Change in Average Prices: Inflation, Quality Change, or Market Frictions?

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This Paper

- In the age of Big Data, retailers and analysts increasingly use average sales price indices (such as unit value indices, UVIs) to track market activity
- UVIs neatly separates sales growth into change in quantity sold and average prices
- We develop exact decomposition of UVIs:
  1. Within component (driven by an arithmetic Laspeyres index)
  2. Changes in product mix (contaminated by quality growth)
- Quality adjustment removes or reduces bias from quality growth, and we provide guidance on using adjustment factors for two distinct approaches:
  1. Uses hedonics to produce adjusted UVI that are are equal to bounds on the rate of inflation (i.e. hedonic Paasche inclusive of entry and Laspeyres inclusive of exit)
  2. An adjusted UVI as an Exact Price Index? Focus on case that relaxes stark implication of quality-adjusted law of one price – via market frictions.

Data

- Data are from Circana covering consumer tech goods from 2017Q1-2020Q4
  - ⇒ Presentation focuses on Notebook Computers
- Point of sales (POS) data at the item level (SKU-level)
- Data are aggregated to national quarterly item-level (consistent with Redding and Weinstein (2020) and Ehrlich et al. (2025) use of POS data)
  - ⇒ This facilitates comparison to alternative quality-adjusted indices
- Item-level prices, quantities and detailed attributes of products
  - ⇒ Quality adjustment incorporates hedonics using Erickson and Pakes (2011) as implemented by Ehrlich et al. (2025)
  - ⇒ Example of attributes for Notebook Computers include differences in battery life, disk space, RAM, screen size, etc.

A Study of UVIs

– UVIs measure the change in quantity-share-weighted average prices:

$$\text{UVI} = \mathbb{P}_t/\mathbb{P}_{t-1} = \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}}{\sum_{k\in\Omega_t} q_{kt} / \sum_{k\in\Omega_{t-1}} q_{kt-1}}$$

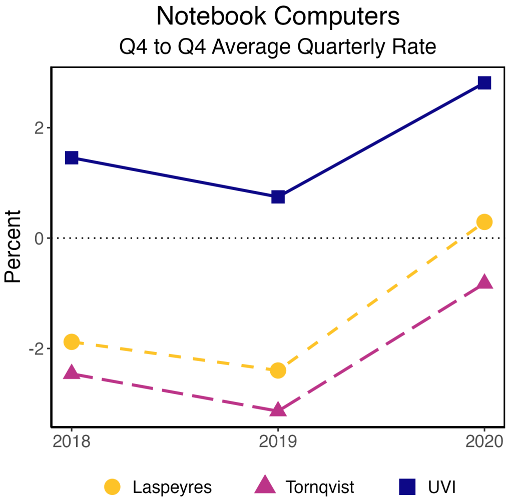
where p_{kt} and q_{kt} are the price and quantity of an item k in basket Ω in period t, $\mathbb{P}_t = \sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_t} q_{kt}$, and $\mathbb{P}_{t-1} = \sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1} / \sum_{k\in\Omega_{t-1}} q_{kt-1}$

– When a basket of goods are homogeneous (e.g. UPCs), the UVI is an exact price index, but it is commonly used in other contexts:

1. ...by retailers and market analysts as indicators of price trends
2. ...with administrative trade data to estimate inflation for specific product classes

UVI versus Matched-Model Indices

- UVI measures relative change in quantity share weighted prices
- . . . permits product turnover and changes in quantity shares
- . . . lies above the upper bound from the arithmetic Laspeyres index



Decomposing the UVI:

$$\text{UVI} = 1 + \underbrace{s_{t-1} \overbrace{\sum_{k \in \mathbb{C}_t} s_{kt-1} \left(\frac{p_{kt}}{p_{kt-1}} - 1 \right)}^{\text{Arithmetic MM Laspeyres}}}_{\text{Within}}$$

$$+ \underbrace{\sum_{k \in \mathbb{C}_t} \Delta w_k \left(\frac{p_{kt}}{\mathbb{P}_{t-1}} \right) + \sum_{k \in \mathbb{E}_t} w_{kt} \left(\frac{p_{kt}}{\mathbb{P}_{t-1}} \right) - \sum_{k \in \mathbb{X}_t} w_{kt-1} \left(\frac{p_{kt-1}}{\mathbb{P}_{t-1}} \right)}_{\text{Product Mix}}$$

where $\mathbb{C}_t$, $\mathbb{E}_t$, and $\mathbb{X}_t$ denote basket of common goods between $t-1$ and t , goods entering between $t-1$ and t , and goods exiting between $t-1$ and t

1. s_{kt-1} is the expenditure share of good k out the basket of common goods in period $t-1$
2. s_{t-1} is the expenditure share of common goods in period $t-1$
3. w_{kt} is the quantity share weight of good k in period t

Decomposing the UVI: Inflation + Product Mix

Notebook Computers

Average Quarterly Price Growth Rate

	Laspeyres (1)	UVI (2)
Within		−1.57
Product Mix		2.08
Total	−1.65	0.51

"Quality-Adjusted" UVIs (QUVIs) - Definition

- QUVIs incorporate adjustment factors to rescale quantity shares and price levels to calculate "quality-adjusted" average prices:

$$\text{QUVI} = P_t^\tau / P_{t-1}^\tau = \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}}{\sum_{k\in\Omega_t} \lambda_{kt}^\tau q_{kt} / \sum_{k\in\Omega_{t-1}} \lambda_{kt-1}^\tau q_{kt-1}}$$

  where λ_{kt}^τ is the adjustment factor of good k in period t, τ refers to the pairwise periods {t-1,t}, $P_t^\tau = \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt}}{\sum_{k\in\Omega_t} \lambda_{kt}^\tau q_{kt}}$, and $P_{t-1}^\tau = \frac{\sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}}{\sum_{k\in\Omega_{t-1}} \lambda_{kt-1}^\tau q_{kt-1}}$

- When tracking the price of bottles of water that vary in size, a simple adjustment factor would rescale quantities by the number of ounces of water in each bottle
- Determining adjustment factors for notebook computers is much more difficult.
- Permit time-varying "quality" adjustment (nests time-invariant)

"Quality-Adjusted" UVIs (QUVIs) - Approach and Interpretation

– How should we interpret adjustment factors in the QUVI?

1. Price dispersion attributed to product characteristics
2. ... Yields perfect substitutes for representative buyer

– Interpretation of factors is motivated by alternative interpretations of the QUVI:

1. QUVI determines "characteristic-adjusted" bounds on the cost-of-living index
2. QUVI is an exact price index using perfect substitutes aggregator:

$$Q_t = \sum_{k \in \Omega_t} \lambda_k q_{kt}, \quad p_{kt} = \lambda_k P_t \ \forall \ k \in \Omega_t, \quad P_t / P_{t-1} = \text{QUVI}$$

where this is simpler case of constant λ_k's that assumes perfect substitutability and yields "quality-adjusted" law of one price. We consider more general case of quality-adjusted law of one price with time-varying adjustment factors below.

A Bounding Approach: Pairwise Time-Invariant

- *Basic adjustment* generalizes work by von Auer (2014) and de Haan (2015) assuming pairwise time-invariant adjustment-factors:

$$\lambda^{\tau}_{kt} = \lambda^{\tau}_{kt-1}$$

- Use observed price dispersion over adjacent periods to estimate:

$$\overline{\lambda}^{\tau}_{k}(\alpha) = p^{\alpha}_{kt} p^{1-\alpha}_{kt-1}$$

  where mixing parameter α determines weight put on period $t-1$ versus t

- In the absence of product turnover, using the basic approach yields Konus bounds:

Mixing Parameter	Adjustment Factors	QUVI Equivalence
$\alpha = 0$	$\overline{\lambda}^{\tau}_{k}(0) = p_{kt-1}$	Matched-Model Paasche
$\alpha = 1$	$\overline{\lambda}^{\tau}_{k}(1) = p_{kt}$	Matched-Model Laspeyres

Bounds Inclusive of Product Entry and Exit: Hybrid Hedonic

- Use $\lambda_{kt}^{\tau} = \lambda_{kt-1}^{\tau} = \overline{\lambda}_{k}^{\tau}(\alpha) = p_{kt}^{\alpha} p_{kt-1}^{1-\alpha}$ for continuing goods
- For missing entry and exit prices use hedonics from Erickson and Pakes (2011):

$$\lambda_{kt-1}^{\tau}(\alpha) = \left(\widehat{p_{kt}/p_{kt-1}}\right)^{\alpha} \times p_{kt-1} \quad \text{exiting}$$

$$\lambda_{kt}^{\tau}(\alpha) = \left(\widehat{p_{kt}/p_{kt-1}}\right)^{-(1-\alpha)} \times p_{kt} \quad \text{entering}$$

  where $\widehat{p_{kt}/p_{kt-1}}$ is the predicted price relative from first difference hedonic model estimated for the difference between $t-1$ and t

- Under values of α, QUVI equivalent to **double-imputation** hedonic bounds:

Mixing Parameter	QUVI Equivalence
$\alpha = 0$	Hedonic Paasche with Entry(double imputation)
$\alpha = 1$	Hedonic Laspeyres with Exit (double imputation)

Bounds Inclusive of Product Entry and Exit: Time-Varying Adjustment

- Use Erickson and Pakes (2011) **full-imputation** (for continuing, entering and exiting goods):

$$\lambda^{\tau}_{kt-1}(\alpha) = \left(\widehat{p_{kt}/p_{kt-1}}\right)^{\alpha} \times p_{kt-1}$$
$$\lambda^{\tau}_{kt}(\alpha) = \left(\widehat{p_{kt}/p_{kt-1}}\right)^{-(1-\alpha)} \times p_{kt}$$

  where $\widehat{p_{kt}/p_{kt-1}}$ is the predicted price relative from first difference hedonic model estimated for the difference between $t-1$ and t

- Under values of α, QUVI equivalent to **full-imputation** hedonic bounds:

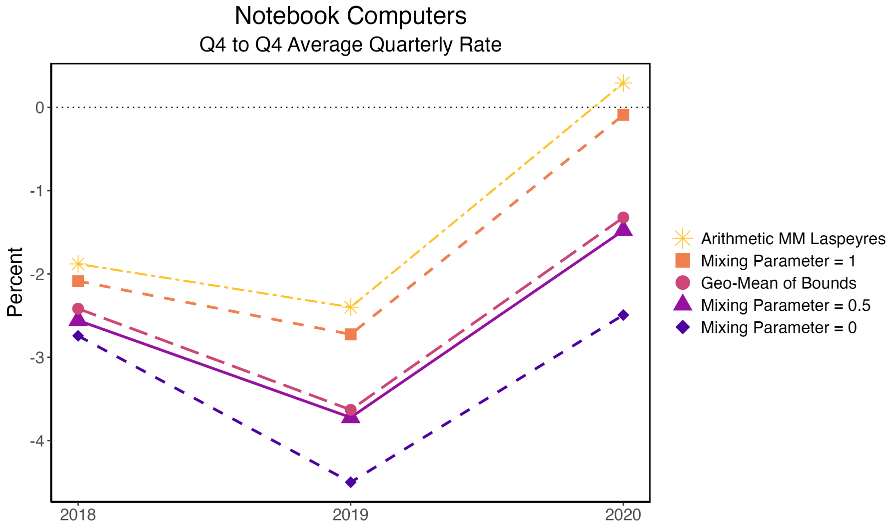
Mixing Parameter	QUVI Equivalence
$\alpha = 0$	Hedonic Paasche with Entry
$\alpha = 1$	Hedonic Laspeyres with Exit
$\alpha = 0.5$	(Approx) Hedonic Tornqvist with Entry and Exit

QUVI and the Hedonic Laspeyres with Product Exit: $\alpha = 1$

$$
\begin{aligned}
\frac{P_t^\tau}{P_{t-1}^\tau} &= \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}}{\sum_{k\in\Omega_t} \lambda_{kt}^\tau(1)q_{kt} / \sum_{k\in\Omega_{t-1}} \lambda_{kt-1}^\tau(1)q_{kt-1}} \\
&= \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}}{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_{t-1}} \left[\widehat{p_{kt}/p_{kt-1}}\right] p_{kt-1}q_{kt-1}} \\
&= \frac{\sum_{k\in\Omega_{t-1}} \left[\frac{\widehat{p_{kt}}}{p_{kt-1}}\right] p_{kt-1}q_{kt-1}}{\sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}} \\
&= \sum_{k\in\Omega_{t-1}} s_{kt-1}\left[\frac{\widehat{p_{kt}}}{p_{kt-1}}\right]
\end{aligned}
$$

where Ω_{t-1} includes all items in $t-1$ ($\Omega_{t-1} = \mathbb{C}_t + \mathbb{X}_t$)

QUVI Hedonic Bound Equivalences



Decomposing the QUVI:

$$\text{QUVI} = 1 + \underbrace{s^c_{t-1} \overbrace{\sum_{k\in\mathbb{C}_t} s^c_{kt-1} \left(\frac{p_{kt}/\lambda^\tau_{kt}}{p_{kt-1}/\lambda^\tau_{kt-1} - 1} \right)}^{\text{QA Laspeyres}}}_{\text{Within}}$$

$$+ \underbrace{\sum_{k\in\mathbb{C}_t} \Delta\omega^\tau_k \left(\frac{p_{kt}/\lambda^\tau_{kt}}{P^\tau_{t-1}} \right) + \sum_{k\in\mathbb{E}_t} \omega^\tau_{kt} \left(\frac{p_{kt}/\lambda^\tau_{kt}}{P^\tau_{t-1}} \right) - \sum_{k\in\mathbb{X}_t} \omega^\tau_{kt-1} \left(\frac{p_{kt-1}/\lambda^\tau_{kt-1}}{P^\tau_{t-1}} \right)}_{\text{Product Mix}}$$

where ω^τ_{kt} is the "quality-adjusted" quantity share of good k in period t:

$$\omega^\tau_{kt} = \lambda^\tau_{kt} q_{kt} / \sum_{k\in\Omega_t} \lambda^\tau_{kt} q_{kt}$$

$$\text{and } P^\tau_{t-1} = \frac{\sum_{k\in\Omega_{t-1}} p_{kt-1} q_{kt-1}}{\sum_{k\in\Omega_{t-1}} \lambda^\tau_{kt-1} q_{kt-1}}$$

Decompositions on a “Quality-Adjusted” Basis

– With time-varying adjustment, we decompose the QUVI with mixing parameter $\alpha = 0.5$

Notebook Computers - Average Quarterly Price Growth Rate

	Laspeyres (1)	UVI (2)	QA Laspeyres (3)	QUVI (4)
Within		−1.57		−2.17
Product Mix		2.08		−0.57
Total	−1.65	0.51	−2.26	−2.74

QUVI as an Exact Price Index?

- QUVI is the exact price index under strong assumptions that adjustment factors makes goods perfect substitutes
- An implication of perfect substitutes is the quality-adjusted law of one price (in more general form allowing for λ to vary over time):

$$p_{kt}/\lambda_{kt}^{\tau} = p_{jt}/\lambda_{jt}^{\tau} \ \forall \ j, \ k \in \Omega_t$$

- Quality-adjusted law of one price is unlikely as not all price dispersion is due to quality
- Market frictions can be introduced to yield frictional quality-adjusted law of one price:

$$z_{kt} p_{kt}/\lambda_{kt}^{\tau} = z_{jt} p_{jt}/\lambda_{jt}^{\tau} \ \forall \ j, \ k \in \Omega_t$$

  where z_{kt} represents residual price dispersion of good k that is attributed to market frictions

Inherent Identification Problem

- Inherent identification problem separating quality (λ) from market frictions (z)

$$z_{kt} p_{kt} / \lambda_{kt}^{\tau} = z_{jt} p_{jt} / \lambda_{jt}^{\tau} \ \forall \ j, \ k \in \Omega_t$$

- Byrne et al. (2017)(BKM) consider market frictions for measuring QUVI for semiconductors. Resolve identification problem with empirical evidence that price dispersion dissipates over the life-cycle. Apply this at supplier level.
- Their approach is not well-suited to our setting – absent the type of careful empirical analysis of evolution of price dispersion in BKM.
- We consider polar cases: $z_t = 1$ at beginning and end of item-level life cycle.
- These polar cases highlight without the type of careful empirical analysis of BKM that these are not generic solution.
- Work-in-progress – significant limitations of our polar case approach.

Taking Stock

- QUVI separates inflation component from "quality growth" present in UVI
- . . . decomposes cleanly into within-good price changes and changing product mix
- Interpreting the QUVI under two distinct approaches:
  1. Bounding approach produces "characteristic-adjusted" bounds on rate of inflation
  2. Exact price index approach needs market frictions to be plausible – inherent identification and measurement issues
     - $\Rightarrow$ BKM identify quality separate of market frictions after careful analysis
- Implications provide guidance for industry/market analysts use of UVI
- Future work:
  1. Explore price dispersion over the life-cycle
  2. Decomposing implied sources of "quality growth"

Thank you!

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Additional Slides

QUVI as an Exact Price Index (λ_k time invariant)

$$\lambda_k P_t = p_{kt} \; \forall \; k \in \Omega_t$$

$$\lambda_k P_t q_{kt} = p_{kt} q_{kt} \; \forall \; k \in \Omega_t$$

$$P_t = \sum_{k \in \Omega_t} p_{kt} q_{kt} / \sum_{k \in \Omega_t} \lambda_k q_{kt}$$

$$\frac{P_t}{P_{t-1}} = \frac{\sum_{k \in \Omega_t} p_{kt} q_{kt} / \sum_{k \in \Omega_t} \lambda_k q_{kt}}{\sum_{k \in \Omega_{t-1}} p_{kt-1} q_{kt-1} / \sum_{k \in \Omega_{t-1}} \lambda_k q_{kt-1}}$$

QUVI and the Matched-Model Laspeyres without Product Turnover

$$
\begin{aligned}
\frac{P_t^\tau}{P_{t-1}^\tau} &= \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_t} p_{kt}q_{kt}}{\sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1} / \sum_{k\in\Omega_{t-1}} p_{kt}q_{kt-1}} \\
&= \frac{\sum_{k\in\Omega_{t-1}} p_{kt}q_{kt-1}}{\sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1}} \\
&= \sum_{k\in\Omega_{t-1}} s_{kt-1}\left[\frac{p_{kt}}{p_{kt-1}}\right]
\end{aligned}
$$

QUVI and the Matched-Model Paasche without Product Turnover

$$
\begin{aligned}
\frac{P_t^\tau}{P_{t-1}^\tau} &= \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt} / \sum_{k\in\Omega_t} p_{kt-1}q_{kt}}{\sum_{k\in\Omega_{t-1}} p_{kt-1}q_{kt-1} / \sum_{k\in\Omega_t} p_{kt-1}q_{kt-1}} \\
&= \frac{\sum_{k\in\Omega_t} p_{kt}q_{kt}}{\sum_{k\in\Omega_t} p_{kt-1}q_{kt}} \\
&= \left(\sum_{k\in\Omega_t} s_{kt} \left[\frac{p_{kt}}{p_{kt-1}} \right]^{-1} \right)^{-1}
\end{aligned}
$$

QUVI and the Hedonic Paasche with Product Entry

$$
\begin{aligned}
\frac{P_t^\tau}{P_{t-1}^\tau} &= \frac{\sum_{k\in\Omega_t} p_{kt} q_{kt} / \sum_{k\in\Omega_{t-1}} p_{kt-1} q_{kt-1}}{\sum_{k\in\Omega_t} \lambda_{kt}^\tau(0) q_{kt} / \sum_{k\in\Omega_{t-1}} \lambda_{kt-1}^\tau(0) q_{kt-1}} \\
&= \frac{\sum_{k\in\Omega_t} p_{kt} q_{kt}}{\sum_{k\in\Omega_t} p_{kt} q_{kt} \left[\widehat{\frac{p_{kt}}{p_{kt-1}}}\right]^{-1}} \\
&= \left(\sum_{k\in\Omega_t} s_{kt} \left[\frac{\widehat{p_{kt}}}{p_{kt-1}}\right]^{-1} \right)^{-1}
\end{aligned}
$$