Consumer Demand Estimation for Heterogeneous U.S. Households

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Motivation

- Consumer demand specification is potentially important for estimating economy-wide impacts of environmental regulations
  - Affects shape of final good demand curve (Cranfield et al, 2002)
    - Pollution control and abatement cost incidence
    - Tax interaction effects (West & Williams, 2007)

- Flexible functional forms align well with observed household behavior but are rarely used in General Equilibrium (CGE) modelling.
  - Many CGE models use simple utility functions (e.g. CES and LES) that constraint price and income elasticities.
  - Flexible functional forms impose less constraints on elasticities.
  - A few CGE models have empirically specified, flexible demand systems but limited to a few sectors and/or national level estimates

Contribution

- Prior empirical literature often
  - Fails to evaluate regularity (i.e., can you credibly extrapolate beyond the prices and incomes in the data?)
  - Focuses on specific good of interest (e.g., gasoline; food)
  - Does not always include leisure

- We empirically estimate full consumption demand system for the U.S.
  - Include leisure (and test weak separability of leisure)
  - Use flexible functional forms
  - Evaluate/impose economic regularity constraints
  - Heterogeneous across regions and income groups
  - Applicable in CGE analysis

Empirically Estimated Consumer Demand Systems

	CES	LES	AIDS	QUAIDS
Regularity	Globally regular	Globally regular	Locally regular	Effectively globally regular
Rank order	1	2	2	3
Flexible budget share	X	✓	✓	✓
Flexible price & income elasticities	X	X	✓	✓

- We explore QUAIDS and AIDS in this presentation
- Also compare them to LES, since often used in CGE applications

Consumer Demand System

- QUAIDS expenditure shares (two goods)
  - Reduces to AIDS if λs =0

$$w_1 = \alpha_1 + \gamma_{11} \ln p_1 + \gamma_{12} \ln p_2 + \beta_1 \left(\frac{\ln(m)}{\ln(a(\boldsymbol{p}))} \right) + \frac{\lambda_1}{p_1^{\beta_1} p_2^{\beta_2}} \left(\frac{\ln(m)}{\ln(a(\boldsymbol{p}))} \right)^2$$

where w_1 is the expenditure share for good 1, p_i is price of good i, m is total household expenditures, and $ln\ a(\boldsymbol{p})$ is a translog price index (including HH demographics)

  - Budget elasticity:

$e_1 = \frac{\mu_1}{w_1} + 1$ where μ_1 is first differential w/respect to $\ln(m)$

  - Uncompensated price elasticity:

$e_{12}^u = \frac{\mu_{12}}{w_1} + \delta_{12}$ where δ_{12} is Kronecker delta (equals 1 if $i = j$; else, 0) and μ_{12} is first differential w/respect to $\ln p_2$

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Empirical Framework

- Our goal:
  - Estimate a full demand system for: leisure, non-durables, consumer services, housing, transport, and utilities

- Identification challenges:
  - Leisure imputation
    - Leisure price: estimate hourly after-tax wage
    - Leisure value= hourly after-tax wage * (time endowment– total hours worked)
  - Durable good purchases (e.g. housing and vehicle purchases): use equivalent rent, calculate vehicle services
  - Zero expenditures/wages: two-step Heckman correction model

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Demand System Estimation

- $w_i = \alpha_i + \sum_{j=1}^{6} \gamma_{ij} \ln p_j + \beta_i \ln\{\frac{m}{a(\boldsymbol{p})}\} + \frac{\lambda_i}{\prod_{i=1}^{6} p_i^{\beta_i}} [\ln \{\frac{m}{a(\boldsymbol{p})}\}]^2$
  - Employ iterated linear least-squares (ILLS) estimator (SUR within each iteration)
  - Drop last equation to address singularity

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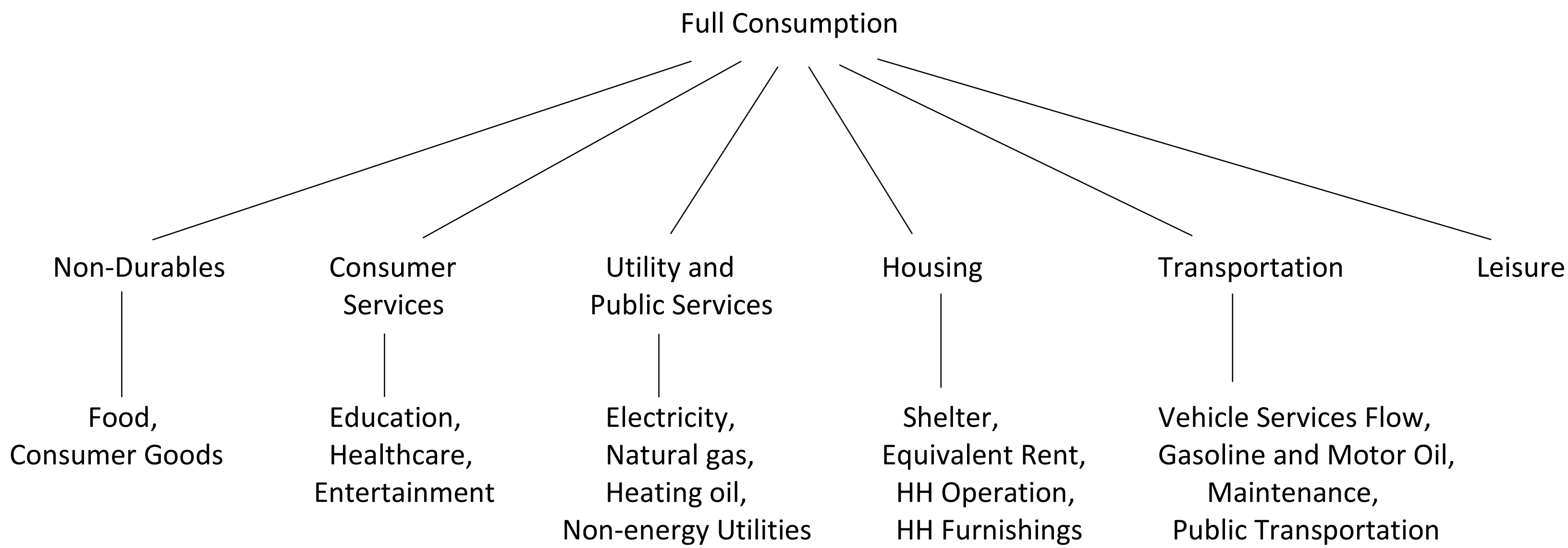
- Introduction
- Empirical Method
- Data and Summary Statistics
- Demand estimation results
- CGE simulation
- Future Work

Consumer Demand Structure



- Categories are chosen based on:
  - Computational tractability
  - Connecting to categories important in EPA models

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Data

- We need price, quantity (expenditure), and demographic controls

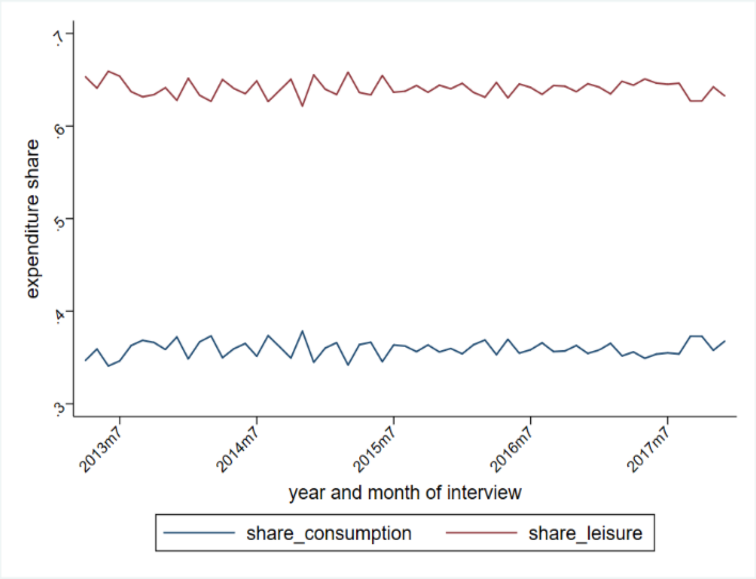
- Price data:
  - MSA-level quarterly Cost of Living Index from CREC
  - State-level annual Regional Price Parity from BEA
  - BLS monthly energy prices (SEDS energy consumption data used for weighted aggregation)
  - Multilateral aggregation across categories is done using Geary method.

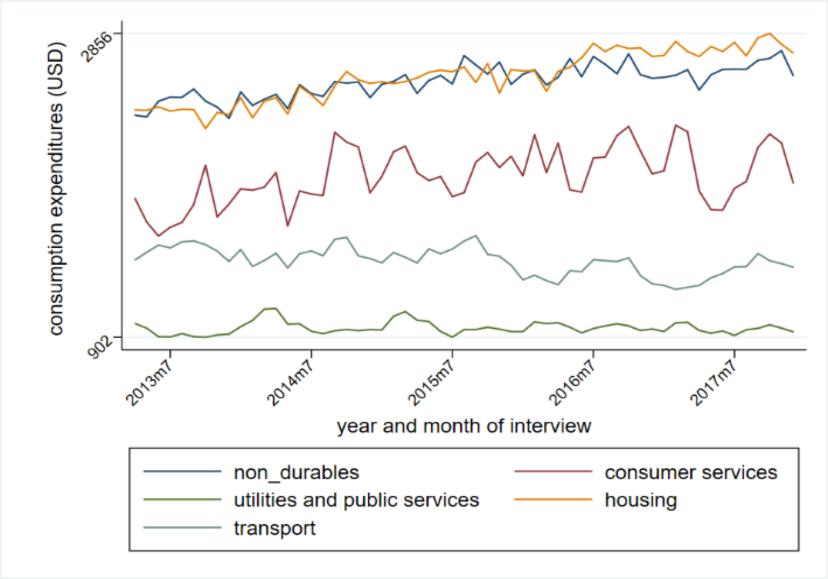
- BLS Consumer Expenditure Interview Survey:
  - 2013-2017 (pooled)
  - HH demographic and socioeconomic information
  - HH quarterly expenditures (rotating panel)

Data Summary: Mean Expenditure Shares

		Income Groups			Census Regions			
	National	Low	Medium	High	Midwest	Northeast	South	West
Non-durable	0.15	0.20	0.13	0.11	0.15	0.15	0.15	0.14
Cons. services	0.09	0.09	0.08	0.08	0.09	0.09	0.08	0.08
Utilities	0.06	0.08	0.05	0.04	0.06	0.06	0.07	0.05
Housing	0.15	0.22	0.14	0.11	0.14	0.17	0.15	0.17
Transport	0.06	0.07	0.06	0.06	0.07	0.06	0.07	0.06
Leisure	0.49	0.33	0.53	0.59	0.49	0.48	0.48	0.50
Observations	73,819	23,264	24,056	26,499	14,595	13,559	27,090	18,575

Consumption Expenditures





- Average Consumption Expenditure Shares (left panel)
- Average Consumption Expenditures by Category (right panel)

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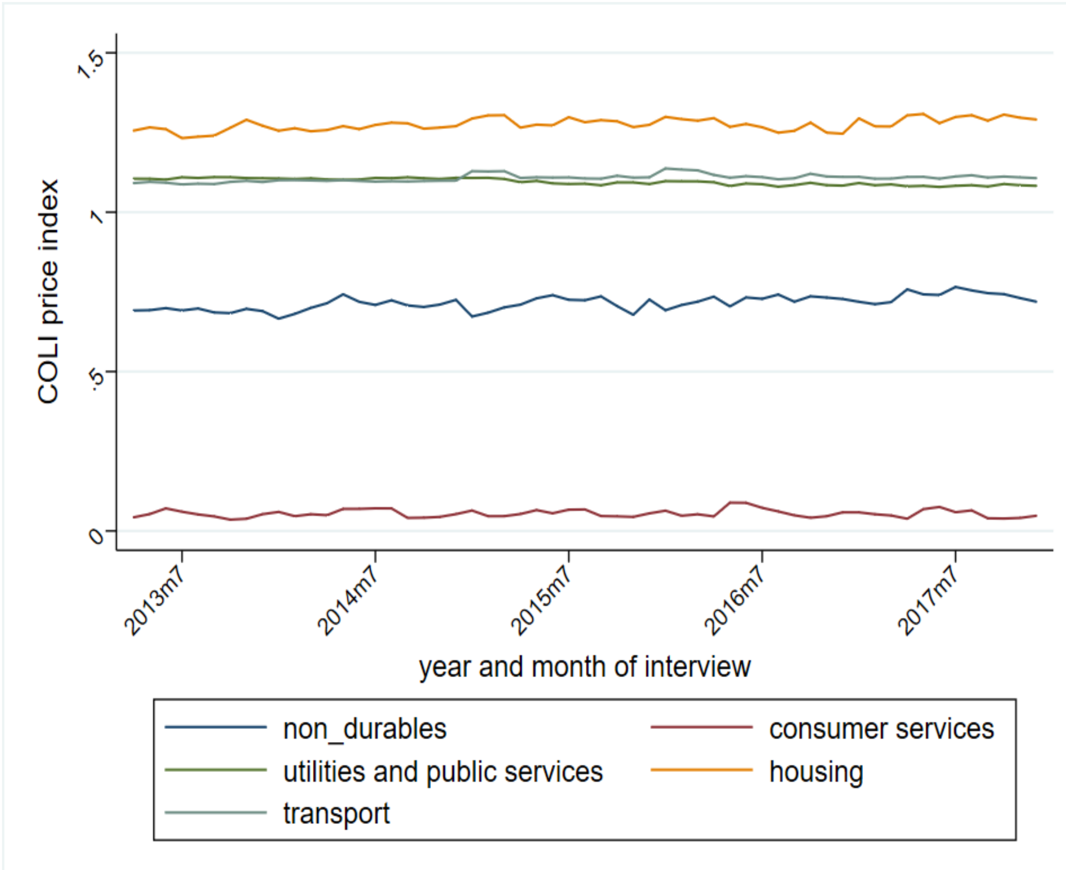
Price Indices



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National Level Elasticity Results

	Budget Elasticity			Un-compensated Price Elasticity		
Non-durables	0.433***	0.418***	0.428***	-0.816***	-0.819***	-0.281***
Consumer services	0.952***	0.924***	1.013***	-0.740***	-0.742***	-0.612***
Utilities	0.345***	0.352***	0.192***	-0.893***	-0.896***	-0.146***
Housing	0.587***	0.592***	0.482***	-0.791***	-0.793***	-0.312***
Transport	0.642***	0.658***	0.482***	-0.857***	-0.859***	-0.276***
Leisure	1.532***	1.543***	1.233***	-0.928***	-0.932***	-0.956***
Sample	National	National	National	National	National	National
Model	QUAIDS	AIDS	LES	QUAIDS	AIDS	LES
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	73,819	73,819	73,819	73,819	73,819	73,819
Bootstrapped standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1.						

- Statistically non-zero λs at each share equation: QUAIDS preferred

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Budget Elasticities

	National	Income Group			Census Region			
		Low	Medium	High	Midwest	Northeast	South	West
Nondurables	0.433***	0.189***	0.418***	0.380***	0.443***	0.26	0.397***	0.455***
Consumer services	0.952***	1.068***	0.678***	0.909***	0.980***	1.045***	0.781***	0.929***
Utilities	0.345***	0.187***	0.288***	0.183***	0.317***	0.520***	0.372***	0.434***
Housing	0.587***	0.238***	0.544***	0.587***	0.541***	0.613***	0.608***	0.535***
Transport	0.642***	0.519***	0.499***	0.533***	0.670***	0.666***	0.537***	0.610***
Leisure	1.532***	1.575***	1.656***	1.376***	1.531***	1.485***	1.534***	1.590***
Model	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS
Price data	COLI	COLI	COLI	COLI	COLI	COLI	COLI	COLI
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	73,819	23,264	24,056	26,499	14,595	13,559	27,090	18,575
Bootstrapped standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1.								

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Uncompensated Price Elasticities

		Income Group			Region			
	National	Low	Medium	High	Midwest	Northeast	South	West
Non-durables	-0.816***	-0.670***	-0.736***	-0.850***	-0.820***	-0.713***	-0.873***	-0.805***
Consumer services	-0.740***	-0.660***	-0.721***	-0.620***	-0.721***	-0.699***	-0.649***	-0.766***
Utilities	-0.893***	-0.785***	-0.839***	-0.928***	-0.926***	-0.923***	-0.774***	-0.995***
Housing	-0.791***	-0.573***	-0.834***	-0.753***	-1.587***	-0.694***	-0.690***	-0.710***
Transport	-0.857***	-0.625**	-0.830***	-0.870***	-1.186***	-1.206***	-0.016	-0.950***
Leisure	-0.928***	-0.942***	-0.811***	-0.895***	-0.947***	-0.918***	-0.968***	-0.927***
Model	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS	QUAIDS
Price data	COLI	COLI	COLI	COLI	COLI	COLI	COLI	COLI
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	73,819	23,264	24,056	26,499	14,595	13,559	27,090	18,575

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Results

- QUAIDS is preferred to AIDS functional form (but very similar).
- At national level, all consumption categories are price inelastic; all except for leisure are income inelastic.
- There is variation for housing and transport elasticities across sub-sample estimations.

Labor supply elasticity

Daily time endowment	Budget elasticity	Uncompensated price elasticity	Compensated price elasticity
10.96	-0.567	0.343	0.094
13.3	-1.012	0.630	0.144
15	-1.334	0.843	0.173

- Recall we assumed 10.96 hours/day, on average, for time endowment in our specifications.
- While the demand system results are not sensitive to alternate assumptions about time endowment and leisure time, the calculated labor supply elasticities are sensitive.

Labor supply elasticity

Sample	Budget elasticity	Un-compensated price elasticity	Compensated price elasticity
All	-0.567	0.343	0.094
Married male	-0.624	0.349	0.095
Married female	-0.632	0.348	0.097
Single male	-0.510	0.331	0.078
Single female	-0.546	0.343	0.099

Functional form	Daily time endowment	Budget elasticity	Un-compensated price elasticity	Compensated price elasticity
QUAIDS	10.96	-0.567	0.343	0.094
AIDS	10.96	-0.571	0.345	0.094
LES	10.96	-0.456	0.354	0.153

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Weak Separability Test

- Leisure is weakly separable from other consumption categories if (Moschini et al., 1994):

$$\frac{\sigma_{ik}}{\sigma_{jk}} = \frac{\eta_i}{\eta_j}$$

  - $\sigma_{ij} = \frac{\varepsilon_{ij}^{c}}{w_j}$ (Allen-Uzawa substitution elasticity)

$$\frac{\gamma_{ik} - \beta_i\beta_k - \alpha_i\beta_k - \alpha_k\beta_i + \beta_i\lambda_k + \lambda_i\beta_k + \lambda_k\alpha_i + \beta_i\beta_k + \lambda_i\alpha_k - 2\lambda_i\lambda_k - \lambda_k\beta_i - \lambda_i\beta_k + \lambda_i\lambda_k + \alpha_i\alpha_k}{\gamma_{jk} - \beta_j\beta_k - \alpha_j\beta_k - \alpha_k\beta_j + \beta_j\lambda_k + \lambda_j\beta_k + \lambda_k\alpha_j + \beta_j\beta_k + \lambda_j\alpha_k - 2\lambda_j\lambda_k - \lambda_k\beta_j - \lambda_j\beta_k + \lambda_j\lambda_k + \alpha_j\alpha_k} = \frac{\beta_i + \alpha_i - 2\lambda_i - \beta_i + \lambda_i\alpha_0}{\beta_j + \alpha_j - 2\lambda_j - \beta_j + \lambda_j\alpha_0}$$

- A size-corrected LR test: the null of weak separability is rejected.

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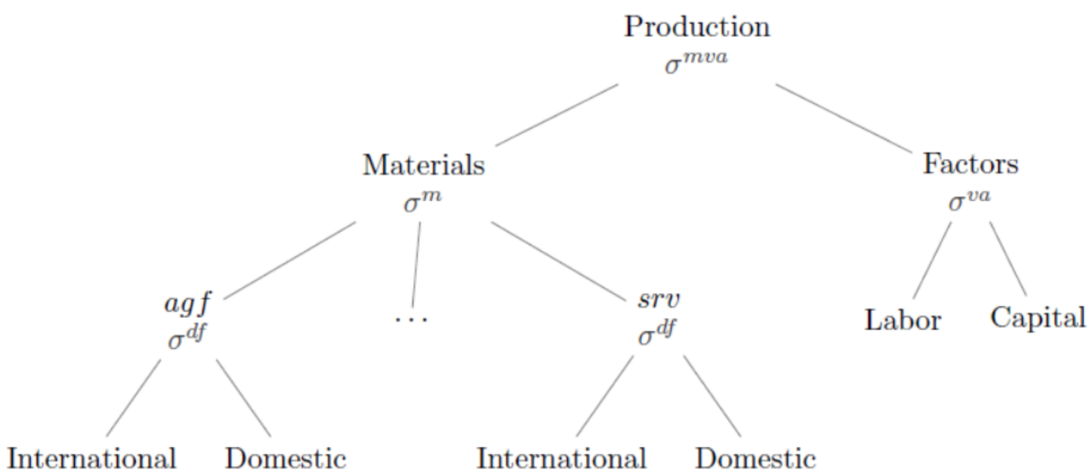
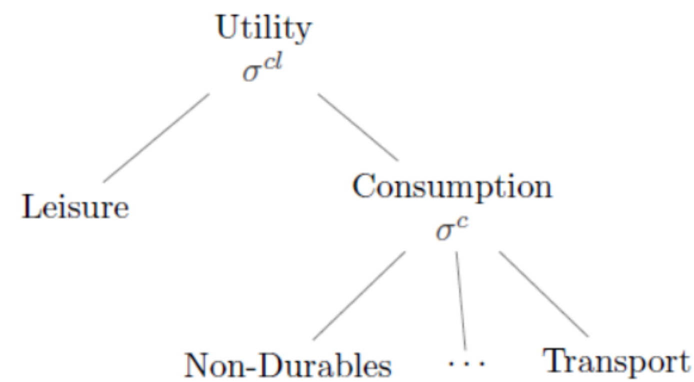
Illustrative CGE Simulation

- Conduct highly stylized simulations to assess importance of demand system on costs of illustrative environmental regulations.
  - Intended to provide a first step into a comprehensive comparison.
- Use the BEIGE (Basic Economy in General Equilibrium) model.
  - Simple static framework based on EPA's SAGE (SAGE is an Applied General Equilibrium) model.
- Shock type: mandate on manufacturing to require more inputs to produce the same amount of output.
  - Input mixture assumed to be split between labor and capital.
  - Vary size of shock from $100 million - $100 billion. Lower end of range in ballpark for many EPA regulations.

BEIGE Model (this version)

- Designed to be constructed flexibly based on the SAGE model.
- 6 sectors: agriculture, energy, construction, manufacturing, transportation and services.
- Single region, representative agent and government
- Small open economy
- Default nested CES production and utility functions:





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Commodity Mappings

- Use BEA's Personal Consumer Expenditure bridge file to map commodity accounts to CEX demand accounts.
- Assume conversion between commodities and demand accounts is Leontief.

	Non-durables	Consumer services	Utilities	Housing	Transport
Agriculture	0.69	0.31			
Manufacturing	0.48	0.27	0.01	0.14	0.11
Transportation	0.00	0.21	0.03	0.05	0.71
Services	0.11	0.52	0.04	0.28	0.06
Energy	0.00	0.51	0.48		

Modeled Demand Systems

- Demand systems modeled:
  - Nested CES (default)
  - LES
  - QUAIDS
- For LES and QUAIDS, we calibrate the model to match our estimated income/price elasticities.
- For a fair comparison of the default framework (nested CES), we estimate the top-level substitution elasticity, σ^{cl}, with the CEX data.
  - Given same assumptions on leisure, we find: $\sigma^{cl} = 0.33$ (statistically significant).

Calibration

- Leisure demands are derived using estimated labor supply elasticities.
- LES:
  - Estimate subsistence demands consistent with estimated income elasticities.
  - Relies on an empirically determined Frisch parameter. This parameter constrains estimated subsistence demands.
    - Defined as the negative ratio of total expenditures to discretionary expenditures. With CEX data, = -1.64.
- QUAIDS:
  - We solve for $\alpha_i, \beta_i, \gamma_{ij}, \lambda_i$ in terms of reference prices, quantities and estimated income and price elasticities.
  - A closed form solution is hard to pin down, particularly because budget shares between the CEX and IO data differ.
  - We use a matrix balancing technique to derive calibrated parameter values.

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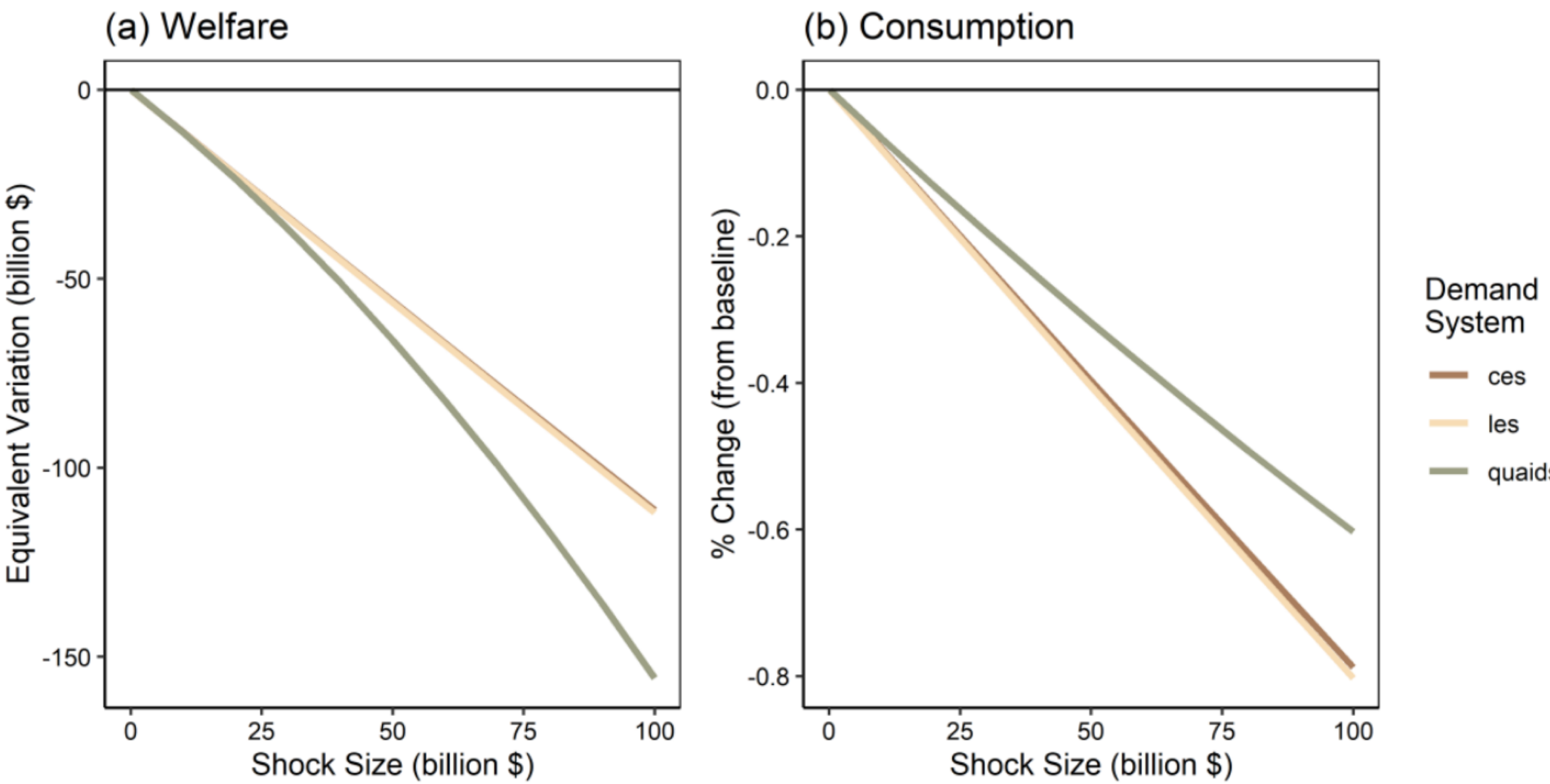
Results: Welfare and Aggregate Consumption



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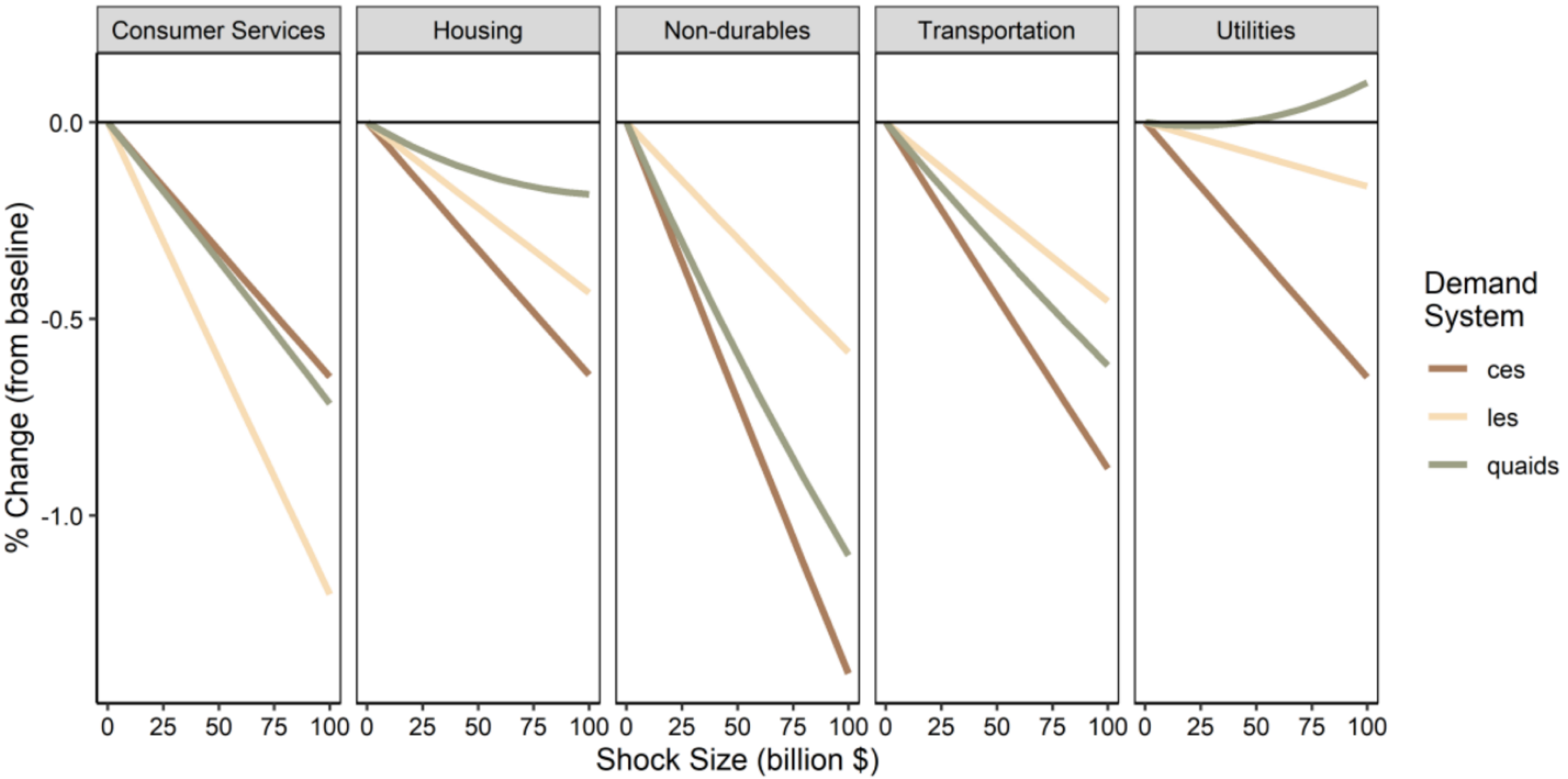
Results: Quantity Demanded



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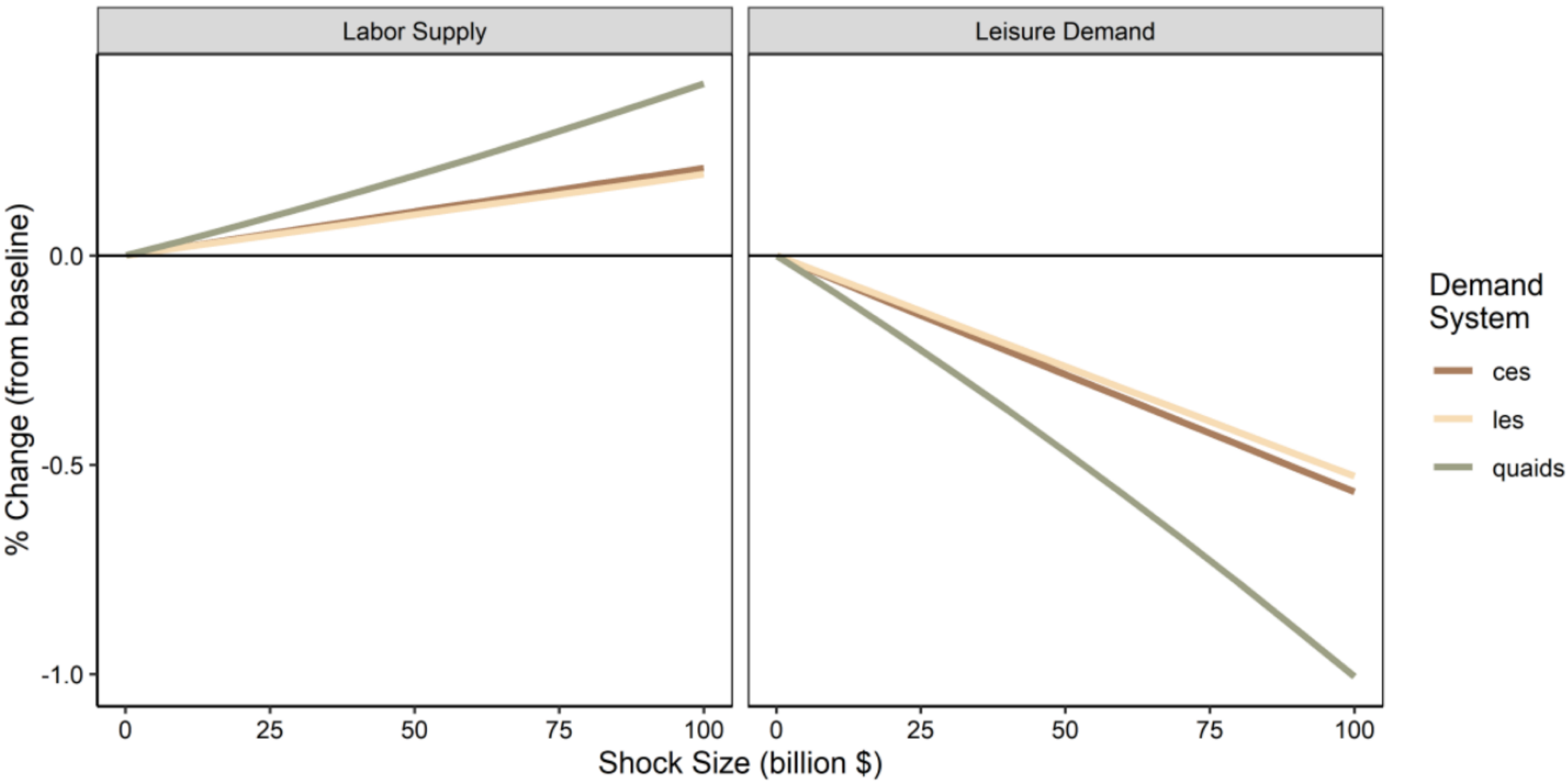
Results: Labor-Leisure



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Future Work

- Empirical next steps:
  - Separability tests to assess which aggregate categories should be modeled.
  - Expand number of demand categories as possible.
- Simulation next steps:
  - Implement alternative demand systems in dynamic settings: Ramsey version of BEIGE, SAGE
  - Assess how heterogeneous preferences and alternative functional forms interact with other salient features of the model.
    - Early simulations suggest that low/middle/upper income preferences lead to distributional implications in the simple BEIGE model.

Thank you!

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Appendix

Leisure Imputation

- Want full consumption but leisure price and quantity not directly reported.
  - Leisure price= hourly after-tax wage
  - Leisure value= hourly after-tax wage * leisure time

$$\text{Hourly after} - \text{tax wage} = \frac{\text{wage}}{\text{hours worked}} (1 - \text{ federal tax marginal rate} - \text{ state tax marginal rate})$$

$$\text{Leisure value} = \text{hourly after} - \text{tax wage} * (\text{time endowment} - \text{total hours worked})$$

  - Time endowment = 10.96 hours/day (4000 hours per year)
    - Leisure time: 2.96 hours/day, on average, if working full time
    - Leisure time: socializing & communicating, watching TV, participating in sport, exercise, and recreation
    - Will explore sensitivity of our estimates to this assumption later

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Durable Good Purchases

- Durable good purchases are large and infrequent and need to be replaced with their services flow.

1. Housing purchases: use equivalent rent

2. Vehicle purchases:
   - Estimate vehicle purchasing price (Meyer and Sullivan, 2017)
   - Calculate vehicle services flow (Slesnick, 2000)

Vehicle services flow

1. Vehicle purchasing price is missing for some CUs
   - Estimate vehicle purchasing price
     - RHS: vehicle age, fuel type, own use, new/used, family size, region, age, education, gender
     - Truck, make, and vehicle year fixed effects

2. Calculate vehicle services flow (S_t) in time, *t:*
   - $S_t = 0.25(r_t + \delta)(1 - \delta)^s P_0$
     - P_0: (predicted from/available in the data) purchasing price
     - *s* (exponent): years since purchase
     - r_t: U.S. 20 Year Real Treasury Rate (assumed)
     - δ: depreciation from Bento, et al. (2018)
     - Depreciation rates are assigned to each vehicle based on vehicle age and year

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Zero Expenditures/Wages

- Selection bias from zero values for wages and expenditures for some goods
  - Common approach: two-step Heckman correction model

  - Heckman correction model for each expenditure category:
    - Estimate inverse mills ratios
    - Use estimated inverse mills ratios in demand system estimation as RHS variable (non-selection hazard)

  - Heckman correction model for wage:
    - $\ln(wage_{it}) = \tau_1 age_{it} + \tau_2\, age_{it}^2 + \tau_3\, educa_{it} + \tau_4\, marriage_{it} + \tau_5\, white_{it} + \tau_6 urban_{it} + \tau_7\, state_i + \epsilon_{it}$
    - Selection variables: marriage status and number of children

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QUAIDS Elasticities

- Expenditure elasticities: $\eta_i = \frac{\mu_i}{w_i} + 1$
  - $\mu_i = \frac{\partial w_i}{\partial \ln(m)} = \beta_i + \frac{2\lambda_i}{\prod_{i=1}^{6} p_i^{\beta_i}} [ln(\frac{m}{P(\boldsymbol{p})})]$
- Uncompensated price elasticities: $\epsilon_{ij} = \frac{\mu_{ij}}{w_i} - \delta_{ij}$
  - $\mu_{ij} = \frac{\partial w_i}{\partial \ln(p_j)} = \gamma_{ij} - \mu_i \left(\alpha_j + \gamma_j \boldsymbol{P}\right) - \lambda_i \beta_j \frac{[m - P(\boldsymbol{p})]^2}{\prod_{i=1}^{6} p_i^{\beta_i}}$
- Compensated price elasticities: $\varepsilon_{ij}^{c} = \epsilon_{ij} + \eta_i w_j$
- Adding up, homogeneity, and symmetry conditions:
  - $\sum_{i=1}^{6} \alpha_i = 1, \sum_{i=1}^{6} \beta_i = 0, \sum_{j=1}^{6} \gamma_{ij} = 0, \sum_{i=1}^{6} \lambda_i = 0,\ \gamma_{ij} = \gamma_{ji}$

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Multilateral aggregation (Geary Method)

- In general, RPP can be calculated from dividing expenditures at area prices by expenditures at national prices.

  - $RPP_{ia} = \frac{e_{ia(pa)}}{e_{ia(pn)}}$ ⟹ $e_{ia(pn)} = \frac{e_{ia(pa)}}{RPP_{ia}}$
    - e_{ia}: expenditures for category i in area a

- Example: $RPP_{cs,a} = \frac{e_{educ,a(pa)} + e_{med,a(pa)} + e_{rec,a(pa)}}{\frac{e_{educ,a(pa)}}{RPP_{educ,a}} + \frac{e_{med,a(pa)}}{RPP_{med,a}} + \frac{e_{rec,a(pa)}}{RPP_{rec,a}}}$

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