned}\mathcal{H}_t V_t(\mu,\widehat{q}) \equiv \partial_t V_t(\mu,\widehat{q}) - \left(r_t + n_t^E + \psi\right) V_t(\mu,\widehat{q}) - \bar{\pi}\mu\partial_\mu V_t(\mu,\widehat{q}) \\ - g_t^Q \widehat{q}\partial_{\widehat{q}} V_t(\mu,\widehat{q}) + \pi_t(\mu,\widehat{q}) + \Lambda_t^I(\mu,\widehat{q}) + \Lambda_t^E - F_t \\ + \gamma\left[V_t\left(\mu_t^u(\widehat{q}),\widehat{q}\right) - V_t(\mu,\widehat{q})\right].\end{aligned} \tag{30}$$

The product-line value satisfies the quasi-variational inequality

$$0 = \max\left\{\mathcal{H}_t V_t(\mu,\widehat{q}),\ V_t\left(\mu_t^u(\widehat{q}),\widehat{q}\right) - \kappa Y_t \widehat{q}^{\sigma-1} - V_t(\mu,\widehat{q})\right\}. \tag{31}$$

The first term describes the value of leaving the current price unchanged. During this period, trend nominal growth erodes the markup, while aggregate quality growth reduces the product's relative quality. The firm earns flow profits $\pi_t(\mu,\widehat{q})$, obtains the option values associated with replacement and expansion innovation, and pays the fixed operating cost F_t. A free price-adjustment opportunity arrives at rate γ.

The product is displaced at rate $n_t^E + \psi$. The first component is creative destruction generated by the expansion innovation of other firms, while the second is exogenous displacement. In either case, the current owner loses the product line and its continuation value falls to zero. The second term in the quasi-variational inequality gives the value of paying the menu cost and resetting the product's markup.

The value of replacement innovation is

$$\Lambda_t^I(\mu,\widehat{q}) = \max_{n^I\geq 0}\left\{n^I\left[V_t\left(\mu_t^u(\lambda^I\widehat{q}),\lambda^I\widehat{q}\right) - V_t(\mu,\widehat{q})\right] - c_t^I(n^I,\widehat{q})\right\}. \tag{32}$$

Replacement innovation introduces a higher-quality product in a line already operated by the firm. Its return therefore equals the value of the new product net of the value of the product it displaces.

The per-line value of expansion innovation is

$$\Lambda_t^E = \max_{n^E\geq 0}\int_0^1\left\{n^E V_t\left(\mu_t^u(\lambda^E\widehat{q}_{it}),\lambda^E\widehat{q}_{it}\right) - c_t^E(n^E,\widehat{q}_{it})\right\}di. \tag{33}$$

The integral reflects that expansion targets a product line uniformly at random. Because the innovator does not already own the targeted line, its return does not subtract the value of an existing product in its portfolio.

Following Akcigit and Kerr (2018), we impose the following tractability restriction on the per-line fixed operating cost.

Assumption 1 (Fixed operating cost)**.** *The per-period fixed operating cost equals the equilibrium per-line option value of expansion innovation:*

$$F_t = \Lambda_t^E. \tag{34}$$

This restriction causes the expansion option value and the fixed operating cost to cancel in the product-line value equation. Expansion innovation continues to affect firms' innovation decisions, creative destruction, aggregate growth, and resource use.

Lemma 1 (Homogeneity and common pricing policies)**.** *Under the fixed-cost assumption:*

1. *Product-line value satisfies*

$$V_t(\mu, \widehat{q}) = \widehat{q}^{\sigma-1} Y_t A_t(\mu), \tag{35}$$

   where $A_t(\mu)$ depends only on the product's markup.

2. *The optimal reset markup and adjustment threshold are common across product lines:*

$$\mu_t^u(\widehat{q}) = \mu_t^u, \qquad \mu_t^\ell(\widehat{q}) = \mu_t^\ell. \tag{36}$$

3. *The replacement-innovation policy depends on a product's markup but not separately on its relative quality.*

The profit flow, replacement R&D cost, and menu cost all scale with $\widehat{q}^{\sigma-1} Y_t$. After the expansion option and fixed operating cost cancel, the product-line problem therefore reduces to the one-dimensional normalized value function $A_t(\mu)$.

Define

$$\widetilde{\pi}_t(\mu) \equiv \frac{\pi_t(\mu, \widehat{q})}{\widehat{q}^{\sigma-1} Y_t} = m_t^{\sigma-1}(\mu - 1)\mu^{-\sigma}, \tag{37}$$

and let

$$A_{u,t} \equiv A_t(\mu_t^u).$$

The normalized value function satisfies

$$\begin{aligned} 0 = \max \Big\{ & \partial_t A_t(\mu) - \left[r_t - g_t^Y + n_t^E + \psi + (\sigma - 1) g_t^Q + \gamma \right] A_t(\mu) - \bar{\pi} \mu A_t'(\mu) \\ & + \widetilde{\pi}_t(\mu) + \widetilde{\Lambda}_t^I(\mu) + \gamma A_{u,t}, \quad A_{u,t} - \kappa - A_t(\mu) \Big\}. \end{aligned} \tag{38}$$

The optimal reset markup and lower adjustment threshold satisfy

$$\mu_t^u \in_{\mu'} A_t(\mu'), \qquad A_t(\mu_t^\ell) = A_{u,t} - \kappa. \tag{39}$$

The normalized replacement-innovation option value is

$$\widetilde{\Lambda}_t^I(\mu) = \max_{n^I \geq 0} \left\{ n^I \left[(\lambda^I)^{\sigma-1} A_{u,t} - A_t(\mu) \right] - \xi^I (n^I)^{\frac{1}{1-\alpha}} \right\}. \tag{40}$$

Consequently,

$$n_t^I(\mu) = \left[\frac{1-\alpha}{\xi^I} \left((\lambda^I)^{\sigma-1} A_{u,t} - A_t(\mu) \right) \right]^{\frac{1-\alpha}{\alpha}}, \tag{41}$$

$$\widetilde{\Lambda}_t^I(\mu) = \xi^I \frac{\alpha}{1-\alpha} \left(n_t^I(\mu) \right)^{\frac{1}{1-\alpha}}. \tag{42}$$

Using $\int_0^1 \widehat{q}_{it}^{\sigma-1} di = 1$, the normalized expansion-innovation option value is

$$\widetilde{\Lambda}_t^E \equiv \frac{\Lambda_t^E}{Y_t} = \max_{n^E \geq 0} \left\{ n^E (\lambda^E)^{\sigma-1} A_{u,t} - \xi^E (n^E)^{\frac{1}{1-\alpha}} \right\}. \tag{43}$$

Thus,

$$n_t^E = \left[\frac{1-\alpha}{\xi^E} (\lambda^E)^{\sigma-1} A_{u,t} \right]^{\frac{1-\alpha}{\alpha}}, \tag{44}$$

$$\widetilde{\Lambda}_t^E = \xi^E \frac{\alpha}{1-\alpha} \left(n_t^E \right)^{\frac{1}{1-\alpha}}. \tag{45}$$

Replacement innovation depends on the current markup because it displaces a product already owned by the firm. Expansion innovation does not subtract the value of an owned product and therefore depends only on the value of a newly introduced product.

4.7 Markup Distribution

The aggregate markup and allocative efficiency depend on the distribution of product-level markups weighted by relative quality. Along the balanced growth path, we define this distribution by

$$\int_{\mu^\ell}^{\mu^u} \varphi(\mu) f(\mu)\, d\mu \equiv \int_0^1 \varphi(\mu_i) \widehat{q}_i^{\sigma-1}\, di \tag{46}$$

for any function φ. Because $\int_0^1 \widehat{q}_i^{\sigma-1} di = 1$, the density satisfies

$$\int_{\mu^\ell}^{\mu^u} f(\mu)\, d\mu = 1. \tag{47}$$

This definition does not require relative quality and markups to be independent.

Using this distribution, the aggregate markup and allocative efficiency defined in Section 4.3 can be written as

$$m = \left(\int_{\mu^\ell}^{\mu^u} \mu^{1-\sigma} f(\mu)\, d\mu \right)^{\frac{1}{1-\sigma}}, \tag{48}$$

$$v = \frac{m^{-\sigma}}{\int_{\mu^\ell}^{\mu^u} \mu^{-\sigma} f(\mu)\, d\mu}. \tag{49}$$

To characterize the stationary distribution, define the interior reset hazard

$$\iota(\mu) \equiv \psi + \gamma + n^E + n^I(\mu). \tag{50}$$

The four components correspond to exogenous displacement, a costless price-adjustment opportunity, expansion innovation by another firm, and replacement innovation by the current owner.

For markups in the interior of the inaction region, the stationary Kolmogorov forward equation is

$$0 = \partial_\mu \left[\bar{\pi} \mu f(\mu) \right] - \left[\iota(\mu) + (\sigma - 1) g \right] f(\mu), \qquad \mu \in (\mu^\ell, \mu^u). \tag{51}$$

The first term captures the deterministic decline in markups generated by trend nominal growth. Its positive sign reflects that $\dot{\mu} = -\bar{\pi}\mu$. The second term removes quality-weighted mass from the current markup. The component $(\sigma - 1)g$ arises because aggregate quality growth reduces each product's relative-quality weight.

All price resets return products to μ^u. The flow of quality-weighted mass entering at the reset markup is

$$\begin{aligned} \mathcal{R} \equiv & \int_{\mu^\ell}^{\mu^u} \left[\gamma + \psi + (\lambda^E)^{\sigma-1} n^E + (\lambda^I)^{\sigma-1} n^I(\widetilde{\mu}) \right] f(\widetilde{\mu})\, d\widetilde{\mu} \\ & + \bar{\pi} \mu^\ell f(\mu^\ell). \end{aligned} \tag{52}$$

The first two terms inside the integral reset prices without changing quality. Expansion and replacement innovation also increase quality, which explains the factors $(\lambda^E)^{\sigma-1}$ and $(\lambda^I)^{\sigma-1}$. The last term is the boundary flow of products that reach μ^ℓ, pay the menu cost, and return to μ^u.

The inflow condition at the reset markup is therefore

$$\bar{\pi} \mu^u f(\mu^u) = \mathcal{R}. \tag{53}$$

Together with the normalization of f, the interior equation and this boundary condition determine the stationary distribution of markups under the quality weights.

4.8 Aggregate Growth and Consumption

Aggregate quality growth is generated by replacement and expansion innovation. For compactness, define n^I as the quality-weighted average of the line-level replacement-innovation policy $n^I(\mu)$:

$$n^I \equiv \int_{\mu^\ell}^{\mu^u} n^I(\mu) f(\mu)\, d\mu. \tag{54}$$

We use n^I for this aggregate throughout; the line-level policy is always written with its argument, $n^I(\mu)$. When needed for the empirical mapping, the corresponding product-count average is computed using the unweighted markup distribution.

Proposition 2 (Aggregate quality growth)**.** *Along the balanced growth path, the growth rate of the quality index is*

$$g = g^E + g^I = n^E \frac{(\lambda^E)^{\sigma-1} - 1}{\sigma - 1} + n^I \frac{(\lambda^I)^{\sigma-1} - 1}{\sigma - 1}. \tag{55}$$

An expansion innovation replaces a product of quality q with one of quality $\lambda^E q$. Because expansion targets product lines uniformly and $\int_0^1 \widehat{q}_i^{\sigma-1} di = 1$, its contribution to growth is

$$g^E = n^E \frac{(\lambda^E)^{\sigma-1} - 1}{\sigma - 1}.$$

Replacement innovation depends on the current markup. Its contribution must therefore be averaged using the quality-weighted markup distribution:

$$g^I = n^I \frac{(\lambda^I)^{\sigma-1} - 1}{\sigma - 1}.$$

Exogenous product displacement and price adjustment do not affect quality and therefore do not contribute directly to growth.

The distinction between the two terms is important. The number of products introduced is determined by innovation rates, whereas their contribution to growth also depends on the corresponding quality improvements. A change in the composition of innovation can therefore cause total product introduction and aggregate growth to move in different directions.

We next characterize the resources devoted to innovation and price adjustment. Aggregate replacement-innovation expenditures are

$$D^I = \xi^I Y \int_{\mu^\ell}^{\mu^u} \left[n^I(\mu) \right]^{\frac{1}{1-\alpha}} f(\mu)\, d\mu. \tag{56}$$

Because expansion innovation is untargeted and the quality weights integrate to one, aggregate expansion-innovation expenditures are

$$D^E = \xi^E Y \left(n^E\right)^{\frac{1}{1-\alpha}}. \tag{57}$$

Under the fixed-cost assumption and the unit measure of active product lines, the aggregate fixed operating cost is

$$\mathcal{F} \equiv \int_0^1 F\, di = F = \Lambda^E = \xi^E \frac{\alpha}{1-\alpha} \left(n^E\right)^{\frac{1}{1-\alpha}} Y. \tag{58}$$

The combined resource cost of expansion innovation and fixed operation is therefore

$$D^E + \mathcal{F} = \frac{\xi^E}{1-\alpha} \left(n^E\right)^{\frac{1}{1-\alpha}} Y. \tag{59}$$

Products reach the lower adjustment threshold at the quality-weighted rate

$$\bar{\pi} \mu^\ell f(\mu^\ell). \tag{60}$$

Because each adjustment uses $\kappa Y \widehat{q}^{\sigma-1}$ units of the final good, aggregate menu-cost expenditures are

$$D^P = \kappa \bar{\pi} \mu^\ell f(\mu^\ell) Y. \tag{61}$$

The goods-market clearing condition is

$$Y = C + D^I + D^E + \mathcal{F} + D^P. \tag{62}$$

Consequently, the consumption share of output is

$$\begin{aligned} \chi^c \equiv \frac{C}{Y} = 1 - \xi^I \int_{\mu^\ell}^{\mu^u} \left[n^I(\mu)\right]^{\frac{1}{1-\alpha}} f(\mu)\, d\mu \\ - \frac{\xi^E}{1-\alpha} \left(n^E\right)^{\frac{1}{1-\alpha}} - \kappa \bar{\pi} \mu^\ell f(\mu^\ell). \end{aligned} \tag{63}$$

The three deductions from output are the resources used for replacement innovation, expansion innovation and fixed operation, and menu-cost price adjustment, respectively.

4.9 Balanced-Growth Equilibrium

We focus on a balanced-growth equilibrium in which normalized product values, pricing and innovation policies, and the quality-weighted markup distribution are stationary. In particular,

$$\partial_t A_t(\mu) = 0, \qquad \partial_t f_t(\mu) = 0.$$

We therefore omit time subscripts from stationary objects.

Definition 1 (Balanced-growth equilibrium)**.** *A balanced-growth equilibrium consists of stationary objects*

$$\left\{A(\mu),\, n^I(\mu),\, n^E,\, f(\mu),\, \mu^\ell,\, \mu^u,\, m,\, v,\, g,\, \chi^c,\, L,\, r,\, R\right\},$$

together with paths for

$$\left\{Q_t, Y_t, C_t, W_t, \widehat{P}_t, M_t, B_t, T_t\right\}_{t\geq 0},$$

such that:

1. *the household's consumption, labor, saving, and money-holding decisions satisfy the optimality conditions in Section 4.1;*
2. *firms solve the pricing and innovation problem in Section 4.6, including the optimal replacement and expansion innovation policies;*
3. *the quality-weighted markup distribution satisfies the stationary forward equation, boundary condition, and normalization in Section 4.7;*
4. *the aggregate markup and allocative efficiency are consistent with the markup distribution;*
5. *aggregate quality growth and the consumption share satisfy the conditions in Section 4.8; and*
6. *the labor, goods, asset, and money markets clear.*

Household optimality and the homogeneity of production imply the following characterization of aggregate variables.

Proposition 3 (Equilibrium aggregates)**.** *Along the balanced growth path,*

$$\frac{\dot{Q}_t}{Q_t} = \frac{\dot{Y}_t}{Y_t} = \frac{\dot{C}_t}{C_t} = g, \qquad L_t = L. \tag{64}$$

Nominal variables satisfy

$$\frac{\dot{M}_t}{M_t} = \frac{\dot{W}_t}{W_t} = \bar{\pi}, \qquad \frac{\dot{\widehat{P}}_t}{\widehat{P}_t} = \bar{\pi} - g, \tag{65}$$

and the nominal and consumption-based real interest rates are

$$R = \rho + \bar{\pi}, \qquad r = \rho + g. \tag{66}$$

Because the markup distribution is stationary, the aggregate markup m, allocative efficiency v, and consumption share χ^c are constant. Aggregate output satisfies

$$Y_t = vQ_tL,$$

so output grows at the same rate as aggregate quality. Because $C_t = \chi^c Y_t$, consumption also grows at rate g.

The quality-adjusted price index grows more slowly than nominal wages because product quality is improving. Nevertheless,

$$\frac{d}{dt}\log\left(\widehat{P}_t Q_t\right) = \bar{\pi}. \tag{67}$$

Thus, the quality-unadjusted price level grows at the money-growth rate, while the quality-adjusted price index grows at $\bar{\pi} - g$. The consumption-based real interest rate consequently satisfies

$$r = R - \frac{\dot{\widehat{P}}_t}{\widehat{P}_t} = \rho + g.$$

Finally, the household's labor-supply condition, $\widehat{P}_t C_t = W_t$, together with $m = \widehat{P}_t Q_t / W_t$, implies

$$C_t = \frac{Q_t}{m}. \tag{68}$$

Combining this expression with $C_t = \chi^c Y_t$ and $Y_t = vQ_tL$ determines equilibrium labor:

$$L = \frac{1}{mv\chi^c}. \tag{69}$$

Labor is therefore constant along the balanced growth path, although its level can differ across stationary equilibria.

4.10 Pricing and Innovation

Optimal reset markup. Let

$$A_u \equiv A(\mu^u)$$

denote the normalized value of a product at the optimal reset markup.

Proposition 4 (Price overshooting). *The optimal reset markup satisfies*

$$\left[\rho + \psi + n^E + (\sigma - 1)g\right] A_u = m^{\sigma-1}(\mu^u - 1)(\mu^u)^{-\sigma} + \widetilde{\Lambda}^I(\mu^u). \tag{70}$$

Suppose that $\bar{\pi} > 0$ and that μ^u is an interior strict maximizer of $A(\mu)$. Then

$$\mu^u > \mu^* = \frac{\sigma}{\sigma - 1}. \tag{71}$$

As pricing frictions vanish because either $\bar{\pi} \to 0$ or $\gamma \to \infty$,

$$\mu^u \to \mu^*. \tag{72}$$

Following a reset, trend nominal growth erodes the product's markup. The firm therefore chooses a reset markup above the static profit-maximizing markup, keeping the markup closer to its desired level over the expected duration of the price spell. When markup erosion disappears or price-adjustment opportunities become arbitrarily frequent, this dynamic consideration vanishes and the reset problem converges to the static pricing problem.

The Calvo rate γ does not appear directly in the reset-value condition because a price-adjustment opportunity has no value when the product is already at its optimal reset markup. Nevertheless, γ affects μ^u indirectly through the value function, the markup distribution, innovation, and the other equilibrium aggregates.

Returns to innovation. The return to replacement innovation can be written as

$$\begin{aligned} x^I(\mu) &\equiv (\lambda^I)^{\sigma-1} A_u - A(\mu) \\ &= \underbrace{A_u - A(\mu)}_{\text{price-realignment value}} + \underbrace{\left[(\lambda^I)^{\sigma-1} - 1\right] A_u}_{\text{quality-improvement value}}. \end{aligned} \tag{73}$$

The first component is the value recovered by replacing a product whose markup has become misaligned. The second is the value generated by improving the quality of the product line. At $\mu = \mu^u$, the price-realignment component is zero, and replacement is motivated only by quality improvement.

The return to expansion innovation is

$$\begin{aligned} x^E &\equiv (\lambda^E)^{\sigma-1} A_u \\ &= \underbrace{A_u}_{\text{value of acquiring a new line}} + \underbrace{\left[(\lambda^E)^{\sigma-1} - 1\right] A_u}_{\text{quality-improvement value}}. \end{aligned} \tag{74}$$

Expansion adds a product line that the firm does not currently own. It therefore obtains the entire value of the newly acquired line and does not subtract the value of an existing product in its portfolio. Although the acquired product is introduced at the reset markup, expansion contains no recovery of a pricing loss on a product already owned by the innovator.

Using this notation, the innovation policies are

$$n^I(\mu) = \left[\frac{1-\alpha}{\xi^I} x^I(\mu)\right]^{\frac{1-\alpha}{\alpha}}, \tag{75}$$

$$n^E = \left[\frac{1-\alpha}{\xi^E} x^E\right]^{\frac{1-\alpha}{\alpha}}. \tag{76}$$

Pricing frictions affect both components of these returns. They change the value A_u of a newly priced product, while markup dispersion creates the additional price-realignment value $A_u - A(\mu)$ for replacement innovation. These effects make the responses of the individual innovation rates ambiguous in general equilibrium. Nevertheless, their relative composition can be signed.

Proposition 5 (Composition of innovation)**.** *Let*

$$n^I = \int_{\mu^\ell}^{\mu^u} n^I(\mu) f(\mu)\, d\mu$$

denote the quality-weighted average replacement-innovation rate, and let superscript flex *denote the flexible-price equilibrium. If $A(\mu) < A_u$ on a set of positive f-measure, as occurs when markup misalignment generates a nondegenerate distribution of product values, then*

$$\frac{n^E}{n^I} < \frac{n^{E,\text{flex}}}{n^{I,\text{flex}}} = \left[\frac{\xi^I (\lambda^E)^{\sigma-1}}{\xi^E \left[(\lambda^I)^{\sigma-1} - 1\right]}\right]^{\frac{1-\alpha}{\alpha}}. \tag{77}$$

The same comparison holds when average replacement innovation is computed using the unweighted product distribution.

Proof. Because μ^u maximizes product value,

$$A_u - A(\mu) \geq 0,$$

with a strict inequality for products whose markups are misaligned. It follows that

$$n^I(\mu) \geq \left[\frac{1-\alpha}{\xi^I}\left[(\lambda^I)^{\sigma-1} - 1\right] A_u\right]^{\frac{1-\alpha}{\alpha}}, \tag{78}$$

with a strict inequality on a positive-measure set when the markup distribution is nondegenerate. Averaging over markups and dividing n^E by the resulting inequality gives

$$\frac{n^E}{n^I} < \left[\frac{\xi^I(\lambda^E)^{\sigma-1}}{\xi^E\left[(\lambda^I)^{\sigma-1}-1\right]}\right]^{\frac{1-\alpha}{\alpha}}. \tag{79}$$

Under flexible prices, all products continuously attain their desired markup, so the price-realignment component of replacement innovation is zero. The reset value in the flexible-price equilibrium cancels from the ratio of the two innovation rates, giving the stated equality. □

The proposition establishes an equilibrium substitution pattern between the two innovation margins: removing pricing frictions raises expansion innovation relative to replacement innovation. This result does not require the reset value to be the same across the two equilibria and therefore survives the general-equilibrium response of product values.

The proposition does not determine the effects on the levels of n^I, n^E, or aggregate growth. More flexible pricing reduces the price-realignment motive for replacement, but it also changes the value of quality improvement, the reset value, and the distribution of markups. Expansion responds to the equilibrium reset value, whose response need not be signed in general. Consequently, the effects on both innovation rates and on

$$g = n^E\frac{(\lambda^E)^{\sigma-1}-1}{\sigma-1} + n^I\frac{(\lambda^I)^{\sigma-1}-1}{\sigma-1}$$

are ultimately quantitative. When $\lambda^E > \lambda^I$, the shift toward expansion raises the average quality improvement associated with innovation, but it does not by itself sign the change in aggregate growth.

5 Model Estimation and Results

This section quantifies the baseline model presented in Section 4. We first calibrate the stationary equilibrium without idiosyncratic productivity shocks, which isolates the interaction between markup erosion, price adjustment, and innovation. We then use counterfactuals to evaluate how pricing frictions affect the level and composition of innovation. Section 5.3 extends the quantitative model to include idiosyncratic productivity shocks and two-sided price adjustment. This extension allows the model to reproduce both positive and negative price changes without changing the paper's central mechanism.

5.1 Estimation

Parameters and calibration targets. The baseline model has 11 parameters,

$$\left\{\sigma, \alpha, \rho, \bar{\pi}, \xi^I, \xi^E, \lambda^I, \lambda^E, \psi, \gamma, \kappa\right\}.$$

We externally calibrate four of them. We set the elasticity of substitution to $\sigma = 6$, the median estimate across product groups in the NielsenIQ data reported by Argente et al. (2024). Following Akcigit and Kerr (2018), we set the innovation elasticity to $\alpha = 0.5$. We set the discount rate to $\rho = 2\%$ and trend money growth to the average inflation rate in our sample, $\bar{\pi} = 2.65\%$.

We calibrate the remaining seven parameters to seven product-level and aggregate moments. For each firm, we classify a newly introduced product as replacement innovation when the firm is already active in its product category and as expansion innovation when the category is new to the firm. To construct empirical counterparts to the two innovation margins, we use the feature-based classification described in Section 3. We classify a new product as replacement innovation when its observed attributes are similar to those already represented in the firm's portfolio, and as expansion innovation when it introduces attributes, or combinations of attributes, that are new to the firm. These measures provide empirical counterparts to the model's innovation margins, although they do not map literally into model product lines. The corresponding innovation rate is the number of newly introduced products divided by the firm's existing product stock. We average these rates across firms within each sector. This procedure yields annual replacement and expansion innovation rates of 6.57% and 4.88%, respectively.

Aggregate sales growth is the average annual growth rate of firm sales. We attribute growth to the two innovation margins using the observed innovation classification and their estimated contributions to sales growth. Expansion innovation accounts for 79.3% of aggregate growth. We construct expected product duration as described in Table 1.

We measure price overshooting as the difference between the average log price of newly introduced and incumbent products within a sector. Its model counterpart is the log reset markup relative to the average log markup in the stationary distribution. Finally, we use the 99th percentile of positive identical-product price changes to discipline the width of the inaction region. The upper tail is more appropriate than the mean because the empirical mean also contains many small, transitory changes associated with sales, short-run shocks, and measurement error, which are outside the model.

Table 3: Model Fit

Moment	Model counterpart	Model	Data
Replacement innovation	n^I	0.0657	0.0657
Expansion innovation	n^E	0.0488	0.0488
Aggregate sales growth	g	0.0203	0.0203
Share of expansion growth	$\frac{n^E}{g}\frac{(\lambda^E)^{\sigma-1}-1}{\sigma-1}$	0.7930	0.7930
Expected product duration	$(n^I+n^E+\psi)^{-1}$	7.500	7.500
Price overshooting	$\log(\mu^u)-\int\log(\mu)f(\mu)\,d\mu$	0.0948	0.0948
P99 of positive price adjustment	$\log(\mu^u)-\log(\mu^\ell)$	0.3330	0.3318

Notes: The table reports the calibration moments. All rates are annualized. The empirical moments are constructed from the NielsenIQ data for 2006–22. Sectors are weighted by their sales shares.

Table 4: Calibrated Parameters

Parameter	Description	Calibration	Value
σ	Elasticity of substitution	External	6
α	Innovation elasticity	External	0.5
ρ	Discount rate	External	2%
$\bar{\pi}$	Trend money growth	External	2.65%
ξ^I	Replacement-innovation cost shifter	Internal	2.725
ξ^E	Expansion-innovation cost shifter	Internal	21.038
ψ	Exogenous displacement hazard	Internal	0.0188
γ	Arrival rate of Calvo opportunities	Internal	0.0849
κ	Menu cost	Internal	0.7426
λ^I	Replacement quality step	Internal	1.057
λ^E	Expansion quality step	Internal	1.215

Notes: Externally calibrated parameters are assigned using the literature or direct empirical counterparts. Internally calibrated parameters are chosen to match the moments in Table 3.

We choose the internally calibrated parameters to minimize the weighted mean absolute percentage deviation,

$$\widehat{\Theta} = \arg\min_{\Theta} \sum_{j\in\mathcal{M}} \omega_j \frac{\left|m_j(\Theta)-\widehat{m}_j\right|}{\left|\widehat{m}_j\right|}, \qquad \Theta = \left\{\xi^I, \xi^E, \lambda^I, \lambda^E, \psi, \gamma, \kappa\right\}, \tag{80}$$

where $\mathcal{M}$ contains the seven moments reported in Table 3. The weights are normalized to sum to one.

The two innovation rates primarily discipline the innovation-cost shifters, ξ^I and ξ^E. Aggregate growth and the share generated by expansion identify the quality steps, λ^I and λ^E. Conditional on the innovation rates, expected product duration identifies the exogenous displacement rate, ψ. Price overshooting and the upper tail of positive price adjustments jointly discipline the Calvo arrival rate, γ, and the menu cost, κ.

Calibration and model fit. Table 3 shows that the model closely matches the seven targeted moments. Table 4 reveals marked differences between the two innovation technologies. Replacement innovation raises product quality by 5.7%, whereas expansion innovation raises quality by 21.5%, nearly four times as much. Expansion is also substantially more costly: $\xi^E = 21.038$, compared with $\xi^I = 2.725$. Consequently, replacement innovation is frequent, relatively inexpensive, and incremental, while expansion innovation is less frequent and more transformative. Expansion represents approximately 43% of innovation events but generates 79% of aggregate growth.

Product replacement has a dual role. It delivers a modest quality improvement and allows the firm to realign a price that has drifted away from its desired level. This feature connects the model to evidence that price changes at product turnover contribute importantly to measured inflation (Nakamura and Steinsson, 2012). Expansion operates differently: although it accounts for fewer introductions, its larger quality step makes it the dominant source of long-run growth. This implication is consistent with the hedonic-price literature, which emphasizes that failing to account for quality upgrading overstates inflation and understates real growth (Boskin et al., 1998).

The calibrated Calvo arrival rate is $\gamma = 0.0849$. It implies an 8.1% probability of receiving a costless adjustment opportunity within one year and, in isolation, an expected waiting time of 11.8 years. The calibrated menu cost is $\kappa = 0.7426$. The optimal reset markup is $\mu^u = 1.3288$ and the lower adjustment threshold is $\mu^\ell = 0.9525$. At the calibrated money-growth rate, and absent innovation, Calvo adjustment, and displacement, it takes 12.57 years for a markup to drift from μ^u to μ^ℓ.

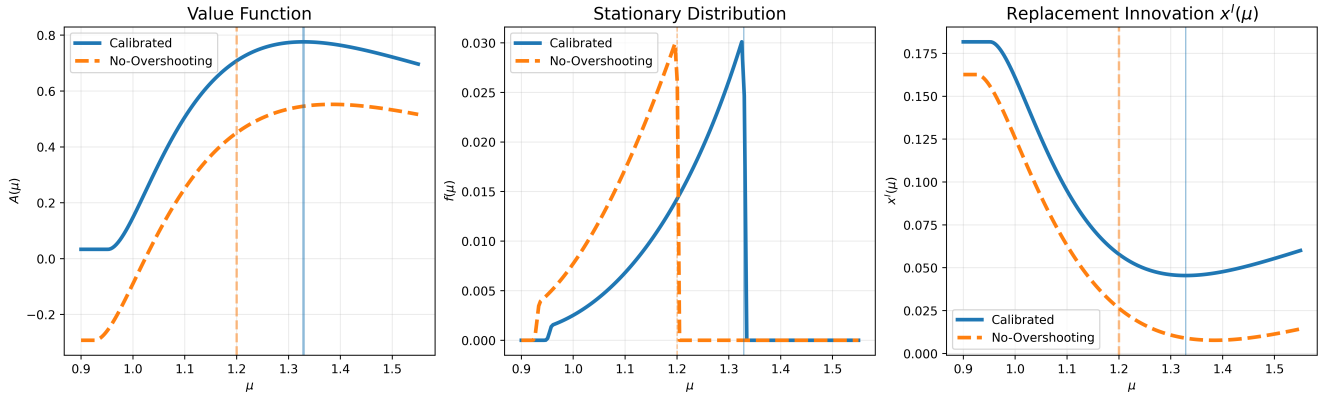
For a continuing product, Calvo and menu-cost adjustment jointly generate 0.095 effective adjustments per product-year, equivalent to a mean spell of 10.53 years or a monthly adjustment frequency of approximately 0.79%. This is well below the nonsale adjustment frequency of 9–12% per month for identical items reported by Nakamura and Steinsson (2008). The gap is intentional: our model captures the low-frequency, persistent realignment of prices over the product life cycle, rather than temporary sales or other short-run price movements. When innovation-driven repricing is also included, the effective product-line price spell falls to 4.71 years. Conditional on no exogenous displacement, innovation accounts for 54.4% of effective price resets, compared with 39.8% for Calvo adjustment and 5.8% for menu-cost adjustment. Innovation is therefore the main mechanism through which product lines obtain a newly chosen price in the calibrated economy.

Table 5: Baseline Economy

	n^I	n^E	μ^u	μ^ℓ	χ^c	v	m	g	Life	Reset spell	Price OS
Baseline	6.57%	4.88%	1.329	0.952	88.52%	97.76%	1.188	2.03%	7.50	4.71	9.48%

Notes: All rates are annualized. Life denotes expected product duration. Reset spell denotes the expected duration between effective price resets at the product-line level, including innovation-driven resets. Price overshooting (OS) is the log reset markup relative to the average log markup.

Figure 6: Value, Markup Distribution, and Replacement Innovation



Notes: Solid lines report the baseline economy. Dashed lines impose a cap that forces the reset markup to equal the static optimum. Vertical lines indicate the reset markup in each economy.

5.2 Quantitative Results

Baseline equilibrium. Table 5 reports the main equilibrium outcomes. The reset markup is approximately 11% above the static profit-maximizing markup, $\mu^* = 1.2$. The lower adjustment threshold lies below one, implying that a firm may temporarily accept a negative flow margin rather than pay the menu cost immediately. Waiting preserves the possibility of obtaining a new price through innovation or a Calvo opportunity.

Markup dispersion reduces allocative efficiency by approximately 2.24%, as measured by $1 - v$. Despite substantial overshooting at introduction, the aggregate markup is only 1.188, close to the static optimum. A decomposition of output shows that 88.5% is allocated to consumption. Replacement and expansion R&D absorb 1.42% and 5.02% of output, respectively, while the fixed operating cost absorbs a further 5.02%. Menu-cost expenditures account for only 0.033%. Their small resource share does not imply that the friction is unimportant: direct adjustment is rare precisely because the calibrated cost is large relative to product value. Innovation is more attractive because it combines repricing with a productive quality improvement.

Figure 6 plots the normalized product value, the stationary markup distribution, and the replacement-innovation policy. Product value is maximized at μ^u. Following a reset, inflation moves markups toward the lower threshold, while innovation, Calvo opportunities, and menu-

Table 6: Pricing Frictions and Price Overshooting

	n^I	n^E	μ^u	μ^ℓ	χ^c	v	m	g	Life	Price OS	Welfare
Frictionless pricing	5.09%	5.47%	1.200	–	86.71%	100.00%	1.200	2.13%	8.03	–	105.3
Baseline	6.57%	4.88%	1.329	0.952	88.52%	97.76%	1.188	2.03%	7.50	9.48%	100.0
No overshooting	6.73%	2.83%	1.200	0.929	94.93%	98.54%	1.089	1.36%	8.74	8.60%	77.6

Notes: Welfare is a consumption-equivalent index normalized to 100 in the baseline. The no-overshooting economy retains the calibrated adjustment frictions but imposes $\mu^u = \mu^*$. Its measured entry premium remains positive because incumbent markups lie below the reset markup on average.

cost adjustment return products to μ^u. The stationary density is therefore concentrated below the reset markup.

The right panel illustrates the central mechanism. Near μ^u, replacement innovation is motivated primarily by its quality improvement and occurs at a rate of approximately 5%. As the markup falls, replacement becomes more valuable because it also restores the product's price. The line-level rate rises to approximately 18% near μ^ℓ. Thus, the price-realignment benefit accounts for most replacement innovation among products with the most misaligned markups.

Pricing frictions and price overshooting. Table 6 compares the baseline with two counterfactuals. The frictionless benchmark allows prices to adjust continuously. The no-overshooting counterfactual retains the calibrated pricing frictions but forces firms to reset at the static optimum, μ^*.

Removing pricing frictions lowers replacement innovation from 6.57% to 5.09% and raises expansion innovation from 4.88% to 5.47%. Total innovation declines, but growth rises from 2.03% to 2.13% because innovation shifts toward the larger-step expansion margin. This is the quantitative counterpart of the composition force described in Section 4.10. The response of each innovation rate is an equilibrium outcome; in the calibrated economy, the decline in the price-realignment motive for replacement shifts innovation toward expansion. More flexible pricing also eliminates markup dispersion, and the combined increase in growth and allocative efficiency raises welfare by 5.3%.

Preventing firms from overshooting lowers the value of a newly priced product and reduces expansion innovation from 4.88% to 2.83%. At each markup, the return to replacement also falls. Aggregate replacement innovation nevertheless rises slightly, from 6.57% to 6.73%, because the stationary distribution shifts toward low-markup states in which replacement provides a particularly valuable price reset. This composition effect does not benefit expansion. Growth falls to 1.36%, and the loss in long-run growth dominates the modest improvement in static allocative efficiency. Price overshooting therefore substantially limits the growth and welfare costs of infrequent price adjustment.

Table 7: Counterfactuals Without Innovation Margins

	n^I	n^E	g	Eff. disc.	A_u	Life	Price OS	Welfare
Baseline	6.57%	4.88%	2.03%	18.90%	0.776	7.50	9.48%	100.0
No replacement innovation	0.00%	4.99%	1.64%	17.10%	0.794	14.54	11.41%	83.1
No expansion innovation	14.98%	0.00%	0.97%	8.76%	2.252	5.91	8.61%	62.3

Notes: The effective discount rate is $\rho + \psi + n^E + (\sigma - 1)g$. All rates are annualized. Welfare is normalized to 100 in the baseline.

The two innovation margins. Table 7 shuts down each innovation margin in turn. The two margins are equilibrium substitutes, but the substitution is highly asymmetric.

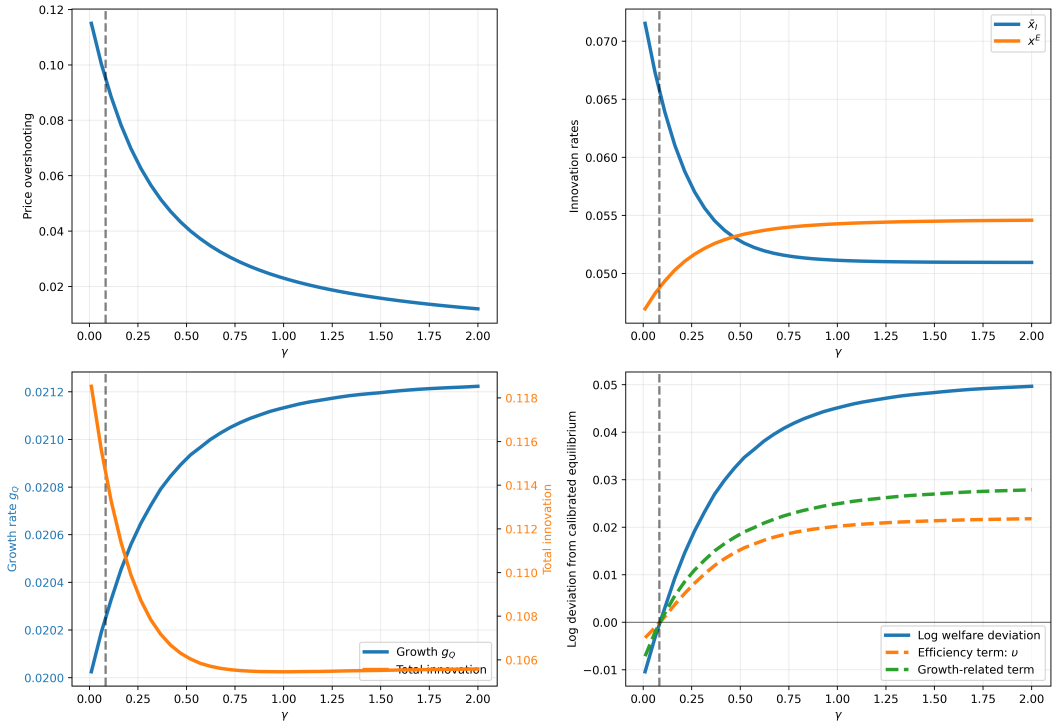
Eliminating replacement innovation raises expansion only slightly, from 4.88% to 4.99%. In contrast, eliminating expansion raises replacement innovation from 6.57% to 14.98%. The asymmetry operates through product valuation. Aggregate quality growth reduces the relative quality of an existing product, while expansion innovation also exposes the product to direct creative destruction. Expansion therefore lowers product values through both aggregate obsolescence and displacement.

Without replacement innovation, the decline in growth raises the value of surviving products and largely offsets the direct loss of the replacement option: A_u rises only from 0.776 to 0.794. Without expansion, growth falls more sharply and the direct creative-destruction hazard disappears. The effective discount rate falls from 18.90% to 8.76%, and A_u rises to 2.252. This increase makes the quality improvement delivered by replacement much more valuable and more than doubles replacement innovation. Neither substitution response, however, offsets the eliminated source of growth.

Comparative statics in pricing frictions. Figure 7 varies the Calvo arrival rate γ, holding the other structural parameters fixed. In the calibrated model, more frequent costless adjustment reduces replacement innovation through two forces. First, it reduces the product-value loss caused by markup erosion, weakening the line-level price-realignment motive. Second, it concentrates the stationary markup distribution near μ^u, where that motive is weakest. Expansion innovation rises because products spend more time near their desired prices, which increases the value of acquiring a line.

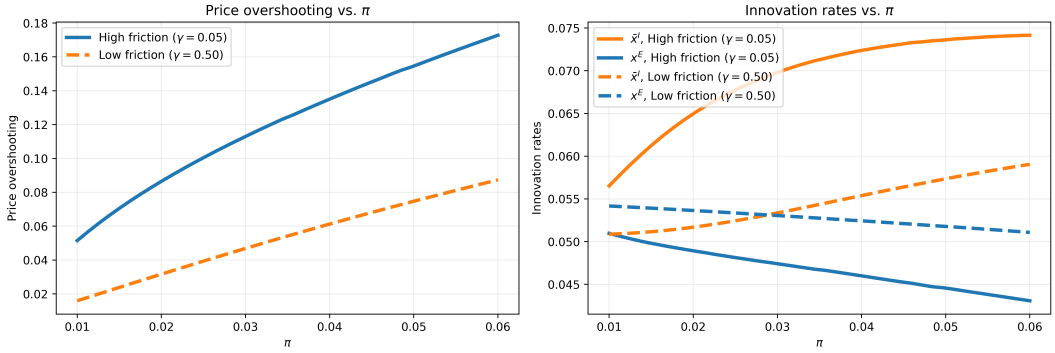
Pricing frictions therefore affect the composition as well as the level of innovation. As γ rises, the calibrated economy shifts from replacement toward expansion. Because expansion produces a larger quality improvement, growth rises even though total innovation falls. Doubling γ from its calibrated value raises welfare by 1.12 log points; approximately 61% of the gain is growth-related and the remainder reflects improved allocative efficiency.

Figure 7: Comparative Statics in the Calvo Arrival Rate



Notes: The figure varies the annual Calvo arrival rate γ. The panels report price overshooting, n^I and n^E, growth and total innovation, and the welfare decomposition. The vertical line indicates the calibrated value.

Figure 8: Inflation and Pricing Frictions



Notes: The figure varies inflation under high pricing frictions ($\gamma = 0.05$) and low pricing frictions ($\gamma = 0.50$). The panels report price overshooting and the two innovation rates. Solid lines denote low frictions and dashed lines high frictions.

Comparative statics in inflation. Figure 8 varies inflation under high and low values of γ. In the calibrated model, higher inflation erodes markups more rapidly and raises the reset markup. It also lowers product values and expansion innovation, while strengthening replacement innovation by increasing the value of restoring the price of an incumbent product. These responses are larger when costless adjustment opportunities are less frequent. Thus, at any given inflation rate, the low-friction economy has more expansion and less replacement innovation.

Table 8: Parameterization with Idiosyncratic Shocks

Parameter	Value	Interpretation
ξ^I	2.476	Replacement-innovation cost shifter
ξ^E	19.642	Expansion-innovation cost shifter
λ^I	1.057	Replacement quality step
λ^E	1.215	Expansion quality step
ψ	0.0188	Exogenous displacement hazard
γ	0.0000	Calvo arrival rate
κ^+	0.3859	Cost of an upward price adjustment
κ^-	0.1004	Cost of a downward price adjustment
σ_z	0.0355	Volatility of productivity shocks

5.3 Extension with Idiosyncratic Productivity Shocks

The baseline model deliberately abstracts from idiosyncratic shocks so that markups move downward between resets. We now allow desired prices to move in both directions. Product i has productivity Z_{it} and production technology

$$y_{it} = Z_{it}\ell_{it}, \qquad d\log Z_{it} = \sigma_z\, d\mathcal{B}_{it}, \tag{81}$$

where $\mathcal{B}_{it}$ is a standard Brownian motion. Nominal marginal cost is W_t/Z_{it}. Define the log markup gap relative to the static optimum as

$$x_{it} \equiv \log\left(\frac{\mu_{it}}{\mu^*}\right). \tag{82}$$

In the absence of adjustment, it evolves according to

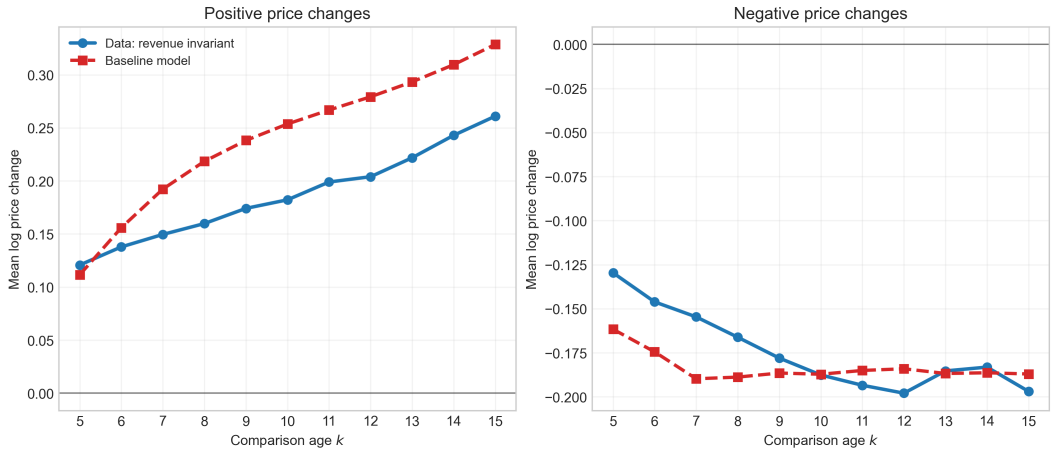
$$dx_{it} = -\bar{\pi}\, dt + \sigma_z\, d\mathcal{B}_{it}. \tag{83}$$

The firm chooses an optimal reset gap x^* and follows a two-sided adjustment policy. At the lower threshold x^ℓ, it raises the price at cost κ^+; at the upper threshold x^h, it lowers the price at cost κ^-. A Calvo opportunity, successful innovation, or exogenous displacement also returns the product to the reset gap. The household and innovation blocks are otherwise unchanged.

We use the same external parameters and aggregate innovation and growth moments as in the baseline. The extension additionally targets the age profiles of positive and negative cumulative price changes for identical products. These profiles jointly discipline σ_z, κ^+, κ^-, and γ. Table 8 reports the resulting parameters.

The extension closely matches the aggregate moments. It generates replacement and expansion innovation rates of 6.56% and 4.91%, aggregate growth of 2.04%, an expansion

Figure 9: Price-Adjustment Profiles with Idiosyncratic Shocks



Notes: The figure compares empirical and model-implied mean cumulative log price changes between age one and comparison age k. At each age, the sample retains products that remain identical through age $k+1$.

Table 9: Innovation Composition with and without Idiosyncratic Shocks

Specification	Pricing	n^I	n^E	g	Price OS	v	Welfare
No shocks	Baseline	6.57%	4.88%	2.03%	9.48%	97.76%	100.0
No shocks	Flexible	5.09%	5.47%	2.13%	–	100.00%	105.3
With shocks	Baseline	6.56%	4.91%	2.04%	9.59%	97.85%	100.0
With shocks	Flexible	5.43%	5.67%	2.22%	0.10%	99.99%	108.4

Notes: Welfare is normalized to 100 within each specification. In the model with shocks, flexible pricing is approximated by setting $\gamma = 50$. All other structural parameters are held at their values for the corresponding specification.

share of growth of 79.4%, expected product duration of 7.5 years, and price overshooting of 9.59%. Figure 9 shows that it also reproduces the increase in the magnitude of both positive and negative cumulative price adjustments over the product life cycle, although it somewhat overstates positive adjustments at long horizons and negative adjustments at short horizons.

The negative price-change profile is particularly informative about σ_z. Inflation moves the markup gap downward, while favorable productivity shocks move it upward and can induce a price reduction. The estimated Calvo arrival rate is zero in this specification: the combination of idiosyncratic shocks and state-dependent adjustment accounts for the persistent price changes in the targeted profiles. The different estimates of γ across specifications reflect the role played by the additional shock process, not a change in the underlying innovation mechanism.

Table 9 compares the central counterfactual across the two specifications. The quantitative conclusion is stable. With flexible pricing, replacement innovation falls and expansion innovation rises in both models. Total innovation declines, yet growth increases because innovation shifts toward the margin with the larger quality step.

Figure 10: Innovation and Pricing Frictions



Notes: The figure plots mean replacement product introduction rates (n^I) and expansion product introduction rates (n^E) across deciles of the module-level frequency of price changes. The horizontal axis measures the average weekly frequency of price adjustment within a module. The innovation measures are residualized by time fixed effects. Observations are weighted by module revenue. Lines show linear fits across deciles.

The richer model also delivers the same comparative-static mechanism. Raising γ from zero to one lowers replacement innovation from 6.57% to 5.44%, raises expansion innovation from 4.93% to 5.53%, and increases growth from 2.05% to 2.17%. Conversely, doubling the cost of an upward price adjustment raises replacement innovation from 6.57% to 7.53% and lowers expansion innovation from 4.93% to 4.68%. Thus, allowing desired prices to move in both directions improves the model's account of observed price changes while preserving the result that tighter pricing frictions shift innovation toward replacement and away from expansion.

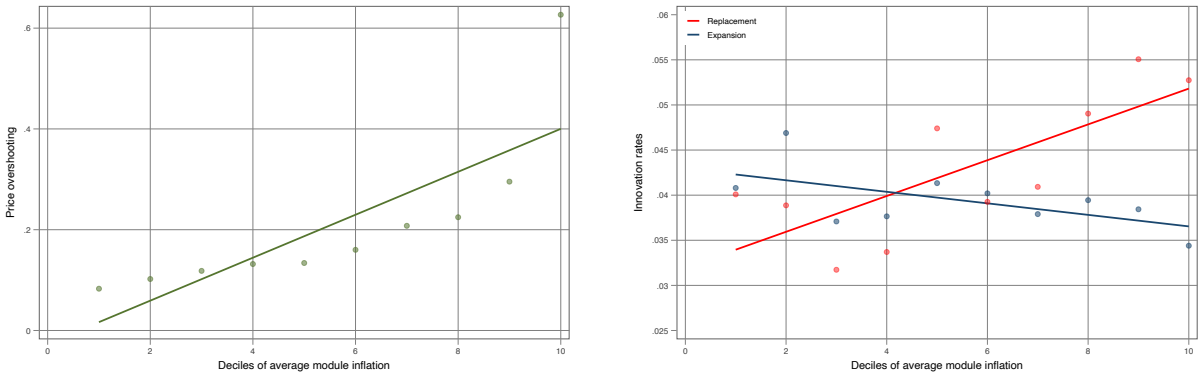
6 Empirical Tests for Model Implications

6.1 Innovation and Pricing Frictions

We begin by examining whether the composition of product introduction varies systematically with the frequency of incumbent price adjustment. Figure 10 plots mean replacement and expansion product introduction rates across deciles of the module-level frequency of price changes, after residualizing the innovation measures by time fixed effects. Modules with more frequent price adjustment exhibit lower replacement innovation and higher expansion innovation.

Appendix Table A4 presents the corresponding regression evidence. More frequent price adjustment is associated with lower total and replacement innovation, a smaller replacement share, and higher expansion innovation. Equivalently, modules with greater pricing frictions exhibit more replacement and less expansion innovation, and may have more product introduction overall. These cross-sectional relationships do not identify causal effects, but they are

Figure 11: Price Overshooting and Innovation by Inflation



Notes: The left panel plots mean price overshooting across deciles of average module-level inflation. The right panel plots mean replacement product introduction rates (n_t^I) and expansion product introduction rates (n_t^E) across the same inflation deciles. Each point represents the average across modules within an inflation decile. Lines show fitted linear trends across deciles.

consistent with the model's composition mechanism: when incumbent prices can be realigned more easily, replacement is less valuable as an alternative opportunity for price adjustment and innovation shifts toward expansion.

6.2 Price Overshooting and Innovation by Inflation

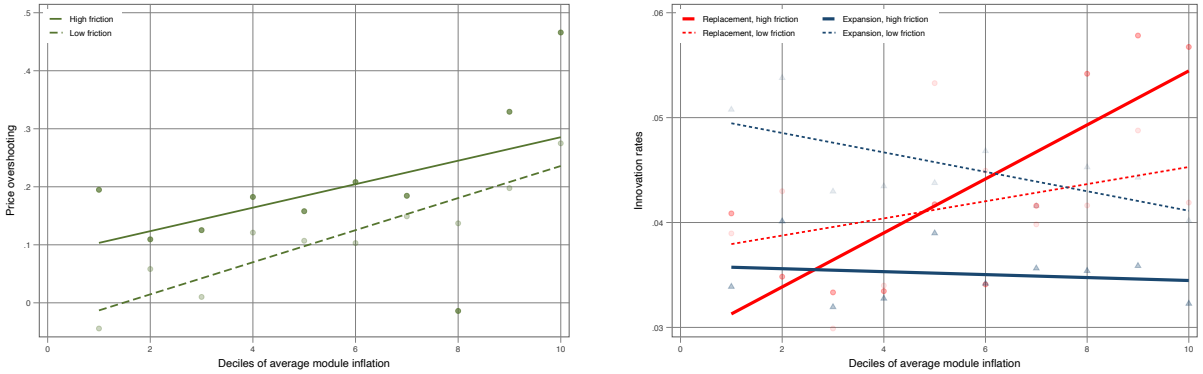
We next examine how price overshooting and innovation vary with inflation. Appendix Table **??** reports the relationship between module-level inflation and the price premium of newly introduced products. Across specifications, higher inflation is associated with significantly larger entry premia. Modules with more frequent price adjustment exhibit lower average price overshooting, and the interaction between inflation and high-frequency price adjustment is negative and statistically significant. Thus, the positive association between inflation and price overshooting is weaker in modules where incumbent prices adjust more frequently.

Figure 11 presents the corresponding patterns across inflation deciles. The left panel shows a positive and approximately monotonic relationship between inflation and the price overshooting of newly introduced products. The right panel shows that replacement innovation rises across inflation deciles, while expansion innovation declines. Higher inflation is therefore associated with a change in the composition, rather than a uniform increase, of product introduction.

The compositional pattern is consistent with firms relying relatively more on products similar to those already in their portfolios in higher-inflation environments, while introducing fewer products with attributes or combinations of attributes that are new to the firm. The evidence is therefore consistent with the quantitative model implication that inflation strengthens the price-realignment benefit associated with replacement innovation.

Figure 12 examines whether these relationships differ with the frequency of price adjustment. Price overshooting increases with inflation in both high- and low-friction modules, but the relationship is substantially steeper among modules with less frequent price adjustment.

Figure 12: Inflation and Innovation across Pricing Environments



Notes: The left panel plots mean price overshooting across deciles of average module-level inflation separately for high- and low-friction modules. The right panel plots mean replacement product introduction rates (n^I) and expansion product introduction rates (n^E) across the same inflation deciles and friction groups. Modules are classified as low-friction if their average frequency of price changes is above the sample mean, and as high-friction otherwise. Each point represents the average across modules within an inflation decile and friction group. Lines show fitted linear trends across deciles.

Similarly, replacement innovation rises more strongly with inflation in high-friction modules, while expansion innovation declines.

Taken together, these patterns suggest that inflation and pricing frictions are jointly associated with the composition of product introduction. The combination of higher inflation and less frequent incumbent price adjustment is associated with greater price overshooting and relatively more replacement innovation. This evidence is consistent with the model mechanism through which firms use product introduction to restore prices that have become misaligned over the product life cycle.

7 Conclusion

This paper studies how long run pricing frictions shape firms' innovation decisions and aggregate growth. Using detailed product and firm longitudinal data, we document that the average nominal prices of incumbent products exhibit little systematic growth over the product life cycle, while their relative prices decline. New products enter at sizable price premia, including products that introduce relatively few new attributes. These premia are larger in sectors with greater pricing frictions, and tariff induced cost increases pass through disproportionately to products introduced after the cost change. Together, these findings show that product introduction provides firms with an important margin of price adjustment.

We develop and estimate an endogenous growth model in which pricing frictions affect both firms' incentives to innovate and the nature of the products they introduce. Pricing frictions operate through two opposing forces. They reduce product values by limiting firms' ability to maintain desired real markups, but they also increase the value of product introduction as a way to reset prices. The model distinguishes between replacement innovation, which

updates an existing product line, and expansion innovation, which creates a new product line. Although both allow firms to choose a new price, the estimates imply that replacement generates substantially smaller quality improvements and contributes less to aggregate growth.

The quantitative results show that pricing frictions shift innovation toward replacement and away from expansion. Moving to frictionless pricing reduces total product introduction but raises aggregate growth because innovation shifts toward products with larger quality improvements. It also compresses markup dispersion over the product life cycle, improves allocative efficiency, and raises consumption equivalent welfare by 5.3 percent. Counterfactuals that vary inflation show that higher inflation produces a stronger shift toward replacement when pricing frictions are greater. Consistent with this prediction, the empirical analysis finds that inflation is associated with more replacement and less expansion innovation, particularly in sectors where prices adjust less frequently.

Taken together, our findings show that the effects of pricing frictions extend beyond the prices of incumbent products. By making product introduction a margin of price adjustment, these frictions change both the level and composition of innovation. More product introduction can therefore coexist with slower growth when innovation shifts toward products that facilitate price adjustment but generate smaller quality improvements. Accounting for this interaction is important for understanding how inflation and pricing frictions affect innovation, allocative efficiency, and long run growth.

Bibliography

Abe, Nobuhiro, Yojiro Ito, Ko Munakata, Shinsuke Ohyama, and Kimiaki Shinozaki, "Pricing Patterns over Product Life-Cycle and Quality Growth at Product Turnover: Empirical Evidence from Japan," Bank of Japan Working Paper Series 16-E-5, Bank of Japan 2016.

Acemoglu, Daron, Ufuk Akcigit, Harun Alp, Nicholas Bloom, and William Kerr, "Innovation, Reallocation, and Growth," *American Economic Review*, November 2018, *108* (11), 3450–3491.

Adam, Klaus and Henning Weber, "Estimating the optimal inflation target from trends in relative prices," *American Economic Journal: Macroeconomics*, 2023, *15* (3), 1–42.

Aghion, Philippe and Peter Howitt, "A Model of Growth through Creative Destruction," *Econometrica*, 1992, *60* (2), 323–351.

Akcigit, Ufuk and William R. Kerr, "Growth through Heterogeneous Innovations," *Journal of Political Economy*, 2018, *126* (4), 1374–1443.

Amiti, Mary, Stephen J. Redding, and David E. Weinstein, "The Impact of the 2018 Tariffs on Prices and Welfare," *Journal of Economic Perspectives*, 2019, *33* (4), 187–210.

Anzoategui, Diego, Diego Comin, Mark Gertler, and Joseba Martinez, "Endogenous Technology Adoption and R&D as Sources of Business Cycle Persistence," *American Economic Journal: Macroeconomics*, 2019, *11* (3), 67–110.

Argente, David and Chen Yeh, "Product life cycle, learning, and nominal shocks," *The Review of Economic Studies*, 2022, *89* (6), 2992–3054.

_ and Munseob Lee, "Cost of Living Inequality During the Great Recession," *Journal of the European Economic Association*, 06 2020, *19* (2), 913–952.

_ , _ , and Sara Moreira, "The life cycle of products: Evidence and implications," *Journal of Political Economy*, 2024, *132* (2), 337–390.

Bai, Liang and Sebastian Stumpner, "Estimating US Consumer Gains from Chinese Imports," *American Economic Review: Insights*, 2019, *1* (2), 209–224.

_ , Torsten Søchting Jaccard, and Sebastian Stumpner, "Tariff Pass-Through into Retail Prices: Measurement, Replacement, and Shrink-flation," December 2025. Working paper.

Beraja, Martin, Erik Hurst, and Juan Ospina, "The Aggregate Implications of Regional Business Cycles," *Econometrica*, 2019, *87* (6), 1789–1833.

Besanko, David, Jean-Pierre Dubé, and Sachin Gupta, "Own-Brand and Cross-Brand Retail Pass-Through," *Marketing Science*, 2005, *24* (1), 123–137.

Bils, Mark, "Do Higher Prices for New Goods Reflect Quality Growth or Inflation?," *The Quarterly Journal of Economics*, 2009, *124* (2), 637–675.

_ and Peter J. Klenow, "Some Evidence on the Importance of Sticky Prices," *Journal of Political Economy*, 2004, *112* (5), 947–985.

Blanco, Andrés, Corina Boar, Callum Jones, and Virgiliu Midrigan, "Nonlinear Inflation Dynamics in Menu Cost Economies," Working Paper 2024-10, Federal Reserve Bank of Atlanta September 2024. FRB Atlanta Working Paper No. 2024-10.

Boskin, Michael J., Ellen R. Dulberger, Robert J. Gordon, Zvi Griliches, and Dale W. Jorgenson, "Consumer Prices, the Consumer Price Index, and the Cost of Living," *Journal of Economic Perspectives*, 1998, *12* (1), 3–26.

Burstein, Ariel, Javier Cravino, and Marco Rojas, "Input Price Dispersion Across Buyers," Working Paper 33128, National Bureau of Economic Research 2026. NBER Working Paper No. 33128, revised June 2026.

Cafarella, Michael, Gabriel Ehrlich, Tian Gao, John C Haltiwanger, Matthew D Shapiro, and Laura Zhao, "Using machine learning to construct hedonic price indices," Technical Report, National Bureau of Economic Research 2023.

Çakır, Metin and Joseph V. Balagtas, "Consumer Response to Package Downsizing: Evidence from the Chicago Ice Cream Market," *Journal of Retailing*, 2014, *90* (1), 1–12.

Calvo, Guillermo A., "Staggered prices in a utility-maximizing framework," *Journal of Monetary Economics*, 1983, *12* (3), 383–398.

Campbell, Jeffrey R and Benjamin Eden, "Rigid prices: Evidence from us scanner data," *International Economic Review*, 2014, *55* (2), 423–442.

Cavallo, Alberto, Brent Neiman, and Roberto Rigobon, "Currency Unions, Product Introductions, and the Real Exchange Rate," *The Quarterly Journal of Economics*, 2014, *129* (2), 529–595.

_ , Gita Gopinath, Brent Neiman, and Jenny Tang, "Tariffs Pass Through as a Domestic Tax: Evidence from U.S. Trade Policy," *American Economic Review*, 2021, *111* (2), 686–719.

Coibion, Olivier, Yuriy Gorodnichenko, and Gee Hee Hong, "The cyclicality of sales, regular and effective prices: Business cycle and policy implications," *American Economic Review*, 2015, *105* (3), 993–1029.

Copeland, Adam and Adam Hale Shapiro, "Price Setting and Rapid Technology Adoption: The Case of the PC Industry," *The Review of Economics and Statistics*, 2016, *98* (3), 601–616.

Deaton, Angus, *The Analysis of Household Surveys: A Microeconometric Approach to Development Policy*, Baltimore: Johns Hopkins University Press for the World Bank, 1997.

Edmond, Chris, Virgiliu Midrigan, and Daniel Yi Xu, "How Costly Are Markups?," Working Paper 30753, National Bureau of Economic Research 2022. NBER Working Paper No. 30753.

Ehrlich, Gabriel, John C. Haltiwanger, Ron S. Jarmin, David Johnson, Ed Olivares, Luke W. Pardue, Matthew D. Shapiro, and Laura Yi Zhao, "Quality Adjustment at Scale: Hedonic vs. Exact Demand-Based Price Indices," NBER Working Paper 31309, National Bureau of Economic Research 2023.

Eichenbaum, Martin, Nir Jaimovich, and Sergio Rebelo, "Reference prices, costs, and nominal rigidities," *American Economic Review*, 2011, *101* (1), 234–262.

Eslava, Marcela, John Haltiwanger, and Nicolas Urdaneta, "The Size and Life-Cycle Growth of Plants: The Role of Productivity, Demand, and Wedges," *Review of Economic Studies*, 2024, *91* (1), 259–300.

Fajgelbaum, Pablo D, Pinelopi K Goldberg, Patrick J Kennedy, and Amit K Khandelwal, "The Return to Protectionism," *Quarterly Journal of Economics*, 2020, *135* (1), 1–55.

Friedman, Milton, "The Role of Monetary Policy," *The American Economic Review*, 1968, *58* (1), 1–17.

Galí, Jordi, *Monetary Policy, Inflation, and the Business Cycle*, Princeton University Press, 2015.

Garcia-Macia, Daniel, Chang-Tai Hsieh, and Peter J. Klenow, "How Destructive is Innovation?," *Econometrica*, September 2019, *87* (5), 1507–1541.

Golosov, Mikhail and Robert E. Lucas, "Menu Costs and Phillips Curves," *Journal of Political Economy*, 2007, *115* (2), 171–199.

Granja, João and Sara Moreira, "Product Innovation and Credit Market Disruptions," *The Review of Financial Studies*, 2023, *36* (5), 1930–1969.

Grossman, Gene M. and Elhanan Helpman, *Innovation and Growth in the Global Economy*, Cambridge, MA: MIT Press, 1991.

Hottman, Colin J., Stephen J. Redding, and David E. Weinstein, "Quantifying the Sources of Firm Heterogeneity," *The Quarterly Journal of Economics*, 2016, *131* (3), 1291–1364.

Janssen, Aljoscha and Johannes Kasinger, "Shrinkflation and Consumer Demand," *Marketing Science*, 2026, *45* (1), 142–158.

Kaplan, Greg and Guido Menzio, "The morphology of price dispersion," *International Economic Review*, 2015, *56* (4), 1165–1206.

Kehoe, Patrick and Virgiliu Midrigan, "Prices are sticky after all," *Journal of Monetary Economics*, 2015, *75*, 35–53.

Kim, In Kyung, "Consumers' Preference for Downsizing over Package Price Increases," *Journal of Economics & Management Strategy*, 2024, *33* (1), 25–52.

Klenow, Peter J and Oleksiy Kryvtsov, "State-dependent or time-dependent pricing: Does it matter for recent US inflation?," *The Quarterly Journal of Economics*, 2008, *123* (3), 863–904.

Klette, Tor Jakob and Samuel Kortum, "Innovating firms and aggregate innovation," *Journal of Political Economy*, 2004, *112* (5), 986–1018.

Ma, Yueran and Kaspar Zimmermann, "Monetary Policy and Innovation," NBER Working Paper 31698, National Bureau of Economic Research 2023.

Moran, Patrick and Albert Queralto, "Innovation, Productivity, and Monetary Policy," *Journal of Monetary Economics*, 2018, *93*, 24–41.

Nakamura, Emi and Dawit Zerom, "Accounting for Incomplete Pass-Through," *Review of Economic Studies*, 2010, *77* (3), 1192–1230.

_ and Jón Steinsson, "Lost in Transit: Product Replacement Bias and Pricing to Market," *American Economic Review*, 2012, *102* (7), 3277–3316.

_ and Jón Steinsson, "Five Facts about Prices: A Reevaluation of Menu Cost Models," *The Quarterly Journal of Economics*, 2008, *123* (4), 1415–1464.

Peters, Michael, "Heterogeneous markups, growth, and endogenous misallocation," *Econometrica*, 2020, *88* (5), 2037–2073.

Rebelo, Sergio, Miguel Santana, and Pedro Teles, "Behavioral sticky prices," *Journal of Monetary Economics*, 2025, p. 103828.

Romer, Paul M., "Endogenous Technological Change," *Journal of Political Economy*, October 1990, *98* (5, Part 2), S71–S102.

Werning, Iván, "Expectations and the Rate of Inflation," Working Paper 30260, National Bureau of Economic Research 2022. NBER Working Paper No. 30260.

Woodford, Michael, *Interest and Prices: Foundations of a Theory of Monetary Policy*, Princeton University Press, 2003.

INNOVATION AND PRICING FRICTIONS

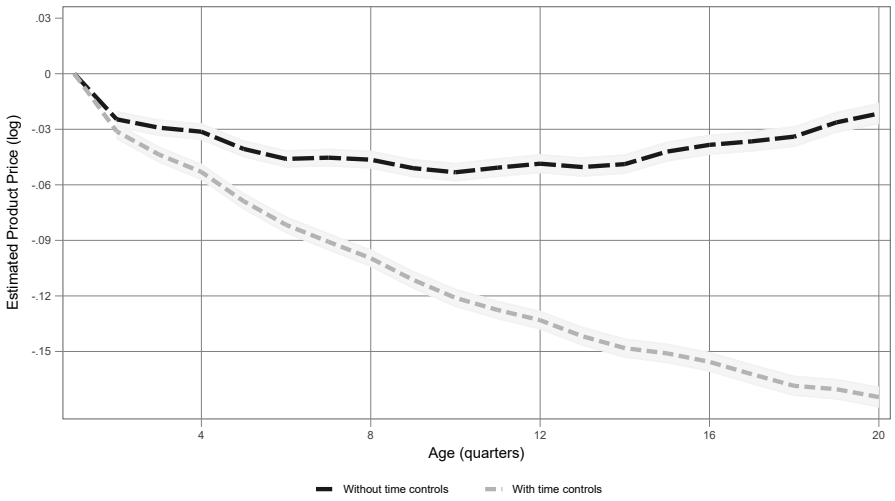
APPENDIX

FOR ONLINE PUBLICATION

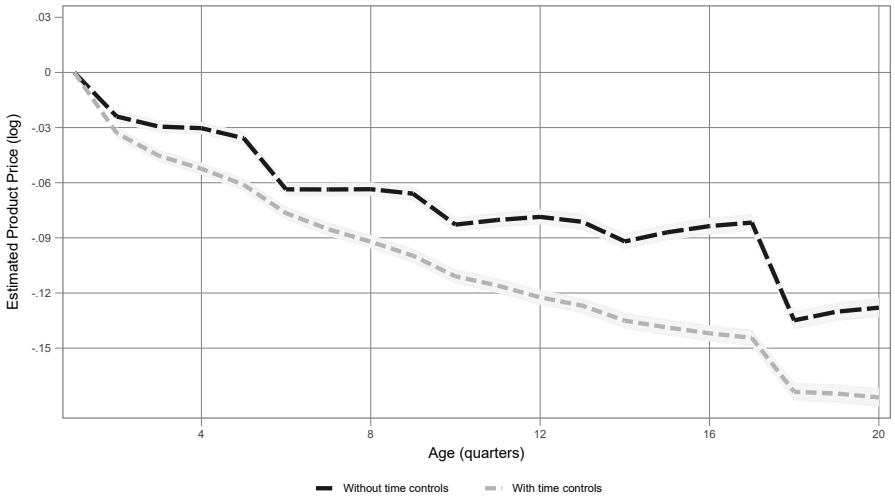
A Additional Results

Figure A1: Prices over the Product Life Cycle: Age effects for Semi-Balanced and Unbalanced Samples

(a) Semi-balanced Sample



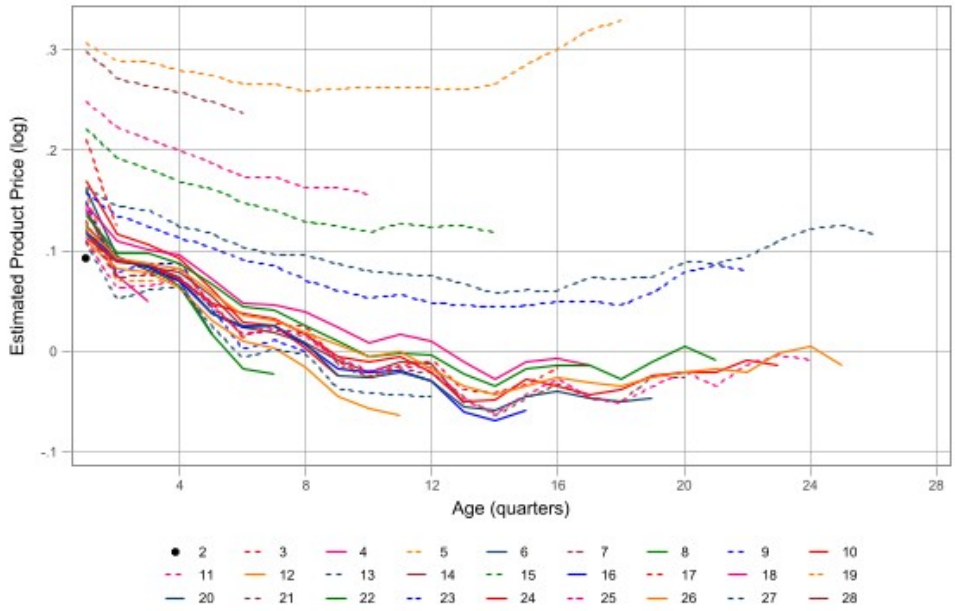
(b) Unbalanced Sample



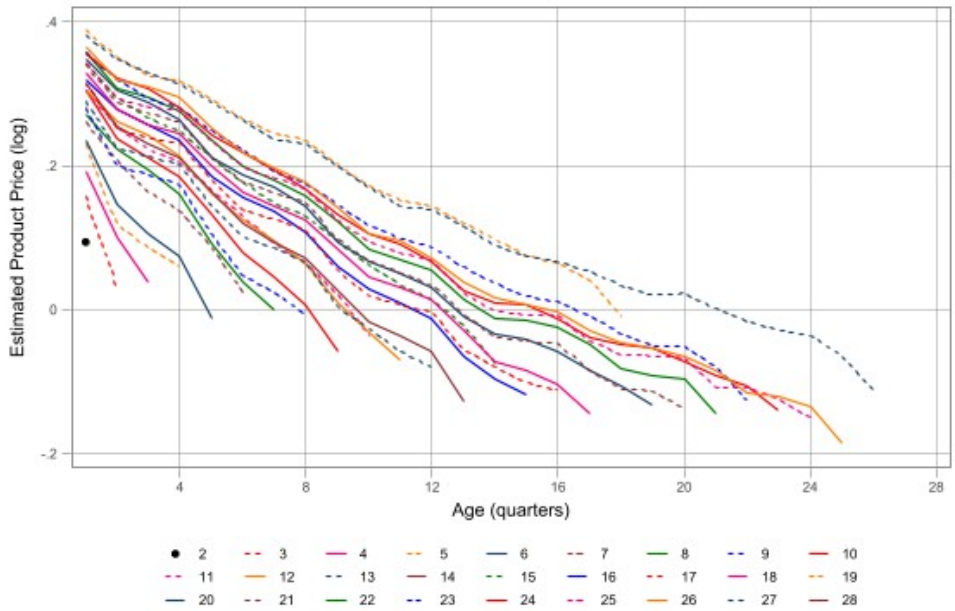
Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). The estimation uses all products. In panel (a) the age fixed effects are computed for cohorts 2006q3-2016q3, including products that exit before they complete 20 quarters of sales. In panel (b) the age fixed effects includes products from cohorts 2006q3 to 2021q4. The gray area indicates the 95% confidence interval.

Figure A2: Prices over the Product Life Cycle: by Duration

Panel (a) - Without time controls

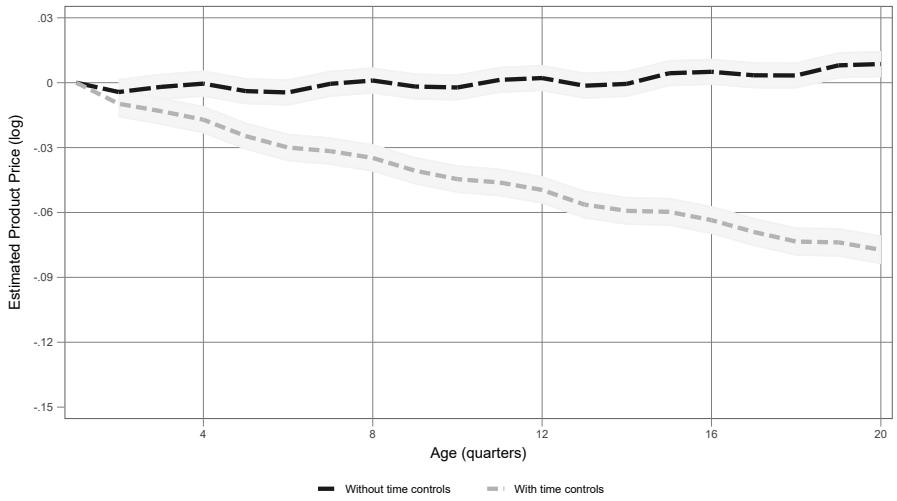


Panel (b) - With time controls



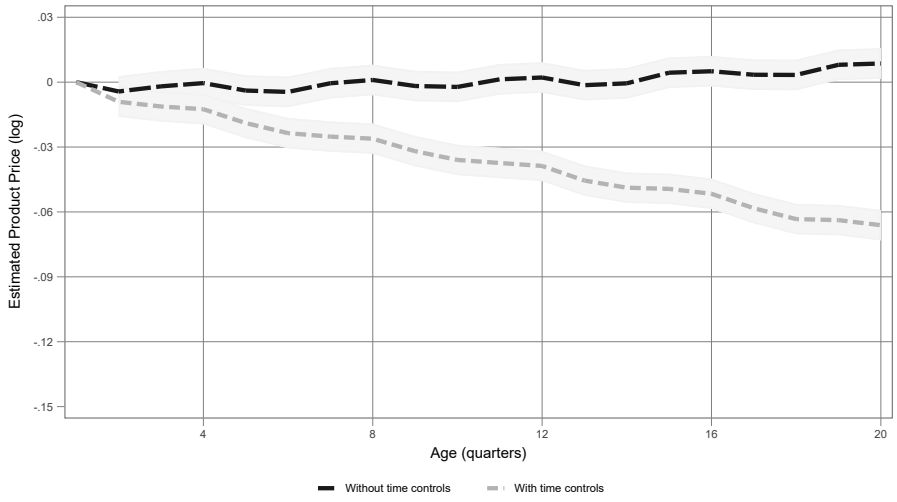
Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3) where age effects are interacted with duration, for products that lasted between 2 and 28 quarters in the market.

Figure A3: Prices over the Product Life Cycle: Alternative Sample



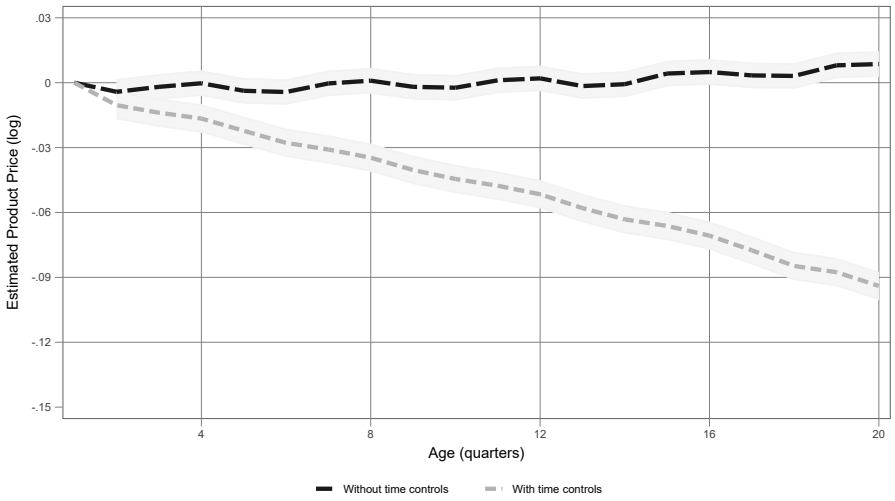
Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). The estimation uses all products and the age fixed effects are computed for products duration of more than 20 quarters. The gray area indicates the 95% confidence interval.

Figure A4: Prices over the Product Life Cycle: Alternative Cohort Effects



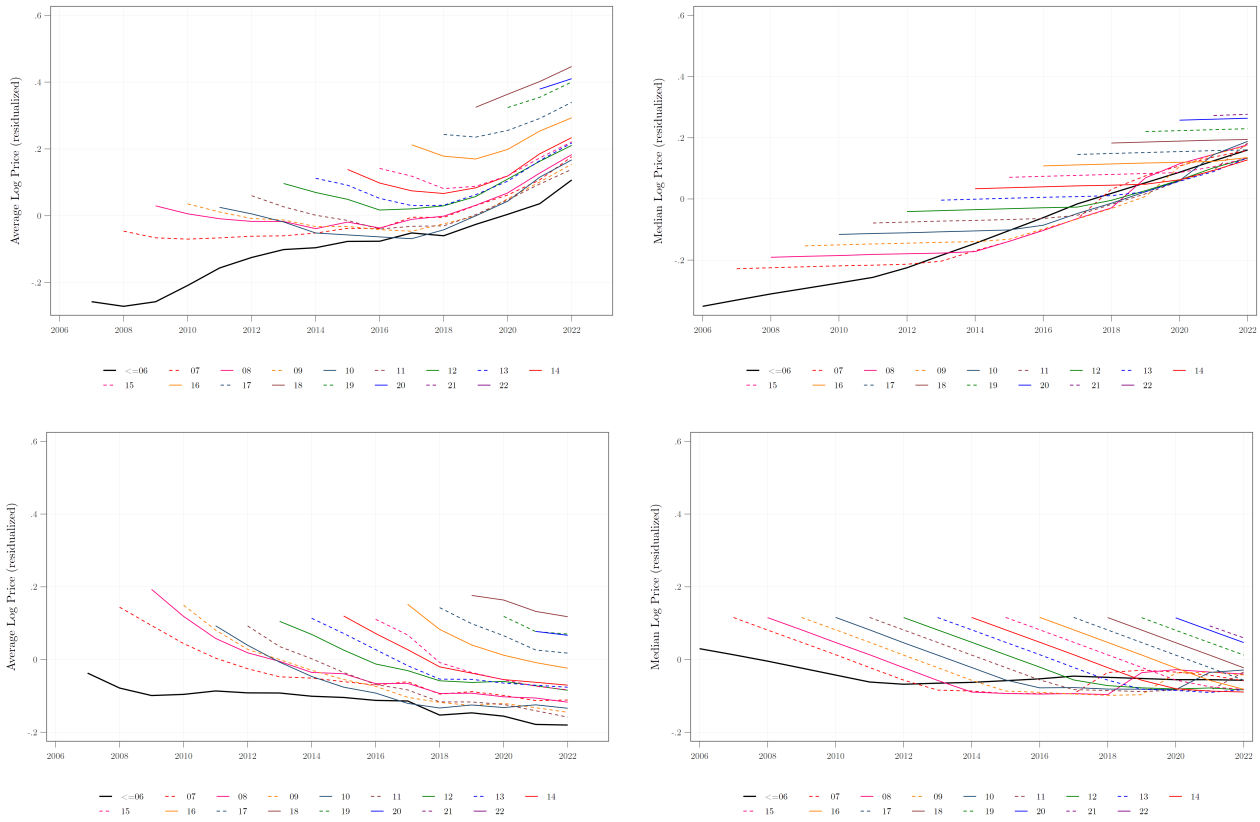
Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). The estimation uses all products and the age fixed effects are computed for products duration of more than 20 quarters. The gray area indicates the 95% confidence interval.

Figure A5: Prices over the Product Life Cycle: Firm Controls



Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). The estimation uses all products and the age fixed effects are computed for products duration of more than 20 quarters. The gray area indicates the 95% confidence interval.

Figure A6: Price Dynamics Fit between simulated data and real data



Notes: The left panel plots the price dynamics that is estimated in the real data. The right panel plots the price dynamics that is estimated in the simulated data.

Table A1: Price Overshooting of New Products and Proxies for Price Frictions (non-weighted)

	Price Overshooting New Products					
	(1)	(2)	(3)	(4)	(5)	(6)
Frequency of price changes	-0.596***	-0.591***	-0.269***			
	(0.036)	(0.036)	(0.057)			
Life-cycle estimate				-2.438***	-2.437***	-1.299***
				(0.094)	(0.094)	(0.113)
Observations	58,207	58,207	58,207	58,207	58,207	58,207
R-squared	0.005	0.011	0.035	0.011	0.018	0.037
Time FE	N	Y	Y	N	Y	Y
Sector FE	N	N	Y	N	N	Y

Notes: The table reports the association between two proxies for the frequency of price changes and the price overshooting of new products, using module–quarter variation, covering 2007q1-2022q4. "Frequency Price Changes" is the average module-level frequency of price adjustments, as defined in Appendix X. "Life Cycle Estimated" is the annualized average price growth over the product life cycle, estimated separately for each module using equation 3. Price overshooting is defined as $\tilde{P}_{m,t} = \left(P^{\text{new}}_{m,t} / P^{\text{inc}}_{m,t}\right) - 1$. Sectors correspond to NielsenIQ product groups.

Table A2: Relative Price New Products and Tariff Exposure

	Relative Price New Products					
	(1)	(2)	(3)	(4)	(5)	(6)
Tariff Exposure	1.3644**	1.3603**	1.5102**			
	(XXX)	(XXX)	(XXX)			
Change Tariff Exposure				1.1827*	1.1721*	1.7296**
				(XXX)	(XXX)	(XXX)
time × category	yes	yes	yes	yes	yes	yes
firm × category	yes	yes	yes	yes	yes	yes
controls	no	yes	yes	no	yes	yes

Notes: The table reports the estimated coefficients of tariff exposure from equation 4 with $k = 2$, using firm–module–year variation for the period 2010–2022. Price overshooting is defined as $\tilde{P}_{i,j,t+k} = \left(P^{\text{new}}_{i,j,t+k} / P^{\text{inc}}_{i,j,t+k}\right) - 1$. Categories correspond to NielsenIQ product modules. Columns (1) and (4) include time–category and firm–category fixed effects. Columns (2) and (5) additionally include controls for the quantity coverage of the tariff exposure measure. Columns (3) and (6) further include the interaction of coverage and tariff variables; the reported coefficients correspond to the estimated effect of tariff exposure evaluated at the average coverage level.

Table A4: Innovation and Pricing Frictions

	(1) Innovation Rate	(2) Replacement Share	(3) Replacement Rate	(4) Expansion Rate	(5) Innovation Rate	(6) Replacement Share
Frequency of Price Changes	-0.030***	-0.243***	-0.063***	0.034***		
	(0.012)	(0.040)	(0.008)	(0.008)		
Life Cycle Estimated					-1.068***	-1.428***
					(0.042)	(0.198)
Observations	16,743	13,610	16,743	16,743	16,743	13,610
R-squared	0.084	0.045	0.104	0.030	0.186	0.050

Notes: The table reports estimates from regressions of innovation outcomes on measures of pricing frictions using module-annual variation over the period 2007–2022. Innovation outcomes include total innovation, replacement innovation, expansion innovation, and the replacement share of innovation. All variables are winsorized at the 1st and 99th percentiles. Regressions include year fixed effects in all specifications. Observations are weighted by module revenue. Robust standard errors are reported in parentheses.

Table A3: Tariff Exposure and Relative Prices of New Products

	k						
	-2	-1	0	1	2	3	4
Tariff Exposure	0.4823	-0.4651	0.2609	1.5726*	2.7002***	3.4068***	-1.1363
	(1.05)	(0.88)	(0.79)	(0.92)	(1.02)	(1.17)	(1.28)
Tariff Exposure ×	-0.7557	0.7307	-0.1452	-1.5020**	-1.7996**	-2.2246**	1.0332
Frequency Price Changes	(0.867)	(0.662)	(0.581)	(0.727)	(0.767)	(0.887)	(1.001)
Observations	51463	60210	66820	59182	49463	42222	35503

Notes: The table shows the estimated coefficients of equation $y_{i,j,t+k} = \beta T_{i,j,t} + \gamma T_{i,j,t} \times Z_j + \omega_{j,t+k} + \phi_{i,j} + \text{controls}_{i,j,t+k} + \varepsilon_{i,j,t+k}$, $k = -2, ..., 0, ..., 4$. The variable $T_{i,j,t}$ is the level of tariff exposure. The outcome is the relative price of new products $\tilde{P}_{i,j,t+k} = \left(P^{\text{new}}_{i,j,t+k} / P^{\text{inc}}_{i,j,t+k}\right) - 1$. The variable Z_j is the standardized frequency of price changes at the product category level. The vertical bands represent +/- 1.96 × st. error of each point estimate.

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Table A5: Price Overshooting of New Products and Inflation

	Price Overshooting New Products					
	(1)	(2)	(3)	(4)	(5)	(6)
Inflation	1.378***	1.470***	1.395***	1.466***	1.509***	1.496***
	(0.021)	(0.022)	(0.021)	(0.034)	(0.034)	(0.032)
High frequency price changes				-0.040***	-0.042***	-0.018***
				(0.003)	(0.003)	(0.007)
Inflation × High frequency price changes				-0.152***	-0.075*	-0.174***
				(0.044)	(0.044)	(0.041)
Observations	58,201	58,201	58,201	58,201	58,201	58,201
R-squared	0.067	0.085	0.219	0.071	0.088	0.219
Time FE	N	Y	Y	N	Y	Y
Sector FE	N	N	Y	N	N	Y

Notes: The table reports the relationship between inflation and the price overshooting of new products using module–quarter variation over the period 2007q1–2022q4. Price overshooting is defined as $\tilde{P}_{m,t} = \left(P^{\text{new}}_{m,t} / P^{\text{inc}}_{m,t}\right) - 1$. "High frequency price changes" is an indicator equal to one for modules whose average frequency of price adjustment is above the sample mean, and zero otherwise. The interaction term captures whether the association between inflation and price overshooting differs across high- and low-frequency pricing environments. Columns (2), (3), (5), and (6) include quarter fixed effects; columns (3) and (6) additionally include NielsenIQ product-group fixed effects. Observations are weighted by module revenue. Robust

B Robustness for Alternative Samples

B1. Alternative Samples

We evaluate four sets of measurement problems: (1) entry and exit of stores; (2) private label products; (3) incomplete spells; (4) coverage of some product categories.

(1) Entry and Exit of Stores

The baseline sample includes products sold in all stores. The number of store available in the dataset every year varies, and this raises two measurement issues. First, estimates of products' entries and exits might be affected by the entries and exits of stores in the sample. Second, estimates of prices over the life cycle can also vary with the entry and exit of stores with varying price levels (Kaplan and Menzio, 2015). Therefore, for robustness of the main results, we consider a balanced sample of stores during our sample period 2006-2022. Table B3 presents the descriptive statistics of this alternative sample. Figures B1 and B2 present the main results.

Table B1: Summary Statistics: Robustness Entry and Exit Stores – E

	All	By Censoring Type			
		Not Censored	Right	Left	Right & Left
Total # of products	675,455	308,383	203,961	116,559	46,552
Duration (quarters)					
average	18	9.7	20	18	68
less than 4	31	44	21	28	0
above 20	27	11	32	31	100
above 28	20	5.4	23	21	100
Revenue (quarterly, $1,000)					
mean	94	30	158	27	294
25th percentile	0.6	0.3	1.6	0.2	5.6
median	4.9	2.6	13	1.4	32
75th percentile	36	16	93	10	183
90th percentile	177	66	365	51	694
95th percentile	404	136	719	119	1,292
Price (quarterly)					
mean	0.047	0.039	0.12	-0.061	0.026
25th percentile	-0.35	-0.39	-0.26	-0.44	-0.32
median	0.079	0.088	0.14	-0.0022	0.0081
75th percentile	0.50	0.53	0.54	0.37	0.37
90th percentile	0.93	0.98	0.96	0.79	0.79
95th percentile	1.20	1.30	1.20	1.10	1.10

Notes: The table presents summary statistics for the products included in the baseline sample for 2006q1–2022q4. Products already active in 2006q1–2006q2 are left-censored, and products with sales in 2022q3–2022q4 are right-censored. "Not Censored" includes products observed from entry to exit. "Right Censored" indicates products still sold at the end of the sample. "Left Censored" refers to products already on the market at the start of the sample. "Right & Left" includes products with both entry and exit censored. Duration is measured in quarters. Revenue and price are calculated per quarter. Revenue is in thousands of dollars. Prices are differenced from the sector×quarter median price.

Table B2: Summary Statistics: Robustness Entry and Exit Stores – Full

	All	By Censoring Type			
		Not Censored	Right	Left	Right & Left
Total # of products	1,789,877	937,703	372,209	395,221	84,743
Duration (quarters)					
average	21	15	22	25	68
less than 4	22	28	18	14	0
above 20	37	26	39	48	100
above 28	26	15	30	35	100
Revenue (quarterly, $1,000)					
mean	51	23	105	23	207
25th percentile	0.2	0.1	0.7	0	2.1
median	1.6	1.2	5.6	0.5	14
75th percentile	14	9.4	45	5	95
90th percentile	79	44	217	35	444
95th percentile	199	98	478	92	930
Price (quarterly)					
mean	0.097	0.14	0.17	-0.059	0.022
25th percentile	-0.36	-0.34	-0.25	-0.51	-0.36
median	0.13	0.18	0.18	-0.0014	0.015
75th percentile	0.62	0.69	0.64	0.43	0.42
90th percentile	1.10	1.20	1.10	0.90	0.85
95th percentile	1.40	1.50	1.40	1.20	1.10

Notes: Same definitions as in Table **??**. Duration is in quarters. Revenue and price are quarterly; revenue is in thousands of dollars; prices are differenced from the sector×quarter median price.

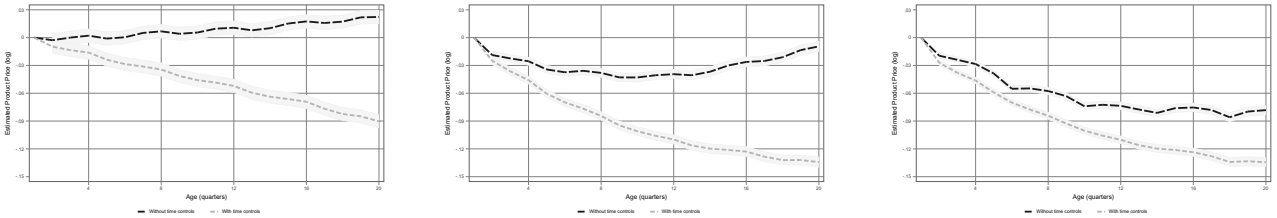
Table B3: Summary Statistics: Robustness Entry and Exit Stores – Full

	All	By Censoring Type			
		Not Censored	Right	Left	Right & Left
Total # of products	1,789,877	937,703	372,209	395,221	84,743
Duration (quarters)					
average	21	15	22	25	68
less than 4	22	28	18	14	0
above 20	37	26	39	48	100
above 28	26	15	30	35	100
Revenue (quarterly, $1,000)					
mean	51	23	105	23	207
25th percentile	0.2	0.1	0.7	0.0	2.1
median	1.6	1.2	5.6	0.5	14
75th percentile	14	9.4	45	5	95
90th percentile	79	44	217	35	444
95th percentile	199	98	478	92	930
Price (quarterly)					
mean	0.097	0.14	0.17	-0.059	0.022
25th percentile	-0.36	-0.34	-0.25	-0.51	-0.36
median	0.13	0.18	0.18	-0.0014	0.015
75th percentile	0.62	0.69	0.64	0.43	0.42
90th percentile	1.10	1.20	1.10	0.90	0.85
95th percentile	1.40	1.50	1.40	1.20	1.10

Notes: The table presents summary statistics for the baseline sample, 2006q1–2022q4. Products already active in 2006q1–2006q2

Figure B1: Price Life Cycle: Robustness Entry and Exit of Stores

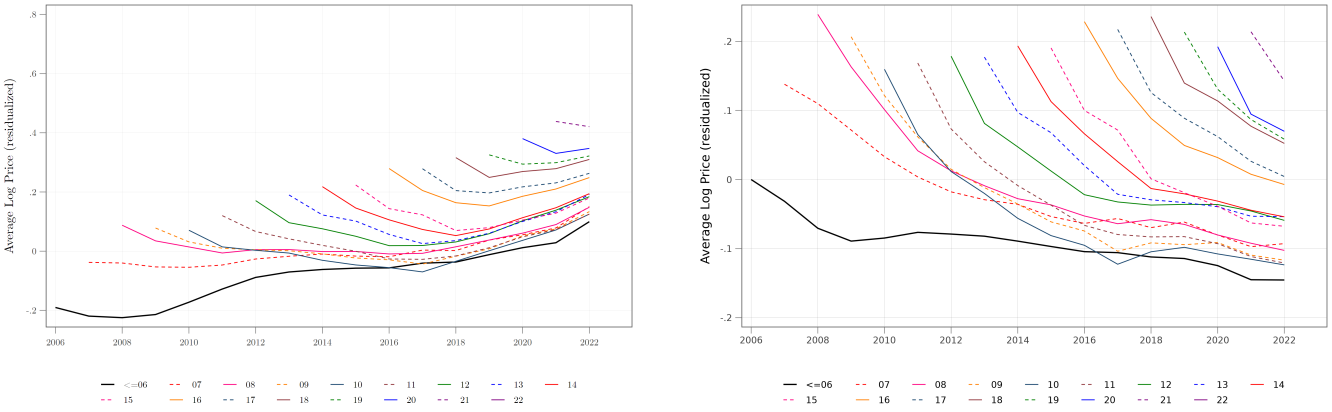
(a) Balanced cohorts w/o exit (b) Balanced cohorts w/ exit (c) Unbalanced cohorts w/exit



Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). We use the sector and sector x time effects, as well as iteration of sector and sector x quarter fixed effects with firm-level fixed effects. The estimation uses all branded products sold in the balanced set of stores active over the entire period 2006-2022. In (a) the age fixed effects are computed for balanced cohort and products duration of more than 20 quarters. In (b) the age fixed effects are computed for balanced cohorts but individual products can exit before 20 quarters of activity. In (c) we use an unbalanced sample of cohorts with exit. Main text provides details on the cohorts used.

Figure B2: Prices by Cohort of Products: Robustness Entry and Exit of Stores

(a) Without Time Controls (b) With Time Controls



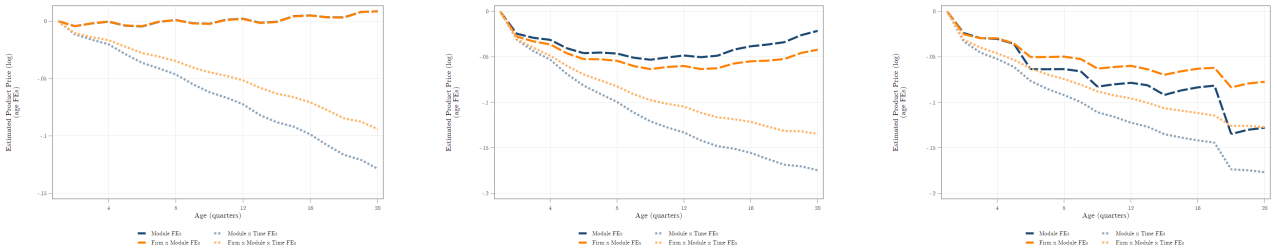
Notes: The figures display average log prices by cohort over time using the baseline annual-level sample. In panel (a), log prices are residualized using sector fixed effects. In panel (b), log prices are residualized using sector-by-year fixed effects. The estimation uses all branded products sold in the balanced set of stores active over the entire period 2006-2022.

(2) Private Label Products

The baseline sample excludes private label products. In order to protect the identity of the retailer, Nielsen alters the UPCs associated with private label goods. As a result, multiple private label items are mapped to a single UPC that makes it difficult to interpret the entry and exit patterns of these items since it is not possible to determine the producer of these goods. We evaluated the impact of this exclusion by having including these products in robustness samples. Figures B3 and B4 present the main results.

Figure B3: Price Life Cycle: Robustness Private Label

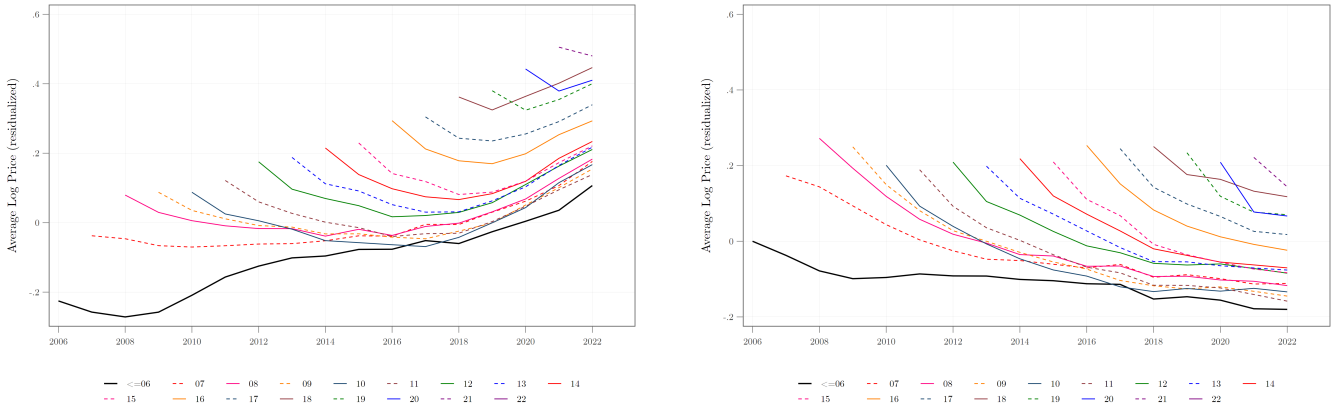
(a) Balanced cohorts w/o exit (b) Balanced cohorts w/ exit (c) Unbalanced cohorts w/exit



Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). We use the sector and sector x time effects, as well as iteration of sector and sector x quarter fixed effects with firm-level fixed effects. The estimation uses all branded products and private label products. In (a) the age fixed effects are computed for balanced cohort and products duration of more than 20 quarters. In (b) the age fixed effects are computed for balanced cohorts but individual products can exit before 20 quarters of activity. In (c) we use an unbalanced sample of cohorts with exit. Main text provides details on the cohorts used.

Figure B4: Prices by Cohort of Products: Robustness Private Label

(a) Without Time Controls (b) With Time Controls



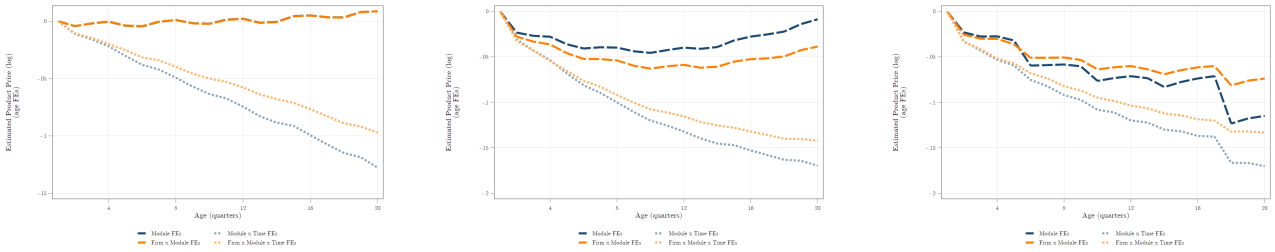
Notes: The figures display average log prices by cohort over time using the baseline annual-level sample. In panel (a), log prices are residualized using sector fixed effects. In panel (b), log prices are residualized using sector-by-year fixed effects. The estimation uses all branded products sold in the balanced set of stores active over the entire period 2006-2022.

(3) Incomplete Spells

In a robustness sample, we exclude products with missing quarters to rule out the possibility that our results are driven by seasonal products, promotional items, or products with very little sales. Figures B5 and B6 present the main results.

Figure B5: Price Life Cycle: Robustness Incomplete spells

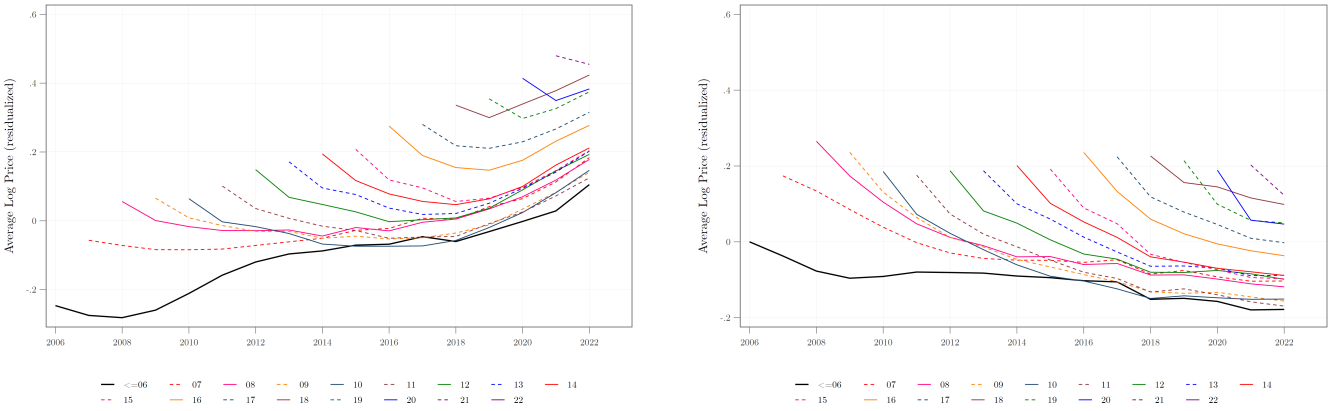
(a) Balanced cohorts w/o exit (b) Balanced cohorts w/ exit (c) Unbalanced cohorts w/exit



Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). We use the sector and sector x time effects, as well as iteration of sector and sector x quarter fixed effects with firm-level fixed effects. The estimation included all branded products, excluding products with incomplete observations. In (a) the age fixed effects are computed for balanced cohort and products duration of more than 20 quarters. In (b) the age fixed effects are computed for balanced cohorts but individual products can exit before 20 quarters of activity. In (c) we use an unbalanced sample of cohorts with exit. Main text provides details on the cohorts used.

Figure B6: Prices by Cohort of Products: Robustness Private Label

(a) Without Time Controls (b) With Time Controls



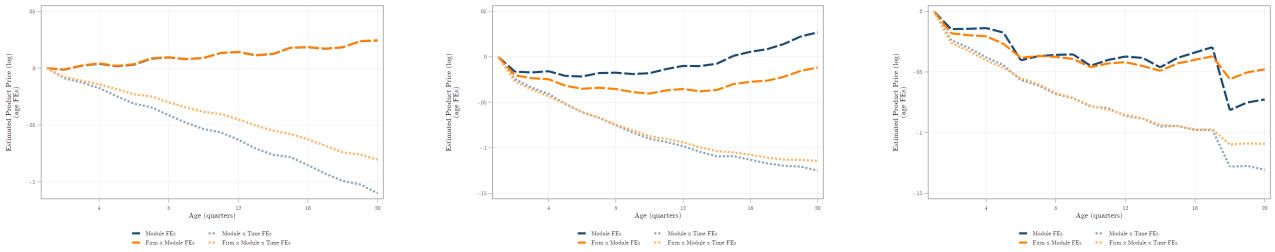
Notes: The figures display average log prices by cohort over time using the baseline annual-level sample. In panel (a), log prices are residualized using sector fixed effects. In panel (b), log prices are residualized using sector-by-year fixed effects. The estimation included all branded products, excluding products with incomplete observations.

(4) Coverage of Some Product Categories

We include robustness where we exclude Alcohol and General Merchandise because these are the departments for which the coverage in Nielsen RMS is smaller and less likely to be representative. Figures B7 and C1 present the main results.

Figure B7: Price Life Cycle: Robustness Coverage of Some Product Categories

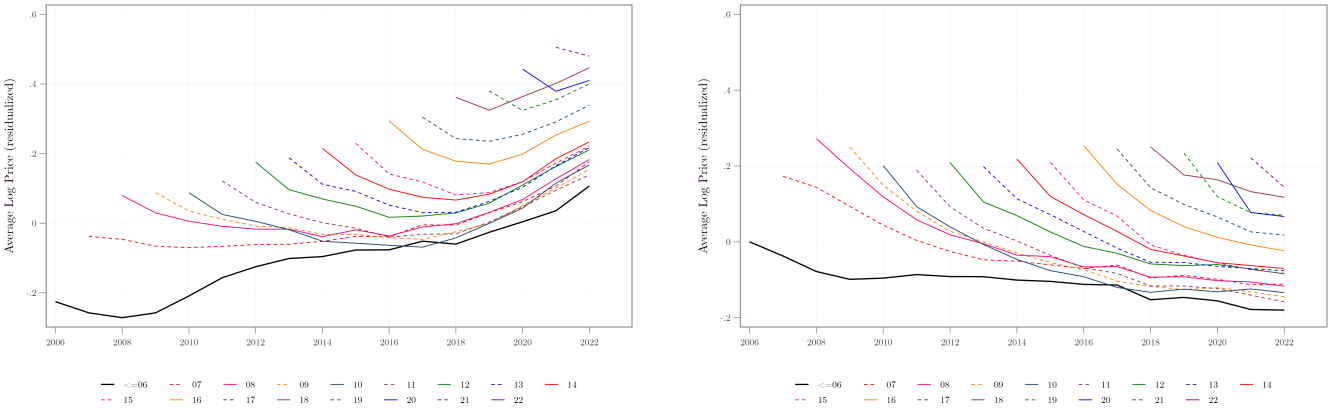
(a) Balanced cohorts w/o exit (b) Balanced cohorts w/ exit (c) Unbalanced cohorts w/exit



Notes: The figure shows the estimated age fixed effects of (log) prices of products computed using equations (**??**) and (3). We use the sector and sector x time effects, as well as iteration of sector and sector x quarter fixed effects with firm-level fixed effects. The estimation uses excludes all branded products except incomplete observations, and products from Alcohol and General Merchandise Sectors. In (a) the age fixed effects are computed for balanced cohort and products duration of more than 20 quarters. In (b) the age fixed effects are computed for balanced cohorts but individual products can exit before 20 quarters of activity. In (c) we use an unbalanced sample of cohorts with exit. Main text provides details on the cohorts used.

Figure B8: Prices by Cohort of Products: Robustness Coverage of Categories

(a) Without Time Controls (b) With Time Controls



Notes: The figures display average log prices by cohort over time using the baseline annual-level sample. In panel (a), log prices are residualized using sector fixed effects. In panel (b), log prices are residualized using sector-by-year fixed effects. The estimation uses excludes all branded products except incomplete observations, and products from Alcohol and General Merchandise Sectors.

C Frequency and Magnitude of Price Changes

C.1 Working Datasets

The raw Nielsen-RMS data has average weekly prices and value at product (upc × upc-version) × store × week. We start by scaling prices (and quantities) such that we use the same unit measure within each product category. We group products of the Nielsen RMS data by assigning an ID to a product (upc × upc-version) at a given store (store_code_uc). To measure price changes, we compute first differences, and detect changes, their magnitude and nature (positive/negative, small/large, and whether it reverts to prior level). Our baseline working dataset aggregates information to product-store-year level.

There are two important measurement issues. First, we have to handle missings in price information. Nielsen RMS does not measure prices when there is no quantity sold in a particular week $l = 1, ..., 52$. Our baseline measure of frequency of price changes only uses consecutive weeks with price information. We build two other measures for robustness, where we make different assumptions for the missing observations. Suppose we observe prices for unit i (product × store) at time t and $t-k$, p_{it-k} and p_{it}, we make the following assumptions: (i) assume $p_{i,t-k+1} = p_{i,t}$, price in $t-k+1$ changes to $p_{i,t}$ and remains the same until t; (ii) assume $p_{i,t-k} = p_{i,t-1}$, all prices between $p_{i,t-k}$ and $p_{i,t}$ do not change and stay at $p_{i,t-k}$.

The second measurement issue is related to the nature of price changes. The literature identified three broad classes of price changes: regular price changes for identical items, temporary sales, and price changes due to product substitution (Nakamura and Steinsson, 2008). Instead of trying to identify regular price changes, our approach consists in estimating all price changes and price changes likely associated with temporary price discounts within product × store, and directly measure product substitution. Nielsen RMS does not directly measure if a product × store is on temporary sale. As in Coibion et al. (2015), we develop distinct measures of temporary price reductions using information on the amount and duration of a price reduction.

C.1.1 Key Variables

Frequency and size of price changes – The measure of frequency of price changes is computed as:

$$\Delta_{it} = \frac{\sum_{l}^{\Omega_{it}} 1\{p_{it,l} - p_{it,l-1} \neq 0\}}{\sum_{l}^{\Omega_{it}} 1_{t,l}} \tag{84}$$

where for the baseline Ω_{it} is the set of consecutive weeks with price information, while for the robustness Ω_{it} includes all weeks. The baseline measures the share of price changes out of all price first differences that can be computed using Nielsen RMS, without imputations. The underlying assumption of the baseline is that the missings in first differences are random. The underlying assumption of the robustness measure is that there were no price changes when no price data is observed.

For both baseline and robustness, we build measures that condition on whether the change is negative or positive, and if the differences are larger than 5% or 10%. We also build measures that capture decline in prices that are likely temporary.

We compute measures of the amount of price changes during the time t. We consider

$$M_{it}^{(1)} = \sum_{l}^{\Omega_{it}} |\ln p_{it,l} - \ln p_{it,l-1}| \tag{85}$$

$$M_{it}^{(2)} = \frac{\sum_{l}^{\Omega_{it}} |p_{it,l} - p_{it,l-1}|}{\bar{p}_{it}} \tag{86}$$

where $\bar{p}_{it}$ is the average price of product. We build measures that only account differences are larger than 5% or 10%. We also build measures that capture decline in prices that are likely temporary.

Temporary price discounts – We apply a sales filter similar to that in Nakamura and Steinsson (2008) and Coibion et al. (2015). Specifically, we consider a product on sale if a price reduction is followed by a price increase of similar magnitude within four weeks. We consider a version where the price increase should be of exact amount such that prices return to previous level, and another version where the price increase to within a level very close to the initial price.

C.1.2 Implementation

We build working datasets for each sector. These sector working datasets are used on the statistics and life cycle exercises.

C.2 Descriptive Statistics

In this section, we provide summary statistics on the frequencies of product price change in the United States from 2006 to 2020. The summary statistics are computed from a panel data set defined by upc × store_code_uc × year × module consisting of 328 modules in the Nielsen scanner data. We include one baseline frequency of price changes, two robust checks for frequencies of price changes, the frequency of positive price changes, the frequency of negative price changes, and three measures for the frequencies of sales in our analysis.

	All Price Changes					Temporary Price Changes		
	Baseline	Opt 1	Opt 2	Opt +	Opt -	Baseline	Opt 1	Opt 2
Median								
Frequency	0.212	0.078	0.078	0.083	0.095	0	0	0
Duration	2.611	5.150	5.150	5.150	5.039	7.739	2.804	2.466
Average								
Frequency	0.291	0.163	0.162	0.139	0.152	0.048	0.143	0.174
Duration	4.962	11.040	11.040	8.186	7.982	9.536	3.557	3.309

Table C1: The Frequency and Duration of Price Changes from 2006-2020

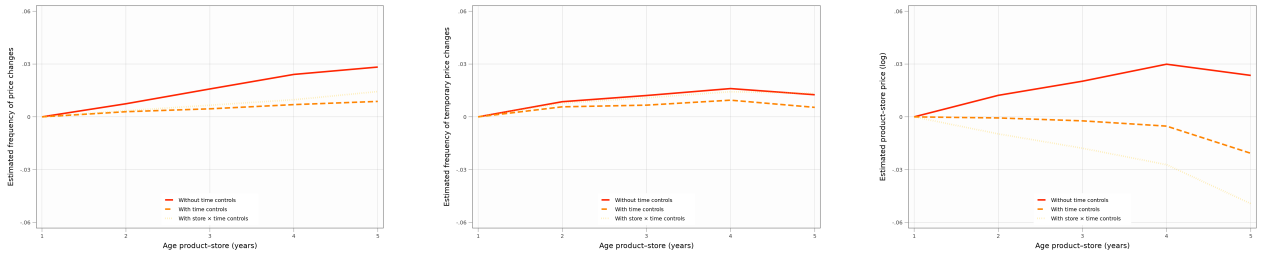
In Table 1, we calculate the median and average frequencies and durations of the price changes in the panel weighted by the revenue of products in each module. We follow Nakamura and Steinsson (2008) and compute the duration of price changes as $\frac{-1}{ln(1-f)}$. The statistics suggest that distributions for the frequencies and durations of price changes are right-skewed.

C.3 Life Cycle

In this section, we provide life cycle estimates on the frequencies of product price change in the United States from 2006 to 2020. The summary statistics are computed from a panel data set defined by upc $\times$ store_code_uc $\times$ year $\times$ module consisting of 328 modules in the Nielsen scanner data.

Figure C1: Prices by Cohort of Products: Robustness Coverage of Categories

(a) All Price Changes (b) Temporary Price Changes (c) Level Prices (log)



Notes: The figures displays the life cycle of upc x store for the balanced sample in the first 5 years of activity.

D Additional Model

D.1 Omitted Proof in Prices and Profits

The quality-adjusted price index is given by,

$$\hat{P}_t = \frac{W_t}{A_t} m_t N_t^{\frac{1}{1-\sigma}} Q_t^{-1} \tag{87}$$

The profit as share of nominal GDP is given by,

$$\frac{\pi_{it}}{\hat{P}_t Y_t} = \frac{1}{\hat{P}_t}(p_{it} - W_t) q_{it}^{\sigma-1} (\frac{p_{it}}{\hat{P}_t})^{-\sigma}$$

Plug in the price index, we get the profit. Next, we derive the aggregate output. The labor demand of firm i is given by,

$$A_t L_{it} = q_{it}^{\sigma-1} p_{it}^{-\sigma} P_t^{\sigma} Y_t \tag{88}$$

$$= \hat{q}_{it}^{\sigma-1} \mu_{it}^{-\sigma} {m_t}^{\sigma} N_t^{\frac{\sigma}{1-\sigma}} \cdot \frac{Y_t}{Q_t} \tag{89}$$

The aggregate labor demand is,

$$A_t L = \int \frac{1}{N} \hat{q}_{it}^{\sigma-1} \mu_{it}^{-\sigma} \, di \cdot {m_t}^{\sigma} N^{\frac{1}{1-\sigma}} \frac{Y_t}{Q_t} \tag{90}$$

Rearrange,

$$A_t \frac{{m_t}^{-\sigma}}{\mathbb{E}_q[\mu_{it}^{-\sigma}]} N_t^{\frac{1}{\sigma-1}} Q_t L = Y_t \tag{91}$$

D.2 Proof for Lemma 2

Proof. Fix a product line with state $(\hat{q}, \mu)$. Under Assumption **??**, flow profits and all R&D costs are proportional to $\hat{q}^{\sigma-1}$, and successful innovation scales quality multiplicatively while allowing a price reset to μ_0. Consider the line-level HJB (in quality-adjusted units). Guess $\Gamma(\hat{q}, \mu) = \hat{q}^{\sigma-1} A(\mu)$. Then for any innovation type $k \in \{I, E, N\}$,

$$\Gamma(\lambda^k \hat{q}, \mu_0) - \Gamma(\hat{q}, \mu) = \hat{q}^{\sigma-1} \Big((\lambda^k)^{\sigma-1} A(\mu_0) - A(\mu) \Big),$$

and the corresponding innovation objective

$$\max_{x^k \geq 0} \Big\{ x^k \big[\Gamma(\lambda^k \hat{q}, \mu_0) - \Gamma(\hat{q}, \mu) \big] - \xi^k (x^k)^{\frac{1}{1-\alpha}} \hat{q}^{\sigma-1} \Big\}$$

is $\hat{q}^{\sigma-1}$ times a function of μ alone. The markup drift term depends only on μ (via $\dot{\mu}/\mu = -\pi$), and the hat-normalization contributes only through the aggregate growth rate, which is common across lines on the BGP. Hence every term in the line HJB is homogeneous of degree $\sigma - 1$ in $\hat{q}$, so dividing the HJB by $\hat{q}^{\sigma-1}$ yields a closed one-dimensional equation for $A(\mu)$, verifying (154).

Because the reduced problem depends on the line state only through μ, the associated optimal policies are also functions of μ alone. In particular, the optimal reset markup μ_0 and the exit cutoff μ_b are identical for all $\hat{q}$, so (μ_0, μ_b) are common across product lines. Moreover, by assumption internal, external, and entrant innovations are feasible on both active and inactive lines and their success hazards and step sizes do not depend on μ or the line's active status. Therefore the stochastic process for $\hat{q}$ is governed solely by the innovation block and is independent of the markup process and exit decisions, implying independence of the stationary distributions.

Finally, the per-line external innovation choice reduces to

$$\max_{x^E \geq 0} \left\{ x^E \, A(\mu_0)(\lambda^E)^{\sigma-1} - \xi^E (x^E)^{\frac{1}{1-\alpha}} \right\},$$

whose first-order condition gives

$$x^{E*} = \left(\frac{1-\alpha}{\xi^E} A(\mu_0)(\lambda^E)^{\sigma-1} \right)^{\frac{1-\alpha}{\alpha}}.$$

Substituting back yields the maximized value

$$\Lambda^E = \xi^E \frac{\alpha}{1-\alpha} \left(x^{E*} \right)^{\frac{1}{1-\alpha}},$$

establishing (161). □

D.3 Proof for Proposition ??:

Proof. In the inactive region $\mu \leq \mu_b$, the HJB implies $\varphi A(\mu) = \Lambda^I(\mu_0)$, hence

$$A(\mu) = \frac{\Lambda^I(\mu_0)}{\varphi} \quad \text{for all } \mu \leq \mu_b,$$

so $A'(\mu_b^-) = 0$. By smooth pasting at the free boundary, $A'(\mu_b^+) = A'(\mu_b^-) = 0$, hence $A'(\mu_b) = 0$.

Evaluate the active-region HJB at $\mu = \mu_b$ and use $A(\mu_b) = \Lambda^I(\mu_0)/\varphi$ and $A'(\mu_b) = 0$:

$$\varphi \cdot \frac{\Lambda^I(\mu_0)}{\varphi} = -\pi \mu_b A'(\mu_b) + m^{\sigma-1} N^{-1} (\mu_b - 1) \mu_b^{-\sigma} + \Lambda^I(\mu_0) + \gamma A(\mu_0).$$

Cancelling $\Lambda^I(\mu_0)$ on both sides and using $A'(\mu_b) = 0$ yields

$$0 = m^{\sigma-1} N^{-1} (\mu_b - 1) \mu_b^{-\sigma} + \gamma A(\mu_0),$$

which is exactly (**??**). □

D.4 Proof for Proposition ??:

Proof. Let $C \equiv m^{\sigma-1} N^{-1}$, $a \equiv \varphi/\pi$, $L \equiv \Lambda(\mu_0)$ and $A_0 \equiv A(\mu_0)$.

Step 1 (Solve the ODE on $\{\mu > \mu_b\}$). For $\mu > \mu_b$ the HJB is

$$\varphi A(\mu) = -\pi\mu A'(\mu) + C(\mu - 1)\mu^{-\sigma} + L + \gamma A_0. \tag{92}$$

Rewrite as $A'(\mu) + \frac{a}{\mu}A(\mu) = \frac{C}{\pi}\big(\mu^{-\sigma} - \mu^{-\sigma-1}\big) + \frac{L+\gamma A_0}{\pi}\mu^{-1}$. Using integrating factor μ^a and assuming $a \neq \sigma$ and $a \neq \sigma - 1$,

$$A(\mu) = \frac{C}{\pi}\Big[\frac{\mu^{1-\sigma}}{a-\sigma+1} - \frac{\mu^{-\sigma}}{a-\sigma}\Big] + \frac{L+\gamma A_0}{\varphi} + K\mu^{-a}, \tag{93}$$

for a constant K. Define

$$\xi_1 = \frac{C}{\pi}(a-\sigma+1)^{-1}, \qquad \xi_2 = \frac{C}{\pi}(a-\sigma)^{-1}.$$

Step 2 (Value matching at μ_b). For $\mu \leq \mu_b$, the HJB gives $\varphi A(\mu) = L$, hence $A(\mu) = L/\varphi$ and value matching implies $A(\mu_b) = L/\varphi$. Plugging $\mu = \mu_b$ into the general solution yields

$$K\mu_b^{-a} = -\xi_1\mu_b^{1-\sigma} + \xi_2\mu_b^{-\sigma} - \frac{\gamma A_0}{\varphi}.$$

Substituting K back and using $\mu_b^{1-\sigma}(\mu_b/\mu)^a = \mu^{1-\sigma}(\mu_b/\mu)^{a+1-\sigma}$ and $\mu_b^{-\sigma}(\mu_b/\mu)^a = \mu^{-\sigma}(\mu_b/\mu)^{a-\sigma}$, we obtain for $\mu > \mu_b$,

$$A(\mu) = \frac{L}{\varphi} + \xi_1\mu^{1-\sigma}\Big(1 - \big(\tfrac{\mu_b}{\mu}\big)^{a+1-\sigma}\Big) - \xi_2\mu^{-\sigma}\Big(1 - \big(\tfrac{\mu_b}{\mu}\big)^{a-\sigma}\Big) + \frac{\gamma A_0}{\varphi}\Big(1 - \big(\tfrac{\mu_b}{\mu}\big)^{a}\Big). \tag{94}$$

Thus the claimed form holds with $\xi_3 = \gamma A_0/\varphi$.

Step 3 (Smooth pasting pins down μ_b). Since $A(\mu) \equiv L/\varphi$ is constant on $\{\mu \leq \mu_b\}$, $A'(\mu_b^-) = 0$ and smooth pasting implies $A'(\mu_b^+) = 0$. Evaluate the continuation HJB at μ_b using $A(\mu_b) = L/\varphi$ and $A'(\mu_b) = 0$:

$$L = C(\mu_b - 1)\mu_b^{-\sigma} + L + \gamma A_0 \quad \Rightarrow \quad C(\mu_b - 1)\mu_b^{-\sigma} + \gamma A_0 = 0.$$

Step 4 (Value maximization pins down μ_0). If $\mu_0 > \mu_b$ is an interior maximizer, then $A'(\mu_0) = 0$. Evaluating the continuation HJB at μ_0 and using $A(\mu_0) = A_0$ gives

$$\varphi A_0 = C(\mu_0 - 1)\mu_0^{-\sigma} + L + \gamma A_0 \quad \Rightarrow \quad (\varphi - \gamma)A_0 = C(\mu_0 - 1)\mu_0^{-\sigma} + \Lambda(\mu_0).$$

□

D.5 Proof for Proposition ??

Proof. Consider the stationary HJB in the inaction region:

$$0 = -(\phi + \gamma - g^Q)A(\mu) - \pi\mu A'(\mu) + \tilde{\pi}(\mu) + \tilde{\Lambda}^I(\mu) + \gamma A(\mu^u). \tag{95}$$

Evaluating (95) at $\mu = \mu^u$ and using $A(\mu^u) = A(\mu^u)$ yields

$$0 = -(\phi + \gamma - g^Q)A(\mu^u) + \tilde{\pi}(\mu^u) + \tilde{\Lambda}^I(\mu^u) + \gamma A(\mu^u),$$

which simplifies to

$$(\phi - g^Q)A(\mu^u) = \tilde{\pi}(\mu^u) + \tilde{\Lambda}^I(\mu^u).$$

This proves (**??**).

Next, because μ^u is an interior maximizer of A, it satisfies

$$A'(\mu^u) = 0, \qquad A''(\mu^u) \leq 0.$$

Differentiating (95) with respect to μ gives

$$0 = -(\phi + \gamma - g^Q)A'(\mu) - \pi\big(A'(\mu) + \mu A''(\mu)\big) + \tilde{\pi}'(\mu) + \tilde{\Lambda}^{I\prime}(\mu).$$

Evaluating at $\mu = \mu^u$ and using $A'(\mu^u) = 0$ yields

$$\tilde{\pi}'(\mu^u) + \tilde{\Lambda}^{I\prime}(\mu^u) = \pi\mu^u A''(\mu^u) \leq 0. \tag{96}$$

It is easy to show $\tilde{\Lambda}^{I\prime}(\mu^u) = 0$, this implies

$$\tilde{\pi}'(\mu^u) \leq 0.$$

Now

$$\tilde{\pi}(\mu) = m^{\sigma-1}(\mu - 1)\mu^{-\sigma}$$

is strictly concave and uniquely maximized at

$$\mu^* = \frac{\sigma}{\sigma - 1}.$$

Hence

$$\tilde{\pi}'(\mu) > 0 \quad \text{for } \mu < \mu^*, \qquad \tilde{\pi}'(\mu^*) = 0, \qquad \tilde{\pi}'(\mu) < 0 \quad \text{for } \mu > \mu^*.$$

Therefore, $\tilde{\pi}'(\mu^u) \leq 0$ implies $\mu^u \geq \mu^*$. If $A''(\mu^u) < 0$ and $\pi > 0$, then the right-hand side of (96) is strictly negative, so $\tilde{\pi}'(\mu^u) < 0$, which implies

$$\mu^u > \mu^*.$$

This proves price overshooting.

Finally, when pricing frictions vanish, the benefit of choosing a reset markup above the static optimum disappears. If $\pi \to 0$, markup drift vanishes after adjustment; if $\gamma \to \infty$, free adjustment opportunities arrive arbitrarily frequently. In either case, the dynamic problem converges to the static pricing problem, so the reset markup converges to the unique maximizer of current profit:

$$\mu^u \to \mu^*.$$

□

D.6 Proof for Proposition ??

Proof. **Markup drift and hazards.** Markups drift deterministically due to inflation. Over a small interval Δt,

$$\mu_{t+\Delta t} = \mu_t(1 - \pi\Delta t) + o(\Delta t), \qquad \Longleftrightarrow \qquad \mu_t \geq \mu \;\Leftrightarrow\; \mu_{t+\Delta t} \geq \mu(1 + \pi\Delta t) \text{ absent events.}$$

Let

$$\kappa \equiv x^I + \tau + \psi, \qquad \lambda \equiv x^I + \tau + \gamma + \psi, \qquad \eta \equiv \frac{\lambda}{\pi}.$$

Here λ is the total *refresh* hazard for the markup while a line is active: internal innovation, takeovers (incumbent external and entrant), Calvo resets, and exogenous obsolescence all restart the pricing cycle at the reset markup μ_u. The parameter κ is the total *reactivation* hazard from the inactive pool into active status: internal innovation, takeovers, and obsolescence-driven replacement all (re)introduce a line at μ_u.

Unconditional markup distribution. Let $\bar{H}(\mu) \equiv \Pr(\text{markup} \geq \mu)$ denote the stationary survival function over the full population of product lines (active and inactive), with support $\mu \in [0, \mu_u]$. For any $\mu < \mu_u$, stationarity implies

$$\bar{H}(\mu) = (1 - \lambda\Delta t)\, \bar{H}\big(\mu(1 + \pi\Delta t)\big) + o(\Delta t), \tag{97}$$

because with probability $\lambda\Delta t$ an event occurs over Δt that refreshes the markup to μ_u (internal/external innovation, a Calvo reset, or obsolescence and replacement), and otherwise the markup drifts deterministically. Using the expansion

$$\bar{H}(\mu(1 + \pi\Delta t)) = \bar{H}(\mu) + \pi\mu\bar{H}'(\mu)\Delta t + o(\Delta t)$$

in (97) and letting $\Delta t \to 0$ yields the ODE

$$\pi\mu\bar{H}'(\mu) = \lambda\, \bar{H}(\mu). \tag{98}$$

Imposing the boundary condition $\bar{H}(\mu_u) = 1$ gives

$$\bar{H}(\mu) = \left(\frac{\mu}{\mu_u}\right)^{\eta}, \qquad \mu \in [0, \mu_u], \qquad \eta = \frac{x^I + \tau + \gamma + \psi}{\pi}. \tag{99}$$

Active-line distribution on $[\mu_b, \mu_u]$. Let $H(\mu)$ be the *unnormalized* stationary CDF over active products,

$$H(\mu) \equiv \text{mass of active products with markup} \leq \mu, \qquad \mu \in [\mu_b, \mu_u],$$

so that $H(\mu_b) = 0$ and $H(\mu_u) = N$, where N is the mass of active products. For $\mu \in [\mu_b, \mu_u)$, stationarity implies

$$H(\mu) = (1 - \lambda\Delta t)\, H\big(\mu(1 + \pi\Delta t)\big) - (1 - \lambda\Delta t)\, H\big(\mu_b(1 + \pi\Delta t)\big) + o(\Delta t), \tag{100}$$

because (i) drift maps the threshold μ to $\mu(1 + \pi\Delta t)$ absent events, (ii) events with total hazard λ remove mass from the interior by resetting it to μ_u, and (iii) the lower boundary μ_b truncates

the active support. Expanding and letting $\Delta t \to 0$ yields

$$\pi \mu H'(\mu) = \lambda\big(H(\mu) - H(\mu_b)\big) = \lambda H(\mu), \qquad \mu \in (\mu_b, \mu_u), \tag{101}$$

since $H(\mu_b) = 0$. Thus the active density takes the power form

$$h(\mu) \equiv H'(\mu) = K\,\mu^{\eta-1}, \qquad \eta = \frac{\lambda}{\pi}. \tag{102}$$

Normalizing by $H(\mu_u) = N$ gives

$$H(\mu) = N\,\frac{\left(\frac{\mu}{\mu_b}\right)^{\eta} - 1}{\left(\frac{\mu_u}{\mu_b}\right)^{\eta} - 1}, \qquad \mu \in [\mu_b, \mu_u], \qquad \eta = \frac{x^I + \tau + \gamma + \psi}{\pi}. \tag{103}$$

Mass of active products. The outflow from active to inactive equals the probability flux hitting the lower boundary μ_b:

$$\text{outflow} = \pi\,\mu_b\,h(\mu_b) = \pi\,\mu_b\,K\,\mu_b^{\eta-1} = \lambda N \cdot \frac{1}{\left(\frac{\mu_u}{\mu_b}\right)^{\eta} - 1},$$

where the last equality uses the normalization implied by (103). The inflow from inactive to active is the reactivation rate κ times the inactive mass $(1 - N)$:

$$\text{inflow} = \kappa(1 - N), \qquad \kappa = x^I + \tau + \psi,$$

because internal innovation, takeovers, and obsolescence-driven replacement all (re)introduce lines at μ_u. Stationarity of the active mass, inflow $=$ outflow, therefore implies

$$N = \frac{\kappa}{\kappa + \dfrac{\lambda}{\left(\frac{\mu_u}{\mu_b}\right)^{\eta} - 1}}, \qquad \kappa = x^I + \tau + \psi, \quad \lambda = x^I + \tau + \gamma + \psi, \quad \eta = \frac{\lambda}{\pi}. \tag{104}$$

Average markup and aggregate efficiency (active lines). Let the stationary conditional density of markups among active lines be

$$f_A(\mu) = \frac{\eta\,\mu^{\eta-1}}{\mu_u^{\eta} - \mu_b^{\eta}}, \qquad \mu \in [\mu_b, \mu_u], \qquad \eta \equiv \frac{x^I + \tau + \gamma + \psi}{\pi}. \tag{105}$$

(Here η uses the total refresh hazard for active markups: internal innovation x^I, takeovers τ, Calvo resets γ, and obsolescence replacement ψ.)

Aggregate markup. Define the average markup over active lines by

$$m_t \equiv \left(\frac{1}{N_t}\int_{i \in \mathcal{N}_t} \mu_{it}^{1-\sigma}\,\hat{q}_{it}^{\sigma-1}\,di\right)^{\frac{1}{1-\sigma}} = \left(\mathbb{E}_A\left[\mu^{1-\sigma}\right]\right)^{\frac{1}{1-\sigma}}, \tag{106}$$

where the second equality uses independence between μ and $\hat{q}$ across active lines (so $\mathbb{E}_A[\hat{q}^{\sigma-1}] = 1$ under the relative-quality normalization). Using (105),

$$\mathbb{E}_A\left[\mu^{1-\sigma}\right] = \int_{\mu_b}^{\mu_u} \mu^{1-\sigma} f_A(\mu)\, d\mu = \frac{\eta}{\mu_u^\eta - \mu_b^\eta} \int_{\mu_b}^{\mu_u} \mu^{\eta-\sigma}\, d\mu$$
$$= \frac{\eta}{\eta-(\sigma-1)} \frac{\mu_u^{\eta-(\sigma-1)} - \mu_b^{\eta-(\sigma-1)}}{\mu_u^\eta - \mu_b^\eta}, \qquad \eta \neq \sigma - 1. \tag{107}$$

Therefore,

$$m_t = \left[\frac{\eta}{\eta-(\sigma-1)} \frac{\mu_u^{\eta-(\sigma-1)} - \mu_b^{\eta-(\sigma-1)}}{\mu_u^\eta - \mu_b^\eta}\right]^{\frac{1}{1-\sigma}}. \tag{108}$$

Letting $\rho \equiv \mu_b/\mu_u \in (0,1)$, this can be written as

$$\frac{m_t}{\mu_u} = \left[\frac{\eta}{\eta-(\sigma-1)} \frac{1-\rho^{\eta-(\sigma-1)}}{1-\rho^\eta}\right]^{-\frac{1}{\sigma-1}}. \tag{109}$$

Aggregate efficiency. Define aggregate efficiency over active lines by

$$v_t \equiv \frac{m_t^{-\sigma}}{\mathbb{E}_A[\mu^{-\sigma}]}. \tag{110}$$

Again using (105),

$$\mathbb{E}_A\left[\mu^{-\sigma}\right] = \int_{\mu_b}^{\mu_u} \mu^{-\sigma} f_A(\mu)\, d\mu = \frac{\eta}{\mu_u^\eta - \mu_b^\eta} \int_{\mu_b}^{\mu_u} \mu^{\eta-\sigma-1}\, d\mu$$
$$= \frac{\eta}{\eta-\sigma} \frac{\mu_u^{\eta-\sigma} - \mu_b^{\eta-\sigma}}{\mu_u^\eta - \mu_b^\eta}, \qquad \eta \neq \sigma. \tag{111}$$

Combining (108) and (111) gives

$$v_t = \frac{\left[\frac{\eta}{\eta-(\sigma-1)} \frac{\mu_u^{\eta-(\sigma-1)} - \mu_b^{\eta-(\sigma-1)}}{\mu_u^\eta - \mu_b^\eta}\right]^{-\frac{\sigma}{1-\sigma}}}{\frac{\eta}{\eta-\sigma} \frac{\mu_u^{\eta-\sigma} - \mu_b^{\eta-\sigma}}{\mu_u^\eta - \mu_b^\eta}}. \tag{112}$$

Equivalently, in terms of $\rho = \mu_b/\mu_u$,

$$v_t = \frac{\eta-\sigma}{\eta} \frac{1-\rho^\eta}{1-\rho^{\eta-\sigma}} \left[\frac{\eta}{\eta-(\sigma-1)} \frac{1-\rho^{\eta-(\sigma-1)}}{1-\rho^\eta}\right]^{\frac{\sigma}{\sigma-1}}. \tag{113}$$

□

D.7 Proof for Proposition 7:

The growth rate involves random destruction of existing products and introduction of new products of higher quality. Since these processes are random, the average quality is just Q_t and Q_t times a function of innovation step.

$$Q_t^{\sigma-1} = \int_{\mathcal{N}} q_{it}^{\sigma-1}\, di$$

$$\begin{aligned}(\sigma-1)\ln Q_{t+\Delta t} &= \ln\left[(1-\tau\Delta t - x^I\Delta t)\int_{\mathcal{N}} q_{it}^{\sigma-1}\, di + \tau\Delta t\int_{\mathcal{N}}(1+\lambda^E)^{\sigma-1}q_{it}^{\sigma-1}\, di + x^I\Delta t\int_{\mathcal{N}}(1+\lambda^I)^{\sigma-1}q_{it}^{\sigma-1}\right.\\ &= \ln\left(\int_{\mathcal{N}} q_{it}^{\sigma-1}\, di + \tau\Delta t\left[(1+\lambda^E)^{\sigma-1}-1\right]\int_{\mathcal{N}} q_{it}^{\sigma-1}\, di + x^I\Delta t\left[(1+\lambda^I)^{\sigma-1}-1\right]\int_{\mathcal{N}} q_{it}^{\sigma-1}\, di\right.\\ &= (\sigma-1)\ln Q_t + \tau\left[(1+\lambda^E)^{\sigma-1}-1\right]\Delta t + x^I\left[(1+\lambda^I)^{\sigma-1}-1\right]\Delta t\end{aligned}$$

The consumption share is straightforward. Now we turn to expected product lifetime

Consider a product with an initial markup μ_0 that decays deterministically at rate π toward an exit threshold μ_b. The product also faces an exogenous shock rate $\psi + x^I + \tau$ and a reset rate γ that restores the markup to μ_0.

The time T required for the markup to reach the floor μ_b in the absence of shocks or resets is:

$$T = \frac{\ln(\mu_0) - \ln(\mu_b)}{\pi} \tag{114}$$

The expected lifetime $E[L]$ is the sum of the expected time spent in the current cycle and the probability-weighted future lifetime if a reset occurs:

$$E[L] = \int_0^T e^{-(\psi+x^I+\tau+\gamma)t}\, dt + P(\text{Reset before } T)E[L] \tag{115}$$

The expected survival time within a single cycle (before a shock, reset, or reaching T) is:

$$\int_0^T e^{-(\psi+x^I+\tau+\gamma)t}\, dt = \frac{1-e^{-(\psi+x^I+\tau+\gamma)T}}{\psi+x^I+\tau+\gamma} \tag{116}$$

The probability that a reset occurs before an exogenous shock and before time T is:

$$P(\text{Reset before } T) = \frac{\gamma}{\psi+x^I+\tau+\gamma}\left(1-e^{-(\psi+x^I+\tau+\gamma)T}\right) \tag{117}$$

Combining the above and solving for $E[L]$ yields the final expression:

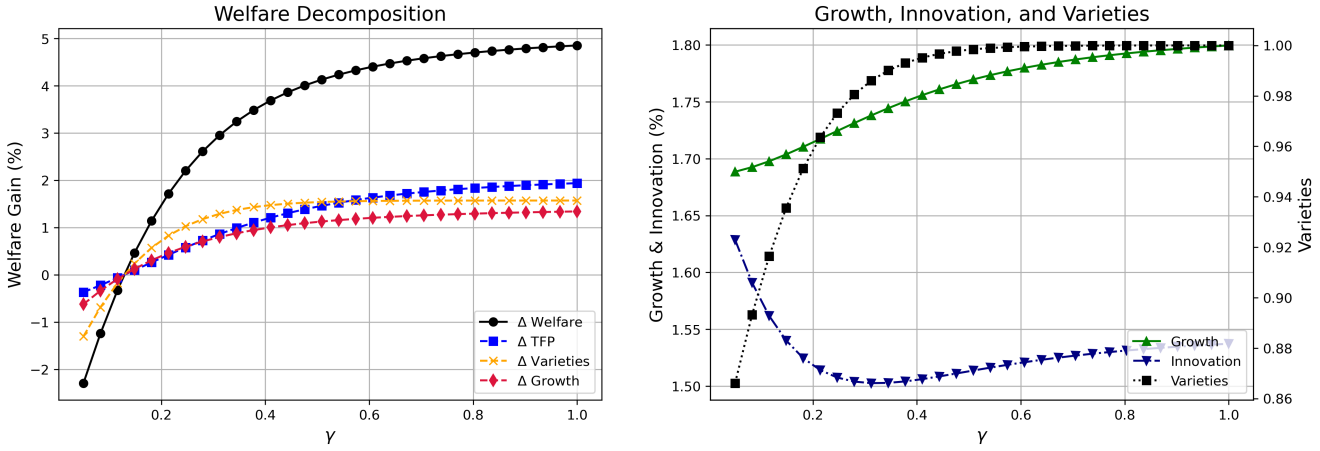
$$E[L] = \frac{1-e^{-(\psi+x^I+\tau+\gamma)T}}{\psi+x^I+\tau+\gamma e^{-(\psi+x^I+\tau+\gamma)T}} \tag{118}$$

where $T = \frac{\ln(\mu_0/\mu_b)}{\pi}$.

D.8 Welfare and Growth Decomposition with $\mu_0 = \mu^*$

Below we show the welfare and growth when the reset markup is constrained to be μ^*.

Figure D1: Welfare and Growth vs. Pricing Friction



Notes: The left panel plots the welfare change compared to the baseline welfare in the range of $\gamma = 0.1$ to $\gamma = 1.5$, and decomposition into misallocation, varieties and growth. The right panel plots the growth rate and its decomposition into innovation rate and number of varieties.

E Model Extension

Motivated by the empirical findings on nominal prices and the price premia of new products, we develop a model of endogenous growth with long-run pricing frictions. Our goal is to understand how these frictions, absent from standard growth frameworks, shape product values, innovation incentives, and aggregate growth.

We build on canonical models of innovation-driven growth featuring creative destruction and quality improvement (Aghion and Howitt, 1992; Klette and Kortum, 2004), but introduce frictions in incumbent firms' price adjustment. Whereas standard models allow firms to reoptimize prices freely and maintain optimal markups, firms in our framework cannot continuously adjust prices over a product's life cycle. Inflation therefore gradually erodes markups and the value of existing products, generating dispersion in markups across products.

We embed these frictions in a continuous-time monetary general equilibrium model with trend money growth. The economy admits a balanced growth path with stationary real allocations. Innovation follows a multi-product framework in which firms improve product quality through replacement innovation and expand their portfolios through expansion innovation. On the nominal side, money enters utility, while prices adjust through Calvo-style random opportunities and state-dependent menu costs (Golosov and Lucas, 2007; Nakamura and Steinsson, 2008).

Innovation plays an additional role in this environment: introducing a new product allows a firm to set a new price. Innovation thus restores markups when incumbent prices are rigid, in addition to improving quality and expanding product portfolios. Consequently, a new product's value reflects not only its quality, but also the subsequent erosion of its markup under price rigidity and the initial gain from resetting its price.

E.1 Monetary Economy

We adopt preferences at the intersection of Golosov and Lucas (2007), which facilitates the analysis of dynamics, and balanced-growth preferences, which imply constant labor share along the BGP. Time is continuous. A representative household consumes the final good C_t, holds nominal money balances M_t, and owns a portfolio of nominal assets A_t (claims to firms and government bonds) that yields the nominal return R_t. Household also supplies labor L_t and get nominal wage W_t. The preference is:

$$\max_{\{C_t, L_t, M_t, B_t\}_{t=0}^{\infty}} \mathbb{E}_0 \int_0^{\infty} e^{-\rho t} \left[\ln C_t - L_t + \chi \ln \left(\frac{M_t}{\hat{P}_t} \right) \right] \tag{119}$$

subject to

$$\dot{A}_t + \dot{M}_t = W_t L_t + R_t A_t - \hat{P}_t C_t,$$

where $\rho > 0$ is the discount rate, and $\hat{P}_t$ is the quality-adjusted price index defined below. The first-order conditions imply,

$$\hat{P}_t C_t = W_t, \quad \hat{P}_t C_t = \chi^{-1} R_t M_t, \quad \frac{\dot{C}_t}{C_t} = R_t - \frac{\dot{\hat{P}}_t}{\hat{P}_t} - \rho. \tag{120}$$

We consider the case where the money supply increases at a constant rate $\bar{\pi}$. The consumption-based real interest rate is $r_t = R_t - g_t^{\hat{P}}$. Our assumptions on household preference thus lead to the following results:

Proposition 6. *Equilibrium aggregates satisfy*

$$R_t = R = \rho + \bar{\pi}, \quad W_t = \chi^{-1} R M_t, \quad \hat{P}_t C_t = \chi^{-1} R M_t. \tag{121}$$

where $\bar{\pi}$ is a constant money growth rate.

To simplify the notation, set $\chi = R$. It then follows that $W_t = M_t$ and $\hat{P}_t C_t = M_t$.

E.2 Production, Product Lines, and Demand

There is a unit measure of product lines. The final good is a CES aggregate of quality-adjusted intermediate inputs:

$$Y_t = \left(\int (q_{it} y_{it})^{\frac{\sigma-1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma-1}}, \tag{122}$$

where $\sigma > 1$ is the elasticity of substitution, q_{it} denotes product quality, and y_{it} is the quantity of intermediate input i.

Intermediate goods are produced using labor according to

$$y_{it} = Z_t z_{it} \ell_{it}, \tag{123}$$

where Z_t is aggregate productivity and z_{it} is idiosyncratic productivity. Idiosyncratic productivity evolves according to

$$d \log z_{it} = -\frac{\sigma - 1}{2} \sigma_z^2 \, dt + \sigma_z \, dB_{it}, \tag{124}$$

where B_{it} is an idiosyncratic Brownian motion. The drift in (124) ensures that $\int z_{it}^{\sigma-1} \, di = 1$ at every date. Cost minimization by the final-good producer yields demand for intermediate good i:

$$y_{it} = q_{it}^{\sigma-1} \left(\frac{p_{it}}{\hat{P}_t} \right)^{-\sigma} Y_t, \tag{125}$$

where p_{it} is the nominal price of good i and

$$\hat{P}_t = \left(\int \left(\frac{p_{it}}{q_{it}} \right)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \tag{126}$$

is the quality-adjusted price index.

Define the aggregate quality-productivity index

$$Q_t \equiv \left(\int (q_{it} z_{it})^{\sigma-1} \, di \right)^{\frac{1}{\sigma-1}}, \tag{127}$$

and relative quality-productivity

$$\omega_{it} \equiv \frac{q_{it} z_{it}}{Q_t}, \qquad \int \omega_{it}^{\sigma-1} di = 1. \tag{128}$$

E.3 Pricing, Markups, and Profits

Define the product-level markup μ_{it} by

$$p_{it} = \mu_{it} \frac{W_t}{Z_t z_{it}}. \tag{129}$$

For any product-level variable g_{it}, define its expectation under the quality-productivity weights as

$$\mathbb{E}_{\omega,t}[g_{it}] \equiv \int g_{it} \omega_{it} \, di. \tag{130}$$

The aggregate markup is

$$m_t = \left(\mathbb{E}_{\omega,t} \left[\mu_{it}^{1-\sigma} \right] \right)^{\frac{1}{1-\sigma}} = \frac{\hat{P}_t Q_t}{W_t / Z_t}. \tag{131}$$

Equivalently, the quality-adjusted price index is

$$\hat{P}_t = \frac{W_t}{Z_t} \frac{m_t}{Q_t}. \tag{132}$$

Combining product demand with the production technology and imposing labor-market clearing, $L_t = \int \ell_{it} \, di$, gives

$$Y_t = Z_t Q_t v_t L_t, \tag{133}$$

where

$$v_t \equiv \frac{m_t^{-\sigma}}{\mathbb{E}_{\omega,t} \left[\mu_{it}^{-\sigma} \right]}. \tag{134}$$

The term $v_t \leq 1$ measures the allocative-efficiency loss generated by markup dispersion. It equals one if and only if markups are identical across product lines.

The aggregate labor share satisfies

$$\frac{W_t L_t}{\hat{P}_t Y_t} = (v_t m_t)^{-1} = \frac{\mathbb{E}_{\omega,t} \left[\mu_{it}^{-\sigma} \right]}{\mathbb{E}_{\omega,t} \left[\mu_{it}^{1-\sigma} \right]}. \tag{135}$$

The aggregate labor share is therefore the sales-weighted harmonic mean of markups.

The real operating profit of product line i, measured in units of the final good, is

$$\pi_{it} \equiv \frac{(p_{it} - MC_{it}) y_{it}}{\hat{P}_t} = m_t^{\sigma-1} Y_t \, \omega_{it} (\mu_{it} - 1) \mu_{it}^{-\sigma}. \tag{136}$$

Profits are proportional to market size Y_t and increasing in aggregate markups. In addition, higher relative quality raises profits, while profits are hump-shaped in the product's own markup with the static optimum at $\mu^* = \sigma/(\sigma - 1)$. With nominal pricing frictions, which we will introduce below, firms face a dynamic trade-off between current and future profits.

E.4 Price Gap and Price Adjustment

Let p_{it} denote the nominal price of product i, and let p_{it}^* denote its static profit-maximizing price:

$$p_{it}^* = \mu^* \frac{W_t}{Z_t z_{it}}, \quad \mu^* = \frac{\sigma}{\sigma - 1}. \tag{137}$$

We define the log price gap as

$$x_{it} \equiv \log p_{it} - \log p_{it}^*. \tag{138}$$

Thus, $x_{it} = 0$ corresponds to the static optimum. A positive price gap indicates that the product is priced above its static optimum, whereas a negative gap indicates that it is priced below it.

Proposition 6 implies that the nominal wage grows at the constant inflation rate $\bar{\pi}$. In the stationary equilibrium, aggregate productivity is constant. Section F.2 considers a one-time, unanticipated aggregate productivity shock on aggregate productivity. Therefore,

$$d \log W_t = \bar{\pi}\, dt, \quad d \log Z_t = 0. \tag{139}$$

Between price adjustments, the nominal price remains fixed. The price gap therefore evolves according to

$$dx_{it} = -\left(\bar{\pi} + \frac{\sigma - 1}{2}\sigma_z^2\right) dt + \sigma_z\, d\mathcal{W}_{it}. \tag{140}$$

A firm can reset its price through three channels. First, it receives a free Calvo adjustment opportunity at Poisson rate γ. Second, it can pay a menu cost when the price gap reaches either boundary of the inaction region. We allow the cost of a price increase, κ^+, to differ from the cost of a price decrease, κ^-. Third, innovation introduces a new vintage whose price can be reset. When a new vintage replaces an existing product, it inherits the predecessor's productivity.

Let x_{it}^* denote the optimal reset price gap and let x_{it}^l and x_{it}^h denote the lower and upper adjustment thresholds, respectively:

$$x_{it}^l < x_{it}^* < x_{it}^h. \tag{141}$$

The firm leaves its nominal price unchanged while $x_{it} \in (x_{it}^l, x_{it}^h)$. A Calvo opportunity, innovation, or menu-cost adjustment resets the price gap to $x_{it} = x_{it}^*$. Because productivity is unchanged at the instant of adjustment, the corresponding log price change is

$$\Delta \log p_{it} = x_{it}^* - x_{it}, \tag{142}$$

The same expression applies to product replacement because the successor inherits the predecessor's productivity.

E.5 Innovation

Innovation raises product quality and involves pricing decisions. Incumbent firms conduct two types of R&D. *Replacement innovation* upgrades product lines already owned by the firm and typically generates only modest quality improvements. Firms mainly use this type of innovation

for incremental changes, such as introducing a new flavor or package, to replace the old vintage. *Expansion innovation* improves product lines not currently owned by the firm; upon success, the innovator acquires the upgraded line and displaces the incumbent owner. This type of innovation can generate large quality improvements and is a major source of economic growth (Aghion and Howitt, 1992). A firm's size is the measure of product lines it operates. When it loses a line, its portfolio shrinks, and it exits once it loses its last remaining line.

Successful innovation interacts closely with pricing. Innovation provides a way to circumvent pricing frictions. Replacement innovation allows the firm to relaunch an existing line as a new vintage, reset its price, and restore its markup. On the other hand, expansion innovation plays an analogous role at the portfolio level: successful innovators acquire newly upgraded lines and optimally price them upon introduction, thereby refreshing the price index of firm's product mix with newly priced products. Thus, replacement innovation relaxes pricing frictions at the line level, whereas expansion innovation does so at the portfolio level through creative destruction.

Following Klette and Kortum (2004), innovation is based on the firm's knowledge capital, proxied by the number of product lines in its portfolio. Formally, a firm operating n lines runs n R&D programs in parallel, so the arrival rate of innovation scales proportionally with n. Accordingly, we work with per-line innovation intensities and costs. We then aggregate innovation costs by summing across the firm's portfolio.

For a product line of relative quality $\hat{q}$, an incumbent can invest in replacement innovation at intensity $n^I > 0$, paying flow cost

$$c^I(n^I, \hat{q}) = \xi^I \left(n^I\right)^{\frac{1}{1-\alpha}} \hat{q}^{\sigma-1}, \tag{143}$$

where $\xi^I > 0$ is a cost shifter and $\alpha \in (0, 1)$ governs the curvature of R&D costs. Upon success, quality improves multiplicatively,

$$q' = \lambda^I q, \qquad \lambda^I > 1, \tag{144}$$

and the firm resets its price when the upgraded product is introduced.

Expansion innovation is untargeted: each innovation attempt draws a product line uniformly at random from the unit mass of lines, regardless of its quality. An incumbent chooses per-line intensity $n^E > 0$ and pays

$$c^E(n^E, \hat{q}) = \xi^E \left(n^E\right)^{\frac{1}{1-\alpha}} \hat{q}^{\sigma-1}, \tag{145}$$

if the quality of the chosen line is $\hat{q}$. Upon success, it acquires the randomly drawn line, displaces the incumbent, upgrades quality to

$$q' = \lambda^E q, \qquad \lambda^E > 1, \tag{146}$$

and resets the price upon takeover.

We assume that each product line is subject to an exogenous exit shock at rate ψ. Whenever a product line exits because of this shock, a new entrant immediately replaces it by introducing a new variety, setting a new price, and entering the market. The quality of the entrant's variety is assumed to be the same as that of the exiting line. Hence, the total measure of product lines remains constant and equal to one.

Because successive vintages within a line may differ in both quality and price, a standard CES demand system would in principle allow multiple vintages to coexist and compete within a line. To preserve the canonical structure that at most one product is operated per line, we impose a simple selection device. Each product line has a single "slot" (shelf space) controlled by a retailer. The retailer receives an ε share of the operating profit generated by the stocked vintage and therefore chooses the vintage that maximizes the line's profit flow. We take $\varepsilon \to 0$, so the device affects selection but not equilibrium payoffs. Under this device, only one vintage is operated on each line in equilibrium, and when a new (improved) vintage arrives, the previously operated vintage is immediately deactivated.

E.6 Firm's Problem

Let $\Omega_{it} = \left\{ \left(x_{jt}, \hat{q}_{jt}, z_{jt} \right) \right\}_{j=1}^{M_{it}}$ denote the price gaps, relative qualities, and productivities of the product lines operated by incumbent firm i. Because innovation costs are independent across product lines, firm value is additive, as in Klette and Kortum (2004):

$$W_t(\Omega_{it}) = \sum_{j=1}^{M_{it}} V_t(x_{jt}, \hat{q}_{jt}, z_{jt}), \tag{147}$$

where $V_t(x, \hat{q}, z)$ is the value of a product line with price gap x, relative quality $\hat{q}$, and productivity z. Let $c_z \equiv \frac{\sigma-1}{2}\sigma_z^2$. Because the same productivity shock moves both x and z, the infinitesimal generator for these two states is

$$\mathcal{L}^{x,z} V_t = -\left(\bar{\pi} + c_z\right) \partial_x V_t + \left(\frac{\sigma_z^2}{2} - c_z \right) z \partial_z V_t + \frac{\sigma_z^2}{2} \left(\partial_{xx} V_t + 2z \partial_{xz} V_t + z^2 \partial_{zz} V_t \right). \tag{148}$$

The product-line value satisfies the quasi-variational inequality

$$\begin{aligned} 0 = \max \Bigg\{ & \partial_t V_t(x, \hat{q}, z) + \mathcal{L}^{x,z} V_t(x, \hat{q}, z) - g_t^Q \hat{q}\, \partial_{\hat{q}} V_t(x, \hat{q}, z) \\ & - \left(r_t + n_t^E + \psi \right) V_t(x, \hat{q}, z) + \pi_t(x, \hat{q}, z) + \Lambda_t^I(x, \hat{q}, z) + \Lambda_t^E(z) \\ & + \gamma \left[V_t(x_{it}^*, \hat{q}, z) - V_t(x, \hat{q}, z) \right] - F_t(\hat{q}, z), \\ & V_t(x_{it}^*, \hat{q}, z) - K_t(x, \hat{q}, z) - V_t(x, \hat{q}, z) \Bigg\}. \end{aligned} \tag{149}$$

The firm can reset its price through a Calvo opportunity, innovation, or payment of a menu cost. The directional menu cost is

$$K_t(x, \hat{q}, z) = \kappa_t(x) (\hat{q} z)^{\sigma-1} Y_t, \quad \kappa_t(x) = \begin{cases} \kappa^+, & x \le x_{it}^*, \\ \kappa^-, & x > x_{it}^*, \end{cases} \tag{150}$$

where κ^+ is the cost of increasing the nominal price and κ^- is the cost of decreasing it.

Brownian productivity shocks and inflation can move the price gap to either side of the reset point, making both upward and downward price adjustments optimal. The resulting adjustment

bands need not be symmetric. Flow profits are asymmetric around the static optimum, and inflation pushes the price gap downward between adjustments. A firm with an excessively high price can therefore wait for inflation to reduce its price gap, whereas inflation moves an underpriced product farther from its desired price and may enter the region with negative operating profit. Therefore, we additionally allow κ^+ and κ^- to differ to capture asymmetry in the costs of price increases and decreases.

The value of replacement innovation is

$$\Lambda_t^I(x,\hat{q},z) = \max_{n^I \geq 0} \left\{ n^I \left[V_t(x_{it}^*, \lambda^I \hat{q}, z) - V_t(x,\hat{q},z) \right] - \xi^I (n^I)^{\frac{1}{1-\alpha}} (\hat{q}z)^{\sigma-1} Y_t \right\}. \tag{151}$$

Replacement innovation both improves quality and allows the successor product to reset its price. The successor inherits the predecessor's productivity z.

The value of expansion innovation is

$$\Lambda_t^E(z) = \max_{n^E \geq 0} \left\{ \mathbb{E}_t \left[n^E V_t(x_{it}^*, \lambda^E \hat{q}, z) - \xi^E (n^E)^{\frac{1}{1-\alpha}} (\hat{q}z)^{\sigma-1} Y_t \right] \right\}. \tag{152}$$

where the expectation is taken over the quality and productivity of the product targeted by expansion innovation.

To preserve tractability, we impose the following restriction on the fixed operating cost, following Akcigit and Kerr (2018).

Assumption 2 (Fixed cost)**.** *The per-period fixed operating cost equals the equilibrium per-line option value of expansion innovation:*

$$F_t(\hat{q},z) = \Lambda_t^E(\hat{q},z). \tag{153}$$

This assumption delivers a one-dimensional pricing problem.

Lemma 2 (Separability and common price-gap thresholds)**.** *Under Assumption 2, the following properties hold:*

1. ***Separability.*** *Product-line value factorizes as*

$$V_t(x,\hat{q},z) = (\hat{q}z)^{\sigma-1} A_t(x) Y_t, \tag{154}$$

   where $A_t(x)$ depends only on the price gap.

2. ***Common pricing policies.*** *The optimal reset gap and menu-cost thresholds are common across product lines:*

$$x_{it}^* = x_t^*, \quad x_{it}^l = x_t^l, \quad x_{it}^h = x_t^h. \tag{155}$$

3. ***One-dimensional distribution dynamics.*** *The marginal distribution of x evolves independently because its drift, diffusion, and reset hazards depend only on x.*

The value function is homogeneous in quality and productivity because profits, innovation costs, menu costs, and operating costs all scale with $(\hat{q}z)^{\sigma-1} Y_t$. After normalizing by this term, the firm's problem reduces to the one-dimensional function $A_t(x)$.

Because the markup can be expressed as $\mu(x) = \mu^* e^x$, the normalized flow profit is

$$\widetilde{\pi}_t(x) = m_t^{\sigma-1} \left(\mu^* e^x - 1\right) \left(\mu^* e^x\right)^{-\sigma}. \tag{156}$$

The normalized value function satisfies

$$\begin{aligned} 0 = \max \Bigg\{ & \partial_t A_t(x) + (-\bar{\pi} + c_z)\, \partial_x A_t(x) + \frac{\sigma_z^2}{2} \partial_{xx} A_t(x) \\ & - \left[r_t - g_t^Y + \psi + x_t^E + (\sigma - 1) g_t^Q + \gamma \right] A_t(x) + \widetilde{\pi}_t(x) + \widetilde{\Lambda}_t^I(x) + \gamma A_t(x_t^*), \\ & A_t(x_t^*) - \kappa_t(x) - A_t(x) \Bigg\}. \end{aligned} \tag{157}$$

The term c_z in the drift arises from applying Itô's lemma to the productivity-normalized value function. The optimal reset gap maximizes product value:

$$x_t^* \in \arg\max_{x'} A_t(x'). \tag{158}$$

The lower and upper adjustment thresholds satisfy

$$A_t(x_t^l) = A_t(x_t^*) - \kappa^+, \quad A_t(x_t^h) = A_t(x_t^*) - \kappa^-, \tag{159}$$

The firm leaves its nominal price unchanged inside (x_t^l, x_t^h). Reaching x_t^l triggers a price increase, while reaching x_t^h triggers a price decrease.

The normalized replacement-innovation option value and optimal intensity are

$$\widetilde{\Lambda}_t^I(x) = \xi^I \frac{\alpha}{1-\alpha} \left[n_t^I(x) \right]^{\frac{1}{1-\alpha}}, \quad n_t^I(x) = \left[\frac{1-\alpha}{\xi^I} \left((\lambda^I)^{\sigma-1} A_t(x_t^*) - A_t(x) \right) \right]^{\frac{1-\alpha}{\alpha}}. \tag{160}$$

Replacement innovation is valuable because it improves quality and resets the price gap.

The normalized expansion-innovation option value and optimal intensity are

$$\widetilde{\Lambda}_t^E = \xi^E \frac{\alpha}{1-\alpha} \left(n_t^E \right)^{\frac{1}{1-\alpha}}, \quad n_t^E = \left[\frac{1-\alpha}{\xi^E} (\lambda^E)^{\sigma-1} A_t(x_t^*) \right]^{\frac{1-\alpha}{\alpha}}. \tag{161}$$

Because expansion innovation creates a new product rather than replacing the current one, its return does not depend on the current price gap.

E.7 Distribution Dynamics

Let $f_t(x)$ denote the density of price gaps on $[x_t^l, x_t^h]$. The interior reset hazard is

$$\iota_t(x) = \psi + \gamma + n_t^E + n_t^I(x). \tag{162}$$

Let J_t^l and J_t^h denote the outward probability flows at the lower and upper menu-cost thresholds. The Kolmogorov forward equation is

$$\begin{aligned}\partial_t f_t(x) = & -\partial_x[(\bar{\pi}+c_z)f_t(x)] + \frac{\sigma_z^2}{2}\partial_{xx}f_t(x) - \iota_t(x)f_t(x) \\ & + \delta(x-x_t^*)\left[\int_{x_t^l}^{x_t^h} \iota_t(\widetilde{x})f_t(\widetilde{x})\,d\widetilde{x} + J_t^l + J_t^h\right],\end{aligned} \tag{163}$$

The first line describes the evolution of price gaps within the inaction region and removes products that reset through Calvo adjustment, innovation, or exit. The second line returns these products to x_t^*, together with products reaching either menu-cost threshold. The flows J_t^l and J_t^h correspond, respectively, to price increases and price decreases.

E.8 Growth Rate and Consumption Share

Goods-market clearing requires

$$Y_t = C_t + D_t + F_t + Y_t\left(\kappa^+ J_t^l + \kappa^- J_t^h\right), \tag{164}$$

where D_t is aggregate R&D expenditure, F_t is the aggregate fixed operating cost, and J_t^l and J_t^h are the flows of products making menu-cost price increases and decreases, respectively.

Aggregate quality growth is driven by expansion innovation and the cross-sectional average of replacement innovation.

Proposition 7. *The growth rate of the quality index is*

$$g_t^Q = n_t^E\frac{(\lambda^E)^{\sigma-1}-1}{\sigma-1} + \overline{n}_t^I\frac{(\lambda^I)^{\sigma-1}-1}{\sigma-1}, \tag{165}$$

where

$$\overline{n}_t^I = \int_{x_t^l}^{x_t^h} n_t^I(x)f_t(x)\,dx. \tag{166}$$

Under Assumption 2, the consumption share is

$$\chi_t^c \equiv \frac{C_t}{Y_t} = 1 - \xi^I\int_{x_t^l}^{x_t^h}\left[n_t^I(x)\right]^{\frac{1}{1-\alpha}} f_t(x)\,dx - \frac{\xi^E}{1-\alpha}\left(n_t^E\right)^{\frac{1}{1-\alpha}} - \kappa^+ J_t^l - \kappa^- J_t^h. \tag{167}$$

The first two terms deducted from output are the resource costs of replacement and expansion innovation. The expansion term also includes the fixed operating cost, which equals the expansion-innovation option value under Assumption 2. The final two terms are the resources used in upward and downward menu-cost adjustments.

E.9 Equilibrium

Definition 2 (Equilibrium). *An equilibrium is a collection of paths*

$$\left\{A_t(x), f_t(x), x_t^*, x_t^l, x_t^h, n_t^I(x), n_t^E, m_t, v_t, g_t^Q, \chi_t^c, Y_t, C_t, \widehat{P}_t, \bar{\pi}_t, r_t\right\}_{t\geq 0} \tag{168}$$

such that: (i) firms solve the pricing and innovation problem in (157)*; (ii) the price-gap distribution evolves according to* (163)*; (iii) aggregate quality growth satisfies* (165)*; (iv) the resource constraint* (167) *holds; and (v) the nominal block satisfies* (120)*.*

Stationary equilibrium. A stationary equilibrium is an equilibrium in which aggregate variables and normalized product values are time-invariant. In particular,

$$\partial_t A_t(x) = 0, \quad \partial_t f_t(x) = 0. \tag{169}$$

Inflation, innovation rates, aggregate growth, the reset gap, and the two adjustment thresholds are constant, and the price-gap distribution is stationary. We omit time subscripts when referring to stationary objects.

F Equilibrium Characterization

This section first characterizes the balanced growth path, including equilibrium aggregates, optimal pricing policies, and long-run welfare. It then describes the transition following unanticipated permanent shocks to aggregate productivity and the money supply.

F.1 Characterization of the Balanced Growth Path

Equilibrium aggregates. Household optimality conditions and the homogeneity of the production side yield the following characterization.

Proposition 8. *Along the balanced growth path,*

$$L_t = L, \qquad \pi = \bar{\pi}, \qquad g^Y = g^Q = g, \qquad \frac{\dot{\widehat{P}}_t}{\widehat{P}_t} = \pi - g, \qquad r = \rho + g. \tag{170}$$

where $\bar{\pi}$ is the money-growth rate.

Output growth is entirely driven by growth in aggregate product quality. Inflation equals money growth, nominal wages grow at rate $\bar{\pi}$, and the real wage $W_t/\widehat{P}_t$ grows at rate g. Under log utility, the income and substitution effects on labor supply offset each other, leaving labor supply constant along the balanced growth path. Because its level is not pinned down, we impose the same L when comparing long-run equilibria.

Long-run welfare. We compare welfare across balanced growth paths. Normalizing $Q_0 = Z_0 = 1$, initial consumption is $C_0 = \chi_c v$. Abstracting from utility derived from money, lifetime

welfare under log utility is

$$U_0(v,g) = \int_0^\infty e^{-\rho t}\left[\log C_t - L\right] dt$$
$$= \underbrace{\frac{1}{\rho}\log\chi_c + \frac{g}{\rho^2}}_{\text{growth-related}} + \underbrace{\frac{1}{\rho}\log v}_{\text{allocative efficiency}} - \underbrace{\frac{L}{\rho}}_{\text{labor disutility}}. \tag{171}$$

Welfare reflects three forces. Faster growth raises future consumption but generally requires greater R&D expenditure, reducing current consumption. Price dispersion lowers allocative efficiency, while labor disutility is held fixed across the long-run equilibria considered here.

Consider two economies indexed by 1 and 2. Let ω denote the proportional adjustment to initial consumption in economy 2 that makes the household indifferent between the two economies:

$$U_0(\omega C_0^2, g_2) = U_0(C_0^1, g_1). \tag{172}$$

The consumption-equivalent welfare change satisfies

$$\log\omega = \underbrace{\frac{g_1 - g_2}{\rho} + \log\left(\frac{\chi_{c1}}{\chi_{c2}}\right)}_{\text{growth-related}} + \underbrace{\log\left(\frac{v_1}{v_2}\right)}_{\text{allocative efficiency}}. \tag{173}$$

F.2 Aggregate Productivity Shocks

We characterize the transition following an unanticipated, one-time permanent shock to aggregate productivity. The economy is initially in its stationary equilibrium. At $t = 0$, aggregate productivity changes by the log amount δ_Z:

$$Z_t = e^{\delta_Z} Z_{0-}, \qquad t \geq 0. \tag{174}$$

The shock changes any price gap by

$$x_{i0} - x_{i0-} = \delta_Z. \tag{175}$$

A negative productivity shock increases marginal cost and the static optimal price, thereby reducing the price gap. Products pushed below the lower adjustment threshold immediately reduce their prices, while the remaining price-gap distribution adjusts gradually.

Under log utility, Proposition 6 implies

$$g_t^C - g_t^Q = \bar{\pi} - \pi_t. \tag{176}$$

Thus, the productivity shock creates a temporary wedge between consumption growth and quality growth whenever inflation differs from its steady-state level.