Usage-Based Pricing and Demand for Residential Broadband

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Motivation

- The telecommunications sector is undergoing major changes
- A driving force: growing importance of data services
  - mergers: Comcast-TWC, ATT-DTV, Sprint-TMobile
  - policy: net neutrality, muni-BB
  - other: Google Fiber
  - similar issues in Europe
- An important ingredient for studying the economics of this industry: demand for residential broadband
- Policy debate over data caps
  - related to, but different than, net neutrality

General Strategy

- Unique high-frequency usage data
- Provide detailed descriptive statistics
- Estimate demand for residential broadband
  - use plan choice
  - more important: three-part tariff makes usage a dynamic problem, generating variation in the (shadow) price of consumption
  - dynamic model to capture usage decisions
  - allow for flexible distribution of types
- Simulation excercises
  1. demand under linear traiffs
  2. usage and welfare under UBP relative to various alternatives
  3. usage and welfare with FTTP networks

Econometric Approach

- Rely on an approach proposed by Bajari et al (2007) and Fox et al (2011)
- 2 step approach
  - step 1: solve the model (once) for many types
  - step 2: estimate weights to put on each type
- Separates computational and econometric problems
- Estimation fast, easy to program and transparent
- Estimate non-normal "distribution of types"
- Closely replicate wide range of behaviors in data

Related Literature

- Demand for broadband
  - Varian (2002), Edell and Varaiya (2002), Lambrecht et al. (2007), McDevitt and Greenstein (2011), Rosston et al. (2010), Goolsbee and Klenow (2006), etc.
- Dynamic demand models
  - Demand: Crawford and Shum (2005), Hendel and Nevo (2006), Gworisankaran and Rysman (2012), Yao et al. (2012)
  - Sales incentive: Copeland and Monnet (2009), Chung et al. (2010), Misra and Nair (2011)
- Evidence of forward-looking behavior
  - Aron-Dine et al. (2012), Grubb (2012), Grubb and Osborne (2012), Chevalier and Goolsbee (2009)

Data Overview

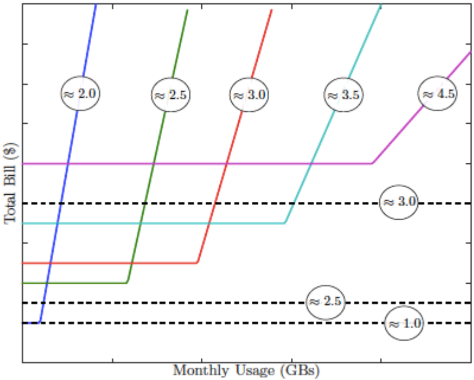
- Proprietary data on residential usage from N.A. ISP
  - Representative markets w/ about 55,000 subscribers
  - 15-minute frequency for 8 weeks, 6/2012
  - Monthly frequency, 5/2011-5/2012
- Information on subscribers' plans.
  - Three-part tariffs and grandfathered unlimited allowances
  - Speed and usage allowance are non-decreasing in fixed fee
  - Consumers on UBP plans receive notices on cumulative usage

Descriptive Statistics of Subscriber Plan Choices and Usage, May-June 2012

	Unlimited Plans	Usage-Based Plans
Number of Subscribers	12,316	42,485
Plan Characteristics		
Mean Access Fee ($)	44.33	74.20
Mean Download Speed (Mb/s)	6.40	14.68
Mean Allowance (GB)	∞	92.84
Mean Overage Price ($/GB)	0.0	3.28
Usage		
Mean (GB)	50.39	43.39
Mean (Access Fee $\leq$ $60) (GB)	48.94	20.40
Mean (Access Fee $>$ $60) (GB)	88.59	69.36
Median (GB)	25.60	23.63
Median (Access Fee $\leq$ $60) (GB)	25.17	12.18
Median (Access Fee $>$ $60) (GB)	42.12	52.04
Median Price per GB ($)	1.68	3.02

Plan Features

Figure 1: *Plan Features and Billing*



Growth and Heterogeneity

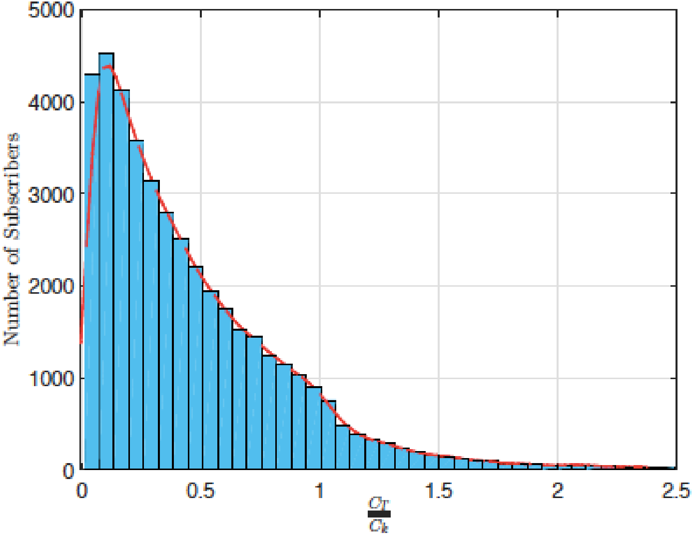
Percentile	May 2011 (GB)	May 2012 (GB)	Growth (GB)	Growth (%)
25	2.49	6.69	4.20	168.67
50	8.99	20.27	11.28	125.47
75	26.85	52.24	25.39	94.56
90	60.83	103.94	43.11	70.87
95	92.62	147.27	54.65	59.00
99	185.81	253.62	67.81	36.49
Mean	23.08	40.29	17.21	74.56

Overages and Optimality of Plan Choice

	5/2011 - 5/2012	6/2012
Number of Subscribers	42,485	42,485
Mean Share of Allowance Used (%)	46.05	49.02
Subscribers Over Allowance (%)	8.62	9.45
Median Overage (GB)	14.31	17.03
Median Overage Charges ($)	44.98	51.19
Subscribers on Dominated Plan (%)	0.13	7.24

- Non trivial fraction of consumers incur overage
- Trivial amount of dominated plans over long horizon

Figure 7: *Proportion of Allowance Used*



Are Consumers Forward-Looking?

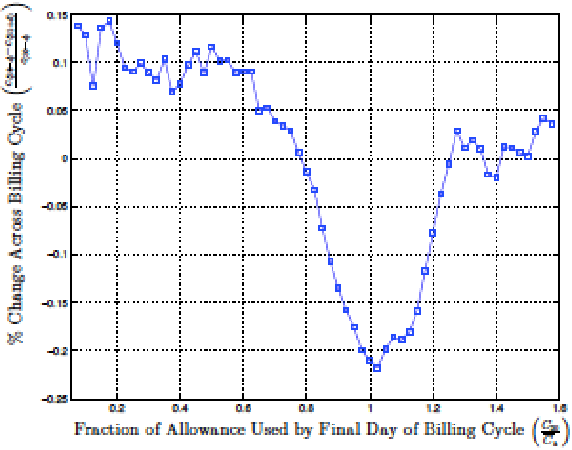
	$\mathbb{1}\left[10 \leq t < 15\right]$	$\mathbb{1}\left[15 \leq t < 20\right]$	$\mathbb{1}\left[20 \leq t < 25\right]$	$\mathbb{1}\left[25 \leq t < 31\right]$
$1\left[0 \leq \frac{C_{jk(t-1)}}{\overline{C}_k} < 0.40\right]$	-0.04**	-0.04**	0.03**	0.08**
	(0.01)	(0.01)	(0.01)	(0.01)
$1\left[0.40 \leq \frac{C_{jk(t-1)}}{\overline{C}_k} < 0.60\right]$	-0.02	-0.12**	-0.12**	-0.04**
	(0.02)	(0.01)	(0.01)	(0.01)
$1\left[0.60 \leq \frac{C_{jk(t-1)}}{\overline{C}_k} < 0.80\right]$	-0.07**	-0.12**	-0.20**	-0.16**
	(0.03)	(0.02)	(0.02)	(0.01)
$1\left[0.80 \leq \frac{C_{jk(t-1)}}{\overline{C}_k} < 1.00\right]$	-0.19**	-0.26**	-0.39**	-0.42**
	(0.05)	(0.03)	(0.02)	(0.02)
$1\left[1.00 \leq \frac{C_{jk(t-1)}}{\overline{C}_k}\right]$	-0.12**	-0.35**	-0.41**	-0.47**
	(0.05)	(0.03)	(0.02)	(0.02)
Adjusted R^2	0.46			

Are Consumers Forward-Looking?

- Price for forward-looking subscribers varies discretely as billing cycle ends, and next begins
- Direction depends on subscribers usage during cycle
  - Well over allowance, and expecting to do so again, face constant price and should not change usage
  - Well below allowance, face higher price and should decrease usage in new month
  - Near or just over allowance, face lower price and should increase usage in new month
- Calculate change in usage across first and last days of billing cycle to test if subscribers respond to across-month price variation

Are Consumers Forward-Looking?

Figure 2: *Across-Month Dynamics*



- Consumers respond to across-month price variation

Utility Function

- The utility of type h on day t and plan k:

$$u_h(c_t, y_t; k) = \upsilon_t \left(\frac{c_t^{1-\beta_h}}{1-\beta_h} \right) - c_t \left(\kappa_{1h} + \frac{\kappa_{2h}}{ln(s_k)} \right) + y_t,$$

  where: c_t – GB of content, y_t – numeraire, s_k – connection speed, $\upsilon_t (\sim G_h(\upsilon))$ – random shock to preferences for content

- type: β_h – curvature, κ_{1h} – opportunity cost of consuming content, κ_{2h} – content wait time, $G_h(\upsilon)$ – uncertainty
- Satiation, even on unlimited plans, due to cost of consuming content that is decreasing in connection speed

The Consumer Problem

- Conditional on choosing plan k, the subscriber

$$\max \sum_{t=1}^{T} E\left[u_h(c_t, y_t; k)\right]$$

  - No discounting, daily decision over a finite and short horizon

- Subject to an income constraint

$$F_k + p_k(C_T - \overline{C}_k)1\left[C_T > \overline{C}_k\right] + Y_T \leq I$$

- Cumulative consumption $C_T = \sum_{t=1}^{T} c_t$, $Y_T = \sum_{t=1}^{T} y_t$
- Plan characteristics: fixed fee, F_k, overage price, p_k, allowance, $\overline{C}_k$
- Assume income, I, enough to afford satiation level

Optimal Consumption

Define the *shadow price* of consumption

$$\widetilde{p}_k(c_t, C_{t-1}) = \begin{cases} p_k & \text{if } \mathcal{O}_{tk}(c_t) > 0 \\ \frac{dE[V_{hk(t+1}(C_{t-1}+c_t)]}{dc_t} & \text{if } \mathcal{O}_{tk}(c_t) = 0\,. \end{cases}$$

Then the consumer's optimal consumption in period t satisfies

$$c^*_{hkt} = \left(\frac{\upsilon_t}{\kappa_{1h} + \frac{\kappa_{2h}}{ln(s_k)} + \widetilde{p}_k(c^*_{hkt}, C_{t-1})} \right)^{\frac{1}{\beta_h}}.$$

Solving the Model

- Solve DP conditional on plan k and υ_t and get $c^*_{hkt}(C_{t-1}, \upsilon_t)$ and $V_{hkt}(C_{t-1}, \upsilon_t)$
  - finite horizon ($T = 30$): solve by backward induction
  - log normal distribution for $G_h(\upsilon)$
  - discretize state space
- Plan choice: each type chooses plan k that maximizes expected surplus (no error)

$$E\left[V_{hk1}(C_1 = 0)\right] = \int_0^{\overline{\upsilon}} V_{hk1}(C_1 = 0, \upsilon) dG_h(\upsilon),$$

- Form conditional state-specific moments from policy functions

$$E\left[c^*_{hkt}(C_{t-1})\right] = \int_0^{\overline{\upsilon}} c^*_{hkt}(C_{t-1}, \upsilon) dG_h(\upsilon),$$

and calculate cdf of cumulative consumption, C_{t-1}

Estimation Overview

- Follow ideas in Ackerberg (2009), Bajari et al (2007)
  - Avoids nested fixed-point algorithms
  - Flexible discrete distribution of types
- Two Steps:
  1. Computational: solve DP for a large number of types, $\{\mu_h, \sigma_h, \beta_h, \kappa_{1h}, \kappa_{2h}\}$, and identify optimal plan
  2. Estimation: estimate mixture of types to *best* match empirical moments of usage from each plan to weighted moments predicted by the model

Step 1: Solving the Dynamic Program

- Identify support and density of types by experimentation
  - Many parameters naturally bounded
  - Cover range of behaviors in data
  - Grid too dense $\rightarrow$ multicollinearity (in step 2)
- Solve dynamic program for 16,807 (7^5) types on every plan once
  - Easily done in parallel or even on separate machines
  - 60,000 total states ($C = 2,000$ and $T = 30$)
- Store the following for each type on optimal plan:
  1. Value functions, $E\left[V_{hkt}(C)\right]$
  2. Conditional expected usage, $E\left[c^*_{hkt}(C)\right]$
  3. CDF of cumulative usage, $F_{hkt}(C)$

Step 2: Estimation

- The goal is to estimate the weight associated with each of the subscriber types
- Weights for types on plan k, $\boldsymbol{\theta_k}$, are chosen to satisfy

$$\widehat{\boldsymbol{\theta}}_{\boldsymbol{k}} = \underset{\boldsymbol{\theta_k}}{argmin} \ \ \mathbf{m_k}(\boldsymbol{\theta_k})'\mathbf{V_k^{-1}}\mathbf{m_k}(\boldsymbol{\theta_k})$$

  such that each $\theta_h \geq 0$ and $\sum_{h=1}^{H_k} \theta_h = 1$
- where:
  - H_k equals number of types optimally choosing plan k
  - $\mathbf{m_k}(\boldsymbol{\theta_k})$ is difference between empirical and predicted moments
  - $\mathbf{V_k}$ is the variance-covariance matrix of empirical moments
- rescale weights to match plan market shares
- Converges to global solution in seconds

Identification

- Goal: identify the distribution of types
- Selection of grid places a uniform "prior"
- Plan selection divides the space into sets (and divides share of each plan across this space)
- Usage distributes the weight within each set
- Weights are identified by the second step regression
  - to avoid multi-collinearity need differences across types in some states (in some moments)
  - need not just average usage, but higher order moments

Linearity of Moments in Type Weights

- Moments must describe state-dependent actions *and* distribution across states, while preserving linearity in θ_h
- The moments are based on (unconditional) mean usage

$$\sum_{h=1}^{H_k} E\left[c^*_{hkt}(C_{t-1})\right] \gamma_{hkt}(C_{t-1})\theta_h,$$

and probability mass at state,

$$\sum_{h=1}^{H} \gamma_{hkt}(C_{t-1})\theta_h,$$

where $\gamma_{hkt}(C_{t-1})$ is the probability type reaches state

Moments Used

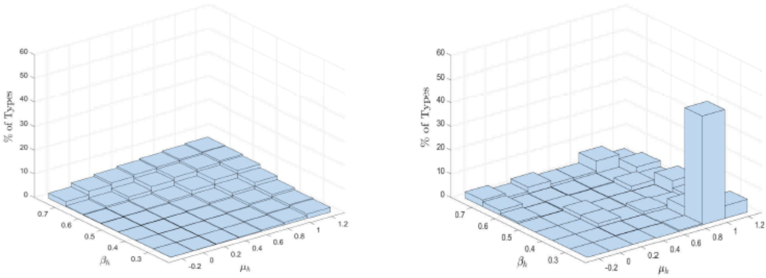
- Calculate moments at each of the 120,000 state space points for each plan.
- Mean usage for each plan (k), billing day (t), and cumulative usage (C)
  - Recovered using nearest-neighbor estimator
- CDF of cumulative usage (C) for each plan (k) and day (t)
  - Recovered using smoothed Kaplan-Meier estimator
- Variance-covariance matrix, V_k^{-1}, calculated using block-resampling to account for dependence

Distribution of Types

- 53 types with positive weights
- Cumulative weight for
  - top 5: 0.65
  - top 10: 0.78
  - top 20: 0.90
- Model fits the data quite well.
- Few-type models miss rich heterogeneity among subscribers
- Most common type: \$12.46/GB opportunity cost of consuming content with 14.7 Mb/s connection and gross surplus of \$186

Sources of Identification

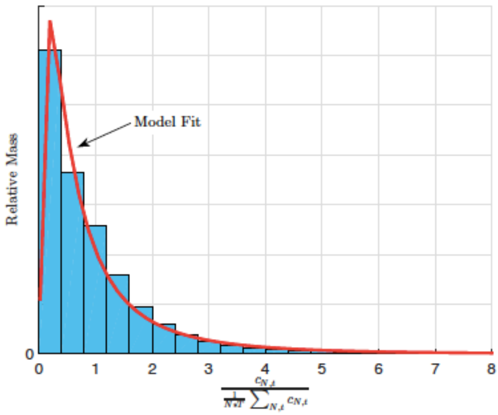
Figure 3: *Sources of Identification: Plan Selection and Usage*



(a) *Only Plan Selection* (b) *Plan Selection and Usage*

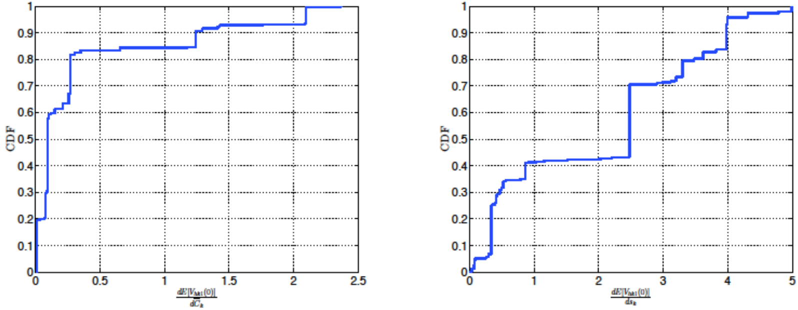
Model Fit

Figure 4: *Model Fit: Distribution of Usage Relative to a Subscriber's Mean*



WTP to Increase Allowance and Speed

Figure 5: *Distribution of Value of Increasing Usage Allowance by 1 GB and Speed by 1 Mb/s*



(a) *Value of Increasing Usage Allowance by 1 GB*

(b) *Value of Increasing Speed by 1 Mb/s*

Demand with Linear Tariff

	Expected Daily Usage (GBs)				
Price ($)	**2 Mb/s**	**14.68 Mb/s**	**50 Mb/s**	**100 Mb/s**	**1,024 Mb/s**
0.00	0.97	2.20	2.97	3.42	4.627
1.00	0.50	1.14	1.50	1.70	2.31
2.00	0.29	0.66	0.86	0.96	1.24
3.00	0.18	0.42	0.54	0.59	0.74
4.00	0.12	0.29	0.36	0.39	0.48
5.00	0.09	0.21	0.25	0.28	0.33

Usage-based Pricing versus Unlimited Plans

	(1)	(2)	(3)	(4)
Scenario Description				
UBP/Unlimited Plan attributes	UBP current	Unlim current	Unlim typical US	Unlim rev-max F_k
Usage and Surplus				
Usage (GBs)	48.22	60.16	62.02	65.42
	(0.203)	(0.261)	(0.264)	(0.322)
Speed (Mb/s)	14.19	10.33	10.83	12.63
	(0.021)	(0.010)	(0.018)	(0.069)
Consumer Surplus ($)	84.67	111.94	113.53	97.08
	(0.810)	(0.791)	(0.789)	(0.810)
Revenue ($)	69.47	42.05	44.82	64.32
	(0.132)	(0.044)	(0.068)	(0.209)

Adoption of FTTP and Usage

	(1)	(2)	(3)	(4)	(5)	(6)
Scenario Description						
Plan attributes	$F_k = 0$	$F_k = 70$	$F_k = 70$	$F_k = 70$	rev-max F_k	rev-max F_k
Competition			KC-cable	U-verse	KC-cable	U-verse
Usage and Surplus						
Usage (GBs)	138.8	136.6	134.5	134.4	125.8	132.0
	(0.855)	(0.857)	(0.856)	(0.871)	(0.921)	(0.897)
Speed (Mb/s)	1024.0	849.2	687.0	673.0	588.1	592.8
	(0.000)	(1.481)	(3.597)	(4.022)	(3.529)	(3.461)
Consumer Surplus ($)	279.4	212.9	213.2	215.5	144.0	175.0
	(1.025)	(1.014)	(0.968)	(0.981)	(0.843)	(0.889)
Revenue ($)	0.00	63.1	55.3	58.5	117.6	95.3
	(0.000)	(0.101)	(0.125)	(0.133)	(0.330)	(0.231)

Conclusions and Future Research

- Welfare implications of UBP
  - Decreases usage
  - Increases total surplus
  - Effect on consumer surplus depends on alternative
- High-speed fiber networks appear to be socially desirable
  - Costs appear to be recoverable, consistent with recent investments by private (Google Fiber/CenturyLink) and public (ECFiber in Vermont/Chattanooga EPB) entities
- Future research.
  - Trial of peak-load pricing
  - Exploit network upgrades to study congestion externalities
  - Bundling and substitutability of video

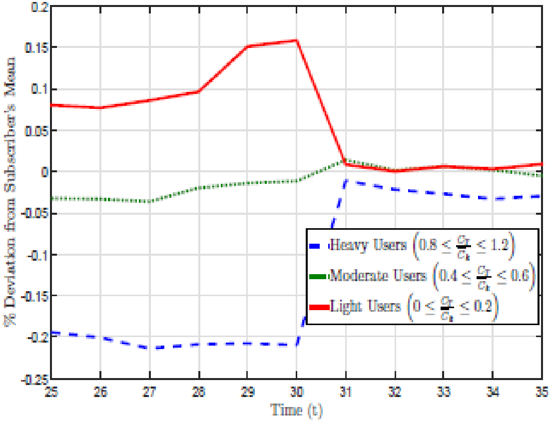
Day-of-Week Dependence

Table: *Average Daily Usage by Day of Week*

Day of Week	**Daily Usage (GBs)**
Sunday	1.55
Monday	1.59
Tuesday	1.50
Wednesday	1.47
Thursday	1.46
Friday	1.46
Saturday	1.48

Across Month Dynamics Extensions

Figure 6: *Transferability of Content, Across-Month Dynamics*



The Source of Serial Correlation

	(1)	**(2)**
$\frac{C_{iT}}{C_{ik}}$	0.047**	0.077**
	(0.002)	(0.003)
$\left(\frac{C_{iT}}{C_{ik}}\right)^2$	–	-0.004**
	–	(0.001)
Constant	0.151**	0.139**
	(0.001)	(0.002)
Observations	42,485	42,485

Figure 8: *Sources of Identification: Plan Selection and Usage*

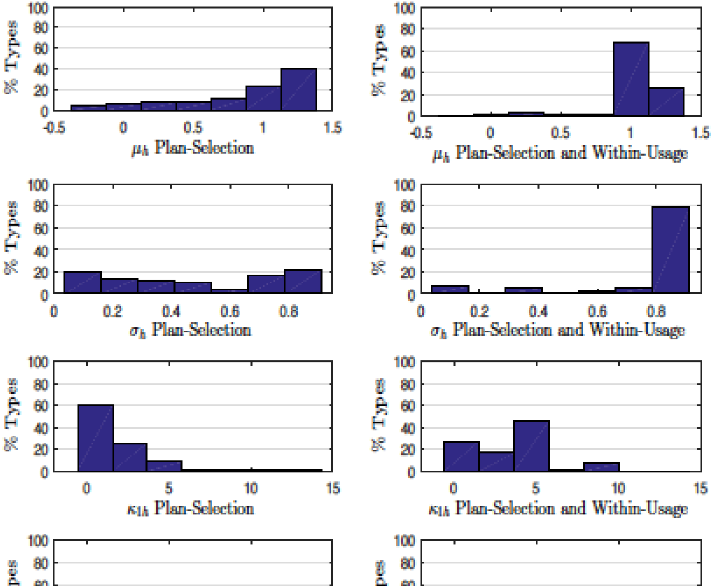


Figure 9: *Predicted Behavior by Type, CDF of C_T*

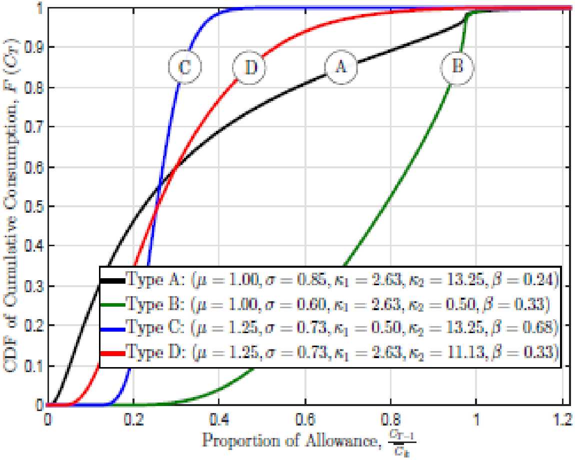


Figure 10: *Predicted Behavior by Type: Expected Usage* $E\left[c_T^*\left(C_{T-1}, \nu_t\right)\right]$

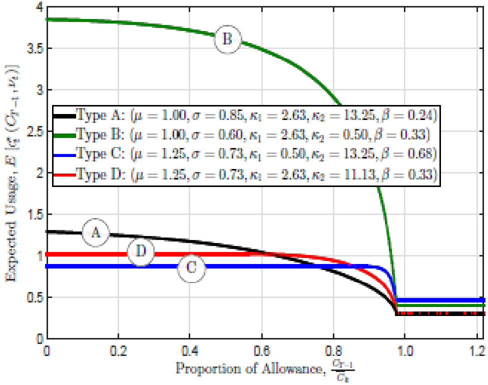


Figure 11: *Perturbation of Parameters, CDF of* C_T

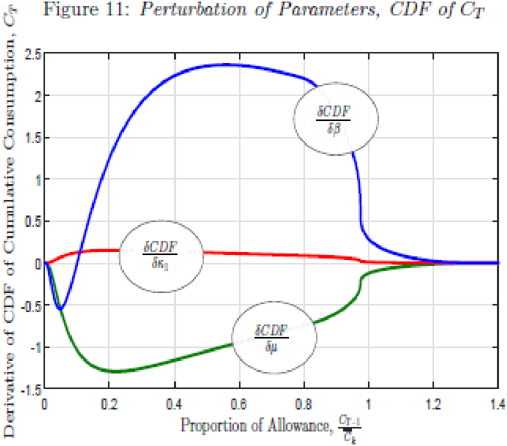


Figure 12: *Perturbation of Parameters, Expected Usage* $c_T^*(C_{T-1})$