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# Individual discounting, energy conservation, and household demand for lighting

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**Abstract**

This paper analyzes household appliance purchase and energy consumption and conservation related to demand for lighting. The behavioral model is estimated using data on consumers' choices between various types of electric light bulbs with large differences in purchase costs, operating costs and lifetimes. The model allows the utility attached to energy conservation per se to vary across consumers and explicitly takes into account the random nature of the lifetimes of lamps. Due to the panel nature of the data and the differences between lifetimes of high-efficiency and low-efficiency lamps, the consumer's discount rate can be estimated without assuming that he correctly perceive the operating costs. The estimated annual discount rate is about 15 percent, somewhat lower than most estimates is earlier studies.

*JEL classification:* D12; Q20

*Keywords:* Energy consumption; Individual discounting; Binary panel data

## 1. Introduction

Household demand for heating, cooling and lighting are examples where the appliances available on the market offer substantial possibilities for tradeoffs between purchase and operating costs. The tradeoff possibilities in the lighting

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case are due to the recent though wide availability of the so-called Compact Fluorescent Lamp (CFL). As compared to a conventional electric light bulb, its initial purchase price is about thirty times as high, but it uses 80 percent less electricity and its lifetime is about eight times as long.

In various countries programs have been initiated which should promote the use of lamps with high energy efficiency. Given the fact that household demand for lighting services accounts for about one quarter of household electricity consumption, [1] the programs might play an important role in energy conservation policies. Most programs include financial incentives such as discounts on the purchase costs of high-efficiency lamps or taxes on low-efficiency versions; see Mills (1991) for a review.

As emphasized by Lewis and Sappington (1992), knowledge of consumer's preferences regarding energy consumption and conservation is crucial for an accurate welfare assessment of incentive programs. Results of some earlier studies have suggested that the returns consumers require on energy efficiency investments are much higher than the capital market rate of return. [2] The debate initiated by these results suggests that the existence of information barriers, in particular regarding the operating costs of durables, is one important explanation.

The present paper provides new empirical evidence on consumers' preferences with respect to energy-using durables using information that differs from that used in earlier studies in a number of respects.

First, we analyze household demand for lighting services. In view of its share in total household electricity consumption and the potential for conservation, the lighting case has received very limited attention as compared to household demand for heating and cooling. From the viewpoint of economic modeling the interesting aspect of the lighting case is the large difference between the lifetimes of high-efficiency and low-efficiency lamps. This introduces an additional element of discounting in the consumer's decision problem. It is not only the trade-off between purchase and operating costs that plays a role, but also the tradeoff between paying a high purchase price relatively infrequently, or paying a lower purchase price more frequently.

Secondly, our data consists of consumer's hypothetical choices between different types of electric light bulbs, for a number of different values of purchase costs. The use of hypothetical survey data is sometimes criticized because of a possible lack of incentives for participants to make accurate assessments. On the other hand, there are important advantages over data on actual purchases. The first is that – as we shall see from the description of the survey – both the consumer's

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[1] Source: Kemna et al. (1991, appendix G).

[2] Hausman (1979) estimated a model of the purchase and utilization of air-conditioners, with an implied average annual discount rate of 26.4 percent. In a similar analysis for water–space heaters, Dubin and McFadden (1984) arrived at an estimate of 20.5 percent. The results have been discussed by Loewenstein and Thaler (1989) and Fisher and Rothkopf (1989).

choice set and information set are defined much more precisely then would be the case with actual purchases data. The second advantage is that the survey allows to confront the consumer with a variation in prices that is much larger than the price variation in actual purchase data. The limited price variation in data on actual purchases would be unlikely to allow for the estimation of the price sensitivity parameters with reasonable precision. [3]

Finally, the panel aspect of the data allows for the incorporation of individual specific fixed effects in the econometric model. Combined with the difference in lifetimes between low-efficiency and high-efficiency versions this makes it possible to estimate the discount rate without assuming that the respondents correctly perceives the operating costs.

The paper is organized as follows. Section 2 develops a behavioral model. In particular, the role of assumptions with respect to the time horizon of the decision maker, the lifetime of the durables, and other characteristics of the durables than costs are investigated. Section 3 briefly describes the data (a more detailed data description is provided in Appendix A. The model is estimated using a method proposed by Chamberlain (1984) for estimating discrete choice models in the presence of fixed effects. The econometric details as well as the empirical results are presented and discussed in Section 4. Section 5 concludes.

## 2. Behavioral model

The questions in our survey refer to replacing a light bulb for a particular type of lamp in the respondent's household. We therefore model the choice between a low-efficiency and a high-efficiency light bulb conditional on a particular degree of utilization. It is important to emphasize that we do not assume that the availability of high-efficiency versions has no effect on utilization. What we do assume is that the respondent, when answering the questions, does not anticipate that he might change utilization.

The following notation will be used:

$R_i$: the purchase price of type $i$, $i = \mathrm{L,H}$;
$T_i$: lifetime (utilization hours) of type $i$, $i = \mathrm{L,H}$;
$\tau_i$: electricity use per hour of utilization (kilowatt hours) of type $i$, $i = \mathrm{L,H}$;
$p$: respondent's perception of electricity price per kilowatt hour;
$h$: hours of utilization per day.

L and H refer to the low-efficiency and high-efficiency version of the durable, respectively. We assume $\tau_\mathrm{L} > \tau_\mathrm{H}$, $R_\mathrm{L} < R_\mathrm{H}$ and $T_\mathrm{L} < T_\mathrm{H}$.

Assume that the consumer compares the discounted costs of types L and H over

[3] Within the context of individual discounting hypothetical survey data have been used before by e.g. Fuchs (1982) and Cropper et al. (1992).

the fixed lifetime $T_H$ of one type H lamp. Suppose that a type H lamp, purchased at $t = 0$, operates $h$ hours per day. Then it provides its services from $t = 0$ until its failure on day $t = T_H/h$. Generating the same services using type L would require purchasing type L lamps at $t = 0$, $t = T_L/h$, $t = 2T_L/h, \ldots, t = (T_H/T_L - 1)T_L/h$. (It is assumed throughout that $T_H/T_L$ is integer). The operating costs are paid continuously, but with a possible time lag of length $D(\geq 0)$. Then the discounted operating and purchase costs of types L and H are given by

$$C_L^* = \int_D^{(T_H/h)+D} ph\tau_L \cdot e^{-\delta t} dt + R_L \left\{ \sum_{k=0}^{(T_H/T_L)-1} e^{-\delta k T_L/h} \right\}$$

$$= \frac{ph\tau_L}{\delta} \cdot e^{-\delta D} \cdot \left(1 - e^{-\delta T_H/h}\right) + R_L \left( \frac{1 - e^{-\delta T_H/h}}{1 - e^{-\delta T_L/h}} \right) \tag{1}$$

and

$$C_H^* = \frac{ph\tau_H}{\delta} \cdot e^{-\delta D} \cdot \left(1 - e^{-\delta T_H/h}\right) + R_H, \tag{2}$$

respectively. Here $\delta$ is the consumer's discount rate per day.

It may also be hypothesized that the operating and purchase costs are evaluated over a multiple $M$ of $T_H$, assuming that in case of failure a lamp is replaced by a new one of the same type. In that case both Eq. (1) and Eq. (2) are multiplied by $(1 - \exp(-\delta M T_H/h))/(1 - \exp(-\delta T_H/h))$. Since this does not affect the sign of $C_L^* - C_H^*$, the choice of $M$ is immaterial. We choose $M = \infty$.

The assumption of deterministic lifetime is unlikely to be a good approximation of reality. In fact, product information often mentions the lifetime 'on average', or makes some other statement in probability terms. Assume that the lifetime $t_i$ is a random variable with expectation $T_i$. Then (for $M = \infty$) the expected discounted purchase and operating costs of type $i$, $i = \mathrm{L}, \mathrm{H}$, are given by

$$C_i = \frac{ph\tau_i}{\delta} \cdot e^{-\delta D} + \frac{R_i}{1 - \mathrm{E}(e^{-\delta t_i/h})} \tag{3}$$

(see Appendix B). In the sequel we shall consider the case with fixed lifetimes and the case with random lifetimes and constant hazard rates. In the latter case $\mathrm{E}(\exp(-dt_i)) = (1 + dT_i)^{-1}$, so that $C_i = e^{-\delta D} \cdot p\tau_i/d + R_i(d + 1/T_i)/d$, with $d := \delta/h$.

Since the high-efficiency and the low-efficiency versions are not exactly identical in all other respects than purchase price, operating costs and lifetime, the choice will most likely not be based on mere cost minimization. Consumers may also prefer a high-efficiency lamp per se because it is claimed that they are preferable from an environmental point of view. For these reasons we assume that the utility generated by a lamp of type $i$ is given by $U_i = \gamma_i - C_i$, $i = \mathrm{L}, \mathrm{H}$, and that behavior is determined by utility maximization. Then type H is chosen if and only if

$$C_{\mathrm{L}}-\gamma_{\mathrm{L}}>C_{\mathrm{H}}-\gamma_{\mathrm{H}}. \tag{4}$$

Substituting Eq. (3) into Eq. (4) and rewriting yields

$$p(\tau_{\mathrm{L}}-\tau_{\mathrm{H}})\cdot \mathrm{e}^{-\delta D}-R_{\mathrm{H}}\left(\frac{d}{1-\mathrm{Ee}^{-dt_{\mathrm{H}}}}\right)+R_{\mathrm{L}}\left(\frac{d}{1-\mathrm{Ee}^{-dt_{\mathrm{L}}}}\right)$$
$$+(\gamma_{H}-\gamma_{\mathrm{L}})d>0. \tag{5}$$

Since $p$ enters linearly in Eq. (5), it may be interpreted as the mean of a distribution function describing the respondent's perception of various possible values of the electricity price. In Section 4 empirical analogues of Eq. (5) will be estimated.

## 3. Data

The information that will be analyzed are the individual's choices out of a set of 9 different electric light bulbs in case A (floor-lamp) and out of 13 different electric light bulbs in case B (hanging-lamp). In both cases two light bulbs were of the high-efficiency type. Let the respondents be indexed by $n=1,\ldots,N$. In each case, the $t$th choice of respondent $n$ is characterized by a price vector $\boldsymbol{p}_{nt}$ and a scalar $y_{nt}$ which is 1 if a high-efficiency lamp is chosen and 0 otherwise. Thus the choice states have been pooled into two groups. [4] The number of choices varies across respondents. Appendix A provides further details on the data collection and explains how the number of choices per respondent is determined. We also observe for each respondent a vector of individual characteristics $\boldsymbol{x}_n$. Table 1 summarizes the data.

The values of h that will be used below are based on a detailed Dutch survey on household electricity use (Kemna et al., 1991). For case A we use $h=0.808$ and $h=0.891$, which are the mean and the median hours, respectively, of utilization per day (yearly average) for floor-lamps in the representative household. For case B we use the mean ($h=1.72$) and the median ($h=2.28$) utilization for hanging-lamps.

[4] To test whether this dichotomization is acceptable I estimated a multinomial logit model and performed a test for pooling states; see Cramer and Ridder (1991). In view of the presence of the fixed effects (see Section 4), the multinomial logit model was estimated using only the first choice of each respondent. The explanatory variables were FEMALE and dummies for AGE and SOCA. The pooling hypotheses were rejected at the 5% significance level but not at the 1% level.

Table 1
Sample characteristics

| Variable | Mean | S.d. | Min | Max |
|---|---|---|---|---|
| *Case A* [a] | | | | |
| No. of choices per individual | 14.6 | 7.3 | 5 | 31 |
| Fraction of type H choices per individual | 0.15 | | | |
| Fraction of resp. who only choose type H | 0.10 | | | |
| Fraction of resp. who only choose type L | 0.60 | | | |
| Price of type H ($R_H$) | 15.60 | 9.61 | 10.00 | 45.00 |
| Price of type L ($R_L$) | 2.48 | 1.15 | 0.90 | 7.44 |
| *Case B* [b] | | | | |
| No. of choices per individual | 13.3 | 8.1 | 5 | 37 |
| Fraction of type H choices per individual | 0.08 | | | |
| Fraction of resp. who only choose type H | 0.02 | | | |
| Fraction of resp. who only choose type L | 0.72 | | | |
| Price of type H ($R_H$) | 13.31 | 7.92 | 10.00 | 45.00 |
| Price of type L ($R_L$) | 2.88 | 1.54 | 0.90 | 9.13 |
| *Individual characteristics* | | | | |
| AGE between 18 and 34 | 0.33 | | | |
| AGE between 35 and 49 | 0.32 | | | |
| AGE between 50 and 65 | 0.35 | | | |
| FEMALE | 0.52 | | | |
| SOCA1 [c] | 0.27 | | | |
| SOCA2 [c] | 0.20 | | | |
| SOCA3 [c] | 0.21 | | | |
| SOCA4 [c] | 0.32 | | | |

[a] Number of individuals: 125.
[b] Number of individuals: 126.
[c] Constructed on the basis of income and education (not provided separately). SOCA1 corresponds to the lowest income and education levels, SOCA4 to the highest.

## 4. Estimation

In view of Eq. (5), the following binary choice model with fixed effects will be estimated:

$$\begin{cases} y_{nt}^* & = \alpha_n + \beta_H R_{H,nt} + \beta_L R_{L,nt} + \epsilon_{nt} \\ y_{nt} & = \mathrm{H} \quad \text{if} \quad y_{nt}^* > 0 \\ & = \mathrm{L} \quad \text{otherwise} \end{cases} \tag{6}$$

with $\alpha_n = p(\tau_L - \tau_H) \cdot e^{-\delta D} + (\gamma_{Hn} - \gamma_{Ln})d$, $\beta_L = d/(1 - E\exp(-dt_L))$ and $\beta_H = -d/(1 - E\exp(-dt_H))$; $y_{nt} = 1$ if respondent $n$ chooses type H at choice $t$, and $y_{nt} = 0$ otherwise. The error term $\epsilon_{nt}$ represents i.i.d. optimization errors. We expect $b_L > 0$ and $b_H < 0$, with $b_i$ being an estimate of $\beta_i$, $i = \mathrm{L}, \mathrm{H}$. Given that

$T_H > T_L$, we should have, moreover, that $|b_L| > |b_H|$. Estimates of $d$ are obtained by solving $d$ from $b_L/b_H = -(1-\exp(-dT_H))/(1-\exp(-dT_L))$ for the case $t_i = T_i$, and from $b_L/b_H = -(1/T_L + d)/(1/T_H + d)$ for the case $t_i \sim \exp(1/T_i)$.

The interesting feature of this way of identifying $d$ is that it does not use any of the components of the fixed effect. Thus the estimate does not require the respondent to have a correct perception of the operating costs, and it allows the preference parameters $\gamma_H$ and $\gamma_L$ to vary across respondents. This is possible due to the panel nature of the data and to the fact that $T_L \neq T_H$. It is the trade-off between different combinations of present and future purchase costs that identifies $d$. Note that d would not be identified if $T_L = T_H$.

Due to the design of the experiment (see Appendix A), a strong preference of a respondent for type H lamps (i.e. a large value $(\gamma_H - \gamma_L)$) will result in a relatively large number of observed price combinations with high values of $R_H$ and low values of $R_L$. In fact, the prices and the number of observations per respondent are endogenous variables in the sense that they depend on the respondent's previous choice. However, the appropriate likelihood function is the likelihood function of choices conditional on prices and number of observations, as shown in Appendix B. The correlation between individual effects and prices is reflected by the upper panel of Table 2 which shows wrong signs for price effects in a logit specification for Eq. (6) with fixed effects ignored. Because the correlation between the individual effects $\alpha_n$ and prices prohibits the use of a random effects estimator, we use the estimator for the fixed effects logit model proposed by Chamberlain (1984). The estimator exploits the fact that in the logit model the probability of observing a particular sequence of choices conditional on $\Sigma_t y_{nt}$ is independent of $\alpha_n$. As a result the $\beta$'s can be estimated consistently without estimating the $\alpha$'s.

Table 2
Estimation results ($t$-values in parentheses)

| | Case A | Case B |
|---|---|---|
| *No fixed effects* | | |
| Constant | −2.17 | −3.88 |
| | (−11.8) | (−16.5) |
| $R_L$ | −0.280 | 0.140 |
| | (−4.8) | (2.6) |
| $R_H$ | 0.060 | 0.065 |
| | (8.7) | (8.2) |
| *With fixed effects* | | |
| $R_L$ | 0.483 | 0.725 |
| | (4.5) | (4.7) |
| $R_H$ | −0.216 | −0.143 |
| | (−6.0) | (−4.5) |

Table 3
Implied discount rates (asymptotic standard errors in parentheses)

| | Median utilization | Mean utilization |
|---|---|---|
| *Case A* | | |
| Fixed lifetimes | 0.173 | 0.191 |
| | (0.045) | (0.050) |
| Constant hazard rates | 0.172 | 0.189 |
| | (0.068) | (0.075) |
| *Case B* | | |
| Fixed lifetimes | 0.122 | 0.092 |
| | (0.055) | (0.041) |
| Constant hazard rates | 0.075 | 0.056 |
| | (0.040) | (0.030) |

The estimation results for the fixed effects logit model are displayed in the lower panel of Table 2. All estimates have the expected signs and relative magnitude and are highly significant.

The annual discount rates implied by the models in the case of fixed lifetimes are reported in Table 3. In accordance with the information on the packaging of the light bulbs, we used $T_L = 1000$ and $T_H = 8000$. The discount rates are somewhat lower than those obtained by Hausman (1979) and Dubin and McFadden (1984). The high estimates of these authors have been partly attributed to a possible ignorance or underestimation of the operating costs from the part of the consumer. The present estimates, however, do not rely on the accurateness of the consumer's perception of the operating costs.

If the consumer anticipates that lifetimes are random, all discounts rates become lower (although in case B the difference is much larger than in case A). In Kooreman (1995) it was shown that the discount rate obtained under the assumption that lifetimes are random cannot exceed the discount rate obtained under the assumption of fixed lifetimes, *if* the two versions have the same lifetime distribution. However, the result need not hold when the lifetimes have different distributions, as in the present case. [5]

We have also estimated the model with the discount rate being allowed to depend on individual characteristics. The results suggest a negative relationship between the discount rate and the respondent's social class and a higher discount for women as compared to men, but the coefficients were not significantly different from zero.

[5] This is illustrated by the following example. Let $R_H = 1200$, $R_L = 800$, $D = 0$, $p\tau_H = 1$, $p\tau_L = 25$, $T_H = 20$, and $T_L = 10$. Denote the solution of $C_L(d) = C_H(d)$ by $d_F$ when lifetimes are fixed, and by $d_S$ when lifetimes follow exponential distributions. Then $0.127 = d_F > d_S = 0.110$. But if $T_H = 40$, with the other parameters unchanged, $0.147 = d_F < d_S = 0.185$.

Table 4
Price elasticities

| Prices | $Pr(y=1)$ | Elasticities with respect to | |
|---|---|---|---|
| | | $R_L$ | $R_H$ |
| *Case A* | | | |
| $R_H=15$; $R_L=2.5$ | 0.15 | 1.03 | −2.72 |
| $R_H=15$; $R_L=5.0$ | 0.37 | 1.52 | −2.03 |
| $R_H=10$; $R_L=2.5$ | 0.34 | 0.80 | −1.42 |
| $R_H=10$; $R_L=5.0$ | 0.64 | 0.88 | −0.79 |
| *Case B* | | | |
| $R_H=15$; $R_L=2.5$ | 0.08 | 1.68 | −1.96 |
| $R_H=15$; $R_L=5.0$ | 0.35 | 2.38 | −1.39 |
| $R_H=10$; $R_L=2.5$ | 0.15 | 1.55 | −1.21 |
| $R_H=10$; $R_L=5.0$ | 0.52 | 1.73 | −0.68 |

The elasticities of the probability of a choice for type H with respect to the purchase prices of both types are given in Table 4. [6] The numbers show strong price responses at all price levels and indicate that price changes will be effective as an instrument to increase the penetration of high-efficiency lamps to the desired level. [7]

The present penetration rate of high-efficiency lamps in the Netherlands is about 9 percent of the total number of light bulbs. [8] At the current electricity price and average market prices of lamps, a consumer who behaves on the basis of mere cost minimization will replace approximately 9 percent of the household's light bulbs by a high-efficiency type if his discount rate is about 30 percent. [9] The fact that our estimated discount rates are lower indicates that for most consumers the preference parameter $(\gamma_H - \gamma_L)$ is negative. Thus most consumers seem to have a ceteris paribus preference for the conventional types. A reason could be that most high-efficiency lamps are larger than their low-efficiency counterparts. This suggests that the production of high-efficiency lamps that are more similar in size and shape to the conventional light bulbs should be encouraged.

[6] The elasticities were calculated using $Pr(y=1)=(1+\exp(-(\alpha+b_L R_L+b_H R_H)))^{-1}$, with $\alpha$ chosen such that at average prices $Pr(y=1)$ equals the sample frequency of $y=1$.

[7] The objective of the Dutch *Environmental Action Plan* is that in 1996 85 percent of all light bulbs should be of the high-efficiency type.

[8] Author's estimate on the basis information in Kemna et al. (1991) and nation wide sales figures.

[9] This follows from solving $\delta$ from $C_L=C_H$ (see Eq. (3)), with $R_H=37.5$, $R_L=1.5$, $T_H=8000$, $T_L=1000$, $\tau_H=0.015$, $\tau_L=0.075$, $p=0.21$, $D=0$ and $h=2.78$). The value for $h$ is the 9% upper quantile of the distribution of utilization hours. The solution for $\delta$ is 36.8 percent with fixed lifetimes and 26.6 percent with constant hazard rates.

## 5. Conclusions

In this paper, an econometric model is estimated which describes consumer behavior with respect to appliance purchase and energy consumption for lighting. All estimated coefficients were in accordance – in sign, size and significance – with the theoretical model, and imply strong responses with respect to purchase prices. The implied discount rates appear to be somewhat lower than the Hausman (1979) estimate within the context of household demand for cooling and the estimate of Dubin and McFadden (1984) within the context of demand for heating. The high estimates of Hausman and Dubin and McFadden have been partly attributed to a possible ignorance or underestimation of the operating costs from the part of the consumer. The present estimates however do not rely on the accurateness of the consumer's perception of operating costs.

The estimated discount rates are still somewhat higher than the capital market rate of return. Apart from possible specification errors with respect to functional form in the econometric model, an explanation might be that the consumer takes the expected lifetime of a high-efficiency lamp to be shorter than indicated by the manufacturer, for example because of the hazard of breakage. This interpretation is supported by the fact that the model in which consumers take the random nature of lifetimes into account yields lower estimated discount rates. If consumers perceive the hazard of failure to be larger than the actual failure rate, incentive programs might include a warranty arrangement for the case of an early failure. Another explanation for a discount that exceeds the market rate of interest is the existence of liquidity constraints, in which case the utility companies could buy the appliances and lease them to their customers. To distinguish between these explanations, future surveys should contain direct questions on liquidity constraints and on the consumer's perception of the actual lifetime of the durable.

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## Appendix A. Description of the survey

The data analyzed in this paper were collected in November 1991 by a Dutch marketing agency. At different locations in the Dutch Rimcity a number of individuals were interviewed about replacing electric light bulbs. Participants in the survey were between 18 and 65 years of age and had indicated that they were the ones in their household who usually decided on lamp replacement.

The participants entered a room with nine burning light bulbs which were different with respect to energy use, lifetime, purchase price, size, shape and possibly character of illumination. The respondent was allowed to read the information on the original packaging of the light bulbs, which included information on lifetime and energy use, but not on the electricity price. Next a picture of a floor-lamp was shown to the respondent and the following question was asked: "Suppose you have to replace a light bulb for a floor-lamp like the one on the picture. Suppose that these products were for sale in a store at the prices as indicated here. Which one would you buy?" After the individual had chosen one type, the price of the preferred type was increased. Next the individual was asked to choose again. The experiment continued until the highest price of a type was reached. For each type five different prices were prespecified. So the minimum number of choices observed for a respondent is five (if he sticks to the type of his first choice) while the maximum possible number of choices is 45.

Next, the experiment was repeated for the case of a hanging-lamp, with a choice set of 13 different light bulbs.

## Appendix B. Derivations

### B.1. Eq. (3)

Let $s_1 < s_2 < s_3 < \ldots$ be the random points in time at which the durable fails and is replaced by a new one of the same type. Using the fact that $s_1, (s_2 - s_1), (s_3 - s_2), \ldots$ are independent drawings from the probability density function of $t_i/h$, the discounted purchase and replacement costs can be written as

$$\begin{aligned} &\mathrm{E}\left[R_i(1 + e^{-\delta s_1} + e^{-\delta s_2} + e^{-\delta s_3} + \ldots)\right] \\ &= \mathrm{E}\left[R_i(1 + e^{-\delta s_1} + e^{-\delta s_1} \cdot e^{-\delta(s_2 - s_1)} \right. \\ &\left. + e^{-\delta s_1} \cdot e^{-\delta(s_2 - s_1)} \cdot e^{-\delta(s_3 - s_2)} + \ldots)\right] \\ &= R_i \sum_{k=0}^{\infty} (\mathrm{E} e^{-\delta t_i/h})^k = \frac{R_i}{1 - \mathrm{E} e^{-\delta t_i/h}}, \end{aligned} \tag{B.1}$$

which is the second term in Eq. (3). The first term gives the discounted operating costs:

$$\int_D^{\infty} ph\tau_i \cdot e^{-\delta s} ds = \frac{ph\tau_i}{\delta} \cdot e^{-\delta D}. \tag{B.2}$$

### B.2. Likelihood function

Let $r_{H,1},\ldots,r_{H,T}$ be the prespecified prices for type H and $r_{L,1},\ldots,r_{L,T}$ the prespecified prices for type L. We consider the case $T=2$; the extension to the general case is straightforward.

At the first choice, the prices are $(R_{H,1}, R_{L,1})=(r_{H,1}, r_{L,1})$. The prices faced at the second choice are $(R_{H,2}, R_{L,2})=(r_{H,2}, r_{L,1})$ if $y_1=1$ and $(R_{H,2}, R_{L,2})=(r_{H,1}, r_{L,2})$ if $y_1=0$. Thus choices are determined by the signs of

$$\begin{cases} y_1^* = \alpha + \beta_H r_{H,1} + \beta_L r_{L,1} + \epsilon_1 \\ y_2^* = \alpha + \beta_H [y_1 r_{H,2} + (1-y_1) r_{H,1}] + \beta_L [y_1 r_{L,1} + (1-y_1) r_{L,2}] + \epsilon_2 \end{cases} \tag{B.3}$$

Due to the recursive nature of Eq. (B.3) ($y_1^*$ does not depend on $y_2$), the model does not require any coherency conditions; cf. Heckman (1978). Since the survey design defines a one-one relationship between choice sequences and price sequences, maximization of the likelihood function of choices conditional on prices constitutes a full information maximum likelihood procedure.

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