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Durables and lemons: Private information and the market for cars

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Private information on car quality means the sale price reflects the average quality of cars sold, which can be lower than the average quality in the population. This difference is the lemons penalty imposed on holders of high-quality cars. We estimate the evolution of the lemons penalty through an equilibrium model of car ownership with private information using Danish linked registry data on car ownership, income, and wealth. We examine the aggregate implications and distributional consequences of these penalties. In the first year of ownership, we estimate that the lemons penalty is 12% of the price. The penalty declines sharply with the length of ownership. It reduces the self-insurance value of cars and leads to a large reduction in transaction volumes and the rate of car turnover. The market does not collapse: income shocks induce households to sell their cars, even if

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they are of good quality, and this helps mitigate the lemons problem. The size of the lemons penalty declines when income uncertainty in the economy increases and when the supply of credit decreases.

KEYWORDS. Lemons penalty, asymmetric information, car market, income uncertainty, life-cycle equilibrium model.

JEL CLASSIFICATION. D15, D82, E21.

1. Introduction

Cars form a substantial fraction of assets for many lower-income and young people, and as such could be a source of wealth available to smooth consumption in difficult times. However, in common with many other durable goods, the market for second-hand cars can be very imperfect because owners often know more about them than buyers. The market thus discounts the price of second-hand cars to match the possibility of hidden defects, and this, in turn, causes a reduction in the quality of cars supplied to the market. As Akerlof (1970) pointed out, the market can unravel, eradicating the role of cars as a store of value. In this paper, we empirically examine the importance and consequences of this insight in an economic environment where there are additional market failures, including credit constraints and missing markets for income risk.

We address two central issues. First, how asymmetric information affects equilibrium in the second-hand car market in an economy with financial constraints—namely, how large is the lemons penalty, how does it affect car turnover, and who benefits or loses from the lack of information. Second, how does asymmetric information—and the resulting price penalty—interfere with households' ability to smooth income shocks by using the value stored in cars, a ubiquitous and high-value durable.

For our empirical work, we use highly detailed Danish population-wide administrative data, focusing on a period with complete information about car ownership from 1992–2009. The core data set is the Central Register of Motor Vehicles (CRMV), a register that contains information about the entire population of cars registered with Danish number plates. We link this register data to longitudinal income-tax records with information about the income and wealth of the owners. Finally, we merge the prices of all new and used cars on the market. To the best of our knowledge, no other data set collects longitudinal information about cars, income, and wealth, and we exploit these unique features of the data to inform the model.

The car market in Denmark has key advantages for quantifying the lemons penalty: there is no manufacture of new cars in Denmark, and the vast majority of Danish households either own no cars or own just one. More than 90% of used car transactions occur through dealerships, the dealership market is thick, and with relatively low levels of concentration. Further, during this period, car leasing was virtually nonexistent in Denmark, allowing us to abstract from the leasing market.[1]

[1] Hendel and Lizzeri (2002) develop a theoretical model of leasing under adverse selection. They highlight that the presence of leasing contracts segments the market and is only preferred by high-income households. In our model, the presence of income shocks plays a significant role in preventing the second-hand market from collapsing.

To define and quantify the lemons penalty and to understand its implications, we specify and estimate an equilibrium life-cycle model of car ownership, consumption, and other asset accumulation with stochastic income and unemployment shocks in an environment with borrowing constraints. We assume cars depreciate at a stochastic rate, with at least part of this depreciation being private information to the owner.

For simplicity, we assume all individual car transactions are intermediated by dealers. Dealers buy cars from households without knowing their exact quality, fix them, and sell them back to households as second-hand cars.[2] In equilibrium, dealers are offered cars that, on average, are of lower quality than similar cars in the population. They, therefore, pay a lower price than they would have if there were no asymmetric information, and this difference is the lemons penalty.

In the standard Akerlof (1970) model, the second-hand market unravels because of such asymmetric information: The lower the price of second-hand cars, the lower the quality of offered cars. However, in our context, the market does not unravel for two key reasons. First, the presence of income shocks and liquidity constraints implies that some people sell their cars to recover liquidity for smoothing consumption. Since income shocks are independent of depreciation, the average quality of these "forced sales" is higher than the quality of cars sold by those without liquidity concerns. Second, some people are willing to bear the implicit transaction cost induced by asymmetric information in order to enjoy the utility of a new car.

In our model, the lemons penalty is an equilibrium concept that endogenously generates a transaction cost for second-hand cars, affecting households who wish to change the quality stock of the car they own (move to a new car or downgrade to a cheaper one, for example). This cost depends on the number and type of cars flowing in and out of the car market. The rate at which cars are bought and sold depends on households' access to credit and their ability to accumulate liquid savings to purchase cars and smooth consumption. Without other means of borrowing, the purchase of a car would have to be financed by sacrificing current consumption, which reduces the flows in and out of the car market. Thus, it is critical to also model liquid asset accumulation.

We use a method of simulated moments estimator (McFadden (1989), Pakes and Pollard (1989)) using data for households where the oldest member is aged 30–60 in the period 1992 to 2009. The targeted moments include the ownership rates of cars, the pro-

[2]Asymmetric information may arise on different sides of the car market. In our model, we assume that dealers either have sufficient access to credit or are large enough to have the ability to offer short-term warranties to buyers of second-hand cars, thereby solving the lemons issue in that segment of the second-hand market. Dealers can sell cars of different quality, but we assume that the presence of short-term warranties makes this as good as observable. Warranties primarily address pre-purchase concerns, providing households with confidence that the car they are purchasing is not a lemon at that time. Warranties do not extend to post-purchase shocks or issues that may arise after the initial sale. Warranties do not eliminate the possibility of lemons in the market, particularly when households sell their cars to dealers. This is consistent with the evidence in Biglaiser, Li, Murry, and Zhou (2020). In our model, the only point at which asymmetric information is an issue is when private households sell to dealers. This market structure also explains why the private-to-private market is limited in Denmark, and indeed in our paper, we assume this market away. Additionally, while the dealer in our model has the ability to refurbish cars, this differs from Akerlof's classic lemons model, where quality deterioration is irreversible.

portion of households buying new cars, the proportion of cars sold by ownership duration, average ownership duration of cars, and holdings of financial assets, with some of these moments split by age and education.

Our empirical results suggest that the lemons penalty is particularly large early on in ownership. This reflects the difference between the average quality in the population and the average quality of cars sold. A car that has been owned for just 1 year has the biggest lemons penalty if it is sold: 12% of the original purchase price. This is in addition to a 19% decline in the price due to expected depreciation. In the second year, the penalty falls to 6% of the original purchase price, in addition to a cumulative decline of 33% of the original purchase price due to expected depreciation. Thereafter, the lemons penalty declines quickly as ownership duration increases. The high lemons penalty for cars of short ownership duration suppresses their transactions, and this, in turn, reinforces the size of the penalty as it is mainly those with particularly low-quality cars who will sell.[3] However, as mentioned above, the second-hand car market does not collapse because households have different motives for selling their cars: income shocks lead some to sell high-quality cars despite the lemons penalty they then have to incur. As a result of this mechanism, we show that the lemons penalty tends to be smaller when the overall income risk is higher and when the credit limit is lower, because more high-quality cars are put on the market. The economic implications of such a mechanism are important. Asymmetric information and car ownership limit income smoothing opportunities. The lemons penalty delays car replacement substantially and reduces the probability of downgrading to another lower-quality car in response to an adverse income shock. Interestingly, in high-risk environments, when the lemons penalty is smaller, cars become more liquid. Finally, the lemons penalty has distributional consequences: owners of good-quality cars lose, and owners of "lemons" benefit because both receive the same price due to asymmetric information.

Such empirical implications are important in themselves and, in addition, help validate the model, supporting the notion that the transaction costs are indeed endogenous and due to asymmetric information. In estimation, we identify the extent of the lemons penalty by fitting the observed duration structure of car ownership. We can then compare how our model fits the rate of car downgrading following an income shock to the fit of a model estimated assuming full information but allowing for a known transaction cost. The implications of the two models for consumption smoothing and car downgrading are fundamentally different, with the symmetric information model implying a much higher rate of downgrading following an income shock than either the data or the asymmetric information model.

Our study links to the literature on consumption smoothing and shocks, including Deaton (1991), Browning and Crossley (2009), Blundell, Pistaferri, and Preston (2008), Low, Meghir, and Pistaferri (2010), and Kaplan and Violante (2014). If there is no private information (generating a transaction cost) and with sufficient continuity in the quality

[3] Hendel and Lizzeri (1999a) show that a sharp price decline correlated with suppressed transactions is evidence of a lemons penalty, whereas a sharp price decline correlated with large transactions is evidence of depreciation.

of cars (as in our model), then a durable good is like a nondurable in that there is perfect reversibility. The transaction cost induced by information asymmetry introduces an irreversibility that reduces the value of a durable good as an asset that can be used to smooth consumption. A key feature of our approach is the recognition that transaction costs are, in part, endogenous and driven by current economic circumstances and credit availability for households to purchase cars. Fluctuations in economic circumstances and restricted access to credit lead to changes in the lemons penalty: the penalty is smaller when car sales are motivated more by the need for liquidity rather than being driven by the presence of low-quality cars.

Our study focuses on understanding the importance of asymmetric information as a mechanism to describe the nature of trade in the car market. However, we also include other features that may be important for describing consumer behavior, such as credit market conditions, fixed transaction costs, and the value placed on having new products rather than used ones. These features are likely to be present in any market for second-hand goods, such as the clothes market, even where asymmetric information is less likely to play a role.

For example, Fernández-Villaverde and Krueger (2011) study the effect of borrowing constraints on the stock of durables in a life-cycle model that allows borrowing against durables. However, they do not have hidden information, and thus abstract from endogenous adjustment costs. Attanasio, Goldberg, and Kyriazidou (2008) and Alessie, Devereux, and Weber (1997) highlight the importance of credit conditions for car demand, and we also document that car transactions are associated with substantial changes in financial asset holdings in our data.[4]

Previous papers have modeled car ownership and replacement decisions as affected by transaction costs. Lam (1991), Eberly (1994), Attanasio (2000), and Foote, Hurst, and Leahy (2000) present Ss-models of car ownership where exogenous transaction costs create inaction regions, or Ss-bands, within which households do not upgrade or downgrade their cars. More recently, Attanasio, Larkin, Ravn, and Padula (2022) and Gavazza and Lanteri (2021) incorporate aggregate shocks into Ss-style models to study the dynamics of durable goods adjustment during the Great Recession. Attanasio et al. focus on exogenous transaction costs, whereas in Gavazza and Lanteri, illiquidity in the secondary market comes from credit constraints and equilibrium price effects. Our paper differs in that it models private information about car quality as the source of endogenous transaction costs, with resale penalties that depend on unobserved heterogeneity. Further, these models do not explore how transaction costs vary with the supply of cars to the secondary market, nor with the age of the car being sold. The distributional implications of endogenous transaction costs related to unobserved quality differ from those arising in models with exogenous transaction costs, as we discuss in Sections 6 and 7 below.

The literature on whether information asymmetry exists in the used car market is mixed. Some papers find no evidence of asymmetric information problems. Adams,

[4]In Figure A.1 in Appendix A, we document using the administrative data that financial asset holdings change significantly at the time when households buy cars.

Hosken, and Newberry (2011), for example, use data for Chevrolet Corvettes sold on eBay auctions and do not find evidence about adverse selection. On the other hand, Genesove (1993) finds evidence supporting adverse selection by comparing the prices of used cars sold in the wholesale used car market by used car dealers and by new-car dealers. Emons and Sheldon (2009) analyze used car sales in Switzerland and find support for the lemons problem by testing both for the adverse selection by sellers and for the quality uncertainty among buyers. Biglaiser, Li, Murry, and Zhou (2020) compare the transaction price of dealers with those in unmediated sales to find evidence of asymmetric information. These papers focus on the market where private individuals buy cars, whereas we focus on asymmetric information when households sell to dealers.

This paper connects with the literature emphasizing the dynamic relationship between the market for new cars and the used car market. Rust (1985) formulates the first dynamic equilibrium model of automobile trading, which assumes perfect information and no transaction costs. Hendel and Lizzeri (1999b) incorporate adverse selection into a dynamic model of new and used cars in which the only shock is a shock to car quality. They show that asymmetric information implies fast price declines and low volumes of transactions.

Our work builds on the dynamic lemons framework pioneered by House and Leahy (2004), who analyze a stylized economy with three-period-lived cars and no quality depreciation. We extend their setup in three ways. First, trade in our model is often “forced” by observed income and liquidity shocks under borrowing constraints, rather than by unobserved match shocks. This mechanism is disciplined by Danish registry data and lets us study how the lemons penalty feeds back into households’ ability to smooth consumption—an interaction that House and Leahy abstract from. Second, we embed the lemons market in a full life-cycle model with liquid assets, credit limits, and cars that can survive up to 12 years. This richer structure is necessary to fit the panel of car ownership, income and wealth, and to study how household income risk and borrowing constraints influence the endogenous penalty. Third, we take the model to population-wide micro data and estimate the penalty and its welfare implications using simulated-moments methods. These extensions allow us to quantify not only the price wedge but also its distributional and self-insurance consequences, which lie at the heart of this paper.

Further literature has focused on policies affecting the secondary car market, and thus the primary market, such as scrappage subsidies (Adda and Cooper (2000), Schiraldi (2011)) and gasoline prices (Busse, Knittel, and Zettelmeyer (2013)). Gavazza, Lizzeri, and Roketskiy (2014) allow households to own up to two vehicles and find that transaction costs have a large effect on equilibrium trade. GIMR+ (2022) develop a dynamic equilibrium model with multiple types of new and used cars, where prices and quantities of used cars are determined endogenously. However, both models rely on exogenous transaction costs to approximate trade frictions and, therefore, cannot capture the evolution of asymmetric information.

The next section presents the model and details about the solution method. Section 3 presents and describes the data, and Section 4 outlines the estimation approach. Section 5 presents the results on the lemons penalty and further shows how the lemons penalty changes as the amount of uncertainty over incomes increases and the credit limit decreases. Section 6 shows the case of symmetric information. In Section 7, we investigate the impact of asymmetric information on the downgrading of cars, and Section 8 concludes.

2. Model of the car market

Households derive utility from the quality of their car, which depreciates stochastically with ownership duration. The key information asymmetry is that the quality of any particular car remains private information to the owner. Used cars are traded only through dealers, who cannot ascertain the car's quality beyond what can be inferred from ownership duration. Dealers can refurbish cars to a functional state comparable to 1-year-old cars. In each period, car owners decide whether to keep, scrap, or sell their car. Those who are not owners have the option to buy either a new or a used car from a dealer. Owners typically want to sell cars of poor quality, but binding liquidity constraints may force them to sell even high-quality cars to meet financial needs. The used car market is, therefore, a mix of lemons and high-quality cars. The price of new cars is set externally to the model, but second-hand car prices are determined in equilibrium to align demand and supply.

More formally, the economy is stationary and consists of T overlapping generations. Households maximize life-cycle expected utility. They draw utility from cars and from other consumption, and they face an exogenous but stochastic stream of income. Their choices include consumption, car purchase or sale, and saving in a liquid asset. All car transactions are mediated by dealers. We denote a period in the life cycle by t, and this should be understood as age. We first describe the nature of cars and car dealer behavior, then the household problem, and finally, the equilibrium in the car market. A period in the model is 1 year. Consumers enter the model at age 21, retire after age 61, and leave the model at age 79.

2.1 *Cars and dealers*

Our focus is on the lemons penalty that arises because of private information that accumulates during the ownership period. We therefore simplify the problem and only keep track of the length of ownership and not of the age of the car since it was new. This is based on the assumption that the car repair by the dealer resets the asymmetric information and the quality of the car sold is fixed at 1. This implies that the dealer offers a short-term warranty, thus removing any concern about hidden defects. By contrast, the actual quality of cars that dealers are buying from households is unknown to the dealer.

A car owned by household i in period t has quality q_{it} and ownership duration $z_{it} \in \{0, 1, \dots, \bar{z}\}$. We use z to denote the duration of ownership and q to denote the car quality. Cars also differ in their type τ: new (n), second-hand (u), or bangers (b). By "bangers," we refer to minimally functional cars at the lowest level of quality, q^b. We use the term "Regular cars" to describe those bought either as new or second-hand. A newly purchased regular car sold by dealers has an ownership duration of 0 in the period of purchase, and its quality is normalized to 1, representing the highest possible quality. Quality is one-dimensional and evolves over time. It cannot be lower than the minimum quality q^b, which is the quality of a banger. Therefore, the quality q_{it} is constrained to the interval $[q^b, 1]$.

Each period, a regular car receives a persistent and idiosyncratic (for household i that is) quality shock:

$$q_{it+1} - q^b = d\varepsilon_{it}(q_{it} - q^b). \tag{1}$$

The term d is the deterministic depreciation factor. The variable $\varepsilon \in [0, 1]$ is the additional stochastic depreciation factor, which is observable only by the owner and follows a beta distribution $\varepsilon \sim \mathcal{B}(\eta_1, \eta_2)$. In Section 6, we contrast our model with the case of symmetric information when all shocks are publicly observed, to highlight the implications of asymmetric information.

We allow the car to be subject to two additional shocks: First, a car becomes a banger when it has been owned for more than $\bar{z}$ years, or if it suffers a "banger quality shock," which occurs with probability δ^r. Second, a banger has to be scrapped if it receives a "scrappage quality shock" with probability δ^b. Banger status is assumed to be fully observable.

A car can only be bought or sold using a dealer as an intermediary.[5] The only observable characteristic of a used car is how long it has been owned, z, and consequently, the price a dealer will pay to buy the car only varies with ownership duration.[6] Thus, a used car of ownership duration z can be sold to a dealer at dealer price p_z^d. This dealer purchase price $\{p_1^d, p_2^d, \dots, p_{\bar{z}}^d\}$ is endogenous and depends on the distribution of car quality among private sellers. Consistent with modeling the car market of a small open economy, we assume an internationally set price for new cars p^n and that the supply of new cars is infinitely elastic. However, the second-hand car market is purely domestic, with prices locally determined in relation to the internationally fixed price of new cars.

Dealers are risk-neutral and profit-maximizing, but free entry means they make zero profits. A dealer buys a used car from a household and then learns the true quality of that particular car. The dealer fixes the car to have quality 1 (the max) and sells it as a second-hand car with an ownership duration of 0.[7] The price of fixed second-hand cars sold by dealers is p^u. Fixed second-hand cars are of quality 1, and so p^u can be thought of as

[5]According to bilbasen.dk, the largest second-hand car website in Denmark, 90% of the second-hand cars are sold by dealers.

[6]Ideally, we would have included both the age of the car and the duration of ownership as state variables, with car prices being contingent on both car age and ownership duration. However, implementing this approach proved computationally infeasible. As a result, we focus on the impact of ownership duration, with information asymmetries being reset by dealers. This implies that the number of times a car is sold and its true age are irrelevant in the model.

[7]We assume that repairs only occur by dealers who have bought cars and then resell them. If the owner of a car were hiring a mechanic directly to repair the car without selling it, then the customer would have no incentive to hide true quality from the mechanic and is likely to pay the actual repair cost. This is in contrast to the incentive the customer has to incentive to pretend the car is of high quality to the dealer. The availability of mechanics would imply that the owner of a high-quality car is more likely to get it repaired rather than sell it, and the owner of a low-quality car is more likely to sell it to a dealer, worsening the lemons penalty for those selling to dealers.

the price for a unit of quality. If the car bought by the dealer is of lower quality than the average quality of cars of that ownership duration that are sold to dealers, the dealer will lose money on that particular car because the sale price is given by the restored quality and the purchase price depends on the average quality of the cars dealers buy. Our modeling of dealers as repairing all cars for resale is in contrast to Biglaiser and Friedman (1994), where the role of the dealer is to screen out and not resell goods that are of low quality.

Dealers do not hold inventories: the number of second-hand cars sold by dealers equals the number of cars they bought from households. The average quality of cars of duration z that are sold to dealers is $\bar{q}_z$, which is determined by who chooses to sell cars in equilibrium and is a function of all prices. On average, to fix a car of duration z, dealers have to improve the quality from $\bar{q}_z$ to 1 at the cost of $p^u(1-\bar{q}_z)$. The zero-profit condition for the dealer trading at a given ownership duration, z, is

$$p^u - \left[p_z^d + p^u(1-\bar{q}_z)\right] = \bar{q}_z p^u - p_z^d = 0. \tag{2}$$

Thus, the price paid by a dealer for a car of average quality and ownership duration z is equal to the expected value of the car priced at the resale price.

2.2 *Households*

A household, i, can own at most one car at a time.[8] Households have education level, e, which is high or low. The level of education determines both the preferences and the income process. For simplicity, we drop the e subscripts. Utility is defined over consumption, c, car type, τ and car quality q:

$$u(c_{it}, \tau, q_{it}) = \frac{\left(c_{it}\left(1+\theta^\tau q_{it}\right)^\alpha\right)^{1-\gamma} - 1}{1-\gamma}.$$

The parameter α determines the utility value of owning a car. θ^τ indicates the relative preference between car types

$$\theta^\tau = \begin{cases} 0 & \text{if no car,} \\ \theta^n & \text{if car new when bought,} \\ 1 & \text{if car used when bought,} \\ \theta^b & \text{if banger.} \end{cases}$$

The parameter θ^n means people may value new cars differently from second-hand cars, which have been fixed by dealers, despite the same underlying quality, q. And θ^b means people may also value bangers differently.

The household holds liquid assets a_{it} at the beginning of the period t. The evolution of the liquid asset is governed by

$$a_{it+1} = (1+r)[a_{it} + y_{it} - c_{it} - B_{it} p_B + S_{it} p_S], \tag{3}$$

[8] In our administrative data from Denmark, only 10% of households hold more than one car.

where $B_{it} = 1$ if the household buys a car, and $S_{it} = 1$ if the household sells a car. The purchase price p_B is equal to p^n if it is a new car; p^u if it is a second-hand car; or p^b if it is a banger. The selling price depends on the ownership duration: $p_S = p_z^d$ if the car has been owned for z periods, and $p_S = p^b$ if it is a banger, independent of the ownership duration.

We assume that the maximum amount of borrowing is the sale price of a car that has been owned for an additional year. This allows the use of credit to purchase a car, and the amount of credit is dependent on equilibrium prices. Hence, we assume that

$$a_{it+1} \geq -p^d_{z_{it+1}}. \tag{4}$$

Cars are a store of credit up to the expected (equilibrium) resale value p_z^d for cars of ownership duration z. The amount of borrowing against the car is determined at the time of car purchase: there is no refinance, and so households can only access wealth in cars by selling.[9]

In the standard life-cycle model, there is one asset that represents the entire accumulated net wealth of the household. Our model includes a second asset, cars, which is distinct from the liquid asset both because cars generate a flow of utility and because cars are less liquid due to the endogenous transaction costs. This difference in the properties of the assets is introduced in order to capture the effect of illiquid assets on the ability of households to smooth out shocks.

2.2.1 *Income process* Households receive an uncertain flow of labor income y_{it} depending on their level of education e:

$$\begin{aligned} \ln y_{it} &= b_{e0} + b_{e1} Age_{it} + b_{e2} Age_{it}^2 + b_{e3} Z_{it} + r_{it}, \\ r_{it} &= v_{it} + w_{it}, \\ v_{it} &= v_{i,t-1} + \epsilon_{it}, \\ w_{it} &= (1 - U_{it}) \rho w_{i,t-1} + U_{it} \kappa_{it}, \end{aligned} \tag{5}$$

where y_{it} is household disposable income in period t. Z_{it} is a vector of observed household demographic characteristics. The term r_{it} is residual income, with two error com-

[9] In Fernández-Villaverde and Krueger (2011), households can borrow up to the point where they have an incentive to repay their debt. Since their model assumes no hidden information, a household's borrowing capacity is influenced by the quality of the car. In contrast, our model incorporates asymmetric information about car quality. We assume that the maximum amount a household can borrow is the equilibrium resale value of the car. This ad hoc borrowing constraint stems from the household's ability to repay the loan and the Inada condition on utility, which is affected by the lemons penalty rather than car quality. Additionally, if a regular car turns into a banger due to a random banger quality shock, the resale value becomes the banger price p^b. If the car was originally purchased with a loan and the loan amount is greater than p^b, the owner must repay the loan amount higher than p^b in the current period. In this case, we assume that if a car randomly turns into a banger (rather than by the gradual process of ageing), and if the car loan is greater than p^b, the owner will automatically receive an insurance payment equal to the difference between the car loan and p^b. This is to insure the owners from bankruptcy. In Section 5.3, we study the effect of different borrowing constraints. We find that when households have less credit to buy cars, they purchase fewer regular cars and more bangers.

ponents: v_{it} and w_{it}. The first component, v_{it}, reflects a permanent stochastic component to household disposable income; it evolves as a random walk with innovations ϵ_{it}. The second component, w_{it}, captures the impact of job separation. Specifically, upon job separation, household income changes by κ_{it} in addition to the permanent shock.[10] Unemployment in Denmark rarely lasts longer than a year; however, it can have lasting effects on household income (see, e.g., Altonji, Smith, and Vidangos (2013)). To capture this, we allow the original realization of the shock to persist, with an effect that depreciates at an annual rate ρ. U_{it} is a dummy variable equal to one if household i experienced a period of unemployment in year t. We assume that retirement income is a fixed fraction of the household's last labor income. There is no further income risk after retirement.

2.2.2 *Value functions and household choices* In each period, households in the model need to decide how much to consume and how much to save, as well as decide on car ownership. Specifically, a household that does not own a car has to decide whether and what type to buy. Car owners need to decide whether to keep or sell their car, possibly replacing it with a new car, a fixed used car from a dealer, or downgrading to a banger.[11] These decisions are made by comparing value functions for each action.

The state space Ω_{it}^s defines the position of the household at the start of period t. The superscript $s \in \{0, b, n, u\}$ indicates the ownership status of the household entering the period, either no car, a banger, a car bought as new, or a car bought as used. In addition to car ownership, the state space includes: liquid assets a_{it}; car quality q_{it}; duration of car ownership z_{it}; permanent income shock component v_{it}; unemployment-related income shock component ω_{it}.

We define the value function conditional on the ownership decision, τ, in period t, given Ω_{it}^s, as $V_{it}^{\tau}(\Omega_{it}^s)$. The superscript $\tau = \{0, b, n_1, u_1, n_z, u_z\}$ indicates the household purchase (or owning) choice during the period: 0 signifies selling the car or continuing to own no car; b signifies a purchase of a banger or continuing to own a banger; n_1 and u_1 signify a purchase of a car (new or used, resp.), which by definition always has quality 1; n_z and u_z signify keeping the existing car that has been owned for z periods. The unconditional value function can then be written as

$$V_{it}(\Omega_{it}^s) = \begin{cases} \max\left[V_{it}^0, V_{it}^b, V_{it}^{n_1}, V_{it}^{u_1}\right] & \text{if } s = 0, b, \\ \max\left[V_{it}^0, V_{it}^b, V_{it}^{n_1}, V_{it}^{u_1}, V_{it}^{n_z}\right] & \text{if } s = n, \\ \max\left[V_{it}^0, V_{it}^b, V_{it}^{n_1}, V_{it}^{u_1}, V_{it}^{u_z}\right] & \text{if } s = u, \end{cases}$$

where, for clarity, we have dropped the dependency of each conditional value function V_{it}^{τ} on the state variable Ω_{it}^s. Households perform this optimization subject to equation (3) that links the control, consumption c_{it}, to the evolution of liquid assets a_{it}.

[10]The separation shock κ can be either positive or negative. A positive value represents a job transition, and the new job is better paid. A negative value represents an unemployment scarring effect.

[11]For clarity: a current owner can replace the car with a new one, a new second-hand, or a banger. This involves selling and buying in the same period.

Consider a household that decides not to own a car in period t, so $\tau = 0$. This will affect utility in period t, and the household will start the subsequent period with no car. The corresponding conditional value function is given by

$$V_{it}^{0}(\Omega_{it}^{s}) = \max_{c_{it}}\left\{\frac{c_{it}^{1-\gamma}-1}{1-\gamma} + \beta\mathbb{E}_t V_{it+1}(\Omega_{it+1}^{0})\right\} \quad \text{for } s = 0, b, n, u.$$

Consider a household that decides to own a banger in period t, that is, $\tau = b$. The ownership status of the household at the start of period $t+1$ is $\Omega_{it+1}^{s} = \Omega_{it+1}^{b}$, but the banger may become scrapped with probability δ^{b}. Ownership duration, z_{it}, and car quality, q_{it}, are not in the state space for banger-owners because the quality of bangers is constant at q^{b} and so ownership duration plays no role. Thus, the corresponding conditional value function becomes

$$\begin{aligned} V_{it}^{b}(\Omega_{it}^{s}) = \max_{c_{it}}\Bigg\{&\frac{\left(c_{it}\left(1+\theta^{b}q^{b}\right)^{\alpha}\right)^{1-\gamma}-1}{1-\gamma} \\ &+ \beta\mathbb{E}_t\left[(1-\delta^{b})V_{it+1}(\Omega_{it+1}^{b}) + \delta^{b}V_{it+1}(\Omega_{it+1}^{0})\right]\Bigg\} \quad \text{for } s = 0, b, n, u. \end{aligned}$$

Consider a household that enters the period with a car (used or new) and decides to keep the existing car, that is, $\tau = \tau_z \in \{n_z, u_z\}$. The household utility will depend on the given quality q_{it}, which is driven by depreciation rather than directly by choice. The corresponding conditional value function is

$$\begin{aligned} V_{it}^{\tau_z}(\Omega_{it}^{s}) = \max_{c_{it}}\Bigg\{&\frac{\left(c_{it}\left(1+\theta^{\tau}q_{it}\right)^{\alpha}\right)^{1-\gamma}-1}{1-\gamma} \\ &+ \beta\mathbb{E}_t\left[(1-\delta^{r})V_{it+1}(\Omega_{it+1}^{\tau_{z+1}}) + \delta^{r}V_{it+1}(\Omega_{it+1}^{b})\right]\Bigg\} \quad \text{for } \tau_z = n_z, u_z \text{ and } s = n, u. \end{aligned}$$

The car owned in t may become a banger at the start of the next period with probability δ^{r}. If ownership duration exceeds $\bar{z}$, the car becomes a banger in the following period for sure ($\delta^{r} = 1$). The utility enjoyed by the car depends on whether it was originally bought as new or from a dealer.

Finally, consider a household that decides to buy a new or fixed used car in period t, that is, $\tau = \tau_1 \in \{n_1, u_1\}$. The ownership status of the household at the start of period $t+1$ is $\Omega_{it+1}^{s} = \Omega_{it+1}^{\tau_q}$, but the car purchased in t may also become a banger at the start of $t+1$ with probability δ^{r}. The household has a conditional value function of

$$\begin{aligned} V_{it}^{\tau_1}(\Omega_{it}^{s}) = \max_{c_{it}}\Bigg\{&\frac{\left(c_{it}\left(1+\theta^{\tau}\right)^{\alpha}\right)^{1-\gamma}-1}{1-\gamma} \\ &+ \beta\mathbb{E}_t\left[(1-\delta^{r})V_{it+1}(\Omega_{it+1}^{\tau_q}) \right. \\ &\left. + \delta^{r}V_{it+1}(\Omega_{it+1}^{b})\right]\Bigg\} \quad \text{for } \tau_1 = n_1, u_1 \text{ and } s = 0, b, n, u. \end{aligned}$$

2.3 *Equilibrium*

The market for cars is characterized by the price of new cars (p^n), $\bar{z}$ prices for each ownership duration of a second-hand car ($p_1^d, \ldots, p_{\bar{z}}^d$), the price of bangers (p^b) and the price for used fixed cars purchased by households from the dealer (p^u). Households take these prices as given in making their decisions. We model a stationary economy with equal-sized generations of life-cycle households, where prices are fixed over time and can only change as a result of factors that change the demand for cars and the technology for consumption smoothing, such as welfare policies insuring income or perhaps scrappage subsidies. We now describe how these prices are determined in equilibrium.

The key issue is asymmetric information. Car owners receive depreciation shocks, which are not observable by the dealers who are potential buyers. We assume that only the ownership duration of the car is observable. Moreover, we assume the dealer cannot observe characteristics of the household that may be pertinent to the motive for selling the car. This implies that only one price is quoted for all cars with a particular ownership duration.

In determining the price of a car of a particular ownership duration that dealers are willing to pay to households, the key component is the average quality of cars of a given ownership duration coming to the market[12]

$$\bar{q}_z = \mathbb{E}\big(q_i | z, p^n, p^u, p^b, p_1^d, \ldots, p_{\bar{z}}^d, \text{sale}\big).$$

Because individual car quality is private information, dealers will have to offer a pooled price across all qualities given the observable characteristics, which here is just the ownership duration. This implies some households will be *overpaid*, in the sense that the hidden quality of the car is worse than average, and others would be *underpaid*, making a loss.

The information set of the dealer is crucial. Car dealers cannot discriminate between households selling cars in terms of the quality of the cars that they bring to the market. In reality, car dealers may, to some extent, be able to discriminate between car sellers and the quality of cars based on observable characteristics, such as education or occupation, but we abstract from this.

2.3.1 *Defining equilibrium* The price of a new car is exogenous, as Denmark does not produce cars and is too small to affect international prices. Implicit in the price of new cars is the (heavy) taxes that Denmark imposes. These then affect the prices of second-hand cars in equilibrium. The price at which dealers sell fixed second-hand cars is given exogenously.[13] In contrast, the prices at which dealers buy second-hand cars and the

[12]The price that the (risk-neutral) dealer will pay to purchase a car depends on the expected quality of a car for sale. The model is assumed to be stationary and the household is a price taker. This means that the household only has the vector of prices and the quality of their own car in the state space, and we do not have to keep track of the entire distribution of car quality in solving the household problem. However, in calculating the equilibrium conditions, we need to simulate the average quality given the decisions taken by households.

[13]The price of the refurbished car is exogenous to the model but estimated in the data. We have data on dealer sales prices, which we use to estimate the price of a repaired car. If we did not have this data, we

price of bangers are endogenous to the model and are determined by the equilibrium behavior of households and dealers.

We define a stationary competitive equilibrium with adverse selection and no inventories as follows:

- A collection of (endogenous) prices $\mathbf{p} = \{p_1^d, p_2^d, \dots, p_{\bar{z}}^d, p^b\}$,
- Consumption and car ownership decision rules for households $\{c(\Omega_i^s, \mathbf{p}), \tau(\Omega_i^s, \mathbf{p})\}$, which include the following decisions: buying a fixed second-hand car, buying a new car,[14] buying a banger, selling to a dealer a car of ownership duration z and quality q, and selling a banger.
- The dealer's decision rules involve purchasing cars of different ownership durations for all $z \in \{1, \dots, \bar{z}\}$ and selling them as fixed second-hand cars.

These household and dealer decisions generate aggregate outcomes as follows:

- Total number of new cars purchased: Q_n
- Total number of fixed second-hand cars sold by dealers: Q_u^{fix}
- Total number of fixed second-hand cars purchased by households: Q_u^d
- Number of cars of each ownership duration sold to dealers by households, Q_{uz}^s
- Average quality of cars of each ownership duration sold to dealers by households, $\bar{q}_z$
- Total quantity of bangers purchased, Q_b^d, and sold, Q_b^s, by households
- Number of cars of each ownership duration owned by households: Φ_z
- Total stock of regular cars owned by households: $\Phi_r = \sum_{z=1}^{\bar{z}} \Phi_z$, which includes cars purchased new or second-hand but does not include bangers
- Total stock of bangers: Φ_b

Equilibrium prices and quantities are determined by the following market clearing and flow conditions, ensuring consistency with the decisions and interactions of households and dealers.

- **Market clearing conditions:**
  1. **Zero-profit condition:** Dealers make zero profits (equation (2)). This condition applies at each ownership duration z.

could, in principle, solve for the equilibrium price that a dealer sells a car for. However, using the data and treating the price as exogenous forces the model to an equilibrium price vector for the remaining prices, which is consistent with the observed dealer sale price.

[14]The supply of new cars always equals the demand due to the assumption of an infinitely elastic supply of new cars.

2. **Second-hand car dealer market:** Household demand for fixed second-hand cars, Q_u^d, equals the supply from dealers, Q_u^{fix}.

3. **No-inventory condition:** Total number of cars sold to dealers equals fixed cars sold by dealers each period:[15]

$$\sum_{z=1}^{\bar{z}} Q_{uz}^s = Q_u^{\text{fix}}.$$

4. **Market for bangers:** Demand for bangers, Q_b^d, equals supply, Q_b^s.

- **Flow conditions:**

1. **Changes to the stock of bangers:** Total outflow of bangers equals total inflow:[16]

$$\delta_b \Phi_b = \delta_r \Phi_r + \left(\Phi_{\bar{z}}(1-\delta_r) - Q_{u\bar{z}}^s\right).$$

2. **Changes to the stock of regular cars:** Net flow of new cars equals the rate at which cars become bangers:

$$Q_n = \delta_r \Phi_r + \left(\Phi_{\bar{z}}(1-\delta_r) - Q_{u\bar{z}}^s\right).$$

2.3.2 *Equilibrium properties and numerical convergence* In this section, we describe the key properties of the model's equilibrium and present numerical evidence regarding existence and uniqueness.[17] Our model assumes that profit-maximizing dealers make zero profits due to free entry. If an equilibrium exists, the pooling price offered by dealers should ensure that they have zero profits, as described in equation (2). Figure 1 visualizes the existence of a vector of dealer purchase prices that satisfy the zero-profit condition. Figure 1a illustrates how variations in the dealer purchase prices of 1-year-old to 3-year-old cars impact dealer profits, while Figure 1b displays the effect of varying the dealer purchase prices of 4-year-old to 12-year-old cars on profits. The figures reveal a negative correlation between price and profit across used car markets with different ownership durations. For example, as the dealer purchase price of 1-year-old cars increases, the profit for the dealer of 1-year-old cars decreases. As the dealer price changes, there is only one crossing point between the dealer profit curve and the zero-profit line. This single crossing is evidence of the existence and uniqueness of the equilibrium dealer purchase price.

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[15] Cars are repaired and sold in the same period as they are bought from households, and so the dealer's decision to sell a repaired car is dictated by the dealer's decision to purchase a second-hand car.

[16] Regular cars can become bangers, either because they receive a banger shock or because they reach quality level $\bar{z}$ because of long ownership duration.

[17] Due to the complexity introduced by heterogeneous agents, endogenous prices across multiple interconnected car markets, and private information about quality, we are unable to provide a formal proof of equilibrium existence and uniqueness. Instead, we numerically demonstrate that our algorithm converges to an approximate equilibrium. Specifically, we show that there is a single crossing of the zero-profit line for dealers at each ownership duration.

(a) Change dealer purchase prices of 1-year-old to 3-year-old car

(b) Change dealer purchase prices of 4-year-old to 12-year-old car

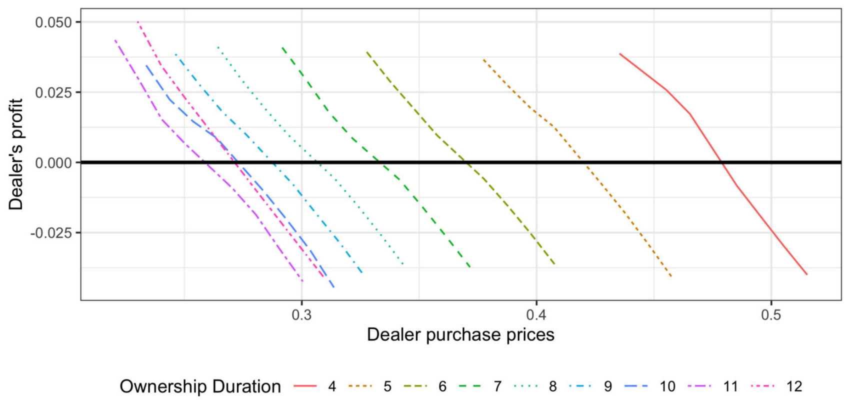


FIGURE 1. The impact of varying dealer purchase prices on dealer profits.

To illustrate the unique crossing of dealers' profits in more detail, we fix the price for a particular ownership duration at different values while varying the price of cars with other ownership durations. For example, we show the cross derivative of 1-year-old car profit with respect to changes in both 1-year-old and 2-year-old car prices. The results, presented in Figure A.3 in Appendix F, reveal a unique crossing between the profit curve of 1-year-old cars and the zero-profit line for different values of 2-year-old car prices. Similar experiments conducted with other age-price pairs yield similar results. Figure A.3 sheds light on the negative correlation between price and profit. As the price paid by dealers for 1-year-old cars rises, the average profit per 1-year-old car decreases through a direct effect. This is offset by the increased quality of the cars that are sold to dealers, which generates a selection effect. The net effect of the direct and selection effects on profits as price increases is a decrease in profits and a single crossing of the zero-profit line.

2.3.3 *Market unraveling* In the original Akerlof (1970) setting, pooled pricing could lead to the market unraveling. The reason is that people holding cars with a quality above the average level will not put their cars on the market. This, in turn, leads to a decline in the dealer purchase price, a downward spiral that continues until the price is zero and no transactions take place. In our model, the market does not unravel for reasons we now outline.[18]

There are three key factors that support the existence of the market in our model. First, the dealer purchase price p_z^d never falls below $q^b p^u$. This means that car owners always have some minimum level of wealth stored in their cars that can be liquidated. To see this, consider the dealer's profit, as defined by equation (2):

$$\pi = p^u - \left[p_z^d + p^u(1 - \bar{q}_z)\right] = \bar{q}_z p^u - p_z^d.$$

Given that used car quality can never dip below the minimum quality q^b, we have

$$\pi = \bar{q}_z p^u - p_z^d \geq q^b p^u - p_z^d.$$

Since dealers always make zero profit, we can deduce

$$\begin{aligned} \pi = 0 &\geq q^b p^u - p_z^d, \\ p_z^d &\geq q^b p^u. \end{aligned}$$

This condition holds true for all $z \in \{1, \dots, \bar{z}\}$. Failure to satisfy this condition would result in dealers earning positive profits from purchasing used cars, which contradicts our model's premise.

Second, there is a utility gain from upgrading. The quality of a car declines with the duration of ownership. An important motivation behind selling an old car is to enjoy the higher quality offered by a new one, and the process of upgrading can be reinforced by a positive income shock.

Third, some households find themselves compelled to sell their cars because they experience adverse income shocks and end up liquidity-constrained. If these constraints become sufficiently binding, they are willing to sell their cars at a price lower than what matches their actual quality, in order to get access to the liquidity otherwise stored in the car. It is precisely such losses that make cars an imperfect smoothing tool and define the transaction costs as endogenous.

To illustrate how income shocks contribute to preventing the used car market from collapsing, in Section 5.2, we present simulations based on the calibrated model where the level of income risk is varied. These simulations show that as the variance of income shocks increases, the percentage of cars being sold rises, as more car sales are driven by income shocks. Conversely, as the variance of income shocks decreases, trade diminishes. This is consistent with the notion that income risk helps sustain market existence, as it is a mechanism that prompts people to put cars on the market for reasons other than possessing private knowledge of their low quality.

[18]This is related to the discussions in Bigelow (1990) and Hendel and Lizzeri (1999a) on constrained efficiency in the Akerlof model and why markets may not unravel.

3. Data

The empirical analysis is based on Danish administrative data. The core data set is the Central Register of Motor Vehicles (CRMV), from which we have data covering the period 1992–2009. This register contains information about the entire population of cars registered with Danish number plates and holds information about the unique identity of all cars in the form of a serial number, the exact registration and deregistration dates, as well as information about the car brand, model, and variant. These data are merged with prices of almost any type of new and used car on the market in the same period as is covered by the CRMV. It is possible to follow the price of any given brand-model-variant-vintage combination from when the car is new until it is 8 years old. The price data are collected by the Association of Danish Car Dealers (DAF) based on market analyses and reports from its members, and they reflect the price of cars in a "normal condition" depending on the age of the car. Going forward, we will refer to these prices as "dealer sale prices," and they define the price at which used cars are bought by households from the dealer.

The CRMV also contains information about the identity of the owner of any given car at any given point in time, and this information is used for linking the car information to other administrative records of the owner. In particular, we link the CRMV with income tax records and a number of other administrative registers, giving longitudinal information about income, wealth, labor market status, education, and family composition of the car owners. In this way, we are able to construct a longitudinal data set, where we can follow the population of Danish households in the period 1992–2009 and give a complete description of their income, wealth, and car ownership. Using this unique feature of the data, we can quantify the extent of the lemons penalty in the car market.

The wealth data can be divided into assets and liabilities, which can further be divided into a number of subcategories. Unfortunately, the definitions of these categories are not stable across the observation period. In particular, the definitions change almost yearly in the period 1992–1996, but from 1997, the definitions are stable, and it is possible to clearly identify financial wealth. Furthermore, the data are longitudinal, which means that we are able to track decisions about the sales and purchases of cars and how these decisions interact with savings decisions. In this way, we are able to examine how households use cars as an asset for smoothing adverse income shocks.

3.1 *Statistics on cars and households*

We consider a 10% extract of the population register, and we include an observation only if the oldest person in the household is between 30 and 60 years old. We then add the partner, if there is one, and we summarize all remaining information at the household level.

Table 1 presents basic summary statistics for two age groups, 30–40 and 41–60.[19] As expected, younger households have accumulated less wealth and are thus more likely to find it difficult to smooth out shocks. We group the summary statistics into three parts,

[19] See Appendix B for summary statistics for the sample of households that experience job loss.

Table 1. Summary statistics.

Age Group	Full Sample			
	30–40		41–60	
Variable	Average (1)	Median (2)	Average (3)	Median (4)
Car				
Car owner	0.69	1	0.74	1
Age of car	8.90	9	8.36	8
Owner of regular car, car owner	0.82	1	0.84	1
Ownership duration of regular car	4.12	4	5.13	4
Income/wealth				
Disposable income (1000 DKK)	309	315	323	318
Financial assets / disp. income	0.31	0.09	0.56	0.15
1[financial assets < 1 month disp. income]	0.49	0	0.35	0
Car owner	0.65	1	0.67	1
Car value (1000 DKK), car owner	90	67	96	72
Car value / disp. income, car owner	0.27	0.21	0.28	0.22
Car value / (fin. assets + car value), car owner	0.70	0.86	0.71	0.86
Housing equity to house value (ETV), home owner	0.24	0.19	0.35	0.31
Housing equity to disp. income (ETI), home owner	0.87	0.51	1.44	0.88
1[financial assets > 1 month disp. income]	0.51	1	0.65	1
Car owner	0.72	1	0.77	1
Car value (1000 DKK), car owner	113	87	118	94
Car value / disp. income, car owner	0.34	0.26	0.35	0.28
Car value / (fin. assets + car value), car owner	0.44	0.47	0.39	0.39
Housing equity to house value (ETV), home owner	0.30	0.25	0.52	0.51
Housing equity to disp. income (ETI), home owner	1.37	0.78	2.58	1.81
Demographics				
Age	35	35	50	50
Married/cohabiting	0.71	1	0.75	1
Has children	0.64	1	0.47	0
Homeowner	0.50	1	0.61	1
Some college	0.26	0	0.21	0
Number of observations	1,451,829		2,558,502	
Number of unique households	214,612		267,630	

Note: A regular car is a car less than 15 years old. All economic variables are CPI-deflated to the level in 2000 and have been censored at the 1st and 99th percentiles, calendar year by calendar year. Car value refers to the value of the stock of cars. Financial assets include cash in banks, bonds, and stocks. ETV and ETI are based on tax-assessed house values. Because of changes in the definition of debt variables, these variables can only be calculated for the years 1997–2009. 1 USD ≈ 6.5 DKK. Percentiles are reported as the mean of the four observations closest to each empirical percentile (this convention applies throughout).

providing information about car ownership, household financial situation, and demographics.

Car ownership is taxed in two ways in Denmark. There is an annual ownership tax, and there is a one-time tax associated with purchasing a new car. The latter, called the registration fee, is the most important, amounting to up to 180% of the wholesale price,

Table 2. Financial assets to disposable income ratio.

Age Group	30–40				41–60			
Variable	Average	Median	p75	p90	Average	Median	p75	p90
No College	0.28	0.08	0.21	0.59	0.52	0.14	0.47	1.28
Some College	0.41	0.13	0.37	0.91	0.67	0.21	0.66	1.66

thus making Denmark one of the most expensive countries to purchase a new car in. As a consequence, 26–31% of the population, depending on age, does not own a car at any given point in time (Table 1, columns 1 and 3). Another consequence of new cars being expensive is that the average age of the car fleet is 8 to 9 years.

The average level of disposable income is 309 thousand DKK (1 USD ≈6.5 DKK) for the young group and 323 thousand DKK for the middle-aged. A substantial fraction of the population in both age groups holds quite modest amounts of financial assets. This is witnessed by the fact that the median level of financial assets to income is 9% for the young group and 15% for the 41–60 year olds. Table 2 further breaks it down by two education groups, some college and no college, highlighting the skewness in the asset distribution and important differences across education groups. In fact, around 35–49% of the households, depending on age, hold financial assets worth less than 1 month of disposable income. These low-financial asset households also have little housing equity and are unlikely to be able to use that as a buffer. In contrast, 65–67% of the households in this group have a car. Consequently, the value of the car stock makes up the overwhelming part of their assets. For the median household in this segment, the value of the car makes up 86% of their total financial and car assets.

When turning to the group of people holding financial assets amounting to more than 1 month's worth of disposable income, the picture looks different. A bigger fraction of the households are car owners, and the ownership rate increases with age. The young households have little housing equity but hold significant amounts of financial assets, so the car only makes up about 44% of the sum of the car and financial assets. The middle-aged group in this segment has far more housing equity, and the car stock only makes up 39% of the sum of car and financial assets. In other words, this group appears well prepared for adverse events.

4. Estimation

The unknown parameters characterizing the model are the preference parameters, the income process parameters, the stochastic process of car quality, as well as car prices and car shocks. The key limitation of the data is that we do not observe dealer purchase car prices, that is, transaction prices when dealers buy cars from households. Consequently, we cannot rely on observed prices during estimation, and instead, we need to solve for the equilibrium price for cars of different ownership durations simultaneously with an estimation of the preference and other parameters.

This feature makes estimation computationally demanding. We therefore separate the estimation into two steps: first, we estimate some parameters outside of the model when the process is exogenous to decisions made in the model, as with the income process, and take others directly from the literature. Second, we estimate the remaining parameters by using the Method of Simulated Moments (MSM). Within this MSM estimation, we compute the vector of prices that households receive when they sell cars to dealers, which is consistent with equilibrium.

Taking as given the set of pre-estimated parameter values, the algorithm for this MSM estimation proceeds as follows (see Appendix E for computational details and Section 2.3.3 for a discussion of the uniqueness of the price vector in step 2):

1. *Make an initial guess of endogenous parameter values.*
2. *Solve for equilibrium prices given these parameters.*
   (a) *Define subscript j as iteration j in the solution of the equilibrium price vector. Take an initial guess of the prices $p^d_{z,j=0}$ for cars of each ownership duration, z.*
   (b) *Given the price vector $p^d_{z,j}$, solve the household's optimization problem to determine optimal actions (e.g., whether to purchase or sell).*
   (c) *Calculate the average quality of cars being sold at each ownership duration.*
   (d) *Update the dealer purchase prices $p^d_{z,j+1}$ using the zero-profit condition.*
   (e) *If $p^d_{z,j}$ and $p^d_{z,j+1}$ are sufficiently close for all ownership durations, this is the fixed point. Otherwise, return to step (ii) using the updated price vector.*
3. *At these equilibrium dealer purchase prices (p^d_z), evaluate the criterion function using simulated and actual moments.*
4. *Update parameters.*

4.1 *Pre-estimated parameters*

The parameter values that are fixed or externally estimated are listed in Table 3. The interest rate measure is the yield of the 2-year Danish government bonds adjusted by the consumer price index averaged over 1996–2009, which gives a rate of 1.6%. The remaining parameters in Table 3 are now discussed in turn.

Constructing dealer car prices We observe data on the list price of new cars. We also observe dealer sale prices (the prices at which households buy used cars from dealers), which we relate directly to the price of fixed second-hand cars. Our concept of a fixed second-hand car refers to a second-hand car restored to its maximum possible quality. Our dealers fix the cars they buy from households to achieve this quality and then resell them. To quantify this price from the data, we use the median dealer sale price of 1-year-old second-hand cars, as these cars typically experience minimal depreciation and retain most of their initial quality, making them the closest approximation of a fixed second-hand car. This determines the price of a fixed second-hand car, which we can then compare to the observed price of a new car. We normalize all the prices and income

TABLE 3. Parameters estimated outside the model.

Parameter	Description	Value	Source
p^n	new car price	1.14 p^u	DAF Car Data (181K DKK)
p^u	fixed car price	normalized to 1	DAF Car Data (159K DKK)
q^b	banger quality	0.2	DAF Car Data
d	deterministic depreciation	0.89	DAF Car Data
r	interest rate	0.016	Bond rate
	Income process by education group		
	No college		
b_0, b_1, b_2	deterministic age profile	−0.37, 0.031, −0.00071	Tax records
$\sigma^2_{v_0}$	variance initial perm.	0.179	Tax records
σ^2_{ϵ}	variance perm. shock	0.018	Tax records
δ_u	probability separation	0.037	Income process
κ_1, κ_2	support separation shock	0.107, −0.245	Income process
ρ	persistence separation shock	0.635	Income process
	Some college		
b_0, b_1, b_2	deterministic age profile	−0.53, 0.070, −0.0014	Tax records
$\sigma^2_{v_0}$	variance initial perm.	0.133	Tax records
σ^2_{ϵ}	variance perm. shock	0.021	Tax records
δ_u	probability separation	0.025	Income process
κ_1, κ_2	support separation shock	0.181, −0.286	Income process
ρ	persistence separation shock	0.734	Income process

by the price of a fixed second-hand car. This implies that $p^u = 1$ and that the price of a new car in the model is $p^n = 1.14$.

We assume a car can be owned for up to 12 years, that is, $\bar{z} = 12$. In our model, information asymmetry arises only during household ownership, as dealers refurbish cars and restore them to maximum possible quality before reselling them. Once a car is purchased from a dealer, any information asymmetry related to its previous ownership is resolved. Therefore, we believe that the observed year-to-year depreciation in dealer sale prices reflects primarily physical depreciation rather than unobserved quality deterioration. Based on the data, we use the year-to-year depreciation rate in dealer sale prices, which is 11%, as the deterministic depreciation rate in the model, $d = 1 - 0.11 = 0.89$. We think of bangers as old cars, which are of minimal quality, and so are not subject to asymmetric information.[20]

Estimation of the income process We estimate the parameters of the household income process (5) separately for each education group (some college and no college) using the Danish income tax records in 1992–2009.[21] We define income to be total household dis-

[20] The median depreciation rate across 1-year-old cars is 12.1%. The median book price of a new car in the data is 181 thousand DKK. We therefore set the price of a fixed second-hand car to $181 \times (1 - 0.121) \approx 159$ thousand DKK. The median dealer sale price of a 13-year-old car is 29 thousand DKK, and so we normalize the quality of a banger in the model to $q^b = \frac{29}{159} \approx 0.2$.

[21] We classify people according to their level of completed education in 2009, the final year in our sample. Education is defined based on the household head.

posable income, which includes the effects of taxes and transfers. The sample used for estimation includes those aged 23–60 only, thus avoiding retirement years. Retirement income is assumed riskless.

To estimate the deterministic age profile, we regress log household disposable income on Age_t, Age_t^2 as well as calendar year dummies and dummy variables for household structure, that is, a dummy for having a partner and 5 dummies for up to 5 children.

In the income process, equation (5), the residual log income r_{it} has two error components: the permanent income shock component v_{it} and the unemployment-related income shock component w_{it}. To account for possibly serially correlated measurement errors (or transitory shocks) in the data, we also introduce a third error component ν_{it} when estimating the parameters of error components:

$$r_{it} = v_{it} + w_{it} + \nu_{it}.$$

In the model, we treat ν_{it} as a measurement error only, which does not affect household behavior.

Estimation is based on moments for residual income growth, which takes the form

$$\triangle r_{it} \equiv g_{it} = \begin{cases} \epsilon_{it} + \triangle\nu_{it}, & \text{for those who have not had job separation,} \\ \epsilon_{it} + \triangle\nu_{it} + \kappa_{it}, & \text{for those employed in t-1, separated in t,} \\ \epsilon_{it} + \triangle\nu_{it} + \rho\kappa_{it-1} - \kappa_{it-1}, & \text{for those with separation in t-1, employed in t} \end{cases}$$

since $v_{it} = v_{i,t-1} + \epsilon_{it}$ and $w_{it} = (1 - U_{it})\rho w_{i,t-1} + U_{it}\kappa_{it}$.

To estimate the variance of the permanent shock σ_ϵ^2, we use the autocovariance structure of the residual income growth for those who have not had a job separation. It is valid to do this because, in our model, a job separation represents an exogenous shock to income, and hence, there is no selection bias. The moments used are as in Meghir and Pistaferri (2004). Given an estimate of σ_ϵ^2, we can then use the autocovariance for households experiencing job separations to estimate the remaining parameters of the income process, as reported in Table 3. Further details of the estimation are in Appendix C.

The estimates of σ_ϵ^2 are 0.018 for the no-college group and 0.021 for the some-college group, which by way of comparison, are substantially lower than the equivalent numbers in the US. To capture initial dispersion, we assume the first draw of the permanent component, v_{i0}, is drawn from a Normal distribution with mean zero and variance $\sigma_{v_0}^2$. The standard deviations are estimated to be 0.2 for the no-college group and 0.15 for the some-college group based on the dispersion of household earnings at age 21.

Assets We do not include housing and pension wealth explicitly in the model in order to avoid excessive computational complexity, but allow for one liquid asset (beyond cars).[22] We assume that the replacement rate for retirement income is 100%. This effectively implies that asset accumulation in our model is for precautionary purposes only, against adverse wage or unemployment shocks, while at the same time, lifetime wealth

[22] It turns out that people in Denmark do not typically extract housing equity during periods when they face adverse income shocks, such as unemployment, but rather adjust their liquid savings and spending (see AJJK+ (2023)).

remains sufficiently high. This simplifies the modeling of the life-cycle savings motive and allows us to focus on the accumulation of assets for precautionary purposes and car buying, which are critical margins in our application.

Initial conditions We need to specify the initial conditions for financial assets, car ownership, and ownership duration. We compute the empirical distribution of the ratio of financial assets to earnings by education group among households aged 20–26 in the Danish administrative data. We set the initial levels of financial assets to earnings to match this distribution, using 10 different values taken from the deciles of the CDF in the data. Initial financial wealth is computed using this ratio and initial earnings estimated above. The initial car ownership position is either that the household does not own a car, or that it owns a regular car with ownership duration $z \in \{1, \dots, 12\}$ or that it owns a banger. We compute moments from age 30, by which time the impact of this initial allocation will be diminished.

4.2 *Estimated parameter values*

We use the Method of Simulated Moments (MSM) to estimate the remaining parameters using data for households where the household head is aged between 30–60 in the period 1992 to 2009. The standard errors of the structural parameters are computed as in Gourieroux, Monfort, and Renault (1993), where the covariance matrix of the data moments is estimated using the block bootstrap. Computational details are discussed in Appendix E.

The targeted moments include the ownership rates of regular cars by age and by education, the proportion of households buying new cars by age and by education, ownership rates of bangers by education, the proportion of cars sold by ownership duration, average ownership duration of regular cars, and holdings of financial assets by education. These moments, together with equilibrium conditions, pin down 12 parameters, whose estimates are presented in Table 4 and include:

- Parameters common to both education groups: the discount factor β, the risk aversion coefficient γ, the arrival rate of the banger quality shock for regular cars δ^r, the scrap rate for bangers δ^b, and the parameters for the distribution of the private depreciation factor $\varepsilon \sim \mathcal{B}(\eta_1, \eta_2)$.
- Parameters that are allowed to differ between education groups: the utility benefit of owning a car α_e, the relative preference for cars bought as new θ_e^n, and the relative preference for bangers θ_e^b.

Based on our estimates, the distribution of the private depreciation factor is $\varepsilon \sim \mathcal{B}(11.832, 1.992)$, which implies a mean of 0.856 and a variance of 0.008. The deterministic depreciation factor, $d = 0.89$, and the overall expected depreciation factor, $d\mathbb{E}(\varepsilon) = 0.76$, imply that the excess quality over and above the basic q^b declines on average at a rate of 24% a year, as shown in equation (1).

Given the estimated utility parameters, households have a higher preference for new cars and a lower preference for bangers. The positive value of α_e implies that cars and

Table 4. Estimated parameter values.

Description	Param.	Value	s.e.
Common parameters			
Discount factor	β	0.974	0.001
Private depreciation factor $\varepsilon \sim \mathcal{B}(\eta_1, \eta_2)$	η_1	11.832	0.146
	η_2	1.992	0.020
Arrival rate of banger quality shock	δ^r	0.103	0.002
Scrap rate for bangers	δ^b	0.259	0.013
Relative risk aversion	γ	1.207	0.048
Some college			
Preference for new car	θ_h^n	1.152	0.002
Preference for banger	θ_h^b	0.975	0.011
Utility benefit of owning car	α_h	0.352	0.003
No college			
Preference for new car	θ_l^n	1.155	0.001
Preference for banger	θ_l^b	0.928	0.018
Utility benefit of owning car	α_l	0.326	0.001

consumption are substitutes in utility: the cross-partial derivative of utility with respect to c and q is negative. The discount factor $\beta = 0.974$ lies within the range of values commonly assumed in dynamic discrete choice models (e.g., Rust (1987)). The estimate of the relative risk aversion coefficient ($\gamma = 1.207$) is in line with previous estimates based on consumption data, which vary between unity and 3 (e.g., Gourinchas and Parker (2002)). Finally, 10% of cars randomly become bangers each year (over and above those that reach that state deterministically because of age). About 26% of bangers become scrapped each year.

Table 5 shows equilibrium prices. Because individual car quality is private information, dealers will have to offer a pooled price across all qualities, given the duration of ownership. There are $\bar{z}$ dealer purchase prices $\{p_1^d, p_2^d, \ldots, p_{\bar{z}}^d\}$. According to equation (2), the dealer purchase price of a regular car with ownership duration z is equal to the expected value of that type of car being sold. The price that dealers are willing to pay for a car that has been owned for just 1 year is 0.69: 69% of the original purchase price.

Table 5. Equilibrium prices.

Description	Price	Value	Description	Price	Value
Dealer purchase price			Dealer purchase price		
1-year-old car	p_1^d	0.69	8-year-old car	p_8^d	0.30
2-year-old car	p_2^d	0.61	9-year-old car	p_9^d	0.29
3-year-old car	p_3^d	0.54	10-year-old car	p_{10}^d	0.27
4-year-old car	p_4^d	0.48	11-year-old car	p_{11}^d	0.26
5-year-old car	p_5^d	0.42	12-year-old car	p_{12}^d	0.26
6-year-old car	p_6^d	0.37			
7-year-old car	p_7^d	0.33	Banger price	p^b	0.08

This 31% discount in price includes quality depreciation and a penalty due to asymmetric information. We will break down these two effects in Section 5. The dealer purchase price of a 2-year-old car is 0.61, and after 4 years, it is about half of the original purchase price. Finally, the banger price is 0.08, which is determined by the household demand and supply of bangers.[23]

4.3 *The fit of the model*

Table 6 shows the moments and model. Regarding car ownership and new car purchases, the model captures that both the ownership rates of regular cars and the fraction of people who buy new cars increase with education and age. In this model, age and education are the primary dimensions of variation across households. The older or more educated a household is, the more wealth it accumulates, allowing it to own a

TABLE 6. Fitted moments.

Moments		Data	Model
Ownership rate of regular cars			
No college	Age 30–40	55.2%	52.2%
	Age 41–60	60.4%	61.2%
Some college	Age 30–40	58.7%	64.8%
	Age 41–60	67.8%	75.6%
% people buy new cars			
No college	Age 30–40	3.9%	3.0%
	Age 41–60	5.2%	6.7%
Some college	Age 30–40	4.8%	4.9%
	Age 41–60	6.2%	12.8%
Ownership rate of bangers			
No college	Age 30–60	22.9%	26.7%
Some college	Age 30–60	19.6%	21.3%
Median financial asset to income at 55			
No college		0.196	0.234
Some college		0.287	0.287
Ownership duration of cars		4.86	4.61
% of cars being sold after 1 year		5.8%	5.3%
% of cars being sold after 2 years		24.9%	27.5%
% of cars being sold after 3 years		41.5%	53.4%
% of cars being sold after 4 years		55.7%	71.1%
% of cars being sold after 5 years		67.0%	77.9%
% of cars being sold after 6 years		75.1%	80.6%

[23]The discrete nature of trading choices in our model can cause a discrete number of agents to switch between their trading options, so exact market clearing is hard to achieve. We have employed a specific approach to approximate the equilibrium: quantifying the deviations of the equilibrium conditions from zero and subsequently minimizing these deviations in choosing prices, while estimating parameter values using the MSM. Our algorithm has demonstrated good performance, with deviations for the equilibrium conditions being 0, 0.01, 0.01, and 0.07, respectively.

regular car or even buy a new one. Both in the model and the data, higher education households have higher asset holdings and lower banger ownership.

Moving on to moments related to used car sales in the bottom half of Table 6, the average ownership duration for households when they sell their cars to dealers is 4.61 years in the model, close to the 4.86 years in the data. The model does a good job of fitting the rate at which households put cars on the market according to their ownership duration, that is, both observed and simulated data show a slow rate of transactions occurring in the first 3 years of ownership duration.

4.4 *Identification*

In this model, identification arises from the timing of car sales by households to dealers, the type of car purchases observed, as well as rates of ownership, and more generally, the interactions between households and dealers. The moments chosen for estimation capture this underlying variation. The parameters are estimated simultaneously, but particular moments contribute more heavily to the identification of particular parameters. We perform an analysis of the informativeness of the moments included in the estimation. The informativeness measure is what Honoré, Jørgensen, and de Paula (2020) refer to as M_4, which shows how the precision of each parameter estimate varies as different moments are excluded. The measure is a matrix where the $(j, k)^{\text{th}}$ element provides an answer to how the precision of the jth parameter of $\hat{\omega}$ depends on the kth moment. It measures how much precision we would lose (i.e., the percentage change in the asymptotic variance of $\hat{\omega}$) if we completely exclude the kth moment:

$$I_k = \frac{\operatorname{diag}\left(\bar{\sum}_k - \sum\right)}{\operatorname{diag}\left(\sum\right)},$$

where $\sum$ is the asymptotic variance of $\hat{\omega}$, and $\bar{\sum}_k$ is the asymptotic variance of $\hat{\omega}$ from removing the kth moment.

Figure 2 reports this informativeness measure. Each column represents a removed estimation moment, and each row represents a parameter. For example, the moment that the estimate of the discount factor β is most sensitive to is the asset-income ratio of households with no college education (`asset_inc_ledu`): leaving out this moment when estimating the model would increase the asymptotic variance of β by about 360%.

The key to quantifying the degree of information asymmetry is that the model predicts a certain rate at which cars are sold to dealers by households, that is, the transaction profile of households selling cars to dealers. The size of hidden shocks to quality is governed by the distribution of the private depreciation factor $\varepsilon \sim \mathcal{B}(\eta_1, \eta_2)$. This is closely related to the observed volume and rate at which used cars of different ownership ages sell. Figure 2 shows that the precision of the estimate of η_1 and η_2 worsens significantly if we exclude moments related to the percentage of cars sold by ownership duration. For instance, the asymptotic variance of η_1 increases by approximately 300% when the percentage of cars sold after 1 year (`pct_sold_1`) is excluded, and by 310% when the percentage of cars sold after 2 years (`pct_sold_2`) is excluded. Similarly, the

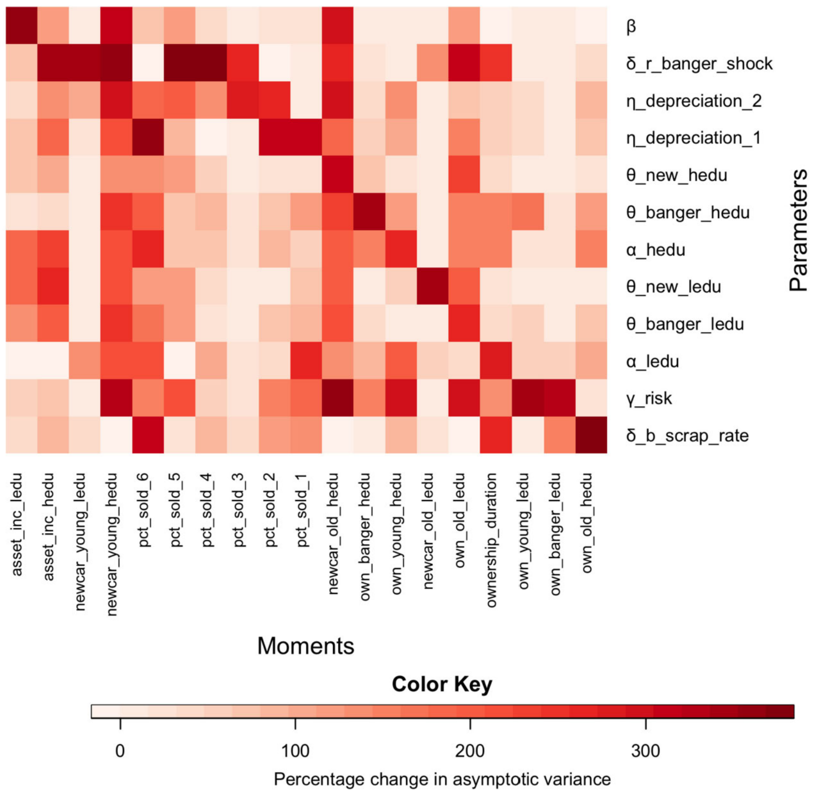


FIGURE 2. Informativeness of estimation moments. *Note*: The figure plots the percentage change in the asymptotic variance of $\hat{\omega}$ from removing each estimation moment one at a time. Each column in the figure represents the removed estimation moment, and each row represents a parameter.

asymptotic variance of η_2 rises by about 280% when the percentage of cars sold after three years (`pct_sold_3`) is excluded.

5. The lemons penalty

Our model implies a lemons penalty that reduces the price received for selling a car, an endogenous transaction cost. This penalty, together with the deterministic depreciation factor, defines the path for how the price changes as the duration of ownership increases. We show how the price evolves with ownership duration, as well as the implications for the timing and volume of transactions. We then show how income uncertainty and access to credit markets affect the lemons penalty.

5.1 *The size of the lemons penalty*

The zero-profit condition, equation (2), means that dealers will purchase cars at a price equal to the expected quality of cars that are being sold. However, the asymmetric information over quality means that the expected quality of cars offered to dealers may be

Table 7. Prices and the lemons penalty.

Ownership Years	1	2	3	4	5	6	7	8	9	10
(1) Dealer price	0.69	0.61	0.54	0.47	0.42	0.37	0.33	0.30	0.29	0.27
(2) Expected car value (in population)	0.81	0.67	0.57	0.49	0.44	0.39	0.36	0.33	0.32	0.30
(3) Lemons penalty	−0.12	−0.06	−0.03	−0.02	−0.02	−0.02	−0.03	−0.03	−0.03	−0.03
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
(4) % of cars being sold	5.3%	27.5%	53.4%	71.1%	77.9%	80.6%	82.5%	83.8%	84.8%	85.7%

Note: To obtain the standard error of the lemons penalty (displayed within brackets), we implement a bootstrap method that involves randomly drawing sets of parameters from their estimated distributions. For each set of parameters drawn, we simulate the model and calculate the associated lemons penalty. This drawing and simulation process is repeated 40 times, allowing us to compute the standard error of the lemons penalty.

lower than the expected quality of cars owned in the population. Dealers will therefore pay less than the expected value of cars that are owned in the population. This difference may vary depending on how long the car has been owned. To define this lemons penalty, we consider the loss incurred by a randomly chosen household selling its car at the going price. The lemons penalty is defined as the difference between the average car value in the population (irrespective of the decision to sell) and the prevailing equilibrium price that dealers pay. Further, the lemons penalty for a car of a particular ownership will impact the penalty at other ages. A high lemons penalty for newly-bought cars implies that households will hold onto good cars, and the average quality of older cars will be better than otherwise.

The resulting transaction costs/lemons penalty are shown in Table 7. The first row of Table 7 shows the equilibrium dealer purchase price, which equals the expected value of cars being sold, according to equation (2) and which ensures zero profits.[24] The second row of Table 7 shows the expected value of cars that are owned in the population. The difference between these is the lemons penalty, shown in the third row, while the corresponding standard errors are enclosed within the brackets below. The columns show how the equilibrium price varies with the duration of ownership. This generates a time path for the lemons penalty, which we show explicitly in Figure 3, but which is unobservable in the data. The size of the lemons penalty initially declines markedly with ownership duration but then stabilizes. A car that has been owned for just 1 year has the largest lemons penalty if it is sold: 12% of the original purchase price. This is in addition to a 19% decline in the price due to expected depreciation. In the second year, the penalty falls to 6% of the original purchase price, in addition to a cumulative decline of 33% of the original purchase price because of expected depreciation. The penalty falls still further with the duration of ownership: after 10 years, the price has fallen over 70% due to expected depreciation, and the lemons penalty is only 3 percentage points.[25]

[24]Since p^u is the price for a unit of quality, and $\bar{q}_z$ is the average quality of cars of ownership duration z sold to dealers, the expected value of cars sold is $\bar{q}_z p^u$.

[25]Our estimate of the lemons penalty captures the endogenous transaction costs associated with the lower price when selling a car of average quality. To assess the significance of the endogenous nature of the transaction cost, we reestimate the asymmetric information model, allowing for an exogenous transaction

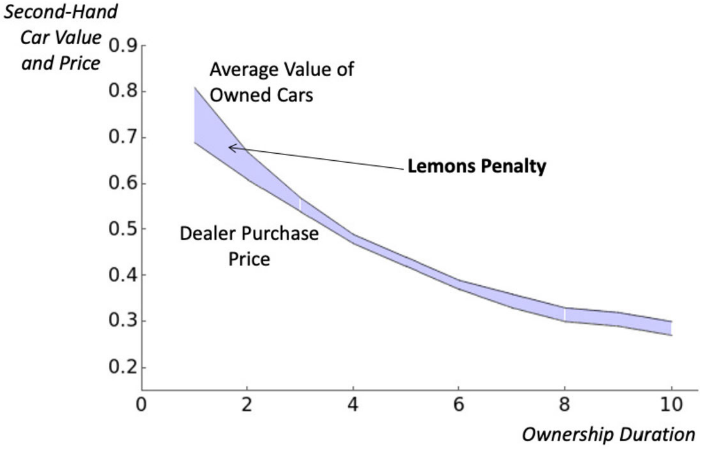


FIGURE 3. Price declines by ownership duration. *Note*: The figure plots, by duration of ownership, the average value of all owned cars and the dealer purchase price for cars that are sold.

The lemons penalty is, of course, only a penalty for those who are selling a car with quality better than the average. For some, the asymmetric information means they receive a price for their car greater than the true quality of the car and the "penalty" is not enough of a discount. Asymmetric information leads to both efficiency and distributional consequences: in terms of efficiency, the penalty captures the transaction cost associated with the lower price when selling a car of average quality; in terms of distribution, there are winners and losers from the lack of information. Figure 4 shows the simulated distribution of quality of cars sold (the solid line) compared to the dealer purchase price (vertical line) and compared to the distribution of cars owned (the dashed line), for different ownership durations. This highlights the low average quality of cars sold, especially for cars with short ownership duration, compared to the distribution in the population. The figure also highlights that some cars are sold when their true quality is above the market price: owners whose cars are on the right of the dealer purchase price make a loss when selling their cars. Nonetheless, some high-quality cars are sold, typically when households suffer income shocks or wish to upgrade relative to the quality of their current car.

5.2 *The lemons penalty and income risk*

Income shocks may induce households to sell cars regardless of quality. This insight means the market does not collapse (Section 2.3.3). We use our model to show how uncertainty impacts the size of the lemons penalty.

We change the variance of permanent shocks to income, holding all other parameters at their baseline values. Figure 5a reports the percentage of cars being sold, and Figure 5b reports the average value of cars being sold, both in the first and second years of

cost that is proportional to the sale price. The estimated exogenous component is small (0.9% of the sale price), which has minimal impact on the resulting lemons penalty (see Appendix D.1).

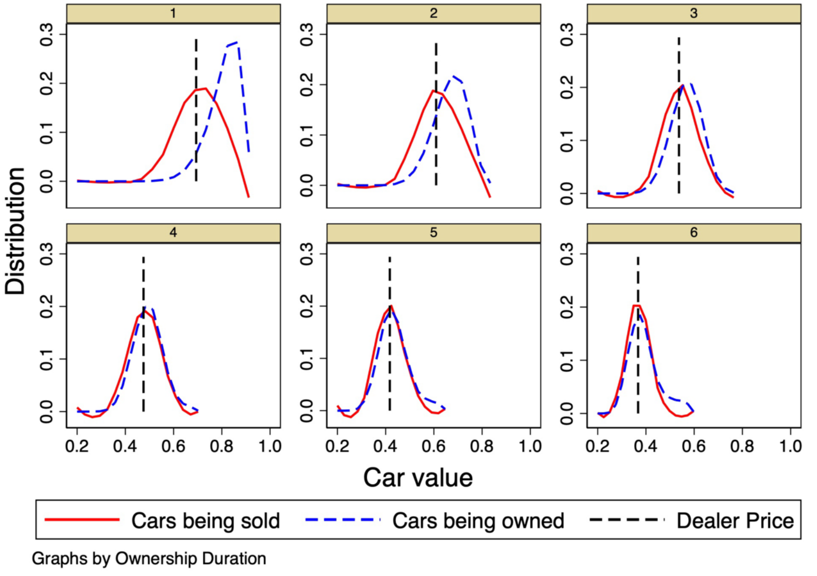


FIGURE 4. Distribution of value of cars sold and of cars in the population by ownership duration. *Note*: The figure plots for each level of ownership duration the distribution of car values in the population and among the subpopulation of cars that are sold.

ownership, for the different variance values. Figure 5c reports the corresponding lemons penalty in the first and second years. Figure 5d reports the effect on the average duration of car ownership.

As the variance of income shocks increases, a higher percentage of cars are sold early on, and the lemons penalty declines. A greater number of car sales are driven by income shocks rather than quality considerations, and so the expected quality of cars sold is closer to the average quality in the population. Further, the average duration of ownership declines. Similarly, when the variance is cut to a quarter of the baseline, less than 1% of cars are sold in the first year, and the lemons penalty is over 20%.

These results on the impact of changes in the variance of income speak to how we might expect the lemons penalty to change over the business cycle. There is now substantial evidence that the variance of permanent income shocks, σ_ϵ^2, increases in recessions (Storesletten, Telmer, and Yaron (2001), Blundell, Low, and Preston (2013)).[26] This countercyclical movement would imply that the lemons penalty is lower during economic downturns when cars are sold for reasons other than being of low quality.

5.3 *The lemons penalty and borrowing constraint*

Our baseline estimates of the lemons penalty assume the car can be used as collateral, with the maximum amount of borrowing given by the sale price of the car in the next year (equation (4)). Households can access this credit for purchasing cars. The

[26]Similarly, Guvenen, Ozkan, and Song (2014) show that changes in labor income become left skewed in recessions.

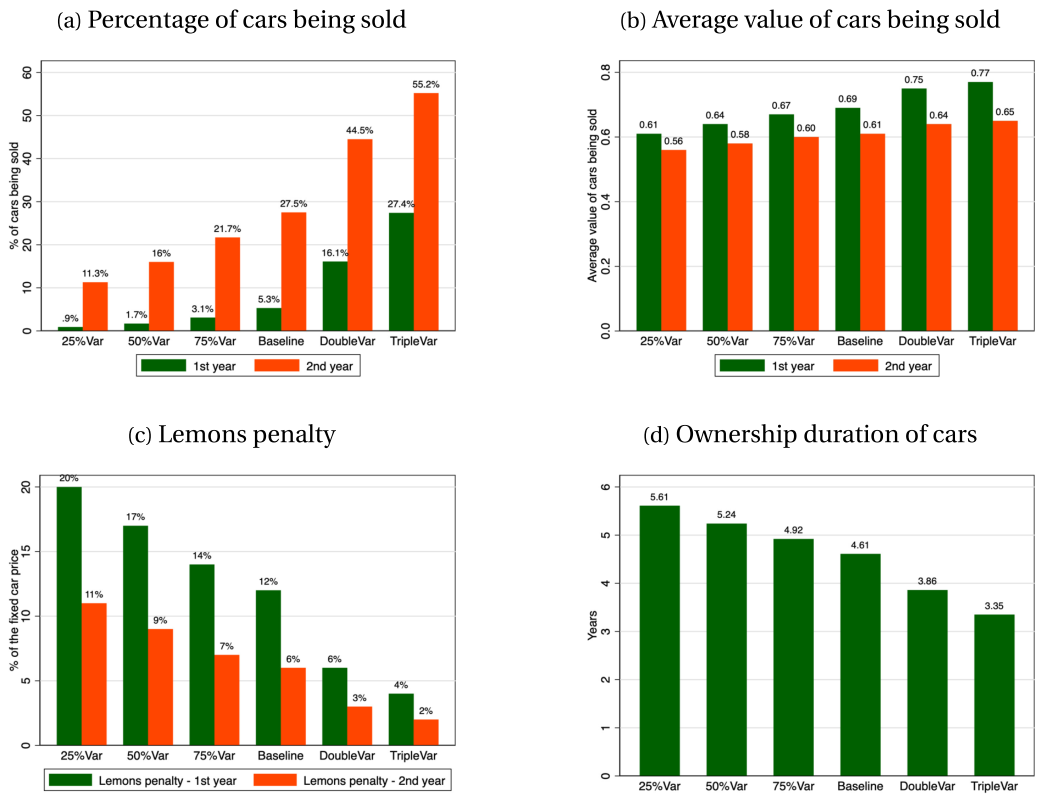


FIGURE 5. Change the variance of permanent income shock.

importance of durables as collateral is explored in Fernández-Villaverde and Krueger (2011), where households increase their purchases of durables to relax the borrowing constraint, but where the borrowing constraint does not affect the price of durables.

Our simulations show the importance of borrowing constraints, although only 5% of households are at the borrowing constraint, which prevents them from borrowing any further. Only 1% of constrained households buy regular cars, while 17% of unconstrained households do.

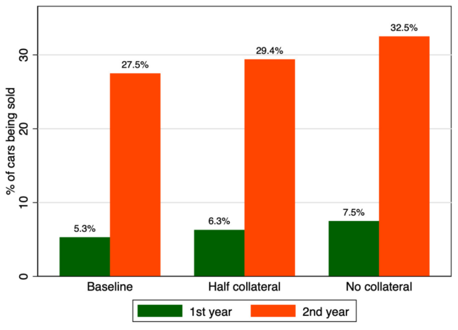
We reduce the fraction, ψ, of the car value that can be used as collateral and so reduce the amount of feasible borrowing:

$$a_{it+1} \geq -\psi p^d_{z_{it+1}}. \tag{6}$$

We consider setting $\psi = 0.5$ and setting $\psi = 0$. Reducing ψ means households buy fewer regular cars and opt to hold more bangers (see Appendix D.3). The ability to borrow impacts the household's choice of car purchase. With the reduction of credit limits, households have to substitute regular cars with bangers.

Figure 6b shows the impact of changing the credit limit on the lemons penalty. When the collateral value of cars is removed ($\psi = 0$), the lemons penalty in the first year decreases from 12% of the baseline to 9%. This is because households' willingness to sell

(a) Percentage of cars being sold



(b) Lemons penalty

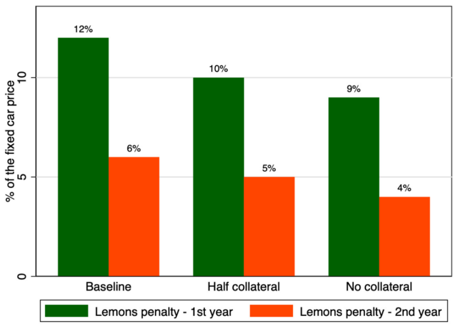


FIGURE 6. The lemons penalty and borrowing constraint.

cars is influenced by the maximum amount of borrowing when they encounter income shocks. When a household can use credit to buy a car, the loan must be repaid when selling the car, resulting in a decline in the asset value of the car. Therefore, when households face income shocks, selling cars does not significantly increase their consumption, leading to their reluctance to do so. On the contrary, when the credit limit is reduced, the asset value of each car increases, providing more funds for consumption when selling the car. Therefore, households are more willing to sell cars to alleviate economic difficulties (Figure 6a). In this case, more owners opt to sell their cars due to liquidity constraints, allowing more high-quality cars to enter the market. As a result, dealers are more willing to offer higher prices, thus reducing the lemons penalty. This reduction in the lemons penalty in turn leads to an increase in the collateral value of cars and an increase in permitted borrowing.[27]

We explore the impact of removing the ability of households to save (and borrow) to understand the importance of saving in our model. In this environment, the purchase of a car must be financed by giving up current consumption, and this further reduces ownership (see Appendix D.4). The resulting lemons penalty is only 6% in the first year of ownership, declining with the length of ownership. When households are unable to borrow or save, cars play a much greater role in consumption smoothing.

6. SYMMETRIC INFORMATION

In our baseline model, shocks to car quality are private information. In this section, to highlight the role played by the information assumption, we compare this to a scenario

[27]To investigate further the effects of the lemons penalty on borrowing, we compare the scale of household borrowing in two distinct models: the asymmetric information model with the lemons penalty and the symmetric information model without the lemons penalty, discussed in the next section. This comparison effectively contrasts borrowing under conditions where the lemons penalty is at its maximum and minimum. Our findings reveal that in the asymmetric information model, the average household borrowing is 0.33, with a maximum collateral value of 0.69. Conversely, in the symmetric information model, the average household borrowing is 0.38, accompanied by a maximum collateral value of 0.81. Therefore, information friction restricts the collateral value of cars and limits borrowing opportunities.

where quality shocks are fully observable, meaning information is symmetric. Using the baseline parameters, we explore the impact of removing asymmetric information from the model, and we illustrate how asymmetric information, rather than other market factors, dampens transaction volumes, turnover rates, and the quality of cars brought to the market. In Section 7, we reestimate the model with symmetric information and exogenous transaction costs, a standard feature in most structural models of the car market.

In the symmetric information model, since p^u is the price for a unit of quality, a household with a car of known quality q_i can sell it at its true value $q_i p^u$. Compared to the asymmetric information case, good cars can be sold at higher prices in the symmetric information case, while bad cars sell at lower prices. Moreover, with symmetric information, cars become more valuable as a store of value since they can be sold at their true quality. On the other hand, the price that the household receives will vary with the true quality rather than being the same regardless of quality, and this introduces more variation into the future value of any car.

Information asymmetry leads to a lower price when selling a car of average quality. Table 8 shows this by comparing our baseline with the symmetric information model using the baseline parameter values.[28] We report average dealer purchase prices under asymmetric and symmetric information in the 1st and 4th rows of Table 8. For the asymmetric information case, the average dealer price is the dealer purchase price faced by everyone, whereas, with symmetric information, the dealer price will vary across cars with the same ownership duration because of quality differences.

Average dealer prices of cars are higher in the symmetric information model than the dealer prices in the asymmetric information model, reflecting the higher average quality of cars being sold under symmetric information. This is seen directly by comparing the average dealer prices with the average value of cars in the population, rows 4 and 5 of Table 8. The values are almost identical, implying that symmetric information leads to

Table 8. Asymmetric and symmetric information: prices and turnovers.

Ownership Years	1	2	3	4	5	6	7	8	9	10
Asymmetric information										
(1) Dealer price	0.69	0.61	0.54	0.47	0.42	0.37	0.33	0.30	0.29	0.27
(2) Expected car value (in population)	0.81	0.67	0.57	0.49	0.44	0.39	0.36	0.33	0.32	0.30
(3) % of cars being sold	5.3%	27.5%	53.4%	71.1%	77.9%	80.6%	82.5%	83.8%	84.8%	85.7%
Symmetric information										
(4) Average dealer price	0.81	0.68	0.57	0.49	0.43	0.38	0.36	0.35	0.34	0.33
(5) Expected car value (in population)	0.81	0.66	0.55	0.47	0.42	0.38	0.35	0.33	0.31	0.30
(6) % of cars being sold	80.8%	85.9%	87.9%	89.7%	91.5%	92.9%	93.8%	94.5%	95.0%	95.5%

Note: In an asymmetric information model, individual car quality is private information; in a symmetric information model, all shocks to car quality are observable.

[28]We reestimate the symmetric information model in Section 7 to study the transaction responses to unemployment events.

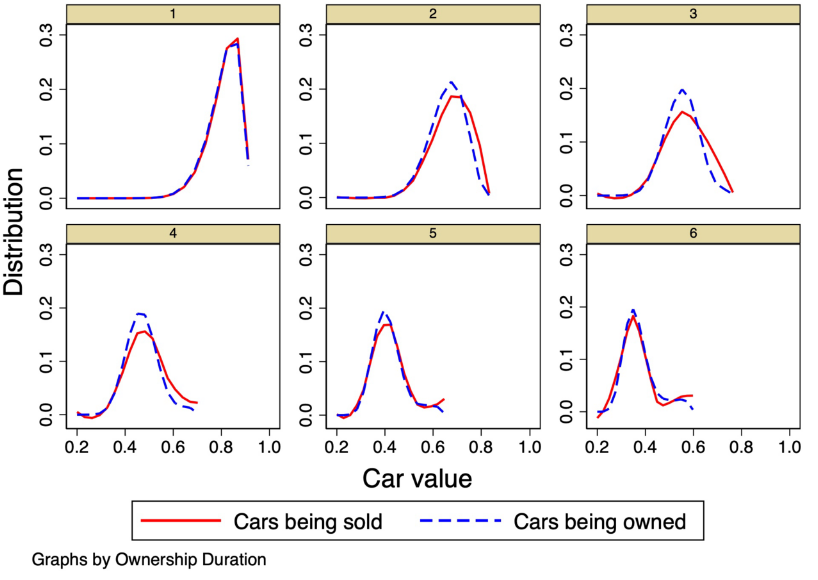


Figure 7. Distribution of value of cars sold and of cars owned: Symmetric information. *Note*: The figure plots for each level of ownership duration, the distribution of car quality in the population of cars owned and among the subpopulation of cars that are sold.

high-quality cars being sold sooner, bringing the average quality sold to dealers closer to the population average. Figure 7 shows the distribution of car quality under symmetric information: the distribution of cars sold is almost identical to cars owned. This stands in contrast to Figure 4, where information asymmetry leads to lower-quality cars being sold.

The 3rd and the 6th rows of Table 8 report how the fraction of cars sold varies with the duration of ownership under asymmetric and symmetric information. Compared to asymmetric information, symmetric information leads to much faster transactions occurring: in the first year, 80.8% of cars are sold under symmetric information, compared to only 5.3% in the asymmetric information case. This means that the aggregate demand for second-hand cars increases: in any given period, the number of people buying a second-hand car increases from 9.1% to 27.6% of the population. The efficiency loss from asymmetric information is characterized by this impact on the number of transactions that do not occur as a result of asymmetric information.

7. Adverse income shocks and downgrading

For many households, a car is a substantial financial asset. However, the presence of the lemons penalty reduces the willingness of households to sell cars of good or even average quality. This is an endogenous transaction cost that reduces the value of holding a car as a way to smooth shocks. This reduces the value of the asset as a consumption smoothing device, which can have important welfare implications for low-income people with low levels of liquid assets, and much of their wealth is accounted for by their car. In contrast, when information is symmetric, this endogenous transaction cost of selling a car is not present, increasing the value of holding a car as a financial asset. In this section, we examine how the propensity to downgrade the car stock is affected by asymmetric information. Here, we focus on an adverse income event caused by an unemployment shock.

We start by examining whether the quantified model is able to match data on the propensity to downgrade upon job separation, that is, the proportion of households that downgrade their cars among car owners hit by unemployment shocks. We then compare simulated responses to unemployment events under the assumptions of symmetric and asymmetric information. We focus on the probability of downgrading, that is, selling a car and either replacing it with a banger or not replacing it at all.

Comparison to the data Evidence on how households respond to job loss was not used in the estimation procedure, and it thus provides some useful validation. We focus on the specific sample of job-losers and perform an event study for outcomes around the job loss. The event is defined as the first job loss observed in the period 1999–2009. We include single adult households and couples.[29] Figure 8a compares the observed downgrading to downgrading in the model following the same job separation shock. Both the amount of downgrading before job loss and the increase in downgrading on job loss are similar between the data and the asymmetric information case. This exercise provides support for the importance of allowing for asymmetric information. Figure 8a reports the amount of downgrade when the sample is split into their asset holdings in the period before job loss: those with less financial assets increase downgrading by more at job loss.

Adverse income shocks under symmetric and asymmetric information Figure 8b compares downgrading behavior under asymmetric information with downgrading when information is symmetric. To make this comparison, we consider two variations of symmetric information: first, symmetric information without transaction costs and using the baseline estimates; second, symmetric information with an exogenous transaction cost and reestimating the model.

The transaction cost is imposed on households selling a car: a used car of quality q_i can be sold to a dealer at its true value $q_i p^u$, with the household incurring a transaction cost $\lambda q_i p^u$ proportional to the sale price. The dealer, in turn, invests in improving the car's quality from q_i to 1 at a cost of $p^u(1 - q_i)$ before selling the fixed second-hand car for p^u. As a result, dealers make zero profits on each car that they buy rather than on average:

$$p^u - \left[q_i p^u + p^u(1 - q_i)\right] = 0.$$

[29]For singles, we define a job loss to take place if the person has been out of a job for a total of at least 60 days during the year. For couples, we define the job loss to take place if the total unemployment accumulates to 120 days when summarized for both partners over the year. This is done to obtain shocks that are of comparable magnitude across singles and couples.

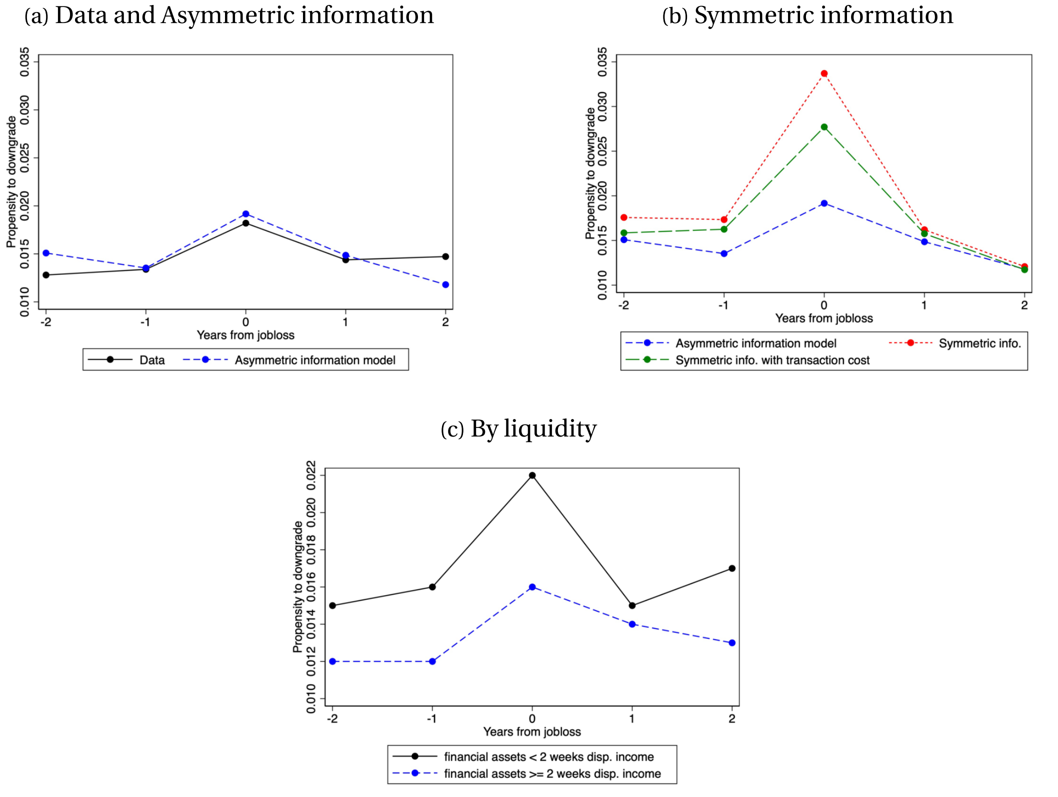


FIGURE 8. Downgrading after job loss. Data and model simulation. *Note*: The event graphs are constructed by ordering observations according to the first year in the data period where households experience being unemployed for at least 2 months on average across the adult household members. Downgrading takes place when a car is sold in period t, and the value of the car stock in year t is at most 40% of the value of the car stock in year $t-1$.

There is no ownership-duration specific price to solve for as the price paid is pinned down by the actual quality of the car sold.[30] In Table A.3 and Table A.4 in Appendix D.2, column "Symmetric Info" presents the estimated parameter values and fitted moments. Our estimate of the exogenous transaction cost λ is 5.6%.

In the first and second rows of Table 9, we compare the average dealer prices with the average value of cars in the population under symmetric information with an exogenous transaction cost. The average value of cars sold remains close to the average value in the population. This stands in stark contrast to the asymmetric information case, where the quality of cars sold is substantially lower than that in the population.

Figure 8b shows that differing information assumptions impact a household's ability to use their car as a means of consumption-smoothing. We show downgrading behavior following the job separation shock under symmetric information to compare to the model with asymmetric information. The blue line represents the asymmetric informa-

[30]We estimate the unknown parameter values using the method of simulated moments, maintaining all equilibrium conditions from Section 2.3.1.

Table 9. Symmetric information with an exogenous transaction cost.

Ownership Years	1	2	3	4	5	6	7	8	9	10
(1) Average dealer price	0.81	0.71	0.63	0.56	0.50	0.44	0.40	0.39	0.37	0.35
(2) Expected car value (in population)	0.85	0.73	0.63	0.55	0.49	0.44	0.40	0.38	0.35	0.33
(3) % of cars being sold	5.8%	30.9%	59.7%	70.2%	76.2%	81.0%	84.0%	85.8%	87.3%	88.6%

Note: We introduce an exogenous transaction cost into the symmetric information model and reestimate the model.

tion case, the red line depicts the symmetric information case (without re-estimation), and the green line shows the symmetric information case with the exogenous transaction cost. Even with the introduction of the exogenous transaction cost, the symmetric information model continues to exhibit significantly higher levels of downgrading cars to smooth income shocks compared to both the asymmetric information model and the data.[31] The lemons penalty reduces the liquidity of cars and the extent to which cars are used as insurance instruments against adverse income shocks.

This difference in the average downgrading probabilities masks substantial differences in how cars of different ownership durations and of different quality are used. Figure 9 shows how cars of different ownership durations are downgraded following the job separation shock. The dashed line shows the asymmetric information case, and the solid line shows the symmetric information case. Panel (a) shows that a 1-year-old car is not downgraded at all under asymmetric information, while it has a high probability of being downgraded for consumption smoothing under symmetric information. Panels (b)–(d) show that as ownership duration increases, cars are less likely to be downgraded under symmetric information and more likely to be downgraded under asymmetric information. Four-year-old cars have a similar probability of being downgraded in both cases. Therefore, newly purchased cars are used extensively for consumption smoothing under symmetric information when the cars can be sold for a fair value but are rarely used when there is a lemons penalty. Under asymmetric information, it is older cars, where there is less of a lemons penalty, that are sold on job loss.

Even when conditioning on the length of car ownership, there are differences in which cars are being used for smoothing job separation shocks. Figure 10 reports how the probability of downgrading differs by the quality of the car. Cars are split into four types, relative to the dealer purchase price: very low-quality cars, which have quality less than 90% of the average quality being sold; low-quality cars, which are between 90% and 100% of average quality; good-quality cars, which are no more than 10% higher quality than the average; and very good-quality cars, which are more than 10% better than average. Figure 10 shows downgrading for asymmetric information on the left-hand side and symmetric information on the right-hand side. The difference is stark: under asymmetric information, it is the very low-quality cars, which are being sold for consumption

[31] Since the propensity to downgrade the car stock before and after unemployment is not targeted in the estimates, this exercise contributes significantly toward establishing the external validity of the asymmetric information model.

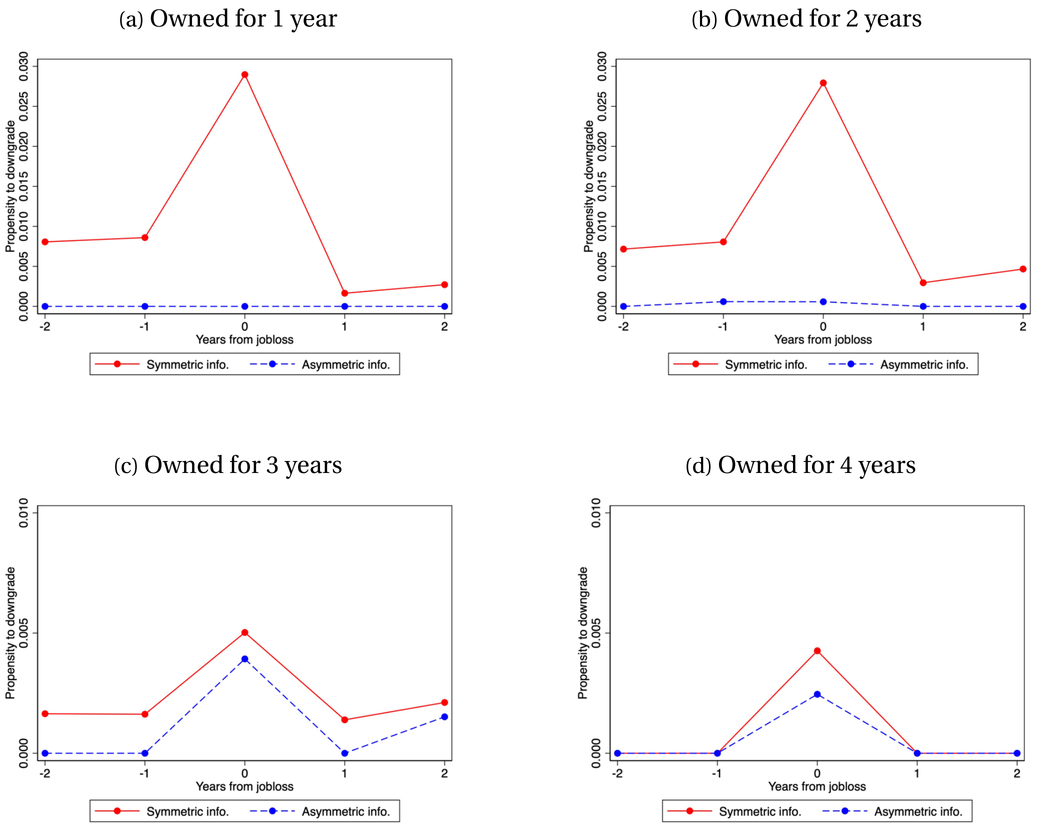


FIGURE 9. Simulated downgrading by ownership duration.

smoothing, whereas under symmetric information, it is the very high-quality cars, which are being sold.

The message from Figure 10 is that the presence of asymmetric information introduces insurance against a car being of low quality: since dealers cannot condition the price on quality because it is unobservable, the owners of bad cars receive a price above the true quality of their car, whereas the owners of good cars receive a price below the true quality. This insurance comes at a price, which is the transaction cost of the lemons penalty, reducing the expected value of the asset.

8. Conclusions

In this paper, we assess the importance and implications of the lemons penalty in the car market. The lemons penalty exists when car sellers know more about the quality of the car they are selling than buyers, that is, when there is asymmetric information about the quality of cars being traded. This type of asymmetric information implies that dealers will pay less than the expected value of cars in the population, and this will systematically affect who sells a car, such that cars put on the market are, on average, of lower quality than the expected quality in the population of cars. This price discount is the

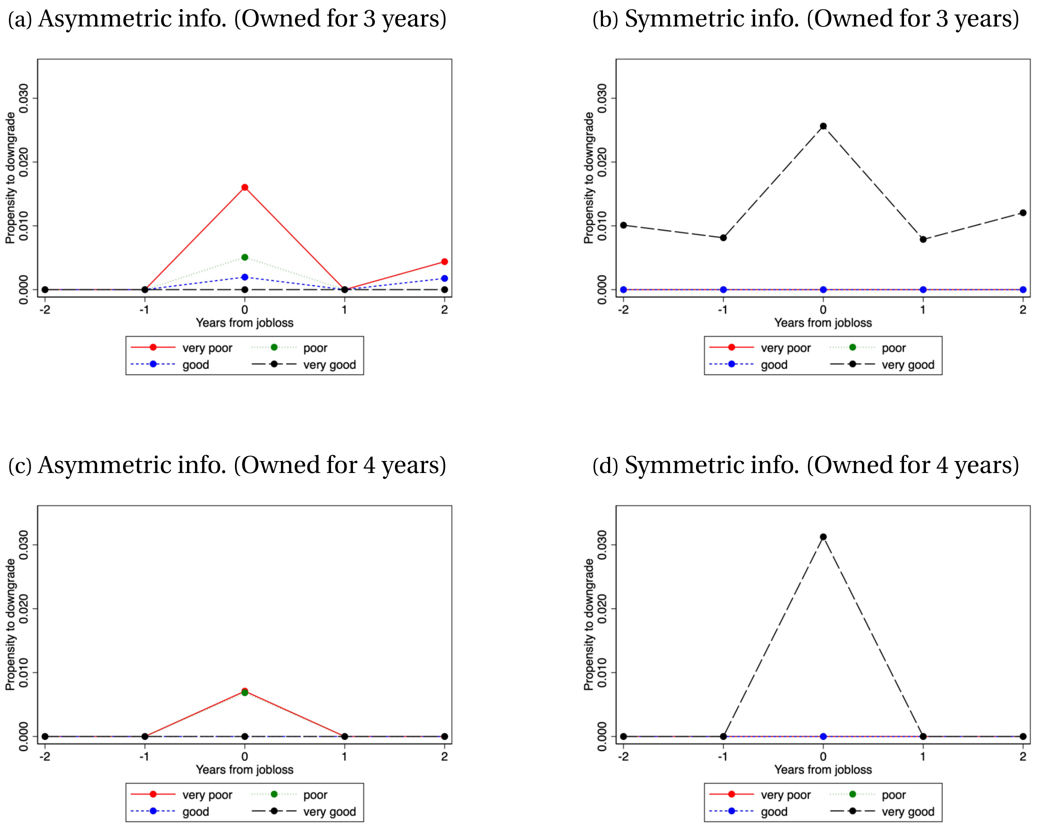


FIGURE 10. Simulated downgrading by car quality. *Note*: There are 4 levels of quality: very poor (quality less than 90% of average among sold cars), poor (between 90% and 100%), good (100% to 110%), and very good (over 110% of average).

lemons penalty, which generates a transaction cost that is endogenous to the quality of cars that are sold in equilibrium.

In order to quantify the quality of cars in the population and the quality of cars put on the market, we formulate and estimate a stochastic life-cycle equilibrium model of car ownership in which dealers buy old cars from households without the dealers knowing the true quality. Car dealers are offered cars that, on average, are of lower quality than similar cars in the population, so the dealers will only pay a lower price. Households selling above-average quality cars, therefore, receive a lower payment than what they would have if there were no informational asymmetry about the quality of the car, and this difference is the lemons penalty. The supply of cars in the used car market varies as households receive news about their income, and this affects the average quality of cars entering the secondary market. This mechanism enables us to study how equilibrium prices and the flow of cars in and out of the market are characterized.

Our results show that the lemons penalty is significant in the first years of car ownership, but it declines quickly with ownership. We show that the lemons penalty reduces transaction volumes and turnover, leading to market inefficiency. The size of the lemons penalty depends on the amount of underlying income uncertainty and the credit limit imposed on households: In settings with greater variance of income shocks and lower credit limits, households are more likely to sell their cars for reasons unrelated to the car's quality, reducing the size of the lemons penalty.

If there were full information about the quality of cars in the market and in the population, sellers would receive a price that reflects the actual quality of cars, that is, there is no lemons penalty and, therefore, owners are more willing to sell their car if it is of high quality. As a consequence, the composition of cars in the market changes, and is, on average, of higher quality, and cars are traded more frequently.

Full information brings a gain for people with high-quality cars, who are then able to get a price that matches their true quality. This is of particular value for owners of cars that have been bought recently and are of high quality: such owners can now better use the car for countering adverse income shocks than in the asymmetric information environment. The effect is the opposite for owners of low-quality cars: full information brings a lower price, and they will be less able to use the car to smooth out during times of low income. For this group, asymmetric information has a benefit and introduces insurance against holding a car of low quality. Asymmetric information has distributional consequences as well as efficiency consequences. Further, this insurance comes at a price—the transaction cost induced by the lemons penalty—which we show significantly reduces the expected asset value of a car, and this has a substantial effect on the market for cars. Further, the transaction cost means that lower-income households, whose cars make up a large fraction of their wealth, are prevented from using this asset efficiently for income smoothing.

Appendix A: Financial assets around time of car purchase

This Appendix documents—see Figure A.1—how net financial asset holdings fluctuate around the time when households in the sample buy a car in an event study. Net financial assets include bank deposits, shares, bonds, and nonmortgage debt. They are measured relative to the household's average disposable income across the years in which the household enters the sample. The event is defined as the first car purchase observed in the period 1999–2009.

Appendix B: Summary statistics for full sample and for job-loss sample

Table A.1 presents summary statistics for the full sample and for the sample of households that experience job loss, split by age group. The job-loss sample includes observations for households affected by job-loss events during the period 1999–2009. An unemployment event is defined as at least 3 months of full-time unemployment within a calendar year. For two-adult households, it is defined as the couple jointly experiencing at least 6 months of unemployment within a calendar year.

Appendix C: Income process

The estimated unconditional autocovariance up to order three is presented in Table A.2 for the two education groups. Second- and higher-order autocovariance is statistically

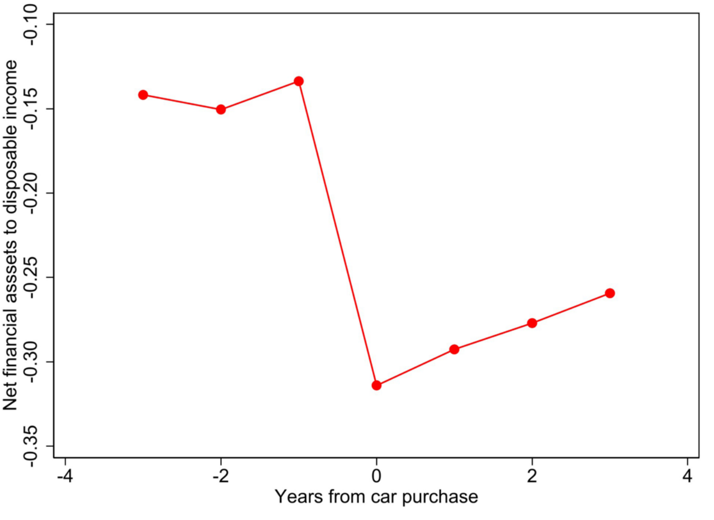


FIGURE A.1. Net financial assets around time of car purchase.

significant, reflecting some persistence in the transitory component. Their size is, however, very small.[32]

The variance of the job separation shock σ_κ^2 can be estimated using the residual income growth for those employed in $t-1$ and unemployed in t, $g_{it,eu} = \epsilon_{it} + \triangle\nu_{it} + \kappa_{it}$ based on the expression $\sigma_\kappa^2 = E(g_{it,eu}^2) - \sigma_\epsilon^2 - 2\sigma_\nu^2$, where the subscript eu denotes "from employment to unemployment." The persistence of the unemployment shock ρ_e is estimated from the variance of residual income growth for those unemployed in $t-1$ and employed in t, $g_{it,ue} = \epsilon_{it} + \triangle\nu_{it} + \rho_e\kappa_{it} - \kappa_{it}$ using the expression $\rho_e^2 = [E(g_{it,ue}^2) - \sigma_\epsilon^2 - 2\sigma_\nu^2 - \sigma_\kappa^2]/\sigma_\kappa^2$, where the subscript ue denotes "from unemployment to employment." The estimates of ρ_e are 0.635 for the No College group and 0.734 for the Some College group.

For simplicity, we assume κ_{it} follows a discrete two-point distribution with support $\{\kappa_{1s}, \kappa_{2s}\}$, each occurring 50% of the time. κ_{1s} is positive, representing a job separation shock that leads to a better new job, and κ_{2s} is negative, representing a serious scarring effect due to unemployment. $\{\kappa_{1s}, \kappa_{2s}\}$ are estimated based on the mean and variance of the residual income growth for those employed in t-1 and unemployed in t using minimum distance methods. The estimates are $\{0.107, -0.245\}$ for the No College group and $\{0.181, -0.286\}$ for the Some College group. Finally, we set the probability of job separation δ_u to be 3.7% for the No College group and 2.5% for the Some College group annually.

APPENDIX D: ALTERNATIVE SPECIFICATIONS

In this section, we consider some alternative specifications of our model, which allow us to test the robustness of our results and assess how various assumptions impact the

[32]We have also estimated autocovariance year-by-year. These estimates (not reported) indicated a very stable pattern across the sample period, and we therefore only report the pooled estimates.

TABLE A.1. Summary statistics.

Age Group	Full Sample				Job-Loss Sample			
	30–40		41–60		30–40		41–60	
	Average	Median	Average	Median	Average	Median	Average	Median
Car								
Car owner	0.69	1	0.74	1	0.66	1	0.69	1
Age of car	8.90	9	8.36	8	9.76	10	9.44	9
Owner of regular car, car owner	0.82	1	0.84	1	0.76	1	0.78	1
Ownership duration of regular car	4.12	4	5.13	4	3.70	3	4.65	4
Income/wealth								
Disposable income (1000 DKK)	309	315	323	318	260	262	265	264
Financial assets / disp. income	0.31	0.09	0.56	0.15	0.31	0.09	0.57	0.14
1[financial assets < 1 month disp. income]	0.49	0	0.35	0	0.49	0	0.36	0
Car owner	0.65	1	0.67	1	0.62	1	0.62	1
Car value (1000 DKK)	90	67	96	72	90	65	91	65
Car value / disp. income	0.27	0.21	0.28	0.22	0.32	0.24	0.32	0.24
Car value / (fin. assets + car value)	0.70	0.86	0.71	0.86	0.79	0.88	0.78	0.88
Housing equity to house value (ETV)	0.24	0.19	0.35	0.31	0.24	0.20	0.34	0.30
Housing equity to disp. income (ETI)	0.87	0.51	1.44	0.88	0.92	0.54	1.46	0.87
1[financial assets > 1 month disp. income]	0.51	1	0.65	1	0.51	1	0.64	1
Car owner	0.72	1	0.77	1	0.70	1	0.74	1
Car value (1000 DKK)	113	87	118	94	109	80	110	83
Car value / disp. income	0.34	0.26	0.35	0.28	0.37	0.27	0.38	0.29
Car value / (fin. assets + car value)	0.44	0.47	0.39	0.39	0.47	0.49	0.41	0.41
Housing equity to house value (ETV)	0.30	0.25	0.52	0.51	0.30	0.24	0.50	0.48
Housing equity to disp. income (ETI)	1.37	0.78	2.58	1.81	1.41	0.78	2.57	1.77
Demographics								
Age	35	35	50	50	35	35	50	50
Married/cohabiting	0.71	1	0.75	1	0.66	1	0.70	1
Has children	0.64	1	0.47	0	0.62	1	0.45	0
Homeowner	0.50	1	0.61	1	0.52	1	0.63	1
Some college	0.26	0	0.21	0	0.23	0	0.17	0
Number of observations	1,451,829		2,558,502		466,295		678,601	

outcomes. We carefully analyze the implications of each alternative specification, providing a comprehensive analysis that contributes to a more holistic understanding of the interactions between information asymmetry, transaction costs, credit constraints, and market outcomes.

Table A.2. The autocovariance of residual log income.

Order	No College	Some College
0	0.0456 (0.00021)	0.0463 (0.00036)
1	−0.0136 (0.00013)	−0.0128 (0.00023)
2	−0.0017 (0.00008)	−0.0017 (0.00013)
3	−0.0005 (0.00007)	−0.0007 (0.00011)

D.1 *Exogenous transaction cost*

In our baseline asymmetric information model, the estimate of the lemons penalty captures the endogenous transaction costs associated with the lower price when selling a car of average quality. To further assess the importance of the endogenous nature of the transaction cost in matching the data, we conduct a reestimation of the model, allowing for an exogenous transaction cost that is proportional to the sale price.

In this extended model, a used car of ownership duration z can be sold to a dealer at dealer price p_z^d, and the household pays a transaction cost λp_z^d proportional to the sale price. Unlike the endogenous transaction cost, this exogenous transaction cost remains identical for car owners who have owned their cars for the same length of time, and thus it does not have the distributional implications of the lemons penalty. We estimate the exogenous transaction cost λ as an additional parameter within the baseline model. The estimated parameter values and fitted moments are presented in the column labelled "Asy Cost" of Table A.3 and Table A.4, respectively. The estimated proportional transaction cost is small (0.9% of the sale price).

Table A.3. Alternative specifications: estimated parameter values.

Parameters		Baseline	Asy Cost	Symmetric Info	No Saving
Common parameters					
Discount factor	β	0.974	0.973	0.975	0.973
Private depreciation factor	η_1	11.8	11.5	16.2	24.0
	η_2	1.992	2.067	1.615	2.244
Arrival rate of banger quality shock	δ^r	0.103	0.109	0.100	0.134
Scrap rate for bangers	δ^b	0.259	0.266	0.260	0.255
Relative risk aversion	γ	1.207	1.254	1.226	1.213
Exogenous transaction cost	λ	N.A.	0.009	0.056	N.A.
Some college					
Preference for new car	θ_h^f	1.152	1.152	1.159	1.174
Preference for banger	θ_h^b	0.975	0.980	0.977	0.970
Utility benefit of owning car	α_h	0.352	0.349	0.318	0.342
No college					
Preference for new car	θ_l^f	1.155	1.157	1.171	1.164
Preference for banger	θ_l^b	0.928	0.925	0.902	0.845
Utility benefit of owning car	α_l	0.326	0.333	0.279	0.390

Table A.4. Alternative specifications: moments.

Moments		Data	Baseline	Asy Cost	Symmetric Info	Half Collateral	No Collateral	No Saving
Ownership rate of regular cars								
No college	Age 30–40	55.2%	52.2%	52.2%	54.8%	31.9%	19.1%	19.4%
	Age 41–60	60.4%	61.2%	61.1%	62.2%	46.1%	32.4%	32.4%
Some college	Age 30–40	58.7%	64.8%	62.3%	71.5%	39.4%	23.2%	20.6%
	Age 41–60	67.8%	75.6%	74.9%	76.4%	62.1%	50.0%	43.3%
% people buy new cars								
No college	Age 30–40	3.9%	3.0%	3.4%	3.6%	2.8%	2.8%	3.0%
	Age 41–60	5.2%	6.7%	6.9%	6.8%	6.5%	6.6%	6.9%
Some college	Age 30–40	4.8%	4.9%	4.6%	3.6%	4.8%	4.2%	4.3%
	Age 41–60	6.2%	12.8%	12.6%	12.1%	14.1%	14.0%	12.2%
Ownership rate of bangers								
No college	Age 30–60	22.9%	26.7%	26.0%	24.7%	44.2%	57.4%	47.5%
Some college	Age 30–60	19.6%	21.3%	21.9%	19.6%	39.4%	52.9%	49.8%
Financial asset to income at 55								
No college		0.196	0.234	0.208	0.237	0.357	0.508	N.A.
Some college		0.287	0.287	0.270	0.279	0.400	0.529	N.A.
Ownership duration of cars		4.860	4.613	4.605	4.406	4.507	4.342	3.372
% of cars sold after 1 year		5.8%	5.3%	4.6%	5.8%	5.8%	7.2%	13.4%
% of cars sold after 2 years		24.9%	27.5%	27.8%	30.9%	28.9%	31.7%	57.6%
% of cars sold after 3 years		41.5%	53.4%	53.7%	59.7%	55.0%	56.9%	77.1%
% of cars sold after 4 year		55.7%	71.1%	71.9%	70.2%	73.4%	74.1%	86.0%
% of cars sold after 5 years		67.0%	77.9%	78.0%	76.2%	79.1%	80.7%	87.5%
% of cars sold after 6 years		75.1%	80.6%	80.7%	81.0%	82.0%	83.6%	88.5%

Upon examining the results, we found that the estimated lemons penalty, shown in the panel labeled "Asy Cost" of Table A.5, is substantially greater than the estimated proportional cost. This observation suggests that the average loss of a transaction imposed by the lemons penalty remains significant even after accounting for the additional exogenous transaction cost parameter. In essence, the presence of the estimated lemons penalty is little changed by the inclusion of the additional transaction cost parameter.

D.2 *Symmetric information model with reestimation*

Here, we estimate the exogenous transaction cost when information is symmetric: all idiosyncratic quality shocks are publicly observed, and sellers receive a price that reflects the actual quality of cars.

The second panel of Table 8 shows that, compared to asymmetric information, symmetric information leads to much faster transactions occurring, that is, high-quality cars are sold much sooner. This fast rate of transactions is at odds with the data, so we introduce an exogenous transaction cost to the symmetric information model to match the rate of transactions. The transaction cost is introduced for a household selling a car: for

Table A.5. Alternative specifications: prices and the lemons penalty.

Ownership Years	1	2	3	4	5	6	7	8	9	10
Baseline										
Dealer price	0.69	0.61	0.54	0.48	0.42	0.37	0.33	0.30	0.29	0.27
Expected car value (in population)	0.81	0.67	0.57	0.49	0.44	0.39	0.36	0.33	0.32	0.30
Lemons penalty	−0.12	−0.06	−0.03	−0.02	−0.02	−0.02	−0.03	−0.03	−0.03	−0.03
% of cars being sold	5.3%	27.5%	53.4%	71.1%	77.9%	80.6%	82.5%	83.8%	84.8%	85.7%
Asy cost (Asymmetric information with exogenous transaction cost)										
Dealer price	0.68	0.61	0.53	0.47	0.41	0.36	0.33	0.30	0.28	0.27
Expected car value (in population)	0.80	0.66	0.56	0.48	0.43	0.38	0.35	0.33	0.31	0.30
Lemons penalty	−0.12	−0.05	−0.03	−0.01	−0.02	−0.02	−0.02	−0.03	−0.03	−0.03
% of cars being sold	4.6%	27.8%	53.7%	71.9%	78.0%	80.7%	82.5%	83.8%	84.8%	85.7%
No saving										
Dealer price	0.79	0.72	0.64	0.58	0.51	0.47	0.43	0.41	0.38	0.36
Expected car value (in population)	0.85	0.74	0.66	0.59	0.53	0.49	0.45	0.42	0.39	0.37
Lemons penalty	−0.06	−0.02	−0.02	−0.01	−0.02	−0.02	−0.02	−0.01	−0.01	−0.01
% of cars being sold	13.4%	57.6%	77.1%	86.0%	87.5%	88.5%	89.2%	89.9%	90.4%	91.2%

a car of value $q_i p^u$, the household pays a transaction cost $\lambda q_i p^u$ proportional to the sale price.

We estimate the symmetric information model, adding the exogenous transaction cost λ as an additional parameter to estimate. The estimated parameter values are in column "Symmetric Info" of Table A.3. The estimated proportional transaction cost is 5.6%. The fitted moments are in column "Symmetric Info" of Table A.4. The ownership rate of regular cars in the symmetric information model is higher than that in the asymmetric information model and data. For moments related to used car sales in the lower half of the table, the rate of transaction is faster in the symmetric information model than that in the asymmetric information model and data. Therefore, the model with asymmetric information and the lemons penalty has a better data fit than the model with symmetric information and transaction costs.

D.3 *Reduce the credit limit*

In this section, we modify the borrowing constraint in our model. Specifically, we assume that lenders can only capture a fraction ψ of the collateral value of cars, as described in equation (6). In the "Half collateral" column of Table A.4, we reduce the collateral value by half ($\psi = 0.5$) and present simulation results from our model. As a result, we observe that households purchase fewer regular cars and, instead, choose to hold more bangers. Moreover, in the "No collateral" column of Table A.4, we entirely remove the collateral value of cars ($\psi = 0$), resulting in cars losing their role as collateralizable assets. Despite this change, cars continue to provide utility to households. As expected, the trends observed in the "Half collateral" scenario continue in the "No collateral" setting, with households further substituting regular cars with bangers. We delve deeper into the impact of lending restrictions on the lemons penalty in Section 5.3.

D.4 *Removing the option to borrow and save*

To understand the importance of saving in our model, we consider the implications of removing the ability of households to borrow or save. We reestimate the model and report estimated parameter values and fitted moments in the column labeled "No Saving" of Table A.3 and Table A.4, respectively. In this environment, the purchase of a car must be financed by giving up current consumption, and this dramatically reduces ownership. The resulting lemons penalty, in the panel labeled "No Saving" of Table A.5, is estimated to be 6% in the first year of ownership, declining with the length of ownership.

When households are unable to borrow or save, the only way to smooth their consumption is for households to buy or sell their cars. After a negative shock, the need for households to access the asset value in cars is much larger compared to an environment where they are able to save. Figure A.2 shows the propensity to downgrade around job loss compared to the baseline. The solid and dashed lines show the propensity to downgrade in the data and in the baseline model, respectively. The dotted line shows the propensity to downgrade in the model without saving. This shows the much greater role of cars for smoothing in the absence of saving, which is not what is observed in the data.

Appendix E: Additional computational details

As described in Section 4, the computation of our model involves three tiers: the inner tier deals with solving the dynamic programming problem for households, the middle

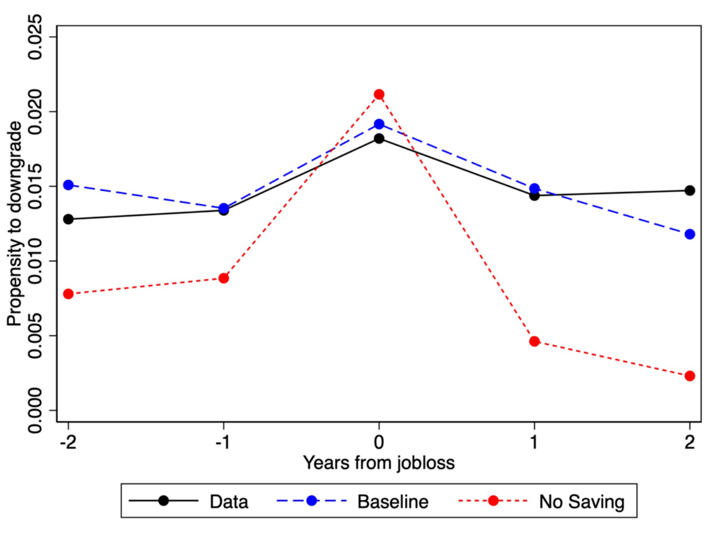


Figure A.2. Downgrading after job loss: No saving.

tier focuses on computing the fixed point for equilibrium prices, and the outer tier involves the optimization in the parameter space.

First, the dynamic programming problem of the household, with a discrete choice concerning car ownership, is solved using value function iteration. We find different "conditional value functions" (one for each of the current choices of car ownership and nonownership) that can be compared to determine the discrete choice. The solution for consumption and car ownership is found recursively from the last period of life, T. In the last period of life, the value function consists of the current utility from car ownership and consumption. Given the optimal choices at $t+1$, the backward recursion then chooses car ownership, consumption, and saving that maximize period t's value function, subject to borrowing constraints.

To compute the solution, we solve at a finite number of points in the asset dimension. We store optimal decisions and value functions at grid points, but in our simulations, households' choices are not restricted to coincide with these points. We perform linear interpolation in all cases where choices lie between points. We use 80 nodes in each "conditional" asset grid (we have separate grids underlying each conditional value function, as assets are limited by different borrowing constraints depending on the car-ownership choice). There are more points in the lower range of the asset grids that better approximate the savings decisions of households with lower assets.

We also use discrete approximations for the specified continuous processes of income shocks and car quality. The permanent income shock component is approximated using a discrete Markov chain with 11 equally spaced points on an age-varying grid chosen to match the age-specific unconditional variances. The unemployment-related income shock component and car quality are approximated using discrete Markov chains with 9 and 17 points, respectively.

In total, agents can be in 2 education levels, 59 age groups, 80 asset grids, 11 permanent income shock grids, 9 unemployment-related income shock component grids, 4 car ownership states, 12 car ownership periods, and 17 car quality grids. We have verified that further increasing the cardinality of the grids does not affect our conclusions. Households' expected lifetime utility is computed by integrating the value functions over the distributions of four stochastic shocks: permanent income shocks, unemployment-related income shocks, banger quality shocks for regular cars, and scrappage quality shocks for bangers.

We solve the dynamic programming problem in R (version 4.3.2), utilizing Rcpp to call C++ functions and employing the global grid search method from the GNU Scientific Library (GSL). The grid points of the asset dimension are essentially independent and can be solved simultaneously by different processors. Using our parallelized computer algorithm on 36 Xeon 6246 processors reduces the computation time by a factor of about 36. Once the optimal decision rules are obtained as functions of the state variables, we simulate the life-cycle behavior of 100,000 households. With this setup, the model solution and simulation take around 12 minutes.

The second tier of computation is to find a fixed point for the equilibrium dealer purchase prices. First, we make an initial guess of the prices p^d_{old}. Second, we solve the model and calculate the new dealer purchase prices p^d_{new} using the zero-profit condition. If p^d_{old} and p^d_{new} are sufficiently close for all ownership durations, we have found the fixed point. Otherwise, set $p^d_{\text{old}} = p^d_{\text{new}}$ and repeat until convergence. In practice, the equilibrium-finding algorithm consistently converged to a fixed point across a wide range of parameter values and initial price guesses. While we are unable to provide formal proof of uniqueness, we did not observe convergence failures in the parameter space explored.

Third, to estimate the model, we use the method of simulated moments. We minimize the relative distance between the data targets and the model moments, which is equivalent to minimizing the absolute difference while using the absolute value of the inverse of the data moments as the weighting matrix. This effectively standardizes the moments and ensures that all moments contribute meaningfully to the objective function, regardless of their scale. We do not use the asymptotically optimal weighting matrix because of its poor small-sample properties, as suggested by Altonji and Segal (1996).

For estimation, we first make an initial guess of the endogenous parameter values and then find a fixed point for the vector of dealer purchase prices. At these equilibrium prices, we evaluate the criterion function using simulated and actual moments, while maintaining all equilibrium conditions from Section 2.3.1. We quantify any deviations of these conditions from zero and minimize them. For parameter optimization, we use the simplex algorithm in the NLopt library. After updating the endogenous parameter values, the process is repeated until convergence. A full estimation run is expensive in time. Because the MSM objective function is nonconvex, we estimate the model from multiple starting points and retain the parameter set that achieves the lowest value of the criterion function.

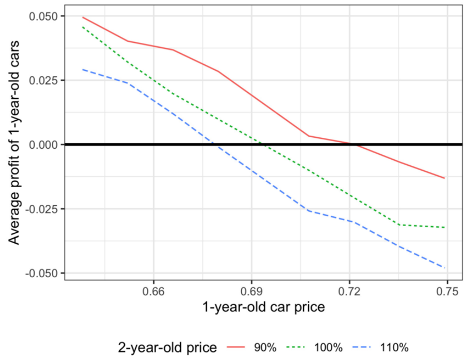
Appendix F: The impact of varying dealer purchase prices

Figure 1 illustrates the impact of varying dealer purchase prices on dealer profits. It shows a negative correlation between price and profit across these used car markets. Moreover, the presence of a single crossing between the dealer profit curve and the zero-profit line is a crucial finding. This is evidence of the existence and uniqueness of the equilibrium dealer purchase price.

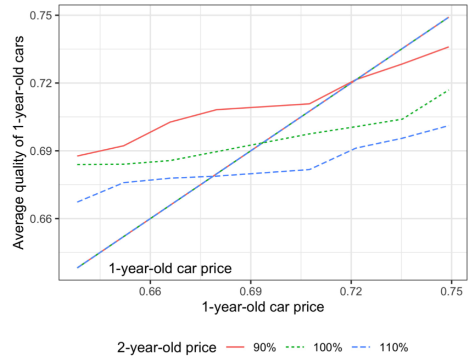
To illustrate the unique crossing of dealer's profit more generally, we conducted an experiment by fixing the 2-year-old car price at different values while varying the 1-year-old car price, that is, the cross derivative of 1-year-old car profit on 1-year-old and 2-year-old car prices. Figure A.3 presents the results. We also explored cross-derivatives of other price pairs, confirming the same outcomes.

In Figure A.3a, we observed a negative correlation between the dealer purchase price and their profit, resulting in a unique crossing between the profit curve and the zero-profit line. A unique crossing exists for different values of 2-year-old car prices. Interestingly, when the 2-year-old car price increases to 110% (reduces to 90%) of its equilibrium value, the profit curve of 1-year-old cars shifts leftward (rightward), and the unique crossing occurs at a lower (higher) profit.

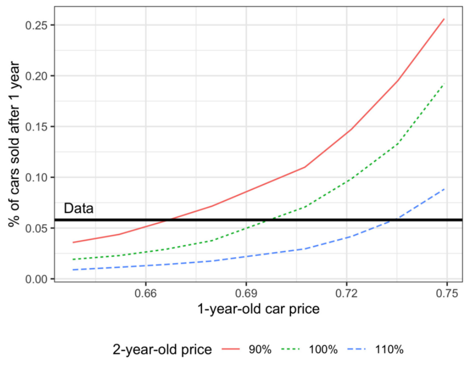
(a) Dealer's average profit for a 1-year-old car



(b) Average quality of a 1-year-old car sold



(c) Percent of cars sold after 1 year



(d) Dealer's total profit in 1-year-old car market

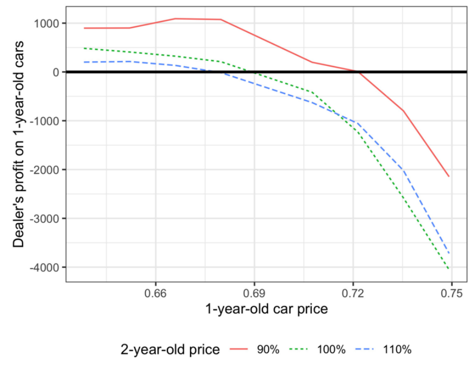


FIGURE A.3. Impact of varying 1-year-old car price, setting 2-year-old price at different values.

Figure A.3b provides further insight into the negative correlation between price and profit. As the price paid by dealers for 1-year-old cars rises, the average profit per 1-year-old car decreases through a direct effect. This is offset by the increased quality of the cars that are sold to dealers. This increased quality is a selection effect. When considering the net consequence of the direct and selection effects on profits as price increases, it leads to a decrease in profits and a unique crossing of the zero-profit line.

Furthermore, Figure A.3c reveals that the price paid by dealers for 1-year-old cars has an impact on the transaction volume of these cars. As the price increases, the transaction volume also rises. Moreover, the price of 2-year-old cars also influences the transaction volume of 1-year-old cars, indicating a link between different used car markets.

Finally, Figure A.3d displays the total profit (unit profit multiplied by transaction volume) of dealers in the 1-year-old car market. Despite the unit profit decreasing and the transaction volume increasing with the increase in the 1-year-old car price, the overall profit exhibits a general downward trend.

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The replication package for this paper is available at https://doi.org/10.5281/zenodo.17067942. The authors were granted an exemption to publish their data because either access to the data is restricted or the authors do not have the right to republish them. However, the authors included in the package a simulated or synthetic dataset that allows running their codes. The Journal checked the synthetic/simulated data and the codes for their ability to generate all tables and

figures in the paper and approved online appendices. However, the synthetic/simulated data are not designed to reproduce the same results.

All authors assume responsibility for all aspects of the paper.