

# Generalized Random Coefficients With Equivalence Scale Applications

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## Abstract

We propose a generalization of random coefficients models, in which the regression model is an unknown function of a vector of regressors, each of which is multiplied by an unobserved error. We also investigate a more restrictive model which is additive (or additive with interactions) in unknown functions of each regressor multiplied by its error. We show nonparametric identification of these models. In addition to providing a natural generalization of random coefficients, we provide economic motivations for the model based on demand system estimation. In these applications, the random coefficients can be interpreted as random utility parameters that take the form of Engel scales or Barten scales, which in the past were estimated as deterministic preference heterogeneity or household technology parameters. We apply these results to consumer surplus and related welfare calculations.

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## 1 Introduction

Suppose an observed variable  $Y$  depends on a vector of observed regressors  $X = (X_1, \dots, X_K)$ , and on a vector of unobserved errors  $U_0, U_1, \dots, U_K$ . These errors represent unobserved

heterogeneity in the dependence of  $Y$  on  $X$  ( $U_0$  could also represent measurement error in  $Y$ ). We propose a generalized random coefficients model given by

$$Y = G(X_1 U_1, \dots, X_K U_K) + U_0 \quad (1)$$

for some unknown function  $G$ . Given observed data, we show that the function  $G$  and the distribution functions of each random coefficient  $U_k$  are nonparametrically identified. Our model permits the random coefficients to be correlated with regressors. Identification in this case uses instruments by assuming each  $U_k$  is conditionally independent of the corresponding  $X_k$ , conditioning on observed control function residuals  $Z$ .

We provide examples of economic models that have been widely applied empirically that take the form of equation (1) but with  $U_k$  specified as deterministic functions of observables. It is an immediate natural generalization of these applications to let  $U_k$  embody unobserved heterogeneity. We provide estimates of two such models from the consumer demand system literature.

Our identification results for the general model of equation (1) impose some strong smoothness assumptions, so we first focus on additive models of the form

$$Y = \sum_{k=1}^K G_k(X_k U_k) + U_0 \quad (2)$$

where the functions  $G_1, \dots, G_K$  are unknown. For these additive models the identifying assumptions are less restrictive. We then give stronger conditions for identifying the nonadditive components of equation (1). We also consider extensions such as adding interaction terms to the model of the form  $X_j X_k U_{jk}$  (that is, additional random coefficients on cross terms), and we consider identification when some  $X_k$  components are discretely distributed.

Nonparametric identification and estimation of random coefficients models is considered by Beran and Hall (1992), Beran, Feuerwerker, and Hall (1996) and Hoderlein, Klemelae, and Mammen (2010). Recent generalizations include random coefficient linear index models in binary choice, e.g., Ichimura and Thompson (1998), Gautier and Kitamura (2010), and semiparametric extensions of McFadden (1974) and Berry, Levinsohn, and Pakes (1995) type models, e.g., Berry and Haile (2009).

Ordinary random coefficients are the special case of the additive model in equation (2) in which each  $G_k$  is the identity function. Additive models are a common generalization of linear models; see, Hastie and Tibshirani (1990), Linton (2000), and Wood (2006), and in the particular applications of additivity to consumer demand systems include Gorman (1976) and Blackorby, Primont, and Russell (1978). Particularly relevant for this paper is Matzkin (2003), which in an appendix describes generic, more high level identifying conditions for a large class of additive models with unobserved heterogeneity.

This paper also contributes to the literature on estimation of models with nonseparable errors, in particular where those errors arise from structural heterogeneity parameters such as random utility parameters. Older examples of such models include Heckman and Singer (1984) and Lewbel (2001). More recent work focusing on general identification and estimation results include Chesher (2003), Altonji and Matzkin (2005), Hoderlein, and Mammen (2007), Matzkin (2007a, 2008), and Imbens and Newey (2009). In particular, Hoderlein, Nesheim, and Simoni (2011) provide high level conditions for identification and estimation of models that, like ours, contain a vector of random parameters. Their results would be applicable to our model if the function  $G$  were finitely parameterized instead of nonparametric.

In our empirical applications, the random coefficients represent equivalence scales in consumer demand models. There is a long history of using equivalence scales to empirically model observed sources of preference heterogeneity. See, e.g., Lewbel (1997) for a survey. Engel (1895) and Barten (1964) type equivalence scales take the form of multiplying total expenditures or each price in a demand function by a preference heterogeneity parameter, as in equation (1). It is therefore a natural extension of this literature to include unobserved preference heterogeneity in these equivalence scales.

We apply these estimated demand functions to do welfare analyses. In particular, we use a Barten scaled energy demand function to obtain consumer surplus calculations for an energy price change (as in Hausman 1981). Our welfare application is essentially a variant or application of the ideas in Hoderlein and Vanhems (2010, 2011), who introduce unobserved preference heterogeneity into the Hausman model. The first of these two papers introduced scalar preference heterogeneity into the model nonparametrically, while the latter incorporated heterogeneity in the form of ordinary random coefficients. The difference in our model from Hoderlein and Vanhems (2010, 2011) is that we follow the prior consumer demand literature by including the preference heterogeneity in the form of Barten equivalence scales, differing from the prior demand literature in that our Barten scales include unobserved heterogeneity (a smaller additional difference is the way we also include an additive measurement error).

Other papers that introduce nonseparable unobserved preference heterogeneity in continuous demand systems include Brown and Walker (1989), Lewbel (2001), Beckert (2006) Matzkin (2007b), and Beckert and Blundell (2008). Lewbel and Pendakur (2009) propose a continuous demand system model in which the standard separable errors equal utility parameters summarizing preference heterogeneity, and do welfare calculations showing that accounting for this unobserved heterogeneity has a substantial impact on the results. Lewbel and De Nadai (2011) show how preference heterogeneity can be separately identified from measurement errors. A related empirical model to ours is Comon and Calvet (2003), who use repeated cross sections and deconvolution to identify a distribution of unobserved

heterogeneity in income effects.

The next two sections provide our main theorems on identification of equation (2) and (1). We then provide two empirical applications of the results. The first is a small analysis of Engel equivalence scales, and the second is a larger study of Barten scales. The latter application includes a new theorem characterizing the solution to a semiparametric class of Hausman (1981) type consumer surplus models. These applications are followed by some additional extensions of our main results to encompass the case of discrete regressors, and to allow interaction terms with more random coefficients into the additive model. We then conclude.

## 2 Additive Model Identification

Our first theorem below shows nonparametric identification of the additive model given by equation (2) with  $X = (X_1, \dots, X_K)$  continuously distributed. Later we extend the results to allow for discrete  $X$ 's or for more general models.

For any random vectors  $A$  and  $B$  let  $F_{A|B}(a | b)$  and  $f_{A|B}(a | b)$  denote the conditional cumulative distribution function and conditional probability density function, respectively, of  $A$  given  $B$ . Let  $e_k$  be the  $K$  vector containing a one in position  $k$  and zeros everywhere else. Let  $X_{(k)}$  denote the  $K - 1$  vector that contains all the elements of  $X$  except for  $X_k$ .

**ASSUMPTION A1:** The conditional distribution  $F_{Y|X,Z}(y | x, z)$  and the marginal distribution  $F_Z(z)$  are identified.  $(U_0, U_1, \dots, U_K) \perp X | Z$  and  $(U_1, \dots, U_K) \perp U_0 | Z$ . Either  $U_0$  has a nonvanishing characteristic function or  $U_0$  is identically zero.  $\text{supp}(U_0) \subseteq \text{supp}(Y)$  and  $\{0, e_1, \dots, e_K\} \subseteq \text{supp}(X)$ .

**ASSUMPTION A2:**  $U_k, X_k | Z$  are continuously distributed, and for every  $r \in \text{supp}(X_k U_k)$  there exists an  $x_k \in \text{supp}(X_k)$  such that  $f_{U_k}(x_k^{-1}r) \neq 0$ .

**ASSUMPTION A3:**  $G_k$  is a strictly monotonically increasing function. The location and scale normalizations  $G_k(0) = 0$  and  $G_k(1) = y_0$  for some known  $y_0 \in \text{supp}(Y)$  are imposed.

Assumption A1 first assumes identification of  $F_{Y|X,Z}(y | x, z)$  and  $F_Z(z)$ , which would in general follow from a sample of observations of  $Y, X, Z$  with sample size going to infinity. Identification of  $F_{Y|X,Z}(y | x, z)$  is actually stronger than necessary for Theorem 1, since only certain features of this distribution are used in the proof. For example,

it would suffice to only identify  $F_{Y|X,Z}(y | x_k e_k, z)$  for  $k = 1, \dots, K$ . More information regarding  $F_{Y|X,Z}$  is used in later extensions to Theorem 1.

Assumption A1 imposes conditional independence and support requirements on  $U$ ,  $X$  and  $Z$ . The role of  $Z$  is to permit the error  $U_0$  and random coefficients  $U_k$  to be correlated with  $X$ , thereby allowing elements of  $X$  to be endogenous. With this type of endogeneity,  $Z$  could be control function residuals as in Blundell and Powell (2003, 2004). In particular, if  $X_k = h_k(X_{(k)}, Q) + Z_k$  for some observed instrument vector  $Q$  and some identified function  $h_k$  (typically  $h_k$  would be  $E(X_k | X_{(k)}, Q)$ ), then the conditional independence assumptions in A1 correspond to standard control function assumptions. Note that  $Z$  can be empty, so all the results given below will hold if there is no  $Z$ , in which case  $U$  is independent of  $X$  and so the regressors  $X$  are exogenous.

Theorem 1 does not require that the random coefficients  $U_k$  for  $k = 1, \dots, K$  be (conditional on  $Z$ ) independent of each other, however, the Theorem only shows identification of the marginal distributions of each  $U_k$ , not their joint distribution.

Assumption A2 assumes that the regressors and random coefficients are continuously distributed. An alternative to Assumption A2 allowing for discrete distributions will be provided later. Assumption A2 also calls for a mild relative support assumption on  $X_k$  and  $U_k$ .

The normalizations in Assumption A3 are free normalizations, because first if  $G_k(0) \neq 0$  then we can redefine  $G_k(r)$  as  $G_k(r) - G_k(0)$  and redefine  $U_0$  as  $U_0 + G_k(0)$ , thereby making  $G_k(0) = 0$ . Next, given a nonzero  $y_0 \in \text{supp}(Y)$ , there must exist a nonzero  $r_0$  such that  $G_k(r_0) = y_0$ . We can then redefine  $U_k$  as  $r_0 U_k$  and redefine  $G_k(r)$  as  $G_k(r/r_0)$ , thereby making  $G_k(1) = y_0$ . These particular normalizations are most convenient for proving Theorem 1 below, but in applications others may be more natural, e.g., choosing location to make  $E(U_0) = 0$ .

**THEOREM 1:** Let  $Y = \sum_{k=1}^K G_k(X_k U_k) + U_0$  and let Assumption A1 hold. Then the distribution function  $F_{U_0|Z}$  is nonparametrically identified, and for every  $k \in \{1, \dots, K\}$  such that Assumptions A2 and A3 hold, the function  $G_k$  and the distribution function  $F_{U_k|Z}$  are nonparametrically identified.

Identification of  $F_Z$  was assumed, and Theorem 1 gives identification of  $F_{U_0|Z}$  and  $F_{U_k|Z}$ , and so by combining these the marginal distributions  $F_{U_0}$  and  $F_{U_k}$  are also identified.

In applications we would generally assume that Assumptions A2 and A3 hold for all  $k \in \{1, \dots, K\}$ , thereby identifying the entire model. However, later we will describe conditions for identification when  $X_k$ ,  $U_k$ , or both are discrete, in which case the assumptions of Theorem 1 would be assumed to hold just for indices  $k$  corresponding to regressors and random coefficients that are continuously distributed.

An immediate corollary of Theorem 1 is the following alternative model. This model could be useful in contexts where  $Y$  is always positive, restricting the support of  $U_0$  to be positive.

**COROLLARY 1:** Let  $Y = \prod_{k=1}^K g_k(X_k U_k) + U_0$  with  $g_k(X_k U_k) > 0$ , and let Assumption A1 hold. Then the distribution function  $F_{U_0|Z}$  is nonparametrically identified, and for every  $k \in \{1, \dots, K\}$  such that Assumptions A2 and A3 hold with  $G_k(X_k U_k) = \ln[g_k(X_k U_k)]$ , the function  $g_k$  and the distribution function  $F_{U_k|Z}$  are nonparametrically identified.

### 3 General Model Identification

We now show identification of the general model given by equation (1) for some unknown function  $G$ . To do so we decompose the function  $G$  into an additive component  $\sum_{k=1}^K G_k$  and a remaining interaction term  $\tilde{G}$  having the property that  $\tilde{G}(X_k e_k) = 0$  for all  $k$ . These two components are then identified separately. Given a function  $G$ , define  $G_k(X_k) = G(X_k e_k)$ , that is,  $G_k$  equals  $G$  after setting all the elements of  $X$  except for  $X_k$  equal to zero. Define the function  $\tilde{G}$  by  $\tilde{G}(X) = G(X) - \sum_{k=1}^K G_k(X_k)$ . Then, by construction,

$$Y = \tilde{G}(X_1 U_1, \dots, X_K U_K) + \sum_{k=1}^K G_k(X_k U_k) + U_0 \quad (3)$$

**ASSUMPTION A4:** Assume that  $U_0, U_1, \dots, U_K, X$  are mutually independent conditional upon  $Z$ , and that  $E(U_k^t) \neq 0$  and is bounded for all integers  $t$ . Assume the support of  $X$  includes a positive measure neighborhood of zero. Assume  $\tilde{G}$  is a real analytic function.

**THEOREM 2:** Let  $Y = G(X_1 U_1, \dots, X_K U_K) + U_0$  and let Assumptions A1, A2, A3, and A4 hold for  $k = 1, \dots, K$ . Then the function  $G$  and the distribution functions  $F_{U_k|Z}$  for every  $k \in \{0, 1, \dots, K\}$  are all nonparametrically identified.

Theorem 1 did not require the random coefficients  $U_k$  to be mutually independent, though only the separate distributions of each  $U_k$  were identified. However, to handle non-additive functions  $G$  we require mutual independence given by Assumption A4. Having  $E(U_k^t)$  be nonzero and bounded means that Theorem 2 also places the stronger requirements of a nonzero mean and thin tails on each  $U_k$ .

Theorem 2 places stronger smoothness assumptions on  $\tilde{G}$  than on each  $G_k$ . Without decomposing  $G$  into  $\tilde{G}$  and  $G_k$  terms, a sufficient but stronger than necessary restriction to satisfy the required assumptions on these functions is that  $G$  be analytic and strictly

monotonically increasing in each of its arguments  $U_k X_k$  when the other elements of  $X$  are set to zero.<sup>1</sup>

However, although the identification proofs are constructive, this conditioning argument suggests that estimation based on copying the steps of the identification proof is likely to be inefficient. For example, Theorem 2 identifies  $\tilde{G}$  using values of  $X$  in a neighborhood of zero. The distribution of  $Y$  given  $X$  provides information about the unknown functions at all values of  $X$ , which should be employed for efficiency in estimation. However, for obtaining closed form identification arguments, at points away from zero this information takes the form of integral equations for  $\tilde{G}$  that are difficult to solve.

## 4 Applications

We have two empirical applications involving consumer demand estimation: incorporation of heterogeneity via Engel and Barten scaling. These two strategies bring unobserved heterogeneity into demand estimation via scaling total expenditures and prices, respectively. These are two of the most long standing methods used to bring preference heterogeneity on the basis of observed variables into continuous demand models<sup>2</sup> and are consequently a natural starting point for the incorporation of random utility parameters representing unobserved preference heterogeneity.

Let a "consumer" refer to a utility maximizing individual or household. Let  $Q_j$  denote the quantity purchased of a good  $j$ . Let  $\alpha_h$  denote preference heterogeneity that is a function of observable consumer attributes  $h$ , specifically, we will let  $\alpha_1$  and  $\alpha_2$  denote constants corresponding to households having  $h = 1$  or  $h = 2$  members. Let  $U$  denote a vector of random utility parameters representing unobserved preference heterogeneity.

Let  $S(Q_1, \dots, Q_J; \alpha_h, U)$  be the direct utility function over the bundle of goods  $Q_1, \dots, Q_J$  of a consumer having heterogeneity parameters  $\alpha_h$  and  $U$ . Assume  $S$  is continuous, non-decreasing, and quasi-concave in  $Q_1, \dots, Q_J$ . Define the reference consumer to be a consumer that has heterogeneity parameters  $\alpha_h$  and  $U$  normalized to equal one. The reference consumer has utility denoted  $\bar{S}(Q_1, \dots, Q_J)$ . Each consumer chooses quantities to maximize utility subject to the standard linear budget constraint  $\sum_{j=1}^J P_j Q_j = M$

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<sup>1</sup>The proof of Theorem 2 involves evaluating the distribution of  $Y$  given  $X$  at  $X = 0$ , which is conditioning on a set of measure zero. The same applies to Theorem 1 regarding conditioning on  $Z$  at a point if  $Z$  is continuous. However, issues of nonuniqueness of the limiting argument (the Borel-Kolmogorov paradox) do not arise here, since the identification proof depends only on transformations of smooth conditional expectation functions. It would also be straightforward to recast the proofs in terms of conditioning on  $\|X\| \leq c$  and taking limits  $c \rightarrow 0$ .

<sup>2</sup>See, e.g., Pollak and Wales (1990), Lewbel (1997), and Lewbel and Pendakur (2007) for surveys on this topic.

where  $P_j$  is the price of good  $j$  and  $M$  is the total amount of money the consumer spends on this bundle of goods. Write the Marshallian budget share functions that result from maximizing utility  $\bar{S}$  as  $W_j^* = \omega_j (P_1/M, \dots, P_J/M)$ , where  $W_j^* = Q_j P_j / M$  is the share of money  $M$  that is spent on good  $j$  (called the budget share of good  $j$ ). Let  $V (P_1/M, \dots, P_J/M)$  denote the indirect utility function corresponding to  $\bar{S}$ , obtained by substituting  $Q_j = \omega_j (P_1/M, \dots, P_J/M) M / P_j$  into  $\bar{S} (Q_1, \dots, Q_J)$  for  $j = 1, \dots, J$ . We will express the utility and demand functions for other consumers in terms of these reference consumer functions.

## 4.1 Unobserved Heterogeneity in Engel Scales

Our first application considers food budget shares. Let  $W^* = g (M) = \omega_j (p_1/M, \dots, p_J/M)$  evaluated at some fixed price vector  $(p_1, \dots, p_J)$ , where good  $j$  is food, so  $W^*$  is the food budget share and  $g (M)$  is the food budget share Engel curve for the reference consumer.

Based on empirical regularities noted by Engel (1895), one method of modeling how Engel curves vary across households is through Engel equivalence scales. See, e.g., Lewbel (1997) and Lewbel and Pendakur (2007) for surveys of various types of equivalence scales in the consumer demand literature, including Engel scales. The traditional Engel scale for a household of size  $h$  is a scalar constant  $\alpha_h$  that multiplies total expenditures in each Engel curve, that is,  $W^* = g (\alpha_h M)$ .

The Engel scale  $\alpha_h$  is a direct measure of the economies of scale of household consumption. The idea is that, if a two person household can attain the same utility level as a single person with only 50% more income, then  $\alpha_2 = 1.5\alpha_1$ . Traditional Engel scales assume that all households of the same size have the same Engel scale. A more reasonable assumption is that households vary in their ability to share goods, and even one person households vary in their ability to derive utility from a given level of consumption, and hence Engel scales should vary in unobserved ways across households. This is especially true since, as noted by Hildenbrand (1994), Browning and Carro (2007), and Lewbel (2007, 2008) among others, there is empirically a great deal of unexplained heterogeneity in consumption across households, in fact, the unexplained variation in budget shares across households is often larger than the variation explained by observed covariates.

In terms of utility functions with observed heterogeneity embodied in  $\alpha_h$  and unobserved heterogeneity embodied in  $U_1$ , Engel scaling is  $S (Q_1, \dots, Q_J; \alpha_h, U_1) = \bar{S} (Q_1 U_1 \alpha_h, \dots, Q_J U_1 \alpha_h)$ . This model for utility implies that budget share functions take the form  $W^* = g (U_1 \alpha_h M)$ , where  $U_1$  varies randomly across households. The equivalence scale is then  $U_1 \alpha_h$ , so  $\alpha_h$  is the systematic, observable variation due to variation in household size, and  $U_1$  is unobserved heterogeneity in the Engel scales.

Let  $W$  denote a household's observed food budget share, which may be observed with



error. Let  $\lambda(W) = \ln[W/(1-W)]$ , which denotes the logit transformation of the household's budget share. For convenience assume that  $\lambda(W) = \lambda(W^*) + U_0$ , where  $U_0$  is measurement (or specification) error in the observed  $W$ . The advantage of this formulation is that  $W$  and  $W^*$  have supports on  $[0, 1]$ , while  $\lambda(W)$  and  $\lambda(W^*)$  have supports on the whole real line, so  $U_0$  can have support on the whole real line. In contrast, if we had specified  $U_0$  to be additive in  $W^*$ , then inequality constraints on  $W$  and  $W^*$  would impose support constraints on  $U_0$  that would make it difficult for  $U_0$  to be independent of the regressor  $M$  or the Engel scale  $U_1$ .

Define  $Y = \lambda(W)$  and  $G(M) = \lambda(g(M))$ . Then we have the logit transformed budget share Engel curve model

$$Y = G(U_1\alpha_h M) + U_0.$$

This model is in the class discussed in Equation (2). To show identification of this model, replace  $M$  with  $X_1$ , let  $Z$  be household size, let  $K = 1$ , and apply Theorem 1.<sup>3</sup> Then, given identification of the function  $G$ , constants  $\alpha_h$ , and the distribution of  $U_1$ , the food budget share Engel curve is  $W^* = \lambda^{-1}(G(U_1 M)) = 1/(1 + e^{-G(U_1 M)})$ .

The unobservables  $U_1$  and  $U_0$  are assumed to be independent of each other, because the former is a structural random utility parameter and the latter is measurement error. Since Engel's original observations, almost all empirical studies have found food budget share Engel curves to be monotonic in  $M$ , so it is safe to assume as required by Theorem 1 that the food budget share function  $g$  and hence the logit transformed budget share  $G$  is strictly monotonic in  $M$ .

We estimate the model  $Y = G(U_1\alpha_h M) + U_0$  nonparametrically using sieve maximum likelihood. For modeling densities using sieves, define the density function  $p_J(v, \theta)$  given by squared Hermite polynomials

$$p_J(v, \theta) = \phi(v) \left( \Lambda_J(\theta) + \sum_{j=1}^J \theta_j H_j(v) \right)^2$$

where  $\phi(v)$  is the standard normal density function and  $H_j(v)$  are the Hermite polynomials

$$H_j(v) = \frac{(-1)^j}{\phi(v)} \frac{d^j \phi(v)}{dv^j},$$

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<sup>3</sup>Theorem 1 identifies the function  $G$ , and the conditional distributions of  $U_1$  and  $U_0$  conditional on household size  $Z$ . The model we have written here assumes in addition that  $U_0 \perp Z$  and  $U_1 | Z = h$  has the same distribution as  $U_1\alpha_h | Z = 1$ . Applying the proof of Theorem 1 to this application includes evaluating  $G$  at  $M = 0$ . We can equivalently exploit continuity of  $G$  and take the limit as  $M \rightarrow 0$ , thereby attaining identification based on consumers with low rather than actually zero levels of expenditures. Note that, unlike consumed quantities, the limiting value of budget shares as  $M \rightarrow 0$  will generally be nonzero. Analogous arguments applied to price will apply later in our Barten scale application.

so, e.g.,  $H_1(v) = v$ ,  $H_2(v) = v^2 - 1$ , and  $H_3(v) = v^3 - 3v$ . To make the density integrate to one set

$$\Lambda_J(\theta) = \left[1 - \sum_{j=1}^J (j) \theta_j^2\right]^{1/2}$$

Following Gallant and Nychka (1987), we model each univariate density using the expansion  $p_J(v, \theta)$ , letting  $J \rightarrow \infty$  as  $n \rightarrow \infty$  for sample size  $n$ . Since  $U_0$  has support  $(-\infty, \infty)$  and  $U_1$  has support  $(0, \infty)$ , we use  $p_J(v, \theta)$  to model the densities of the standardized variables  $U_0/\sigma_0$  and  $\ln U_1/\sigma_1$ . This makes the sieve basis density functions of  $U_0$  and  $U_1$  be  $f_{0J}$  and  $f_{1J}$  where

$$f_{0J}(U_0, \delta, \sigma_0) = \frac{1}{\sigma_0} p_J\left(\frac{U_0}{\sigma_0}, \delta\right) \quad \text{and} \quad f_{1J}(U_1, \gamma, \sigma_1) = \frac{1}{U_1 \sigma_1} p_J\left(\frac{\ln U_1}{\sigma_1}, \gamma\right)$$

respectively, for parameter vectors  $\delta$  and  $\gamma$  (only  $J$  terms of which are estimated).

We model  $G$  using polynomial basis functions

$$G_L(m, \beta) = \beta_0 + \beta_1 m + \dots + \beta_L m^L$$

letting  $L \rightarrow \infty$  as  $n \rightarrow \infty$ . Note that in terms of identifying normalizations, we can if desired interpret  $\beta_0$  as adding to the mean of  $U_0$  rather than as the constant term in  $G$  to enforce  $G(0) = 0$ .

For a given household size  $h$ , the conditional density function of  $Y$  is then

$$f_{Y|M}(y | m; \alpha_h, \beta, \gamma, \delta) = \int_0^\infty f_0[y - G(u_1 \alpha_h m, \beta), \delta, \sigma_0] f_1(u_1, \gamma, \sigma_1) du_1$$

Let  $y_i = \lambda(w_i)$ , and let  $m_i$  be the household expenditure of household  $i$ . Assuming iid observations  $y_i, m_i, h_i$  of consuming households  $i$ , estimation then proceeds by substituting in the sieve functional forms  $G_L, f_{0J}$ , and  $f_{1J}$  for the unknown functions  $G, f_0$ , and  $f_1$ , and searching over parameter vectors  $\alpha, \beta, \gamma, \delta$  and  $\sigma$  to maximize the log likelihood function

$$\sum_{i=1}^n \ln f_{Y|M}(y_i | m_i; \alpha_{h_i}, \beta, \gamma, \delta, \sigma)$$

We do not list here the formal assumptions for consistency and asymptotic inference of sieve maximum likelihood estimation in this application, because the generic conditions for validity of these estimators in an independently, identically distributed data setting are well established. See, e.g., Chen (2007) and references therein.<sup>4</sup>

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<sup>4</sup>Depending on the supports and tail thickness of the model errors and regressors, it is possible in problems like ours for identification to be weak, in the sense that recovering the structural functions of the model could entail ill-posed inverse problems. See, e.g., Hoderlein, Nesheim, and Simoni (2011), who document these issues in a framework similar to ours, though in their model only the error distributions are nonparametric. The assumptions required for standard sieve maximum likelihood inference may rule out at least some forms of weak identification, though our use of sieves could even then be interpreted as a choice of regularization for structural function estimation.

## 4.2 Empirical Engel Curve Results

We estimate the Engel curve model using Indian household expenditure microdata from the 2003 National Sample Survey of India (Expenditures Module). Our data file consists of 3173 observations of households comprised of one or two adults aged 19 to 64. Expenditures are expressed in proportion to average household expenditures of all households (not just those comprised of one or two adults). We drop households with expenditures below the 5th and above the 95th percentile of the expenditure distribution. Table 1 gives summary statistics for food shares  $w_i$ , total expenditures  $m_i$  and an indicator  $d_i$  that the household has 2 members.

	mean	std dev	min	max
3173 observations				
food share, $w_i$	0.55	0.14	0.02	0.92
total expenditures, $m_i$	0.44	0.24	0.13	1.18
two-adult household, $d_i$	0.54	0.50	0	1

A standard parametric functional form for food Engel curves going back to Working (1943) is  $W$  linear in the log of  $M$ . Allowing for traditional constant Engel scales with households having one or two members gives the functional form  $W = \beta_0 + \ln(\alpha_h M) \beta_1 + \varepsilon = \beta_0 + (\ln M) \beta_1 + d (\ln \alpha_2) \beta_1 + \varepsilon$  where  $\alpha_2$  is the traditional Engel scale for a two person household, and the Engel scale for one person household is  $\alpha_1 = 1$ . So  $\alpha_2$  in this parametric model can be recovered from a linear regression of  $W$  on  $\ln M$  and on the two person household dummy  $d$ . This regression yields coefficients of  $-0.14$  on  $\ln M$  and  $0.08$  on  $d$ , giving an Engel equivalence scale of  $\alpha_2 = 0.57$ . The Engel scale interpretation of this parameter is that a two person household needs to spend  $1/0.57 = 1.75$  times as much money as an individual living alone to attain the same level of utility as the individual.

While having a plausible magnitude, this traditional Engel scale model has two serious drawbacks: it imposes a parametric structure on  $W$  as a function of  $M$  and it requires that the equivalence scale be constant across all households of each size. Our model relaxes these restrictions.

We estimate the sieve maximum likelihood described in the previous section, with  $L = J = 3$ . This makes the likelihood function to be maximized be

$$\sum_{i=1}^n \ln \int_0^{\infty} f_0 \left( y_i - \beta_0 - u_1 \alpha_{h_i} m_i \beta_1 - (u_1 \alpha_{h_i} m_i)^2 \beta_2 - (u_1 \alpha_{h_i} m_i)^3 \beta_3, \delta, \sigma_0 \right) f_1(u_1, \gamma, \sigma_1) du_1$$

where  $\alpha_{h_i} = d_i \alpha_2 + (1 - d_i)$ ,

$$f_{1J}(u_1, \gamma) = \frac{1}{u_1 \sigma_1} \phi \left( \frac{\ln u_1}{\sigma_1} \right) \left( 1 - \gamma_1^2 - 2\gamma_2^2 - 6\gamma_3^2 \right)^{1/2} + \left( \frac{\ln u_1}{\sigma_1} \right) \gamma_1 \\ + \left( \left( \frac{\ln u_1}{\sigma_1} \right)^2 - 1 \right) \gamma_2 + \left( \left( \frac{\ln u_1}{\sigma_1} \right)^3 - 3 \left( \frac{\ln u_1}{\sigma_1} \right) \right) \gamma_3^2$$

$$f_{0J}(u_0, \delta, \sigma_0) = \frac{1}{\sigma_0} \phi \left( \frac{u_0}{\sigma_0} \right) \left( 1 - \delta_1^2 - 2\delta_2^2 - 6\delta_3^2 \right)^{1/2} + \left( \frac{u_0}{\sigma_0} \right) \delta_1 \\ + \left( \left( \frac{u_0}{\sigma_0} \right)^2 - 1 \right) \delta_2 + \left( \left( \frac{u_0}{\sigma_0} \right)^3 - 3 \left( \frac{u_0}{\sigma_0} \right) \right) \delta_3^2$$

and  $\phi()$  is the standard normal density function. Evaluating this likelihood requires numerical integration, but just a single one dimension integral is involved, which is not numerically onerous. We implemented this model in Stata. Estimated coefficients are given below. Standard errors are provided with the caveat that they treat the sieve basis functions as finite model parameterizations.

Parameters of $G$	est	<i>sd</i>	Parameters of $U_0, U_1$ distributions	est	<i>sd</i>
$\beta_0$	1.21	0.99	$\sigma_0$	0.52	0.04
$\beta_1$	-7.21	0.94	$\delta_1$	-0.12	1.30
$\beta_2$	9.21	2.44	$\delta_2$	-0.21	0.10
$\beta_3$	-4.06	1.67	$\delta_3$	0.01	0.21
$\alpha_2$	0.57	0.02	$\sigma_1$	0.44	0.04
			$\gamma_1$	-0.55	0.03
			$\gamma_2$	0.29	0.05
			$\gamma_3$	-0.06	0.02

The equivalence scale is now  $U_1 \alpha_h$ . The deterministic part of these scales is  $\alpha_1 = 1$  (a normalization) and  $\alpha_2 = .57$ , which surprisingly is the same numerical value we obtained in the simple parametric model above. Thus, for a given value of  $U_1$ , the Engel equivalence scale is 0.57.

We find considerable variation in  $U_1$  and hence in the equivalence scales across households of each size. Figures 1 and 2 show the estimated distributions of  $U_0$  and  $\ln U_1$ . The estimated distribution of  $U_0$  is roughly symmetric, and somewhat heavy-tailed. The estimated distribution of  $\ln U_1$  is skewed to the left. The implied distribution of  $U_1$  is less

skewed, with a mean of 0.54, median of 0.47, and its 5th and 95th percentiles are 0.25 and 1.02, respectively.

The estimated distribution  $f_{1J}$  of  $U_1$  has a standard deviation of 0.29 (which is smaller than  $\sigma_1$ , because the higher order terms in the hermite expansion reduce the variance in this case). This can be compared to the standard deviation of  $\alpha_{h_i} = d_i \alpha_2 + (1 - d_i) \alpha_1$ , which is 0.21, showing that variation in the traditional equivalence scales  $\alpha_h$  due just to variation in household size is somewhat smaller than the variation due to unobserved heterogeneity  $U_1$  across households of each given size.

Figures 3 and 4 show the estimated budget share functions,  $W^*$ , for single- and two-adult households, respectively, where  $W^* = \lambda^{-1} (G(U_1 \alpha_h M)) = 1 / (1 + e^{-G(U_1 \alpha_h M)})$  and  $G$  is a third-order polynomial. These are shown at various quantiles of the  $U_1$  distribution, illustrating how the Engel curves shift as the Engel scale varies.

## 5 Random Barten Scales

Our second, larger application of generalized random coefficients will use Barten scales. Barten (1964) proposed the model in which consumers have utility functions of the form  $S(Q_1, \dots, Q_J; \alpha_{h1}, \dots, \alpha_{hJ}) = \bar{S}(Q_1/\alpha_{h1}, \dots, Q_J/\alpha_{hJ})$ , where  $\alpha_{h1}, \dots, \alpha_{hJ}$  are positive parameters (functions of observable household attributes  $h$ ), called Barten scales, that embody variation in preferences across consumers. See, e.g., Lewbel (1997) for a survey of various types of equivalence scales in the consumer demand literature, including Barten scales. Barten scales are a generalization of Engel scales, specifically, the Barten scale model becomes equivalent to the Engel scale model when  $\alpha_{h1} = \alpha_{h2} = \dots = \alpha_{hJ}$ .

We propose random Barten scales, assuming that consumers have utility functions of the form  $S(Q_1, \dots, Q_J; U_1, \dots, U_{hJ}) = \bar{S}(Q_1/U_1, \dots, Q_J/U_J)$ , where  $U_1, \dots, U_J$  are positive random utility parameters embodying unobserved preference heterogeneity across consumers. More formally, we could write each random Barten scale as  $U_j(h)$ , since for each good  $j$ , the distribution function  $U_j$  is drawn from could depend on observable household attributes  $h$ . Barten's original model is then the special case where the distribution of each  $U_j(h)$  is degenerate with a mass point at  $\alpha_{hj}$ .

Define normalised prices  $X_j = P_j/M$  for each good  $j$  and rewrite the budget constraint as  $\sum_{j=1}^J X_j Q_j = 1$ . Recall that  $\bar{S}(Q_1, \dots, Q_J)$  and  $V(X_1, \dots, X_J)$  are the direct and indirect utility functions of the reference consumer, and that  $\omega_j(X_1, \dots, X_J)$  is the Marshallian budget share demand function of the reference consumer. It can be immediately verified from the first order conditions for utility maximization that a consumer will have Marshallian demand functions of the form  $W_j^* = \omega_j(U_1 X_1, \dots, U_J X_J)$  for each good  $j$  if and only if the consumer's direct and indirect utility function equal, up to

an arbitrary monotonic transformation,  $\bar{S}(Q_1/U_1, \dots, Q_J/U_J)$  and  $V(U_1X_1, \dots, U_JX_J)$ , respectively. Also, given a specification of reference indirect utility  $V(X_1, \dots, X_J)$ , the corresponding Barten scaled demand functions can be obtained by the logarithmic form of Roys identity:

$$\omega_j(U_1X_1, \dots, U_JX_J) = \frac{\partial V(U_1X_1, \dots, U_JX_J)}{\partial \ln X_j} / \left( \sum_{\ell=1}^J \frac{\partial V(U_1X_1, \dots, U_JX_J)}{\partial \ln X_\ell} \right) \quad (4)$$

Notice that the functional form of each  $\omega_j$  only depends on the functional form of  $\bar{S}$  or equivalently of  $\bar{V}$ , so  $U_1, \dots, U_J$  can vary independently of  $X_1, \dots, X_J$  across consumers. The Barten scaled Marshallian demand functions have precisely the form of our generalized random coefficients given in equation (1).

For households with multiple members, Barten scales can be interpreted as representing the degree to which each good is shared or jointly consumed. The smaller the Barten scale  $U_j$  is, the greater the economies of scale to consumption of good  $j$  within the household. This is then reflected in the demand functions, where smaller Barten scales have the same effect on demands as lower prices. For example, if a couple with one car rides together some of the time, then in terms of total distance each travels by car, sharing has the same effect as making gasoline cheaper. The more they drive together instead of alone, the lower is the effective cost of gasoline, and the smaller is the couple's Barten scale for gasoline.

More generally, Barten scales provide a measure of the degree to which different households get utility from different goods. Barten scales are a popular method of modeling preference heterogeneity in empirical work. However, up until now, Barten scales have always been modeled as deterministic functions of observable characteristics of consumers. Here we consider using Barten scales to embody unobserved heterogeneity of preferences across consumers.

**COROLLARY 2:** Assume that consumers have preferences given by an analytic, Barten scaled indirect utility function  $V(U_1X_1, \dots, U_JX_J)$ ; no good  $j$  exists that is Giffen at some values of  $X_j$  and not Giffen at others; the conditional distribution  $F_{Q|X}(q|x)$  is identified; and Barten scales  $U_j$  are each positive with bounded support, satisfy Assumption A2 with  $Z$  empty, and are mutually independent of each other and of  $X$ . Then the demand functions  $\omega_j(U_1X_1, \dots, U_JX_J)$  and the distribution functions  $F_{U_j}(U_j)$  are identified for  $J = 1, \dots, J$ .

Corollary 2 shows that consumer demand systems with random Barten scales are non-parametrically identified. By standard revealed preference theory, the direct and indirect utility functions are therefore also nonparametrically identified up to an unknown monotonic transformation.

Corollary 2 refers to Giffen goods. A Giffen good is a good that has a positive own price elasticity in its Marshallian quantity demand function, and hence an upward sloping demand curve. Corollary 2 rules out goods that have sometimes positive and sometimes negative own price elasticities, and hence rules out goods that are sometimes but not always Giffen. While possible in theory, almost no empirical evidence has been found for the existence of goods that are Giffen at all, and even less for goods that are only sometimes Giffen.<sup>5</sup>

Regarding other assumptions in Corollary 2, virtually all empirically implemented consumer demand systems assume functional forms for indirect utility  $V$  that are analytic. Barten scales must be positive to preserve the standard property that utility is increasing in quantities. Similarly, the economic rationale for Barten scales suggest that they would be bounded<sup>6</sup>

Applying Theorem 2 separately to each demand function would require that each demand function be monotonic in all prices, which does not hold in general. However, monotonicity in all prices is not necessary for identification here because we have multiple demand functions, and each contains the same Barten scales. We can therefore use just the standard monotonicity of own price effects, leaving the signs of cross price effects unconstrained, to identify the Barten scale distributions. This is done in Corollary 2 by using the demand function of each good  $j$  to just identify the distribution of the Barten scale  $U_j$ . The fact that we have multiple equations each containing the same scales means that the system of equations provides overidentifying information, relative to a single equation model.

Matzkin, (2007a), (2007b), (2008) discusses identification of systems of equations where the number of equations equals the number of random parameters, assuming it is possible to invert the reduced form of the system to express the random parameters as functions of observables. Although our model has  $J$  Barten scales  $U_j$  and  $J$  demand equations, Matzkin's identification method for systems of equations cannot be applied here because there are actually only  $J - 1$  distinct demand functions  $\omega_1, \dots, \omega_{J-1}$ , with the remaining demand function  $\omega_J$  determined by the adding up constraint that  $\sum_{j=1}^J \omega_j = 1$ .

To simplify our empirical analysis, we let  $\omega_1$  be the budget share of a single good of interest, and let  $\omega_2$  denote the share of all other goods, so  $\omega_2 = 1 - \omega_1$ , corresponding to the general Barten scaled model with  $J = 2$ , and hence only requiring estimation of a single equation. Allowing for more goods would provide overidentifying information. This

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<sup>5</sup>The only exception we know of is Jensen and Miller (2008), who show that some grains may have been Giffen goods for extremely poor households in rural China.

<sup>6</sup>Boundedness rules out lexicographic preferences in which consumers would not prefer an unlimited quantity of the good with the unbounded Barten scale over an infinitesimal amount any other good. This is extremely unlikely to hold when goods are defined as broad categories like food, energy, clothing, etc.

decomposition of consumption into two good is often done in empirical work when one wishes to focus on the welfare effects of price changes on a particular good, as we will do empirically. See, e.g., Hausman (1981), Hausman and Newey (1995), Blundell, Horowitz, and Parey (2010), and Hoderlein and Vanhems (2010, 2011). This construction is formally rationalizable by assuming utility is separable into good 1 and a subutility function of all other goods. See, e.g., Blackorby, Primont, and Russell (1978). Alternatively Lewbel (1996) provides conditions on the distribution of prices (stochastic hicksian aggregation) under which Marshallian demand functions have the same properties with nonseparable utility as with separable utility.

With  $J = 2$  goods, our model is  $W_1^* = \omega_1 (U_1 X_1, U_2 X_2)$  and  $W_2^* = 1 - W_1^*$ , and we can rewrite Roys identity as

$$\lambda (W_1^*) = \ln \left( \frac{\partial V (U_1 X_1, U_2 X_2)}{\partial \ln X_1} \right) - \ln \left( \frac{\partial V (U_1 X_1, U_2 X_2)}{\partial \ln X_2} \right) \quad (5)$$

where  $\lambda (W_1^*)$  again is the logit transformation  $\lambda (W_1^*) = \ln [W_1^* / (1 - W_1^*)]$ . This model falls into the class covered by equation (2). With  $J = 2$  and the adding up constraint  $\omega_1 + \omega_2 = 1$ , the single demand equation (5) embodies all the information in the demand system, and so we don't need to consider multiple equations as in the proof of Corollary 2.

## 5.1 Additive Model Random Barten Scales

The regularity conditions for identifying random coefficients in the additive model, given by Theorem 1, are milder than for the full model of Theorem 2, so we will first consider identification and estimation of random Barten scales in an additive model, and later consider more general nonadditive specifications.

Due to the constraints of Slutsky symmetry, additivity in Marshallian demand functions  $\omega_1 (X_1, X_2)$  results in extreme restrictions on behavior. See, e.g., Blackorby, Primont, and Russell (1978). So we instead for now impose additivity on the logit transformation of  $\omega_1 (X_1, X_2)$  (later this will be relaxed to allow for interaction terms), thereby assuming demands have the additive form

$$\lambda (W_1) = \lambda [\omega_1 (U_1 X_1, U_2 X_2)] + U_0 = g_1 (U_1 X_1) + g_2 (U_2 X_2) + U_0 \quad (6)$$

Here the functions  $g_1$  and  $g_2$  are nonparametric and  $U_0$  is interpreted as measurement error in the observed budget share  $W_1$  relative to the true budget share  $W_1^*$ . This implies that the underlying demand function is given by

$$W_1^* = \omega_1 (U_1 X_1, U_2 X_2) = \left( 1 + e^{-g_1(U_1 X_1) - g_2(U_2 X_2)} \right)^{-1} \quad (7)$$



Use of the logit transformation here, and assumed additivity in logit transformed budget shares, has as far as we know not been considered before in the estimation of continuous demand functions. However, this logit transformed model has a number of advantages. First,  $\lambda (W_1)$  has support on the whole real line, so the measurement error  $U_0$  has unrestricted support, instead of a support that necessarily depends on covariates. Second, with this transform no constraints need to be placed on the range of values the nonparametric functions  $g_1$  and  $g_2$  take on. Third, unlike all other semiparametric or nonparametric applications of the Hausman (1981) consumer surplus type methodology (such as those cited above), a closed form expression for the indirect utility function that gives rise Marshallian demands (7) and hence (6) exists, and is given by Theorem 3.

**THEOREM 3:** The demand function  $\omega_1$  satisfies  $\lambda [\omega_1 (U_1 X_1, U_2 X_2)] = g_1 (U_1 X_1) + g_2 (U_2 X_2)$  for some functions  $g_1$  and  $g_2$  if and only if  $\omega_1$  is derived from an indirect utility function of the form

$$V (U_1 X_1, U_2 X_2) = H [h_1 (U_1 X_1) + h_2 (U_2 X_2), U_1, U_2].$$

for some functions  $h_1$ ,  $h_2$ , and  $H$ . The functions  $g_1$ ,  $g_2$ ,  $h_1$ , and  $h_2$  are related by

$$h_1 (U_1 X_1) + h_2 (U_2 X_2) = \int_{-\infty}^{\ln X_1} e^{g_1(U_1 X_1)} d \ln X_1 + \int_{-\infty}^{\ln X_2} e^{-g_2(U_2 X_2)} d \ln X_2 \quad (8)$$

and

$$g_1 (U_1 X_1) + g_2 (U_2 X_2) = \ln \left( \frac{\partial h_1 (U_1 X_1)}{\partial \ln X_1} \right) - \ln \left( \frac{\partial h_2 (U_2 X_2)}{\partial \ln X_2} \right) \quad (9)$$

Also, the functions  $h_1 (U_1 P_1/M)$  and  $h_2 (U_2 P_2/M)$  are each nonincreasing, and their sum is strictly increasing in  $M$  and quasiconvex in  $P_1, P_2$ , and  $M$ .

The function  $H$  has no observable implications, and is present only because utility functions are ordinal and therefore unchanged by monotonic transformations. So in practice we can just write the indirect utility function in Theorem 3 as

$$V (U_1 X_1, U_2 X_2) = h_1 (U_1 X_1) + h_2 (U_2 X_2). \quad (10)$$

Preferences  $V (X_1, X_2)$  are defined to be indirectly additively separable (see, e.g., Blackorby, Primont, and Russell 1978) if, up to an arbitrary monotonic transformation,  $V (X_1, X_2) = h_1 (X_1) + h_2 (X_2)$  for some functions  $h_1, h_2$ . So an equivalent way to state the first part of Theorem 3 is that  $\omega_1$  satisfies equation (7) if and only if preferences are given by a Barten scaled indirectly additively separable utility function. The second part of Theorem 3 then provides closed form expressions for the indirect utility function given the nonparametric (additive in the logit transformation) demand function and vice versa.

Using Theorem 3, and in particular equation (9), we can nonparametrically estimate  $g_1$  and  $g_2$  by nonparametrically specifying  $h_1$  and  $h_2$  in terms of sieve basis functions (imposing the shape restrictions possessed by indirect utility functions if desired) To illustrate, consider a polynomial in logs sieve basis

$$\ln h_k (U_k X_k) = \sum_{s=0}^S \beta_{ks} (\ln (U_k X_k))^s \quad (11)$$

with constants  $\beta_{ks}$ , for  $k = 1, 2$ , letting  $S \rightarrow \infty$  as  $n \rightarrow \infty$ . Logarithmic specifications like these are common in demand models, e.g., with  $S = 1$  equations (10) and (11) correspond to Barten scaled Cobb Douglas preferences, and with  $S = 2$  this gives a separable version of the Translog indirect utility function of Jorgenson, Lau, and Stoker (1982), though in their model the Barten scales have the traditional form of being functions only of observable characteristics. Having  $S = 3$  without Barten scales corresponds to an additively separable version of the third-order Translog budget share function as in Nicol (1984).

In this model we impose the free normalization  $\beta_{20} = 0$ . This is imposed without loss of generality, because if  $\beta_{20} \neq 0$  then we can multiply the indirect utility function  $V (U_1 X_1, U_2 X_2)$  by  $e^{-\beta_{20}}$  (which is a monotonic transformation of  $V$ ) and redefine  $\beta_{10}$  as  $\beta_{10} - \beta_{20}$  to get an observationally equivalent representation of indirect utility that has  $\beta_{20} = 0$ . Applying Theorem 3 and equation (6) to this model gives the demand function

$$\begin{aligned} \lambda (W_1) &= \omega_{S1} (U_1 X_1, U_2 X_2, \beta) + U_0 \\ &= \beta_{10} + \left( \sum_{s=1}^S [\ln (U_1 X_1)]^s \beta_{1s} - [\ln (U_2 X_2)]^s \beta_{2s} \right) + \ln \left( \frac{\sum_{s=1}^S (\ln (U_1 X_1))^{s-1} s \beta_{1s}}{\sum_{s=1}^S (\ln (U_2 X_2))^{s-1} s \beta_{2s}} \right) + U_0. \end{aligned} \quad (12)$$

where  $\omega_{S1} (U_1 X_1, U_2 X_2, \beta)$  denotes the sieve representation of  $\omega_1 (U_1 X_1, U_2 X_2)$  with  $S$  terms in the parameters  $\beta$ . Here,  $\lambda (W_1)$  is additive as in (6) since the logged ratio may be written as a difference of logs.

As in the Engel curve application, we model the density functions of  $U_0$  and  $U_k$  for  $k = 1, 2$ , by using Hermite polynomial seive densities<sup>7</sup>

$$f_{0J} (U_0, \delta, \sigma_0) = \frac{1}{\sigma_0} p_J \left( \frac{U_0}{\sigma_0}, \delta \right) \quad \text{and} \quad f_{kJ} (U_k, \gamma_k, \sigma_k) = \frac{1}{U_k \sigma_k} p_J \left( \frac{\ln U_k}{\sigma_k}, \gamma_k \right) \quad (13)$$

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<sup>7</sup>We impose the usual assumption that the additive model error  $U_0$  is mean zero. Some algebra reveals that the expected value of  $U_0$  for a 3rd order expansion is  $\sigma_0 \left( 2 \left( (1 - \delta_1^2 - 2\delta_2^2 - 6\delta_3^2)^{1/2} - \delta_2 \right) \delta_1 + 6\delta_1\delta_2 + 12\delta_2\delta_3 \right)$ . In our applications we did not find it useful empirically to include more than  $J = 3$  terms. so we translate  $U_0$  in the density  $f_{0J}$  by this function to generate a mean zero distribution for  $U_0$ .

For a given consumer with observed values  $x_1$  and  $x_2$ , the conditional density function of  $W_1$  is then

$$f_{W_1|X_1, X_2}(w_1 | x_1, x_2; \beta, \sigma, \delta, \gamma) = \int_0^\infty \int_0^\infty f_0 \left[ \ln \left( \frac{w_1}{1-w_1} \right) - \omega_{S1}(u_1 x_1, u_2 x_2, \beta), \delta, \sigma \right] f_1(u_1, \gamma_1, \sigma_1) f_2(u_2, \gamma_2, \sigma_2) du_1 du_2$$

Assuming independently, identically distributed observations  $w_{1i}, x_{1i}, x_{2i}$  of consuming households  $i$ , estimation then proceeds by searching over parameter vectors  $\beta, \sigma, \delta$ , and  $\gamma$  to maximize the sieve log likelihood function

$$\sum_{i=1}^n \ln f_{W_1|X_1, X_2}(w_{1i} | x_{1i}, x_{2i}; \beta, \sigma, \delta, \gamma) \quad (14)$$

## 5.2 Empirical Additive Model Random Barten Scales

We estimate the model of the previous subsection using Canadian household expenditure microdata from the 1997 to 2008 Surveys of Household Spending. We consider households comprised of one adult (as of 31 Dec) aged 25-45 residing in provinces other than Prince Edward Island (due to data masking). We consider the share of total nondurable expenditures commanded by energy goods, and drop observations whose expenditures on energy goods are zero, and those whose total nondurable expenditures are in the top or bottom percentile of the total nondurable expenditure distribution. This leaves 9413 observations for estimation.

Total nondurable expenditures are comprised of the sum of household spending on food, clothing, health care, alcohol and tobacco, public transportation, private transportation operation, and personal care, plus the energy goods fuel oil, electricity, natural gas and gasoline. Total nondurable expenditures are scaled to equal one at its mean value, which is a free normalization of units.

Prices vary by province (9 included) and year (12 years) yielding 108 distinct price vectors for the underlying commodities comprising nondurable consumption. These underlying commodity prices are normalised to equal one in Ontario in 2002. To maximize price variation, following Lewbel (1989) and Hoderlein and Mihaleva (2008), we construct  $P_1$  as the Stone price index using within group household specific budget shares of energy goods, and  $P_2$  is constructed similarly for non-energy goods. These price indices all have a value of one in Ontario in 2002. Finally, the regressors  $X_1$  and  $X_2$  are defined as the prices for energy and non-energy divided by total nondurable expenditure for the households.

Table 3 gives summary statistics for budget shares, expenditures, prices and normalised prices.

We estimate equation (14) in Stata, plugging in equations (12) and (13) with  $S = 3$  and  $J = 2$ . Estimated coefficients are given in Table 4 below. Standard errors are provided with the same caveat as before.

	mean	std dev	min	max
9413 observations				
energy share, $W$	0.14	0.09	0.00	0.73
total nondurable expenditure, $M$	1.00	0.50	0.1	2.90
price of energy goods, $P_1$	1.00	0.23	0.43	2.28
price of nonenergy goods, $P_2$	0.96	0.08	0.76	1.35
energy normalised price, $X_1$	1.31	0.92	0.19	10.27
nonenergy normalised price, $X_2$	1.30	0.94	0.29	9.41

Figures 5 and 6 show the estimated distributions of  $\ln U_1$  and  $\ln U_2$ . We do not show the distribution of  $U_0$ , because it is insignificantly different from a normal ( $\delta_1$  and  $\delta_2$  are jointly insignificant). These two distributions of unobserved heterogeneity parameters are not far from log normal and hence rather strongly right-skewed, with modes well below zero.

Parameters of $h_1$ and $h_2$	est	se	Parameters of $U_0, U_1, U_2$ distributions	est	se
$\beta_0$	-2.144	0.137	$\sigma_0$	0.070	0.026
$\beta_{11}$	1.046	0.033	$\sigma_1$	0.636	0.031
$\beta_{12}$	-0.120	0.016	$\sigma_2$	0.983	0.045
$\beta_{13}$	0.040	0.005	$\delta_1$	-0.452	0.925
$\beta_{21}$	0.554	0.048	$\gamma_{11}$	-0.663	0.038
$\beta_{22}$	0.087	0.010	$\gamma_{21}$	-0.322	0.063
$\beta_{23}$	0.024	0.004	$\delta_2$	-0.348	0.482
			$\gamma_{12}$	0.154	0.038
			$\gamma_{22}$	-0.056	0.029

The estimated standard deviations of  $\ln U_1$  and  $\ln U_2$  in Figures 5 and 6 are 0.52 and 0.84, (these differ from  $\sigma_1$  and  $\sigma_2$  because the  $\gamma$  parameters affect the second moments). The standard deviations of  $\ln X_1$  and  $\ln X_2$  are 0.54, indicating that unobserved preference heterogeneity in the Barten scales contributes variation to energy demand of the roughly the same order of magnitude as that contributed by observed variation in prices and total expenditures across consumers. The standard deviation of the additive error  $U_0$  is 0.26, showing that both additive errors and unobserved preference heterogeneity contribute substantively to observed variation in demand.

We postpone more thorough empirical analyses to later, when we report estimated results from a richer model.

### 5.3 Interaction Terms in Utility

The additive utility model in Theorem 3, estimated in the previous subsection, restricts price interaction effects. Using identification based on Theorem 2 instead of Theorem 1, we could instead nonparametrically estimate any sufficiently smooth demand function  $\omega_1(U_1X_1, U_2X_2)$ , and identify the function  $\omega_1$  and distribution of the associated Barten scales  $U_1$  and  $U_2$ . However, doing so would lose the benefits we gained from Theorem 3 of having closed form expressions for the corresponding indirect utility function  $V(U_1X_1, U_2X_2)$ , which is useful for welfare analyses and convenient for imposing constraints associated with utility maximization. We will therefore instead generalize the class of indirect utility functions given by Theorem 3.

Theorem 3 yielded the indirectly additive utility function  $V(X_1, X_2) = h_1(X_1) + h_2(X_2)$ . To relax the restrictiveness (in terms of cross effects) of additive demand functions, we now consider adding second and third order interaction terms to the model of Theorem 3, giving an indirect utility function of the form

$$V(X_1, X_2) = h_1(X_1) + h_2(X_2) + X_1X_2\alpha_0 + X_1^2X_2\alpha_1 + X_1X_2^2\alpha_2 \quad (15)$$

For unknown functions  $h_1(X_1)$  and  $h_2(X_2)$  along with unknown constants  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$ . Higher order interactions could be similarly identified if necessary, indeed, we could interpret these interactions as the first terms in a sieve expansion for an arbitrary indirect utility function. Barten scaling this indirect utility function, substituting the result into equation (5), and adding the error term  $U_0$  as before gives the demand model

$$Y = \ln[g_1(U_1X_1) + M_1(U_1X_1, U_2X_2, \alpha)] - \ln[g_2(U_2X_2) + M_2(U_1X_1, U_2X_2, \alpha)] + U_0 \quad (16)$$

where  $Y = \lambda(W_1)$ ,  $g_k(U_kX_k) = U_kX_k \partial h'_k(U_kX_k) / \partial(U_kX_k)$  for  $k = 1, 2$  and

$$M_1(U_1X_1, U_2X_2, \alpha) = U_1X_1U_2X_2\alpha_0 + 2U_1^2X_1^2U_2X_2\alpha_1 + U_1X_1U_2^2X_2^2\alpha_2, \quad (17)$$

$$M_2(U_1X_1, U_2X_2, \alpha) = U_1X_1U_2X_2\alpha_0 + U_1^2X_1^2U_2X_2\alpha_1 + 2U_1X_1U_2^2X_2^2\alpha_2. \quad (18)$$

Identification of this demand model follows directly from Theorem 3.<sup>8</sup>

For estimation of the model, we let the functions  $h_k$  in equation (15) be represented by the same polynomial in logs sieve basis functions as before. Barten scaling this indirect

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<sup>8</sup>It's possible to directly prove identification of the demand model of equations (16), (17), and (18) under weaker conditions than those of Theorem 3. Specifically, identification follows if Assumptions A1, A2, and A3 hold with  $G_k(X_k) = \ln g_k(X_k)$  for  $k \in \{1, 2\}$ , the functions  $g_1$  and  $g_2$  are differentiable, and either  $g'_k(0)E(U_k)$  for  $k = 1$  or for  $k = 2$  is nonzero and finite. See earlier versions of this paper for a proof.

utility function gives, by equation (16), the demand function

$$\begin{aligned}
\lambda(W_1) &= \omega_{S1}(U_1 X_1, U_2 X_2, \beta) + U_0 & (19) \\
&= \ln \left[ \left( e^{\beta_{10} + \sum_{s=1}^S (\ln(U_1 X_1))^s \beta_{1s}} \right) \left( \sum_{s=1}^S (\ln(U_1 X_1))^{s-1} s \beta_{1s} \right) + M_1(U_1 X_1, U_2 X_2, \alpha) \right] \\
&\quad - \ln \left[ \left( e^{\sum_{s=1}^S (\ln(U_2 X_2))^s \beta_{2s}} \right) \left( \sum_{s=1}^S (\ln(U_2 X_2))^{s-1} s \beta_{2s} \right) + M_2(U_1 X_1, U_2 X_2, \alpha) \right] + U_0
\end{aligned}$$

The demand function given by equation (19) is the same as (12), except for the addition of the functions  $M_1$  and  $M_2$  given by equations (17) and (18), which embody the additional desired price interaction terms. We estimate equation (19) using the same sieve maximum likelihood method as before.

## 5.4 Empirical Barten Scales with Interaction Terms

Table 5 presents estimated parameters for the demand equation (19), that is, the Barten scale model with interaction terms. Again, we use a 2nd order Hermite expansion around the normal for  $U_0$ ,  $\ln U_1$  and  $\ln U_2$ , and a 3rd order polynomial in  $\ln X_j$  for  $G_j$ . In this model, if any of the interaction coefficients  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  are negative, then for large values of either  $U_1$  or  $U_2$ , the utility function will violate monotonicity. In the demand and likelihood functions, this would make the argument of the log function in  $Y$  negative. We therefore restrict  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  to be non-negative.

As Table 5 shows, two of the interaction terms are statistically significant (and all three are jointly significant). For comparison, we also estimated the model imposing the constraint that  $U_1 = U_2 = 1$ , thereby removing unobserved preference heterogeneity. This corresponds to a more traditional demand model in which the only error term is additive, albeit additive in the logit transform of the budget share.

In Figures 7 and 8, we give the estimated densities of  $\ln U_1$  and  $\ln U_2$ . Here the standard deviations of  $\ln U_1$  and  $\ln U_2$  are 0.44 and 0.81, respectively, which is similar to what we observed in the model without interaction terms. So after allowing for interaction terms, unobserved heterogeneity is of similar importance in energy and non-energy preferences.

Recall  $X_j = P_j/M$  where  $M$  is total expenditures. Figure 9 displays estimated energy budget share functions (Engel curves) evaluated at prices  $P_1 = P_2 = 1$ , for each quartile of the  $U_1$  and  $U_2$  distribution. Nine Engel curves are displayed, corresponding to each of the combinations of one quartile of  $U_1$  and one quartile of  $U_2$ . Each Engel curve was obtained by simulation, drawing 10,000 observations of total expenditures  $M$  from a nonparametric estimate of the distribution of real expenditure (nominal expenditure deflated by the Stone index) and evaluating the estimated budget share equations for each given  $U_1$  and  $U_2$  quartile at each total expenditure  $M$  draw. Here, we see that variation in the random Barten scales  $U_1$  and  $U_2$  causes substantial shifts in the Engel curves. For comparison, Figure 9

also displays, with a thick grey line, the Engel curve from a model which imposes  $U_1 = U_2 = 1$ .

Parameters of $h_1$ and $h_2$	est	se	Parameters of $U_0, U_1, U_2$ distributions	est	se
$\beta_0$	-2.546	0.174	$\sigma_0$	0.166	0.039
$\beta_{11}$	1.084	0.056	$\sigma_1$	0.540	0.046
$\beta_{12}$	-0.143	0.030	$\sigma_2$	0.854	0.041
$\beta_{13}$	0.056	0.013	$\delta_1$	-0.822	1.732
$\beta_{21}$	0.947	0.064	$\gamma_{11}$	-0.646	0.072
$\beta_{22}$	0.276	0.032	$\gamma_{21}$	-0.482	0.039
$\beta_{23}$	0.066	0.008	$\delta_2$	0.002	2.517
$\alpha_0$	0.000	0.001	$\gamma_{12}$	0.141	0.063
$\alpha_1$	0.006	0.002	$\gamma_{22}$	0.134	0.016
$\alpha_2$	0.017	0.004			

The shape of the Engel curve without unobserved preference heterogeneity in Figure 9 is rather different from those that allow for unobserved preference heterogeneity. For example, at low expenditure levels, allowing for unobserved preference heterogeneity reduces the slope of the energy Engel curve, suggesting that it is not as much of a necessity as would appear in the absence of such heterogeneity.

Because  $U_1$  and  $U_2$  affect budget shares in different ways, it is difficult to see the joint effect of these two unobserved heterogeneity parameters on the distribution of implied behaviour. We address this in our remaining figures. Figure 10 displays a contour plot of the density of estimated energy budget shares evaluated at  $P_1 = P_2 = 1$ . This is again obtained by simulation, based on 10,000 draws of  $M$  as before. This time, for each real expenditure draw we also draw a value of  $U_1$  and  $U_2$  from their estimated distributions, and evaluate the estimated energy budget share at these drawn values of  $M$ ,  $U_1$  and  $U_2$ . For comparison, we also display, as a thick gray line, the simulated shares from the model without preference heterogeneity.

The standard deviation of the marginal distribution of energy budget shares is 0.09 in the model which accounts for both unobserved preference heterogeneity and observed expenditure variation. In contrast, it is only 0.02 in the model which accounts only for observed expenditure variation. Thus, the variation in budget shares due to heterogeneity in preferences is large relative to that due to variation in total expenditures.

## 5.5 Consumer Surplus Effects of a Carbon Tax

We now apply our model to evaluate the distribution of effects of a large change in the price of energy, as might result under a carbon tax.<sup>9</sup> Using equation (15), even with nonparametric demand components we have a closed form expression for indirect utility. We can therefore compute consumer surplus effects without approximations of the type proposed by Vartia (1984). Instead, we numerically invert the indirect utility function (15) to obtain the cost of living impact of a price change. We would otherwise need to numerically solve a differential equation as in Hausman and Newey (1995), but such a solution would need to be calculated for every value on the continuum of points that  $U_1$  and  $U_2$  can take on.

The cost-of-living impact for the change from initial prices  $\bar{P}_1, \bar{P}_2$  to new prices  $P_1, P_2$ , is  $\pi(U_1, U_2, M, P_1, P_2, \bar{P}_1, \bar{P}_2)$  defined as the solution to

$$V\left(\frac{U_1 \bar{P}_1}{M}, \frac{U_2 \bar{P}_2}{M}\right) = V\left(\frac{U_1 P_1}{\pi M}, \frac{U_2 P_2}{\pi M}\right).$$

Here  $\pi$  is the proportionate change in costs  $M$  needed to compensate for the energy price change. To show price effects clearly, we consider a large price change: doubling the price of energy. So we solve for the  $\pi$  function at the initial price vector  $\bar{P}_1 = \bar{P}_2 = 1$  and the new price vector  $P_1 = 2, P_2 = 1$ . Figure 11 gives the resulting estimated joint distribution (contour plot) of  $\ln \pi$  and  $\ln M$ . This plot is constructed by calculating the surplus for each of 10,000 draws of  $U_1, U_2$ , and  $M$ , and, as in Figure 10, the thick gray line gives estimates based on the model without preference heterogeneity.

Table 6 gives a numerical version of the information presented in Figure 11. Here, we present summary statistics on consumer surplus unconditionally for the model with and without unobserved preference heterogeneity, and conditionally at quartiles of the expenditure distribution for the model with unobserved preference heterogeneity.

The estimated energy budget shares shown in Figure 10 have an average of 0.14. It has long been known that first order approximations to cost of living effects of marginal price changes can be evaluated without estimating demand functions and associated demand elasticities (see, e.g., Stern 1987). However, the estimated average cost-of-living impacts given in Table 6 are much less than the value of 0.14 that would be used for first order approximations, showing that price substitution effects are large. This supports findings

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<sup>9</sup>Our model is not a general equilibrium model, so we are only estimating the consumer's responses to a change in energy prices. Moreover, these should only be interpreted as short run responses, since in the longer run consumers could change their energy elasticities and demand by, e.g., buying more energy efficient cars and appliances. Also, we just consider a change in the overall price of energy, and so do not consider impacts of possible changes in the composition of energy goods.



in, e.g., Banks, Blundell, and Lewbel (1996) that, contrary to the first order approximation results, it is necessary to estimate demand functions and associated price elasticities to properly evaluate consumer surplus and welfare effects when price changes are large rather than marginal.

	Mean	Std Dev	Lower Qtl	Median	Upper Qtl
log-cost of living					
Overall—without heterogeneity	0.111	0.012	0.105	0.113	0.120
Overall—with heterogeneity	0.128	0.072	0.073	0.120	0.172
At lower Qtl of $M$ ( $\ln M = -0.38$ )	0.140	0.079	0.070	0.137	0.204
At median of $M$ ( $\ln M = -0.03$ )	0.130	0.071	0.070	0.123	0.181
At upper Qtl of $M$ ( $\ln M = 0.26$ )	0.113	0.057	0.068	0.110	0.151
consumer surplus (loss) as a fraction of total nondurable expenditure					
Overall—without heterogeneity	0.115	0.042	0.087	0.116	0.144
Overall—with heterogeneity	0.133	0.087	0.066	0.119	0.185

Table 6 also shows that the average cost-of-living impact ascribed to a price change depends quite substantially on whether or not we account for unobserved preference heterogeneity. The model without unobserved preference heterogeneity shows an average cost-of-living impact of 11.1 per cent. In contrast, when we allow for unobserved preference heterogeneity, the estimated average is 12.8 per cent. This difference in the averages is large, accounting for more than a tenth of the overall impact.

Given that our preferred model has variation in both preferences and budgets, it is not surprising that the variance of cost-of-living impacts is higher than in the model with just variation in budgets. However, the magnitude of this difference is surprisingly large. Variation in budgets (stemming from variation across consumers in prices faced and in total expenditures) with no preference heterogeneity induces a standard deviation of cost-of-living impacts of 1.2 percentage points. In contrast, variation in budgets and preferences in the model with preference heterogeneity induces a standard deviation in cost-of-living impacts six times as large (7.2 percentage points). Thus, unobserved preference heterogeneity is dramatically more important than variation in budgets for this particular policy experiment.

Another way to see this point is to assess how much variation in cost-of-living impacts there is at a given level of expenditure. The middle part of Table 6 addresses this. Here, we see that at the median expenditure level, unobserved preference heterogeneity induces a standard deviation of 7.1 percentage points, comparable in magnitude to the unconditional standard deviation. However, it is interesting to note that for richer consumers, unobserved preference heterogeneity induces less variation in cost-of-living impacts. The standard

deviation is 5.7 percentage points at the upper quartile of expenditures in comparison with 7.9 percentage points at the bottom quartile cutoff. This shows that, due to nonseparability of preference heterogeneity, even independently distributed preference heterogeneity may have effects on economic variables that are correlated with observables.

The bottom panel of Table 6 gives estimates of the negative of total consumer surplus as a fraction of nondurable expenditure. Whereas the top panel gives averages and quartile cutoffs for the log cost-of-living at the household level, which under some circumstances may be taken as a welfare measure (see, Crossley and Pendakur 2010), the bottom panel gives the sum of the dollar cost changes across all households, expressed as a fraction of total nondurable expenditure. The bottom panel exponentiates, and weights by household expenditure. Here, too, we see a similar pattern in the results: accounting for unobserved preference heterogeneity matters a great deal in the consumer surplus measurement, even in assessing its sum. Without accounting for unobserved preference heterogeneity, the total loss in consumer surplus is 11.5 per cent of total nondurable expenditure. Accounting for preference heterogeneity increases the estimated loss substantially to 13.3 per cent of total nondurable expenditure.

It is clear from Figure 11 that accounting for unobserved heterogeneity makes a big difference in our assessment of the consumer surplus associated with an increase in energy prices. Here, we see that the variance in consumer surplus conditional on total nondurable expenditure,  $M$ , is much larger than the variance across values of  $M$ , so accounting for unobserved heterogeneity has a bigger impact than accounting for observed heterogeneity in  $M$ .

## 6 Extensions

Theorem 2 provided one extension of our base case additive model of Theorem 1. Here we consider two alternative extensions. The first concerns identification when some regressors are discrete, while the second looks at identification of models containing additional random coefficients on interaction terms.

### 6.1 Discrete Regressors

Much of the literature on nonseparable errors and unobserved heterogeneity focuses on continuous regressors, but in empirical econometric applications, discrete regressors are common. Here we extend the results of Theorem 1 to allow for discrete regressors. Define the random variable  $\tilde{Y}_k$ , the function  $\delta_k$ , and the set  $\Psi_k$  as follows.  $\tilde{Y}_k = G_k(X_k U_k)$ . Let  $\delta_k(x_k, z) = 1$  if and only if there exists a  $\tilde{y}_k \in \text{supp}(\tilde{Y}_k | X = x_k e_k, Z = z)$  such

that  $F_{\tilde{Y}_k|X,Z}(y_0 | e_k, z) = F_{\tilde{Y}_k|X,Z}(\tilde{y}_k | e_k x_k, z)$  if  $x_k > 0$  or  $F_{\tilde{Y}_k|X,Z}(y_0 | e_k, z) = 1 - F_{\tilde{Y}_k|X,Z}(\tilde{y}_k | e_k x_k, z)$  if  $x_k < 0$ . Let  $\Psi_k = \{x_k : \text{for some } z \in \text{supp}(Z), \delta_k(x_k, z) = 1\}$ .

ASSUMPTION A2': The function  $F_{U_k|Z}(u_k | z)$  is invertible in  $u_k$  for all  $u_k \in \text{supp}(U_k | Z = z)$ . If  $G_k(r)$  is known for all  $r \in \Psi_k$ , then  $G_k(r)$  is known for all  $r$  on the support of  $X_k U_k$ .

For a given  $k$ , Assumption A2' essentially provides identification for a discrete regressor  $X_k$  by taking a value  $x_k$  that  $X_k$  can take on, and finding a value  $\tilde{y}_k$  such that the distribution  $F_{\tilde{Y}_k|X,Z}$  evaluated at  $\tilde{y}_k$  and  $x_k e_k$  matches a known value for the distribution at which  $G_k$  is identified by normalization. This is then used to identify the function  $G_k(r)$  at the point  $r = x_k$ . The set  $\Psi_k$  is then the set of all such points for which  $G_k$  can be identified by matching. The last part of Assumption A2' then assumes that identifying  $G_k$  at all the points in  $\Psi_k$  suffices to identify  $G_k$  everywhere.

This last condition will hold nonparametrically if  $\Psi_k$  contains all the values that  $X_k U_k$  can take on. This will generally require that  $X_k$  and  $U_k$  have compatible supports. For example, if  $X_k$  and  $U_k$  are binary (each taking the values zero or one with strictly positive probability) and  $Z$  is empty, then it is straightforward to verify that Assumption A2' will hold if there exists a  $\tilde{y}_k$  such that  $F_{\tilde{Y}_k|X}(y_0 | e_k) = F_{\tilde{Y}_k|X_k}(\tilde{y}_k | 0)$ . As this example shows, unlike Assumption A2, Assumption A2' does not require  $X_k$  or  $U_k$  to be continuously distributed. Assumption A2' could also be used in place Assumption A2 if  $X_k$  is continuously distributed and  $U_k$  is not.

Assumption A2' can alternatively be satisfied if  $G_k(r)$  is parameterized to be identifiable just from the values of  $r \in \Psi_k$ . So, e.g., if it is known that  $G_k(r) = \theta_{k0} + \theta_{k1}r + \theta_{k2}r^2$ , then as long as  $\Psi_k$  contains at least three elements (associated with three different values of  $\tilde{y}_k$ ), Assumption A2' will be satisfied, because only three points are required to identify a quadratic. This will suffice for identification even if  $U_k$  is continuous and  $X_k$  is discrete.

**THEOREM 4:** Let  $Y = \sum_{k=1}^K G_k(X_k U_k) + U_0$  and let Assumption A1 hold. Then the distribution function  $F_{U_0|Z}$  is identified, and for every  $k \in \{1, \dots, K\}$  such that Assumptions A2' and A3 hold, the function  $G_k$  and the distribution function  $F_{U_k|Z}$  are nonparametrically identified.

Note that Theorems 1 and 3 can be combined, using Assumption A2' and Theorem 3 to identify  $G_k$  and  $F_{U_k|Z}$  for indices  $k$  in which  $X_k$ ,  $U_k$ , or both are discrete, and using Assumption A2 and Theorem 1 for identification for the remaining continuous regressors and random coefficients.

## 6.2 Additional random coefficients on interaction terms

Consider models of the form

$$Y = \left( \sum_{k=1}^K G_k (X_k U_k) \right) + \left( \sum_{j=1}^{K-1} \sum_{k=j+1}^K X_j X_k U_{jk} \right) + U_0 \quad (20)$$

Equation (20) relaxes the additivity restriction of Theorem 1 by adding pairs of interacting regressors to interact, and allowing each of these pairs to have their own random coefficients, in addition to the random coefficients in each  $G_k (X_k U_k)$  term.

Assumptions A1 and A2 are extended to this model as follows. Let  $e_{jk}$  be a  $K$  vector that equals one in positions  $j$  and  $k$  and zero elsewhere. Note that when  $j = k$ ,  $e_{jk} = e_k$ .

**ASSUMPTION B1:** The conditional distribution  $F_{Y|X,Z}(y | x, z)$  and the marginal distribution  $F_Z(z)$  are identified.  $(U_0, U_1, \dots, U_K, U_{12}, U_{13}, \dots, U_{K-1,K}) \perp X | Z$ ,  $(U_1, \dots, U_K, U_{12}, U_{13}, \dots, U_{K-1,K}) \perp U_0 | Z$ ,  $U_0, U_1, \dots, U_K$  are mutually independent conditional upon  $Z$ , and for all  $j < k$ ,  $(U_j, U_k) \perp U_{jk} | Z$ . Either  $U_0$  has a non-vanishing characteristic function or  $U_0$  is identically zero.  $\text{supp}(U_0) \subseteq \text{supp}(Y)$  and  $\{0, e_{11}, e_{12}, \dots, e_{KK}\} \subseteq \text{supp}(X)$ . For all  $j \neq k$ ,  $G_k(U_k) + G_j(U_j) + U_0$  has a nonvanishing characteristic function.

**ASSUMPTION B2:** For  $k = 1, \dots, K$ :  $U_k, X_k | Z$  are continuously distributed, and for every  $r \in \text{supp}(X_k U_k)$  there exist an  $x_k$  on the support of  $X_k$  such that  $f_{U_k}(x_k^{-1} r) \neq 0$ . For  $j = 1, \dots, K-1$  and  $k = j+1, \dots, K$ :  $U_{jk}, X_j X_k | Z$  are continuously distributed, and for every  $r \in \text{supp}(X_j X_k U_{jk})$  there exist an  $x_j x_k$  on the support of  $X_j X_k$  such that  $f_{U_{jk}}(x_j^{-1} x_k^{-1} r) \neq 0$ .

These are all direct extensions of Assumptions A1 and A2, and A3 to include the interaction terms. The main additional assumptions we now require are that  $U_0, U_1, \dots, U_K$  be mutually independent as in Assumption A4, and that  $U_{jk}$  to be independent of  $(U_j, U_k)$  conditioning on  $Z$ . We then get the following generalization of Theorem 1.

**THEOREM 5:** Let equation (20) and Assumptions B1, B2, and (for  $k = 1, \dots, K$ ) A3 hold. Then the distribution function  $F_{U_0|Z}$ , the regression and distribution functions  $G_k$  and  $F_{U_k|Z}$  for every  $k \in \{0, 1, \dots, K\}$ , and the distribution functions  $F_{U_{jk}|Z}$  for every  $j = 1, \dots, K-1$  and  $k = j+1, \dots, K$ , are all nonparametrically identified.

The proof of Theorem 5 immediately extends to identification of triplets like  $X_j X_k X_\ell U_{jkl}$  added to the model, and similarly for all higher order 'tuples up to the product of all  $K$  regressors.

## 7 Conclusions

We have shown nonparametric identification of a generalized random coefficients model, and provided empirical applications in which the generalized random coefficient structure arises from extending existing commonly used economic models of observed heterogeneity to models of unobserved heterogeneity. In our applications to Engel and Barten scales, allowing for general forms of unobserved heterogeneity is shown to be important for empirically evaluating the welfare effects of potential policy interventions such as a carbon tax. For example, we find that failure to account for preference heterogeneity would result in underestimating the total cost of an energy tax (measured as the effect on total consumer surplus) by over ten percent, and in underestimating the variation in impacts (measured as the standard deviation in cost of living impacts across consumers) by over eighty percent.

A straightforward extension of our model is to combine Theorem 1, 2, 4, or 5 with a special regressor as in Lewbel (2000) to identify discrete choice models like  $D = I[V + G(X_1U_1, \dots, X_KU_K) + U_0 \geq 0]$ , where  $V$  is an exogenous regressor with large support and  $D$  is an observed binary dependent variable. In this case, even though  $Y$  is not observed, if  $V \perp U \mid X$  Then  $1 - E(D \mid V = v, X = x, Z = z) = F_{Y|X,Z}(-v \mid x, z)$  identifies  $F_{Y|X,Z}$ , and this paper's theorems can then be applied to identify  $G$  and each  $U_k$  distribution. This structure is related to that of Berry and Haile (2009), and could be useful in applications that involve discrete choices with both substantial unobserved heterogeneity and substantial nonlinearity in the latent index.

In terms of empirical applications, it would be useful to extend the applications to collective household models, e.g., our Engel scale application resembles a model for unobserved variation in resource share allocations, and Barten scales have been applied to collective models in, e.g., Browning, Chiappori, and Lewbel (2010). Useful areas for further work on the theory of generalized random coefficients would be extensions to identify joint rather than marginal distributions of the random coefficients, and to relax the smoothness assumptions that were imposed for identification of the nonadditive model.

## 8 Proofs

Before proving Theorem 1, we prove a couple of lemmas.

LEMMA 1: Let  $\tilde{Y}_k = G_k(X_kU_k)$  where  $G_k$  is a strictly monotonically increasing function. Assume  $U_k \perp X \mid Z$ . The marginal distributions of  $U_k$  and  $X_k$  are continuous. The support of  $X_k$  includes zero, the support of  $U_k$  is a subset of the support of  $\tilde{Y}_k$ , and for every  $r$  such that  $G_k(r)$  is on the support of  $\tilde{Y}_k$  there exist an  $x_k$  on the support of  $X_k$  such that  $f_{U_k}(x_k^{-1}r) \neq 0$ . Assume the location and scale normalizations  $G_k(0) = 0$

and  $G_k(1) = y_0$  for some known  $y_0$  in the support of  $\tilde{Y}_k$  are imposed. Let  $r = H_k(\tilde{y}_k)$  be inverse of the function  $G_k$  where  $\tilde{y}_k = G_k(r)$ . Define  $X_{(k)}$  to be the vector of all the elements of  $X$  except for  $X_k$ . Define the function  $S_k(\tilde{y}_k, \tilde{x})$  by

$$S_k(\tilde{y}_k, \tilde{x}) = E \left[ F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | \tilde{x}^{-1}, 0, Z) \right] = \int_{\text{supp}(Z)} F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | \tilde{x}^{-1}, 0, z) f_z(z) dz.$$

Then

$$H_k(\tilde{y}_k) = \text{sign} \left( \text{sign}(x_k) \frac{\partial S_k(\tilde{y}_k, x_k^{-1})}{\partial x_k^{-1}} \right) \exp \left( \int_{y_0}^{\tilde{y}_k} \frac{x_k \partial S_k(\tilde{y}_k, x_k^{-1}) / \partial \tilde{y}}{\partial S_k(\tilde{y}_k, x_k^{-1}) / \partial x_k^{-1}} d\tilde{y} \right) \quad (21)$$

Note that if  $Z$  is discretely distributed, then the integral defining  $S_k$  becomes a sum. If  $Z$  is empty (so  $U_k$  and  $X$  are unconditionally independent) then  $S_k(\tilde{y}_k, \tilde{x}) = F_{\tilde{Y}_k | X_k, X_{(k)}}(\tilde{y}_k | \tilde{x}^{-1}, 0)$ . The main implication of Lemma 1 is that if the distribution  $F_{\tilde{Y}_k | X, Z}$  is identified, then the function  $H_k$  is identified by construction.

PROOF of Lemma 1: For any  $\tilde{y}_k$  and any  $x_k > 0$  we have

$$\begin{aligned} F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | x_k, 0, z) &= \Pr(G_k(x_k U_k) \leq \tilde{y} | X_k = x_k, X_{(k)} = 0, Z = z) \\ &= \Pr(U_k \leq x_k^{-1} H_k(\tilde{y}) | X_k = x_k, X_{(k)} = 0, Z = z) \\ &= F_{U_k | X_k, X_{(k)}, Z}[x_k^{-1} H_k(\tilde{y}) | x_k, 0, z] = F_{U_k | Z}[x_k^{-1} H_k(\tilde{y}) | z] \end{aligned}$$

where the last equality uses  $U_k \perp X | Z$ . Similarly for any  $x_k < 0$  we have

$$\begin{aligned} F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | x_k, 0, z) &= \Pr(G_k(x_k U_k) \leq \tilde{y} | X_k = x_k, X_{(k)} = 0, Z = z) \\ &= \Pr(U_k \geq x_k^{-1} H_k(\tilde{y}) | X_k = x_k, X_{(k)} = 0, Z = z) \\ &= 1 - F_{U_k | Z}[x_k^{-1} H_k(\tilde{y}) | z] \end{aligned}$$

Together these equations say

$$F_{U_k | Z}[x_k^{-1} H_k(\tilde{y}_k) | z] = I(x_k < 0) + \text{sign}(x_k) F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | x_k, 0, z).$$

So

$$\begin{aligned} F_{U_k}[x_k^{-1} H_k(\tilde{y}_k)] &= \int_{\text{supp}(Z)} \left[ I(x_k < 0) + \text{sign}(x_k) F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | x_k, 0, z) \right] f(z) dz. \\ &= I(x_k < 0) + \text{sign}(x_k) S(\tilde{y}_k, x_k^{-1}) \end{aligned}$$

It follows that for any  $x_k \neq 0$ ,

$$\frac{\partial S(\tilde{y}_k, x_k^{-1})}{\partial x_k^{-1}} = \text{sign}(x_k) f_U \left[ x_k^{-1} H_k(\tilde{y}_k) \right] H_k(\tilde{y}_k)$$

and

$$\frac{\partial S(\tilde{y}_k, x_k^{-1})}{\partial \tilde{y}_k} = \text{sign}(x_k) f_U \left[ x_k^{-1} H_k(\tilde{y}_k) \right] x_k^{-1} \frac{\partial H_k(\tilde{y}_k)}{\partial \tilde{y}_k}$$

So for  $f_U \left[ x_k^{-1} H_k(\tilde{y}_k) \right] \neq 0$  it follows that

$$\frac{x_k \partial S(\tilde{y}_k, x_k^{-1}) / \partial \tilde{y}_k}{\partial S(\tilde{y}_k, x_k^{-1}) / \partial x_k^{-1}} = \frac{\partial H_k(\tilde{y}_k) / \partial \tilde{y}_k}{H_k(\tilde{y}_k)} = \frac{\partial \ln |H_k(\tilde{y}_k)|}{\partial \tilde{y}_k}$$

so

$$\begin{aligned} \exp \left( \int_{y_0}^{\tilde{y}_k} \frac{x_k \partial S(\tilde{y}_k, x_k^{-1}) / \partial \tilde{y}_k}{\partial S(\tilde{y}_k, x_k^{-1}) / \partial x_k^{-1}} d\tilde{y}_k \right) &= \exp \left( \int_{y_0}^{\tilde{y}_k} \frac{\partial \ln |H_k(\tilde{y}_k)|}{\partial \tilde{y}_k} d\tilde{y}_k \right) \\ &= \exp(\ln |H_k(\tilde{y}_k)| - \ln |H_k(\tilde{y}_0)|) = |H_k(\tilde{y}_k)| \end{aligned}$$

where  $H_k(\tilde{y}_0) = 1$  follows from  $G_k(1) = \tilde{y}_0$ . Finally

$$\begin{aligned} \text{sign} \left( \text{sign}(x_k) \frac{\partial S(\tilde{y}_k, x_k^{-1})}{\partial x_k^{-1}} \right) &= \text{sign} \left( \text{sign}(x_k) \text{sign}(x_k) f_U \left[ x_k^{-1} H_k(\tilde{y}_k) \right] H_k(\tilde{y}_k) \right) \\ &= \text{sign} \left( f_U \left[ x_k^{-1} H_k(\tilde{y}_k) \mid z \right] H_k(\tilde{y}_k) \right) = \text{sign}(H_k(\tilde{y}_k)) \end{aligned}$$

So the right side of equation (21) equals  $\text{sign}(H_k(\tilde{y}_k)) |H_k(\tilde{y}_k)| = H_k(\tilde{y}_k)$  as claimed.

LEMMA 2: If Assumption A1 holds, then  $F_{U_0|Z}$  and the distribution function  $F_{\tilde{Y}|X,Z}(\tilde{Y} \mid x, z)$  are identified, where  $\tilde{Y} = \sum_{k=1}^K G_k(X_k U_k)$ .

PROOF of Lemma 2:

$$F_{Y|X,Z}(y \mid 0, z) = \Pr(G(0) + U_0 \leq y \mid X = 0, Z = z) = F_{U_0|X,Z}(y \mid 0, z) = F_{U_0|Z}(y \mid z)$$

identifies the distribution function  $F_{U_0|Z}$  on the support of  $Y$ , which contains the support of  $U_0$ . Next define  $\tilde{Y} = Y - U_0$ . Then since  $Y = \tilde{Y} + U_0$  and the distributions of  $Y | X, Z$  and  $U_0 | X, Z$  are identified, for each value of  $X = x, Z = z$  apply a deconvolution (using the nonvanishing characteristic function of  $U_0$ ) to identify the distribution of  $\tilde{Y} | X, Z$ , where  $\tilde{Y} = \sum_{k=1}^K G_k(X_k U_k)$ .

PROOF of Theorem 1: When  $X_{(k)} = 0$  (equivalently, when  $X = e_k x_k$  for some  $x_k$ ) we get  $\tilde{Y} = G_k(X_k U_k) + \sum_{j \neq k} G_j(0) = G_k(X_k U_k)$ . Define  $\tilde{Y}_k = G_k(X_k U_k)$ . It follows that  $F_{\tilde{Y}_k | X_k, X_{(k)}, Z}(\tilde{y}_k | x_k, 0, z) = F_{\tilde{Y} | X, Z}(\tilde{y}_k | x_k e_k, z)$ , so the distribution function on the left of this identity is identified, given by Lemma 1 that  $F_{\tilde{Y} | X, Z}$  is identified. Let  $r = H_k(\tilde{y})$  denote the inverse of the function  $G_k$  where  $\tilde{y} = G_k(r)$ . It follows by construction from Lemma 1 that  $H_k(\tilde{y})$  is identified for every value of  $\tilde{y}_k$  on the support of  $\tilde{Y}_k$  satisfying the property that, for some  $x_k$  on the support of  $X_k$ ,  $f_{U_k} [x_k^{-1} H(\tilde{y})] \neq 0$ . This identification of  $H_k(\tilde{y})$  in turn means that the function  $G_k(r)$  is identified for every  $r$  such that  $G_k(r)$  is on the support of  $\tilde{Y}_k$  and there exist an  $x_k$  on the support of  $X_k$  such that  $f_{U_k|Z}(x_k^{-1} r) \neq 0$ . This then implies identification of  $G_k$  on its support. Finally, given identification of  $F_{\tilde{Y} | X, Z}$  and of  $H_k(\tilde{y}_k)$ , the distribution function  $F_{U_k|Z}$  is identified by  $F_{U_k|Z}[H(\tilde{y})/x_k | z] = F_{\tilde{Y} | X_k, X_{(k)}, Z}(\tilde{y} | x_k, 0, z)$  for  $x_k > 0$  and  $F_{U_k|Z}[H(\tilde{y})/x_k | z] = 1 - F_{\tilde{Y} | X_k, X_{(k)}, Z}(\tilde{y} | x_k, 0, z)$  for  $x_k < 0$ .

PROOF of Corollary 1: Applying the proof of Lemma 2 to the model of Corollary 1 shows that  $F_{U_0|Z}$  and the distribution function  $F_{\tilde{Y} | X, Z}(\tilde{Y} | x, z)$  are identified, where  $\tilde{Y} = \prod_{k=1}^K g_k(X_k U_k)$ . It therefore follows that  $F_{\tilde{Y} | X, Z}(\tilde{Y} | x, z)$  is identified where  $\tilde{Y} = \ln(\tilde{Y}) = \sum_{k=1}^K \ln[g_k(X_k U_k)] = \sum_{k=1}^K G_k(X_k U_k)$ , and the remainder of the identification therefore follows applying the proof of Theorem 1.

PROOF of Theorem 2: By construction, the function  $\tilde{G}(X_1 U_1, \dots, X_K U_K)$  is zero when evaluated at  $X = 0$  or at  $X = X_k e_k$  for any  $k$ , so evaluated at any such value of  $X$ , equation (3) is equivalent to equation (2). For equation (2), the proof of Theorem 1 showed identification of the marginal distributions of each  $U_k$  and each function  $G_k$  only using  $X = 0$  and  $X = X_k e_k$ , so these functions are also identified for equation (3). What remains is to identify the function  $\tilde{G}$ . Define  $R(X) = E[\tilde{G}(X_1 U_1, \dots, X_K U_K) | X]$ . The function  $R(X)$  is identified for all  $X$  because  $R(X) = E[Y - \sum_{k=1}^K G_k(X_k U_k) - U_0 | X]$ , which depends only on the already identified distributions and functions. For nonnegative



integers  $t_1, \dots, t_K$  define  $R_{t_1, \dots, t_K}$  by

$$R_{t_1, \dots, t_K}(x) = \frac{\partial^{t_1 + \dots + t_K} R(x)}{\partial x_1^{t_1} \dots \partial x_K^{t_K}}$$

and similarly for  $\tilde{G}_{t_1, \dots, t_K}$ . Then

$$R_{t_1, \dots, t_K}(x) = E(U_1^{t_1}, \dots, U_K^{t_K} \tilde{G}_{t_1, \dots, t_K}(x_1 U_1, \dots, x_K U_K))$$

so  $\tilde{G}_{t_1, \dots, t_K}(0) = R_{t_1, \dots, t_K}(0) / E(U_1^{t_1}, \dots, U_K^{t_K})$  is identified for all sets of nonnegative integers  $t_1, \dots, t_K$ . Now  $\tilde{G}$  is analytic so can write the Maclaurin series

$$\tilde{G}(r) = \sum_{t_1=0}^{\infty} \dots \sum_{t_K=0}^{\infty} \frac{r_1^{t_1} \dots r_K^{t_K} \tilde{G}_{t_1, \dots, t_K}(0)}{(t_1 + \dots + t_K)}$$

which shows that the function  $\tilde{G}(r)$  is identified, since  $\tilde{G}_{t_1, \dots, t_K}(0)$  is identified for all sets of nonnegative integers  $t_1, \dots, t_K$ .

PROOF of Corollary 2: For a given  $j \in \{1, \dots, J\}$  let  $Y = -Q_j$  if  $j$  is not a Giffen good, otherwise let  $Y = Q_j$ . Then the function  $G$  in Theorem 2 is given by  $-\omega_j(U_1 X_1, \dots, U_J X_J) / U_j X_j$  which makes the function and  $G_j$  in Theorems 1 and 2 be  $-\omega_j(0, \dots, 0, U_j X_j, \dots, 0) / U_j X_j$  (remove the minus signs if the good  $j$  was Giffen). Then  $G_j$  is strictly monotonically increasing, and we have taken  $U_0 = 0$ , so by Theorem 1, the distribution function  $F_{U_j|Z}$  is identified. Repeating this procedure for each  $j \in \{1, \dots, J\}$  identifies all of the  $F_{U_j|Z}$  distributions. Given identification of all of the  $F_{U_j|Z}$  distributions, we can now apply the remainder of the proofs of Theorems 1 and 2 to each demand function  $Q_j X_j = \omega_j(U_1 X_1, \dots, U_J X_J)$  for  $j \in \{1, \dots, J\}$  to identify each function  $\omega_j$ , observing that by Roys identity (and boundedness of budget shares) each  $\omega_j$  will be analytic, and having each  $U_j$  be positive and bounded makes the remaining assumptions of Theorem 2 hold.

PROOF of Theorem 3: As discussed in the text, a property of Barten scales (which can be readily verified using Roys identity) is that, if  $V(X_1, X_2)$  is the indirect utility function corresponding to the demand function  $\omega_1(X_1, X_2)$ , then up to an arbitrary monotonic transformation  $H(V, U_1, U_2)$  of  $V$ , the indirect utility function corresponding to  $\omega_1(U_1 X_1, U_2 X_2)$  is  $V(U_1 X_1, U_2 X_2)$ , and vice versa. It therefore suffices to prove that the theorem holds with  $U_1 = U_2 = 1$ .

By equation (4), given any indirect utility function  $V$ , the corresponding demand function  $\omega_1$  is given by

$$\omega_1(X_1, X_2) = \frac{\partial V(X_1, X_2) / \partial \ln X_1}{[\partial V(X_1, X_2) / \partial \ln X_1] + [\partial V(X_1, X_2) / \partial \ln X_2]}$$

Similarly, given any demand function  $\omega_1$ , if this equation holds then  $V$  equals, up to an arbitrary monotonic transformation, the indirect utility function that corresponds to  $\omega_1$ . It follows that

$$\lambda [\omega_1 (X_1, X_2)] = \ln \left( \frac{\partial V (X_1, X_2)}{\partial \ln X_1} \right) - \ln \left( \frac{\partial V (X_1, X_2)}{\partial \ln X_2} \right) \quad (22)$$

Given any functions  $g_1 (X_1)$  and  $g_2 (X_2)$ , define a corresponding function  $V (X_1, X_2)$  by

$$V (X_1, X_2) = \int_{-\infty}^{\ln X_1} e^{g_1(X_1)} d \ln X_1 + \int_{-\infty}^{\ln X_2} e^{-g_2(X_2)} d \ln X_2. \quad (23)$$

Substituting equation (23) into equation (22) gives

$$\lambda [\omega_1 (X_1, X_2)] = g_1 (X_1) + g_2 (X_2) \quad (24)$$

which shows that, up to monotonic transformation, equation (23) is the indirect utility function that generates the demand equation (24). Since equation (23) is additive, this shows that the indirect utility function that generates the demand equation (24) is additive.

To go the other direction, given any differentiable functions  $h_1 (X_1)$  and  $h_2 (X_2)$ , if  $V (X_1, X_2) = h_1 (X_1) + h_2 (X_2)$  equation (22) equals

$$\lambda [\omega_1 (X_1, X_2)] = \ln \left( \frac{\partial h_1 (X_1)}{\partial \ln X_1} \right) - \ln \left( \frac{\partial h_2 (X_2)}{\partial \ln X_2} \right) \quad (25)$$

which is in the form of equation (24), showing that any additive indirect utility function generates a demand equation in the form of (24).

Together these results prove the first part Theorem 3. Adding back the Barten scales  $U_1$  and  $U_2$  to the functions  $g_1$ ,  $g_2$ ,  $h_1$ , and  $h_2$  proves equations (9) and (8). The properties of the functions  $h_1$  and  $h_2$  given at the end of Theorem 2 follow from the fact that the indirect utility function  $h_1 (U_1 P_1 / M) + h_2 (U_2 P_2 / M)$  must possess the standard properties of all indirect utility functions, i.e., homogeneity and quasiconvexity in  $P_1, P_2$ , and  $M$ , nondecreasing in each price, and increasing in  $M$ .

**PROOF of Theorem 4:** When  $X_{(k)} = 0$  we get  $\tilde{Y} = G_k (X_k U_k) + \sum_{j \neq k} G_k (0) = G_k (X_k U_k)$ . Define  $\tilde{Y}_k = G_k (X_k U_k)$ . It follows that  $F_{\tilde{Y}_k | X_k, X_{(k)}, Z} (\tilde{y}_k | x_k, 0, z) = F_{\tilde{Y} | X, Z} (\tilde{y}_k | x_k e_k, z)$ , so  $F_{\tilde{Y}_k | X_k, X_{(k)}, Z} (\tilde{y}_k | x_k, 0, z)$  is identified, given by Lemma 1 that  $F_{\tilde{Y} | X, Z}$  is identified. Let  $r = H_k (\tilde{y}_k)$  be inverse of the function  $G_k$  where  $\tilde{y}_k = G_k (r)$ . Now consider any particular positive  $x_k \in \Psi_k$ . For that  $x_k$  we have  $F_{\tilde{Y}_k | X, Z} (y_0 | e_k, z) = F_{\tilde{Y}_k | X, Z} (\tilde{y}_k | e_k x_k, z)$  and

since the function  $F_{\tilde{Y}_k|X,Z}$  is identified, the particular value  $\tilde{y}_k$  that satisfies this equation is identified. Then

$$\begin{aligned} \Pr(G_k(x_k U_k) \leq \tilde{y}_k \mid X = x_k e_k, Z = z) &= \Pr(G_k(U_k) \leq y_0 \mid X = x_k e_k, Z = z) \\ &= \Pr(G_k(U_k) \leq y_0 \mid Z = z) \\ F_{U_k|Z}[H_k(\tilde{y}_k)/x_k, z] &= F_{U_k|Z}[H_k(y_0), z] \end{aligned}$$

similarly, if we have a given negative  $x_k \in \Psi_k$  then

$$\begin{aligned} 1 - \Pr(G_k(x_k U_k) \leq \tilde{y}_k \mid X = x_k e_k, Z = z) &= \Pr(G_k(U_k) \leq y_0 \mid X = x_k e_k, Z = z) \\ 1 - \Pr(U_k \geq H_k(\tilde{y}_k)/x_k \mid X = x_k e_k, Z = z) &= \Pr(U_k \leq H_k(y_0) \mid Z = z) \\ F_{U_k|Z}[H_k(\tilde{y}_k)/x_k, z] &= F_{U_k|Z}[H_k(y_0), z] \end{aligned}$$

By invertibility of  $F_{U_k|Z}$  these equations show that for any  $x_k \in \Psi_k$  we get  $H_k(\tilde{y}_k)/x_k = H_k(y_0)$  where the  $\tilde{y}_k$  corresponding to the given  $x_k$  is known. Now  $G_k(1) = y_0$  means that  $H_k(y_0) = 1$ , so  $H_k(\tilde{y}_k) = x_k$ , and therefore  $\tilde{y}_k = G_k(x_k)$ , so the value of the function  $G_k$  evaluated at this particular  $x_k$  is known. This holds for any and hence all  $x_k \in \Psi_k$ , so by Assumption A2' this suffices to identify the function  $G_k$  everywhere, and hence also identifies the function  $H_k$  everywhere.

Given identification of  $F_{\tilde{Y}_k|X,Z}$  and of  $H_k(\tilde{y}_k)$ , the distribution function  $F_{U_k|Z}$  is identified by  $F_{U_k|Z}[H(\tilde{y}_k)/x_k \mid z] = F_{\tilde{Y}_k|X,Z}(\tilde{y}_k \mid e_k x_k, z)$  for  $x_k > 0$  and  $F_{U_k|Z}[H(\tilde{y}_k)/x_k \mid z] = 1 - F_{\tilde{Y}_k|X,Z}(\tilde{y}_k \mid e_k x_k, z)$  for  $x_k < 0$ .

**PROOF Theorem 5:** First observe that Lemma 2 still holds in this model, identifying  $F_{U_0|Z}$  by taking  $X = 0$ . Similarly, all the interaction terms  $X_j X_k$  equal zero when  $X = e_k x_k$  for any  $k$ , so the proof of Theorem 1 goes through to identify each  $F_{U_k|Z}$  and  $G_k$  function. Next, for each  $j, k$  pair evaluate the model at  $X = e_{jk}$  to get  $Y = V_{jk} + U_{jk}$  where  $V_{jk} = U_0 + G_k(U_k) + G_j(U_j)$ . At this stage the distribution of  $V_{jk} \mid Z$  is identified (because each component is identified), so  $F_{U_{jk}|Z}$  can be identified by a deconvolution of  $Y \mid Z$  with  $V_{jk} \mid Z$ .

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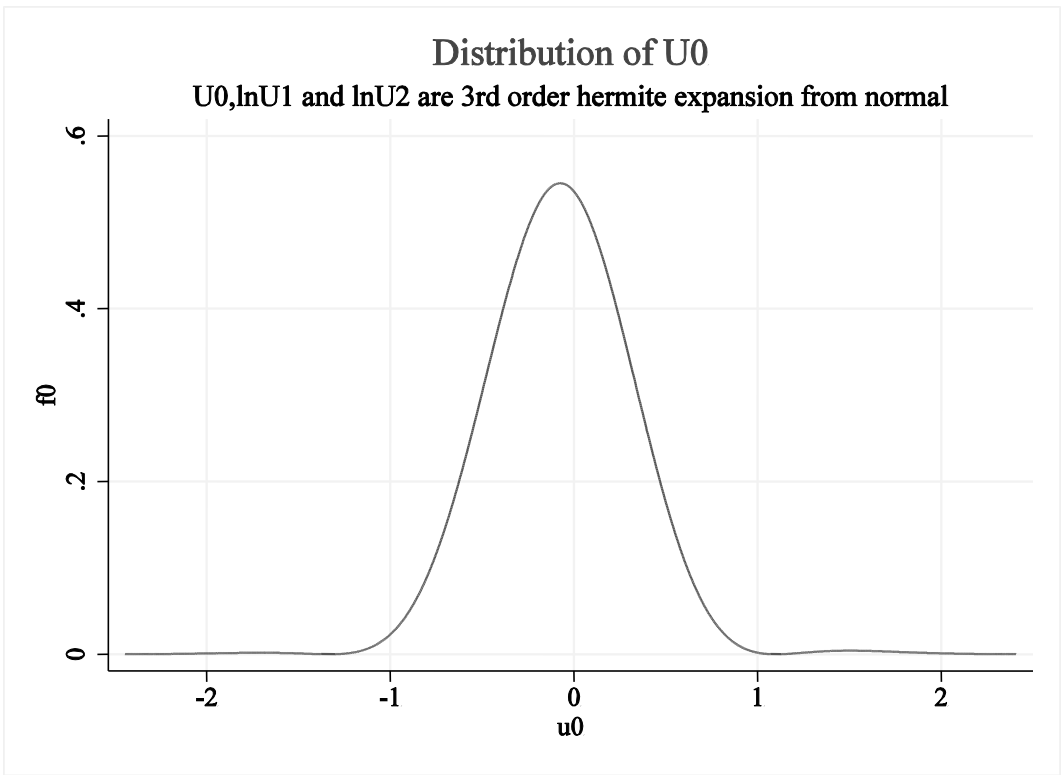
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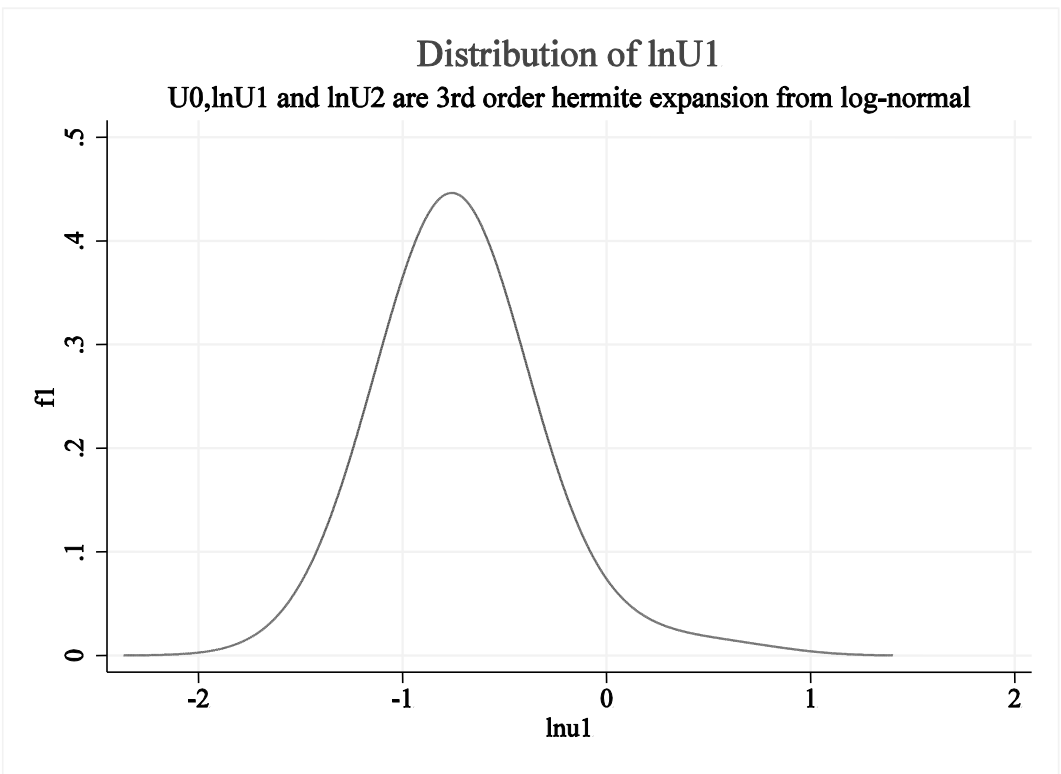
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**Figure 1**



**Figure 2**



### Single-Adult (Reference) Households, India, 2003

5th,10th,25th,50th,75th,90th,95th percentiles of U1

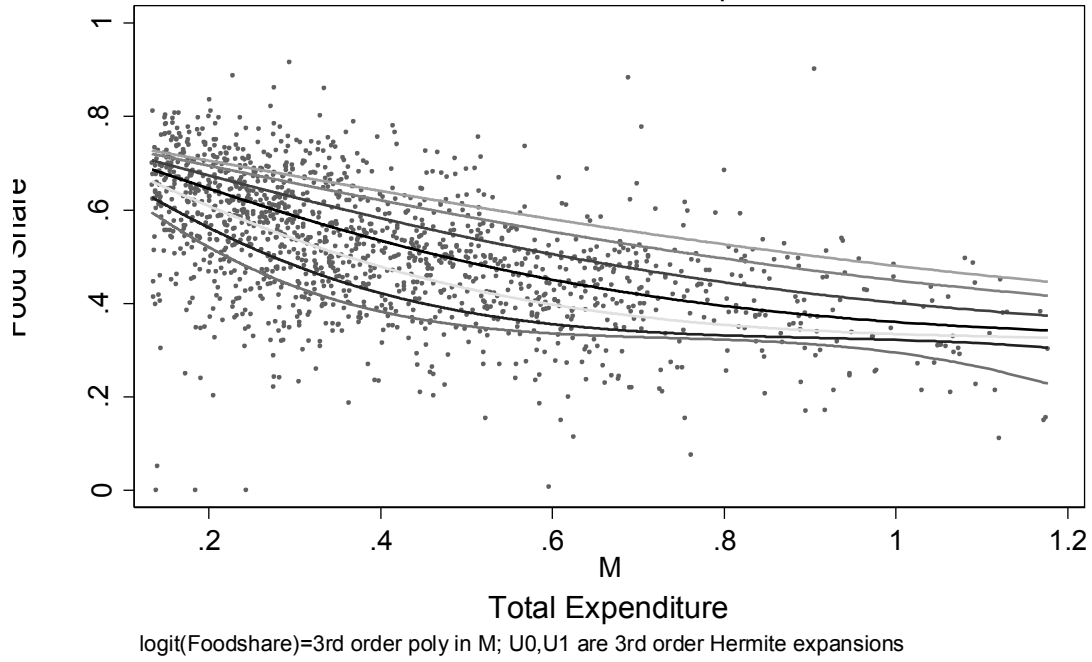


Figure 3

### Two-Adult Households, India, 2003

5th,10th,25th,50th,75th,90th,95th percentiles of U1

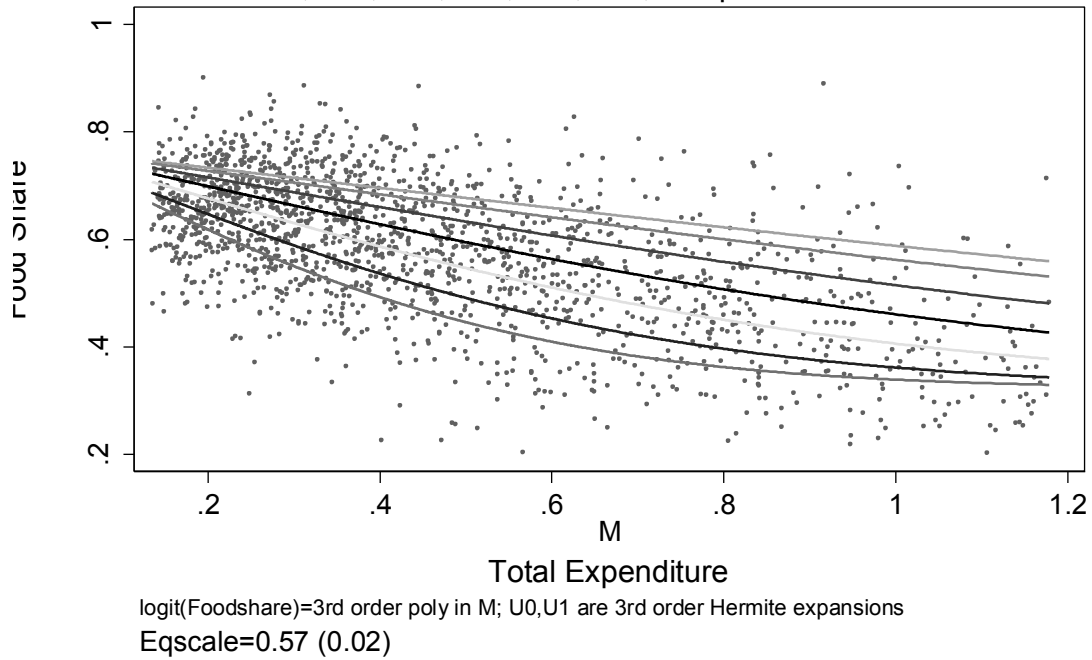


Figure 4

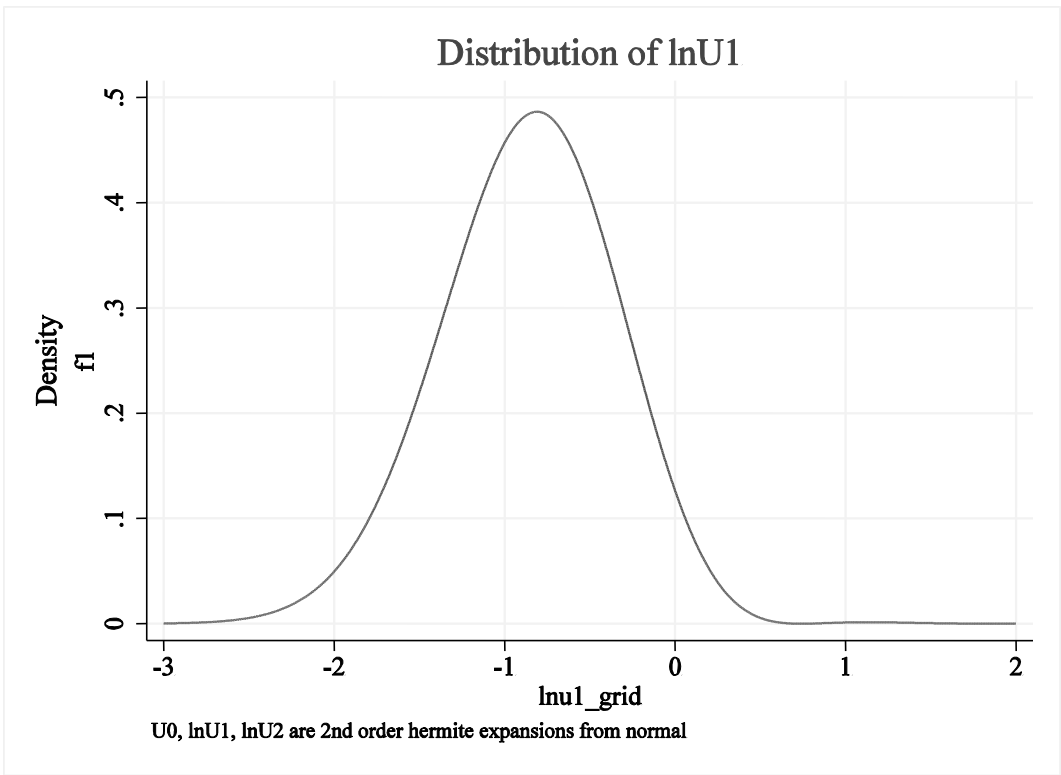


Figure 5

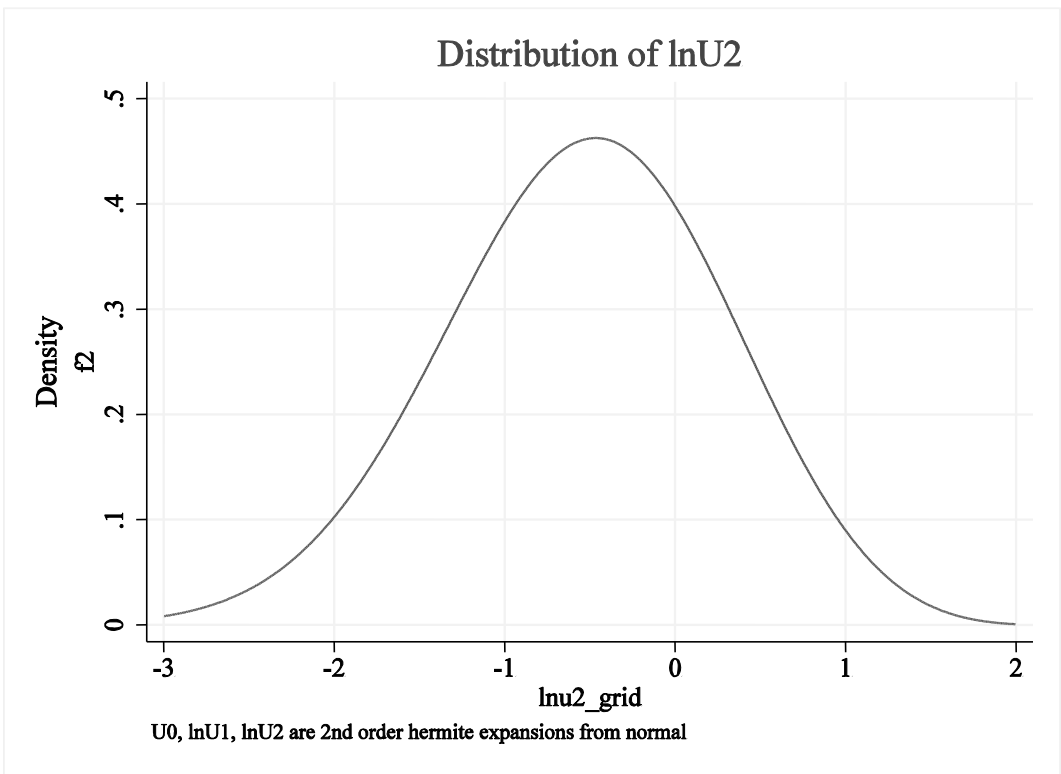
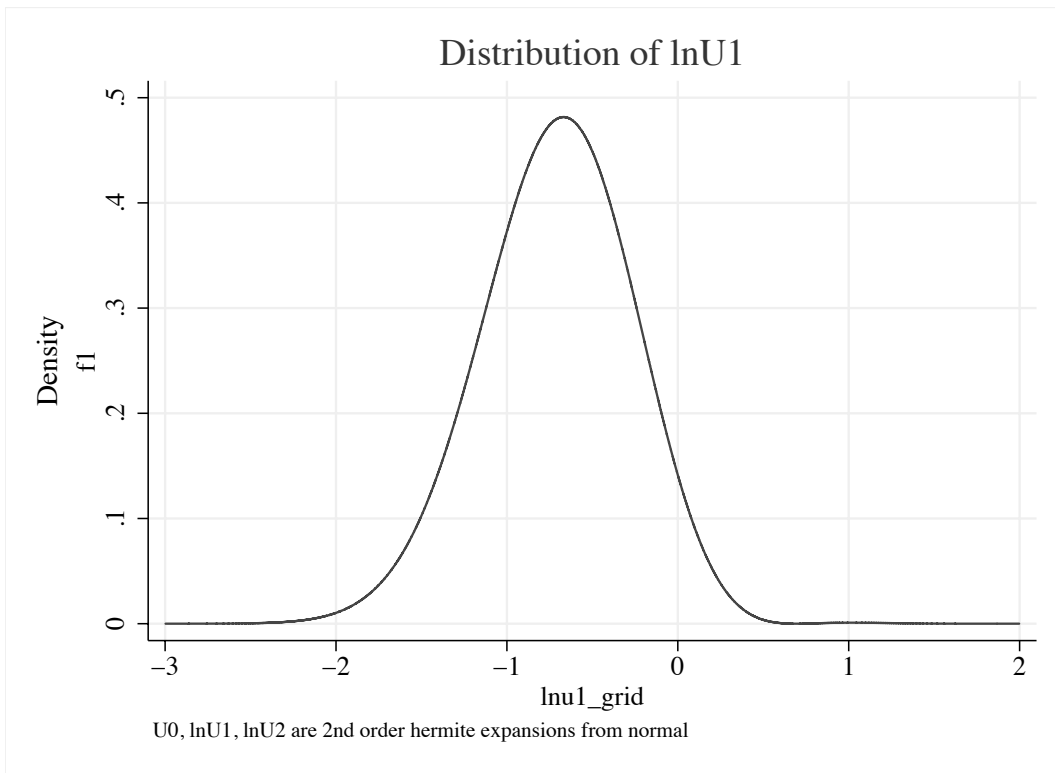
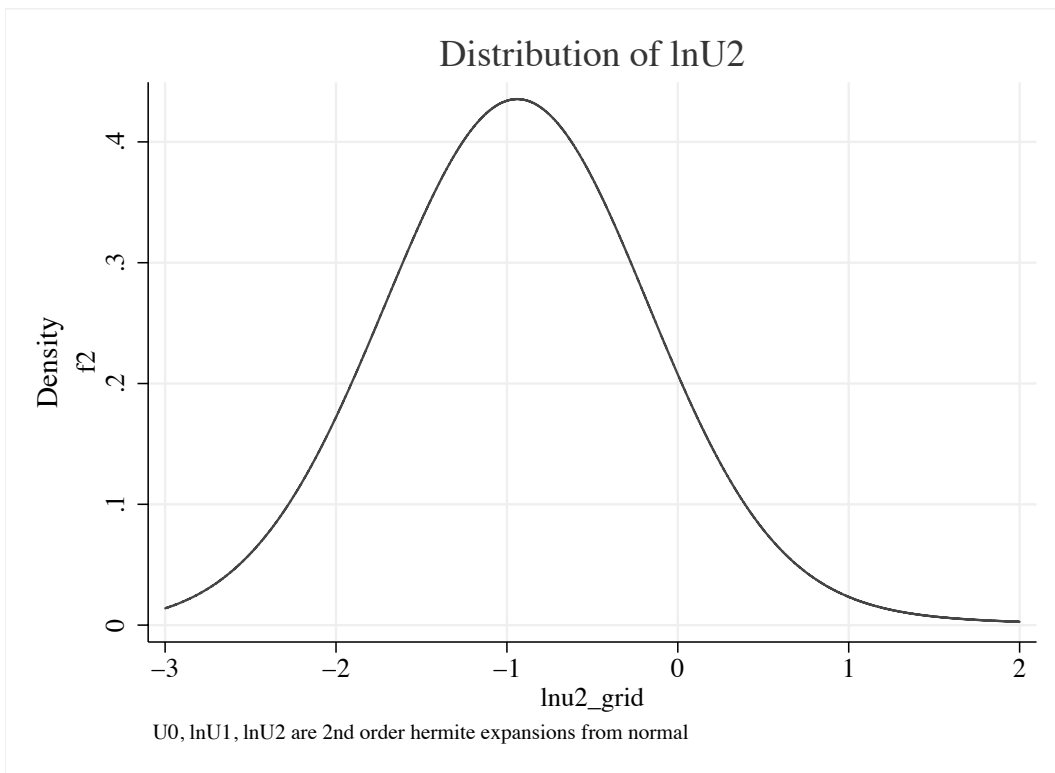


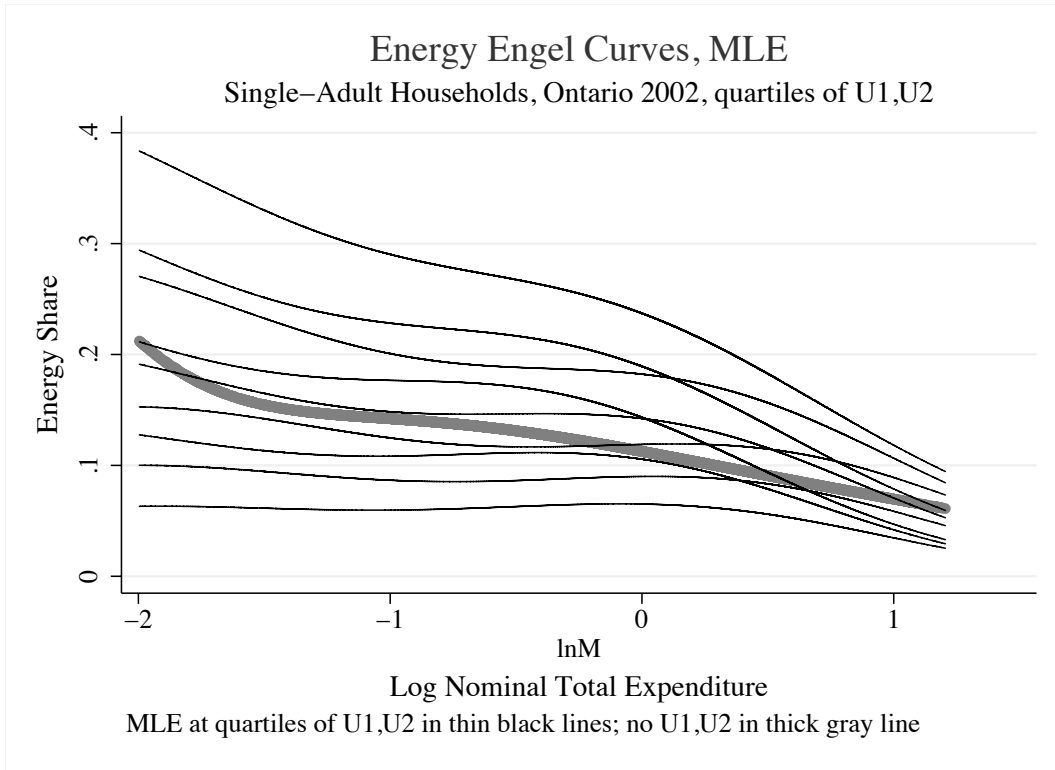
Figure 6



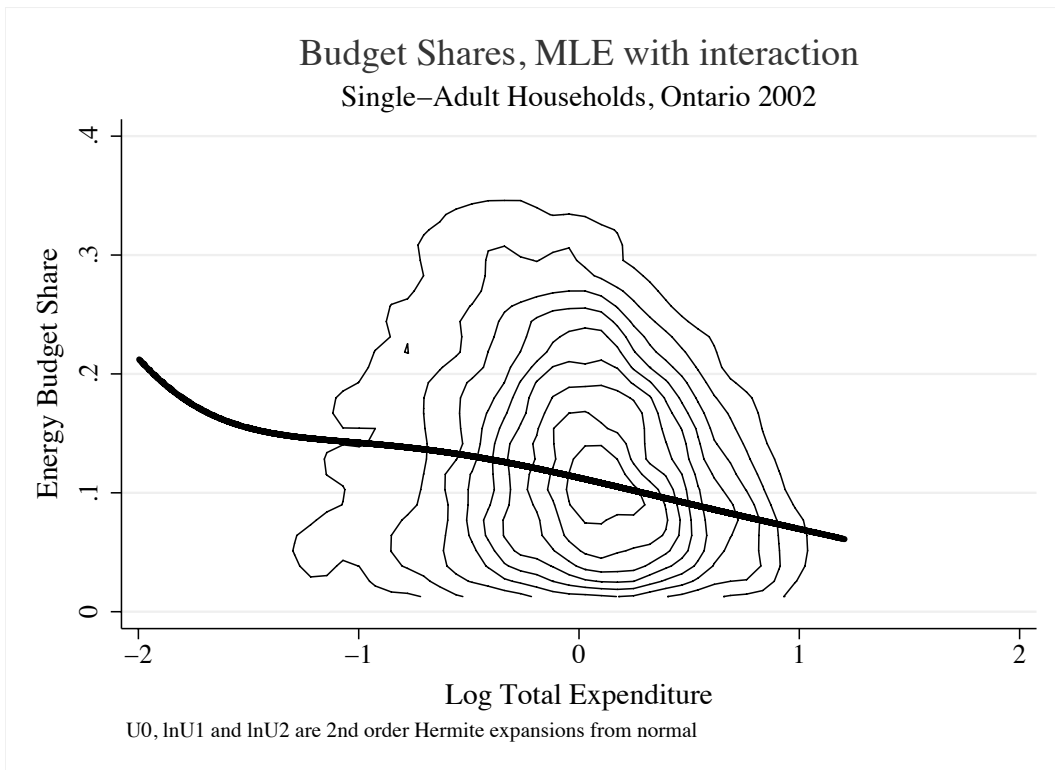
**Figure 7**



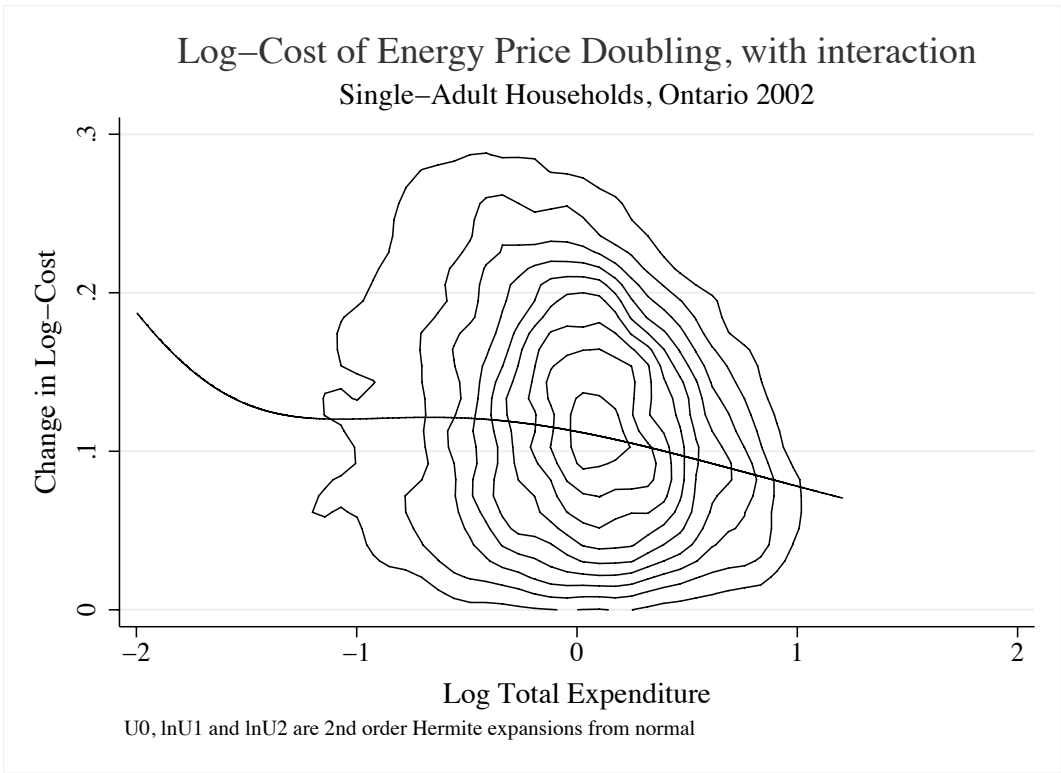
**Figure 8**



**Figure 9**



**Figure 10**



**Figure 11**