Durables and Lemons: Private Information and the Market for Cars*

Richard Blundell† Ran Gu‡ Soren Leth-Petersen§

Hamish Low¶ Costas Meghir‖

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Abstract

We examine the aggregate implications and distributional consequences of asymmetric information in durable goods markets, with a focus on the car market. Private information introduces a lemons penalty, a wedge between the sale price and the average car value in the population, consequently reducing turnover. We estimate an equilibrium model of car ownership with private information using Danish linked registry data on car ownership, income, and wealth. In the first year of ownership, we estimate the lemons penalty is 12% of the price. The penalty declines sharply with the length of ownership. The penalty reduces the self-insurance value of cars and leads to a large reduction in transaction volumes and the rate of turnover of cars. The market does not collapse: income shocks induce individuals to sell their cars, even if 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 credit limit decreases.

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

JEL Codes: D15, D82, E21

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†University College London, Institute for Fiscal Studies, TSE and CEPR

‡University of Essex and Institute for Fiscal Studies

§University of Copenhagen, CEBI and CEPR

¶University of Oxford and Institute for Fiscal Studies

‖Yale University, NBER, IZA, CEPR and the Institute for Fiscal Studies

1 Introduction

As with many durable goods, car owners know more about their own car's quality than buyers. This asymmetric information affects the price that buyers are willing to pay and, in turn, the quality of cars that owners are willing to sell, leading to a lemons penalty and, potentially, to the collapse of the market. The aim of this paper is to examine empirically the importance, distributional consequences and limitations of this insight in an economic environment where there are additional market failures, primarily related to a lack of insurance against income risk.

The lemons penalty reflects the difference between the average quality in the population and the average quality of cars sold, conditional on observed characteristics. Asymmetric information about the quality of cars means dealers will pay less than the expected value of cars that are owned in the population, and this will further affect who sells a car to a dealer. This price discount is the lemons penalty. To quantify the lemons penalty, we develop an equilibrium model of the car market, where individuals are life-cycle consumers facing stochastic income and subject to liquidity constraints.

We use our framework to address two central issues. First, although in the standard Akerlof framework, the lemons penalty would lead the market for second-hand cars to unravel, we show this is not the case with idiosyncratic income risk and car quality declining with the duration of ownership. Some households will sell their cars for liquidity purposes, and since income shocks are not perfectly aligned with the unobserved characteristics of the car, these sales can be of higher quality and prevent the average quality of cars sold from collapsing. In other words, the average quality of cars in the second-hand market is partly driven by the distribution of the shocks to car quality and partly by the distribution of income shocks themselves. Second, the presence of asymmetric information about the arrival of shocks to car quality has direct implications for the extent of insurance that households have against owning a low-quality car and insurance against income shocks.

Asymmetric information means that cars with the same verifiable characteristics are sold at the same price, and this means that households have implicit, albeit partial, insurance against owning a car of lower quality than average. On the other hand, the lemons penalty implies a cost to selling a car of better-than-average quality. This is an endogenous transaction cost that reduces the value of holding a car as a way to smooth income shocks. It is a central feature of durable goods in the presence of asymmetric information and incomplete markets. This aspect of durable goods implies that wealth in a car is an imperfect store of value, and the use of wealth in cars to effectively smooth consumption is limited. As a result, when the underlying income uncertainty in the economy increases, such as in recessions, the lemons penalty declines as more cars are sold out of necessity. As the penalty declines, the use of cars as a store of wealth against negative shocks can increase. Despite the limited value of cars as a means of smoothing consumption, if cars directly yield utility, owning a car means that utility may be smoothed through bad income shocks.

We apply these ideas to high-quality Danish population-wide administrative register data, focusing on a period with complete information about car ownership from 1992-2009. This data and period of study have particular advantages for our modelling approach. First, 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. Second, the register data is linked to longitudinal income-tax records with information about the income and wealth of the owners. Third, we are able to merge with information on 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 during the period under study also has certain advantages for our approach. First, there is no manufacture of new cars in Denmark. Second, the vast majority of households either own no cars or one car. Third, more than 90% of used cars are bought and sold via dealerships. Fourth, the dealership market is thick with relatively low levels of concentration. Finally, during this period, leasing was virtually non-existent in Denmark, allowing us to abstract from the leasing market.[1]

To define and quantify the lemons penalty and to understand the distributional implications of the penalty, we specify and estimate a stochastic life-cycle equilibrium model of car ownership, consumption and other asset accumulation. We assume cars depreciate at a stochastic rate, with at least part of this depreciation being private information to the owner. Additionally, we allow for a deterministic depreciation, which is known and is the minimum amount of depreciation that can occur. For simplicity, we assume individuals sell cars to car dealers and purchase either new cars or second-hand cars from dealers or choose not to own a car at all. 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. Dealers, therefore, pay a lower price than they would have done if there was no asymmetric information, and this difference is the lemons penalty. Crucially, for the support of the equilibrium, some people sell their cars due to idiosyncratic shocks to income rather than due to their cars being of low quality. It is the presence of income shocks in our model that makes the second-hand market unlikely to unravel. The key to the identification of the model is information on second-hand car sales by duration of ownership. Using the equilibrium model, we can then establish the extent of

[1] Hendel and Lizzeri (2002) develop a theoretical model of leasing under adverse selection. They show 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 prevents the second-hand market from collapsing.

[2] Asymmetric information may arise on different sides of the car market. However, we assume that dealers have sufficient access to credit or are large enough to have the ability to offer short-term guarantees to buyers of second-hand cars that solve the lemons issue in that part of the second-hand market. Dealers can sell cars of different quality, but we assume the presence of short-term guarantees makes this as good as observable. Thus, the only point at which asymmetric information is an issue is when private individuals 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.

the lemons penalty by quantifying the average quality in the population and the average quality of cars put on the market.

For the purposes of quantifying the lemons penalty and to accurately assess the extent of consumption smoothing through car ownership, modelling asset accumulation in addition to wealth held in cars is critical. In our model, the lemons penalty is an equilibrium concept that captures the endogenous cost of car adjustment and 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 individual access to credit and their ability to accumulate savings to purchase cars. In related work, 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. They do not have hidden information and thus abstract from endogenous adjustment costs. Attanasio et al. (2008) and Alessie et al. (1997) also 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.[3] Without other means of saving, the purchase of a car must be financed by sacrificing current consumption, and this reduces the flows in and out of the car market.

We use a Method of Simulated Moments estimator (McFadden, 1989; Pakes and Pollard, 1989) using data for households where the oldest household member is aged 30-60 in the period 1992 to 2009. Our approach is to choose the parameters to minimize the relative deviations between moments calculated in the data and corresponding simulated moments, where the targeted moments include the ownership rates of cars by age and by education, the proportion of households buying new cars by age and by education, the proportion of cars sold by ownership duration, average ownership duration of cars, and holdings of financial assets.

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 one 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. The second-hand car market does not collapse because individuals have different motives for selling their cars: income shocks lead some individuals to sell high-quality cars despite the lemons penalty they then have to pay. As a result of this mechanism, we show the lemons penalty tends to be smaller when the overall

[3] In Figure 10 in Appendix A, we document using the administrative data that financial asset holdings change significantly at the time when households buy cars.

income risk is higher and when the credit limit is lower, because more high-quality cars are put on the market. Moreover, these differences in the lemons penalty matter because the presence of the penalty delays replacement substantially and reduces the probability of downgrading to another lower-quality car in response to an adverse income shock. The final point we stress is that 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.

An important characteristic of durable goods is that they have an asset value as well as delivering a flow of consumption services. Consequently, durable goods have the potential to act as a savings instrument that can be used to provide self-insurance when faced with adverse income shocks, depending on the cost of liquidation. To take this into account, we explicitly model cars as an asset accumulation device. Our study thus links up to an extensive literature about consumption smoothing and shocks: Deaton (1991), Browning and Crossley (2009), Blundell et al. (2008), Low et al. (2010), and Kaplan and Violante (2014). If there is no private information (generating a transaction cost), then a durable good is like a non-durable good 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 will 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 estimated model allows us not only to identify the transaction costs but also to quantify the self-insurance value of cars and the extent to which this is reduced by asymmetric information. We use the model to explore the implications of asymmetric information for the extent of car quality downgrading. When information is symmetric, sellers receive a price that reflects the actual quality of cars and therefore owners are willing to sell their car even if it has been bought recently and is of high quality. In this case, owners downgrade in order to liquidate the asset value, which can then be used for non-car spending. When there is asymmetric information, car owners are less willing to sell cars that have been bought recently and are of high quality: the offered price does not reflect the true quality of the car but rather reflects the average quality of cars for sale.

Previous papers have modelled household ownership and replacement of cars and recognized that the car replacement decision is associated with transaction costs. Lam (1991), Eberly (1994), Attanasio (2000), and Foote et al. (2000) present Ss-models of car ownership where exogenous transaction costs create inaction regions, or Ss-bands, within which the household does not upgrade or downgrade the car. Generally, Ss-models are concerned with the consumer decision and do not model the endogenous determination of prices in the second-hand market and hence do not provide an explicit economic explanation of why transaction costs arise or why they vary as the supply of cars to the secondary market changes. Goldberg (1995) focuses on the market for new cars and consequently is not concerned directly with the pricing in the second-hand market. There is also a close connection between models of car replacement and models of firms' durable goods. Ramey and Shapiro (2001), Cooper and Haltiwanger (2006), and Bloom (2009) estimate high investment adjustment costs in the markets for used capital.

The literature on whether information asymmetry exists in the used car market is mixed. Some papers find no evidence of asymmetric information problems. Adams et al. (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 et al. (2020) compare the transaction price of dealers with those in unmediated sales to find evidence of asymmetric information. These papers focus on the market when private individuals buy cars, whereas we focus on the asymmetric information when private individuals sell to dealers.

This paper connects with the literature emphasizing the interaction 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 (1999) incorporate adverse selection into a dynamic model of new and used cars in which the only shock is a shock to car quality. They assume cars last for just two periods and motivate trade in the secondary market by assuming that agents differ in their taste for quality. House and Leahy (2004) consider a model with three-period-lived cars and no quality depreciation. They show how adjustment costs arise endogenously because of adverse selection. As the match value of a consumer/car pair stochastically deteriorates over time, consumers sell their cars to improve their match. 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 et al., 2013). Gavazza et al. (2014) allow households to own up to two vehicles and find that transaction costs have a large effect on equilibrium trade. Gillingham et al. (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 use exogenous transaction costs to approximate trade frictions in the used car market; therefore, they do not model how the lemons penalty is endogenously determined, nor can they analyze the evolution of asymmetric information. In this paper, we emphasize how variations in household resources, together with the car market determine the prices of second-hand cars and thus how the lemons penalty is determined. The key contribution is to assess the importance of asymmetric information on the car market by estimating a dynamic general equilibrium model of the car market. In the model, we explicitly model the demand and supply of cars to the secondary market while allowing for asymmetric information about the quality of used cars. The key parameters of the model are estimated using very detailed and high-quality data about household income fluctuations and car replacement decisions.

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

The economy is stationary and consists of T overlapping generations. Households maximise 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 behaviour, then the household problem, and finally, 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

A car, owned by individual i in period t, has quality q_{it} and ownership duration $z_{it} \in \{0, 1, \dots, \bar{z}\}$.[4] Quality is one-dimensional and evolves over time, but cars differ in their type. Households can buy any one of three types of car: new, second-hand or bangers. We normalize the quality of second-hand cars sold by dealers to be 1 when they are sold. A banger is a car at the minimum level of quality. We use the term "Regular cars" to describe those bought either as new or second-hand.

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

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

Quality cannot be lower than the minimum quality q^b, which is the quality of a banger. The term d is the deterministic depreciation factor. The variable $\varepsilon \in [0, 1]$ is the additional stochastic depreciation

[4] We use notation as follows: z signifies duration of ownership and and q car quality. The subscripts it, such as on z_{it}, indicate the household i of age t. A newly purchased car has an ownership duration of 0 in the period of purchase.

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 for two further changes to quality: 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 quality 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 $\left\{p_1^d, p_2^d, \ldots, p_{\bar{z}}^d\right\}$ is endogenous, and depends on the distribution of car quality among private sellers. Consistent with modelling 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. 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 the price for a unit of 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.

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

[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 both the age of the car and the duration of ownership as state variables and have prices for cars which depend on both car age and ownership duration. This proved computationally infeasible, and 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 is irrelevant in the model.

car repair by the dealer resets the asymmetric information and the quality of the car sold is fixed to 1. This implies that the dealer offers a short-term guarantee, thus removing any concern of hidden defects. By contrast, the actual quality of cars that dealers are buying from households is unknown to the dealer.

2.2 Households

A household, i, can own at most one car at a time.[7] Households have education level, e, which is either high or low. The level of education determines both 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:

$$u\left(c_{it}, \tau, q_{it}\right) = \frac{\left(c_{it}\left(1+\theta^{\tau} q_{it}\right)^{\alpha}\right)^{1-\gamma} - 1}{1-\gamma} \tag{3}$$

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:

$$a_{it+1} = (1+r)\left[a_{it} + y_{it} - c_{it} - B_{it} p_{B} + S_{it} p_{S}\right] \tag{4}$$

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 ownership duration: $p_S = p^d_z$ if the car has been owned for z periods, and $p_S = p^b$ if it is a banger, independent of 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

$$a_{it+1} \geq -p^{d}_{z_{it+1}} \tag{5}$$

Cars are a store of credit up to the expected (equilibrium) resale value p^d_z for cars of ownership duration z. The amount of borrowing against the car is determined at the time of car purchase: there is no

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

refinance, and so households can only access wealth in cars by selling.[8]

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.

We assume a state pension with a replacement rate of 100 percent. This is higher than the actual replacement rate in Denmark, but it allows us to match observed liquid savings. Moreover, it simplifies the modelling of the life cycle savings motive and allows us to focus on the accumulation of assets for precautionary purposes and car buying, which are the critical margins in our application. There is no further income risk after retirement.

2.2.1 Income Process

Households receive an uncertain flow of labour income y_{it} depending on their level of education e:

$$\begin{aligned} \ln y_{it} &= b_{e0} + b_{e1} Age_{it} + b_{e2} Age_{it}^2 + b_{e3} Z_{it} + r_{it} \qquad (6) \\ r_{it} &= v_{it} + w_{it} \\ v_{it} &= v_{i,t-1} + \epsilon_{it} \\ w_{it} &= (1 - U_{it})\, \rho w_{i,t-1} + U_{it} \kappa_{it} \end{aligned}$$

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 components: 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.[9] Unemployment in Denmark rarely lasts longer than a year; however, it can have lasting effects on household income (see for example Altonji et al., 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.

[8] 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 higher than p^b, the owner needs to repay the loan 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 which equals 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, more bangers, and save more.

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

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. 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 $V_{it}^{\tau}\left(\Omega_{it}^{s}\right)$. 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 signifies a purchase of a car (new or used respectively), which by definition always has quality 1; n_z and u_z signifies keeping the existing car that has been owned for z periods. The unconditional value function can then be written as:

$$V_{it}(\Omega_{it}^{s}) = \begin{cases} \max\left[V_{it}^{0}, V_{it}^{b}, V_{it}^{n_1}, V_{it}^{u_1}\right] & \text{if s= 0, b} \\ \\ \max\left[V_{it}^{0}, V_{it}^{b}, V_{it}^{n_1}, V_{it}^{u_1}, V_{it}^{n_z}\right] & \text{if s= n} \\ \\ \max\left[V_{it}^{0}, V_{it}^{b}, V_{it}^{n_1}, V_{it}^{u_1}, V_{it}^{u_z}\right] & \text{if s= u} \end{cases} \tag{7}$$

where for clarity we have dropped the dependency of each conditional value function V_{it}^{τ} on the state variable Ω_{it}^{s}.

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:

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

Consider a household that decides to own a banger in period t, i.e. $\tau = b$. 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

$$V_{it}^{b}\left(\Omega_{it}^{s}\right)=\max_{c_{it}}\left\{\frac{\left(c_{it}\left(1+\theta^{b}q^{b}\right)^{\alpha}\right)^{1-\gamma}-1}{1-\gamma}+\beta\mathbb{E}_{t}\left[\left(1-\delta^{b}\right)V_{it+1}(\Omega_{it+1}^{b})+\delta^{b}V_{it+1}(\Omega_{it+1}^{0})\right]\right\}$$

$$\text{for } s=0,b,n,u$$

Consider a household that enters the period with a car (used or new) and decides to keep the existing car, i.e. $\tau=\tau_z\in\{n_z,u_z\}$. 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:

$$V_{it}^{\tau_z}\left(\Omega_{it}^{s}\right)=\max_{c_{it}}\left\{\frac{\left(c_{it}\left(1+\theta^{\tau}q_{it}\right)^{\alpha}\right)^{1-\gamma}-1}{1-\gamma}+\beta\mathbb{E}_{t}\left[\left(1-\delta^{r}\right)V_{it+1}(\Omega_{it+1}^{\tau_{z+1}})+\delta^{r}V_{it+1}(\Omega_{it+1}^{b})\right]\right\}$$

$$\text{for } \tau_z=n_z,\ u_z \text{ and } s=n,u$$

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, i.e. $\tau=\tau_1\in\{n_1,u_1\}$. 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 become a banger at the start of $t+1$ with probability δ^r. The household has a conditional value function of:

$$V_{it}^{\tau_1}\left(\Omega_{it}^{s}\right)=\max_{c_{it}}\left\{\frac{\left(c_{it}\left(1+\theta^{\tau}\right)^{\alpha}\right)^{1-\gamma}-1}{1-\gamma}+\beta\mathbb{E}_{t}\left[\left(1-\delta^{r}\right)V_{it+1}(\Omega_{it+1}^{\tau_q})+\delta^{r}V_{it+1}(\Omega_{it+1}^{b})\right]\right\}$$

$$\text{for } \tau_1=n_1,\ u_1 \text{ and } s=0,b,n,u$$

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 each car 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

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

Because individual quality is private information, dealers will have to offer a pooled price across all qualities given the observable characteristics, which here is just the duration of ownership. 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. Denmark produces no 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 that second-hand car dealers sell cars is given exogenously. The endogenous prices are the prices that dealers buy second-hand cars and the price of bangers. We define a stationary competitive equilibrium with adverse selection and without inventories as follows:

- A collection of (endogenous) prices $\mathbf{p} = \left\{p_1^d, p_2^d, \ldots, p_{\bar{z}}^d, p^b\right\}$,
- Consumption and car ownership decision rules for the household $\{c\left(\Omega_i^s, \mathbf{p}\right), \tau\left(\Omega_i^s, \mathbf{p}\right)\}$, which include the following decisions:
  - The decision to buy a (fixed) second-hand car,
  - The decision to buy a new car,[10]
  - The decision to buy a banger,
  - The decision to sell to a dealer a car of ownership duration z and quality q,
  - The decision to sell a banger.
- Decision rules of the dealer:
  - Dealer's purchase decision for cars of different ownership durations, $\forall\, z \quad q_{uz}^d\left(\bar{q}_z, \mathbf{p}\right)$.
  - Dealer's decision to sell a (fixed) second-hand car.

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

These individual and dealer decisions generate aggregate outcomes as follows:

- The total number of new cars purchased: Q_n
- The total number of (fixed) second-hand cars sold by dealers: Q_u^{fix}
- The total number of (fixed) second-hand cars purchased by households: Q_u^d
- The number of cars of each ownership duration sold to dealers by households, Q_{uz}^s
- The average quality of cars of each ownership duration sold to dealers by households, $\bar{q}_z$
- The total quantity of bangers purchased, Q_b^d, and sold, Q_b^s, by households
- The number of cars of each ownership duration owned by households: Φ_z
- The 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.
- The total stock of bangers: Φ_b

To determine equilibrium prices, we apply the following market clearing and stock conditions.

Market clearing conditions:

1. **Zero Profit Condition:** Dealers make zero profits (as in Equation 2).
2. **Second-hand car dealer market:** Household demand for (fixed) second-hand cars, Q_u^d, equals the number of (fixed) second-hand cars supplied by dealers, Q_u^{fix}
3. **No-inventory condition:** The total number of cars sold to dealers equals the number of (fixed) cars sold by dealers in each period:
$$\sum_{z=1}^{\bar{z}} Q_{uz}^s = Q_u^{fix}$$
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.
4. **The market for bangers:** Demand for bangers, Q_b^d, must equal supply, Q_b^s.

Flow conditions:

1. **Changes to the stock of bangers:** The total outflow of bangers equals the total inflow:
$$\delta_b \Phi_b = \delta_r \Phi_r + \left(\Phi_{\bar{z}} \left(1 - \delta_r\right) - Q_{u\bar{z}}^s\right)$$
Owners of regular cars that become bangers, either through a banger quality shock or through age being $\bar{z}$, become owners of bangers.

2. **Changes to the stock of regular cars:** The net flow of new cars must equal the rate that cars become bangers

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

2.3.2 Existence and Uniqueness of Equilibrium

Our model encompasses a dynamic lemons market with interconnected used car markets. We provide evidence of the existence and uniqueness of equilibrium by demonstrating that our model satisfies a single crossing result. 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). To visualize the existence of a vector of dealer purchase prices that satisfy the zero-profit condition, please refer to Figure 12 in Appendix F. Figure 12a illustrates how variations in dealer purchase prices of 1-year-old to 3-year-old cars impact dealer profits, while Figure 12b displays the effect of varying 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 the used car markets of different vintages. For example, as the dealer purchase price of one-year-old cars increases, the profit for the dealer of one-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.

To illustrate the single crossing property of dealers' profits more generally, we fix the price of a particular vintage at different values while varying the car price of cars of different vintages. For example, we show the cross derivative on 1-year-old car profit of varying 1-year-old and 2-year-old car prices. The results, presented in Figure 13 in Appendix F, reveal a consistent single crossing between the profit curve of 1-year-old cars and the zero-profit line for different values of 2-year-old car prices. We explore similar experiments with other price pairs. Figure 13 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 Unravelling

In the standard Akerlof (1970) setting, pooled pricing would lead to the market unravelling. 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 because there are reasons beyond cars being of low quality for cars to be sold.

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:

$$\pi = 0 \geq q^b p^u - p_z^d$$

$$p_z^d \geq q^b p^u$$

This condition holds true for all $z \in \{1, \ldots, \bar{z}\}$. 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.

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 de-registration 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 eight 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 individuals 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, labour 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 at least 30 years old and at most 60 years old. To these individuals, we add the partner, if there is one, and we summarize all the remaining information at the household level.

Table 1 presents basic summary statistics for two age groups, 30-40 and 41-60.[11] As expected, younger individuals have less accumulated wealth and are thus more likely to find it difficult to smooth out shocks. We group the summary statistics into three parts, providing information about car ownership, the financial situation of the household and demographics.

Car ownership is taxed in two ways in Denmark. There is an annual ownership tax, and there is

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

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, 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 eight to nine 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 hold quite modest amounts of financial assets. This is witnessed by the fact that the median level of financial assets to income is 9 percent for the young group and 15 percent for the 41-60 year old. 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 percent of the households, depending on age, hold financial assets worth less than one 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 percent 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 percent of their total financial and car assets.

When turning to the group of people holding financial assets amounting to more than one 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 percent 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 percent 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, i.e., 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

Table 1: Summary Statistics

	Full sample			
Age group	30-40		41-60	
	Average	Median	Average	Median
Variable	(1)	(2)	(3)	(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	1,452,171		2,559,063	
Number of unique households	214,662		267,688	

Notes: A regular car is a car aged less than 15 years. All economic variables are CPI deflated to the level in 2000 and have been censored at 1st and 99th percentile 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 the debt variables, these variables can only be calculated for the years 1997-2009. 1 USD $\approx$6.5 DKK

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	1.69

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 details):

1. Make an initial guess of endogenous parameter values.

2. Find a fixed point for the dealer purchase prices p_z^d using the zero-profit condition (Equation 2), separately for cars of each ownership duration, and the equilibrium conditions in Section 2.3.1. As one price changes, the average quality at each ownership duration $\bar{q}_z$ changes.

3. At these equilibrium dealer purchase prices (p_z^d), evaluate the criterion function .

4. Parameters are updated, and the process is repeated from step 2 until convergence.

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 two-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, which we relate directly to the price of fixed second-hand cars. Our concept of a fixed second-hand car is the second-hand car at the maximum quality. Our dealers fix cars they buy from households to achieve this quality and then sell them. From the data, we quantify this price in the following way: we use the median dealer sale price of second-hand cars that are one year old. This determines the price of a fixed second-hand car, which we can compare to the observed price of a new car. We normalize all the prices and income 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, i.e. $\bar{z} = 12$. We use the year-to-year depreciation rate in dealer sale prices, which is 11 percent, 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 not subject to asymmetric information.[12]

Estimation of the Income Process We estimate the parameters of the household income process (6) separately for each education group (some college and no college) using the Danish income tax records in 1992-2009.[13] We define income to be total household disposable 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, i.e., a dummy for having a partner and five dummies for up to five children.

In the income process, equation (6), 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 behaviour.

Estimation is based on moments for residual income growth take the form

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

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 individuals with job separations to estimate the remaining parameters of the income process 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

[12] The median depreciation rate across one-year-old cars is 12.1 percent. 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 $q^b = \frac{29}{159} \approx 0.2$.

[13] 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.

initial dispersion, we assume the first draw of the permanent component, v_{i0}, is drawn from a Normal distribution with mean zero and variance $\sigma^2_{v_0}$. 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). We assume that the replacement rate for retirement income is 100 percent. 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 remains sufficiently high.

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 $z \in \{1, ..., 12\}$ 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 et al. (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 $\varepsilon \sim \mathcal{B}(\eta_1, \eta_2)$.

Table 3: Parameters estimated outside the model

Parameter	Description	Value	Source
p^n	new car price	$1.14p^u$	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
σ^2_{v0}	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
σ^2_{v0}	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

- Parameters that are allowed to differ between education groups: the utility benefit of owning car α_e, the relative preference for cars bought as new θ^n_e, and the relative preference for bangers θ^b_e.

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 $d\mathbb{E}(\varepsilon) = 0.76$ implying 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 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. 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 four 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.[14]

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^{nl}	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

[14] 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. As outlined in Section 2.3 of the paper, achieving equilibrium requires four conditions to be satisfied. We quantify the deviations of these equilibrium conditions from zero and minimize these deviations. Deviations for the four equilibrium conditions are 0.0, 0.01, 0.01, and 0.07.

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

4.3 Structural Model Fit

Table 6 shows the moments and model. Regarding car ownership and new car purchases, the model captures that both 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 variations across households. The higher the age or education level, the more wealth a household accumulates, allowing them to own a 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, i.e., both observed and simulated data show a slow rate of transactions occurring in the first two years of ownership duration.

4.4 Identification

The parameters are determined 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 et al. (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 $(j,k)^{th}$ element provides an answer to how the precision of the j^{th} parameter of $\hat{\omega}$ depends on the k^{th} 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 k^{th} moment:

$$I_k = \frac{\operatorname{diag}(\bar{\sum}_k - \sum)}{\operatorname{diag}(\sum)} \tag{8}$$

Table 6: Fitted Moments

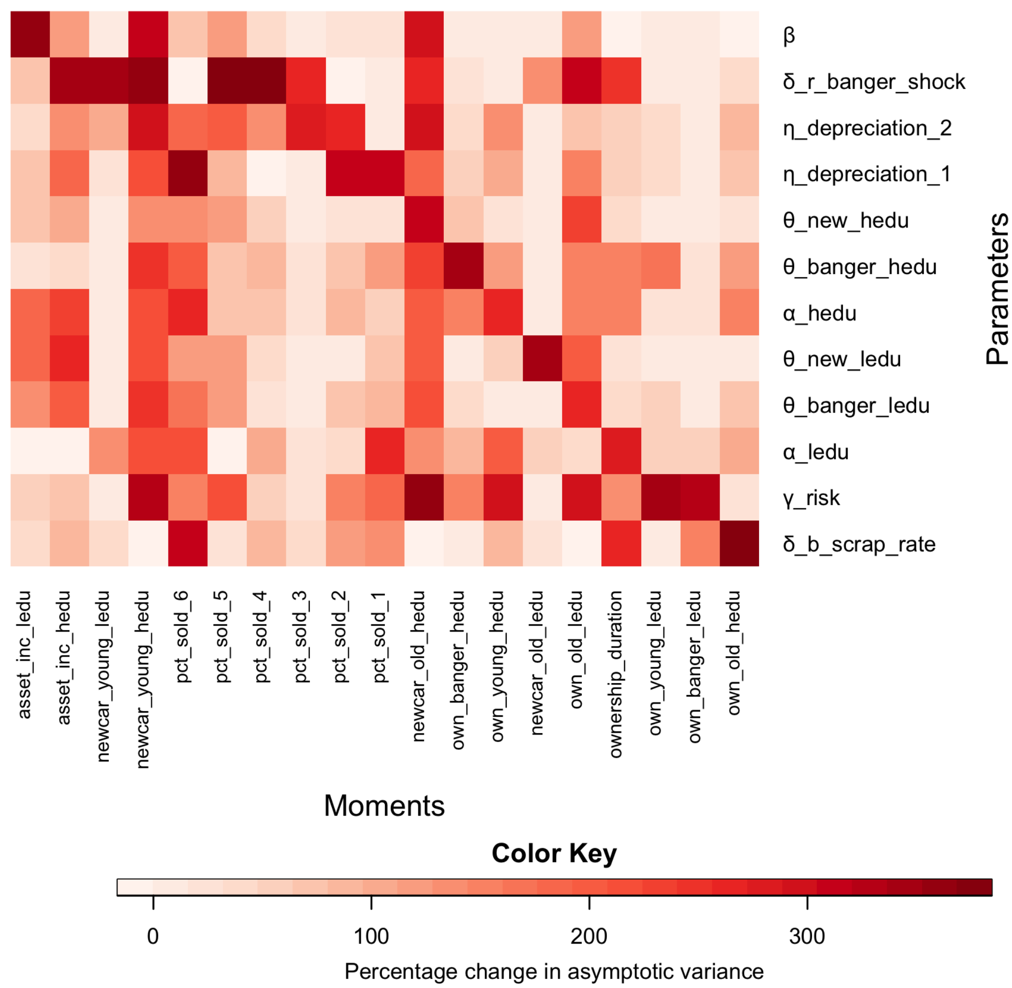
Moments		Data	Model
Ownership rate of regular cars			
No College	Age 30 - 40	55.2%	52.2%
	Age 41 - 60	60.4%	61.2%
Some College	Age 30 - 40	58.7%	64.8%
	Age 41 - 60	67.8%	75.6%
% people buy new cars			
No College	Age 30 - 40	3.9%	3.0%
	Age 41 - 60	5.2%	6.7%
Some College	Age 30 - 40	4.8%	4.9%
	Age 41 - 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%

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 1 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 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, i.e. the transaction profile of households selling cars to dealers. The size of hidden shocks to quality, governed by the distribution of the private depreciation factor $\varepsilon \sim \mathcal{B}(\eta_1, \eta_2)$, is adjusted until the model matches the observed volume and rate at which used cars sell. Figure 1 shows that the precision of the estimate of η_1 and η_2 increases significantly if we exclude moments on ownership duration.

Figure 1: Informativeness of Estimation Moments



Notes: 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.

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 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 individual who sells their 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.[15] 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. 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 2, 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.[16]

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

[15] 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 $\bar{q}_z p^u$.

[16] 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 re-estimate the asymmetric information model, allowing for an exogenous transaction 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).

than the true quality of the car and the "penalty" is not enough of a discount. Asymmetric information leads to distributional consequences as well as efficiency 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 3 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 individuals suffer income shocks or when their owners wish to upgrade relative to the car quality they own.

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	0.48	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
(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%

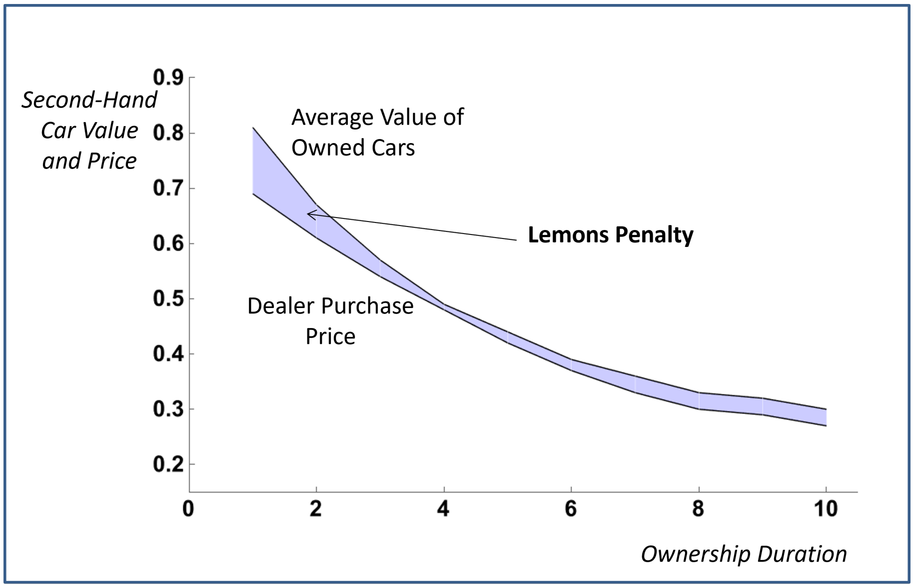
5.2 The Lemons Penalty and Income Risk

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 4a reports the percentage of cars being sold in the first and second year of ownership for the different variance values. Figure 4b reports the corresponding lemons penalty in the first and second years. Figure 4c reports the effect on the average duration of car ownership.

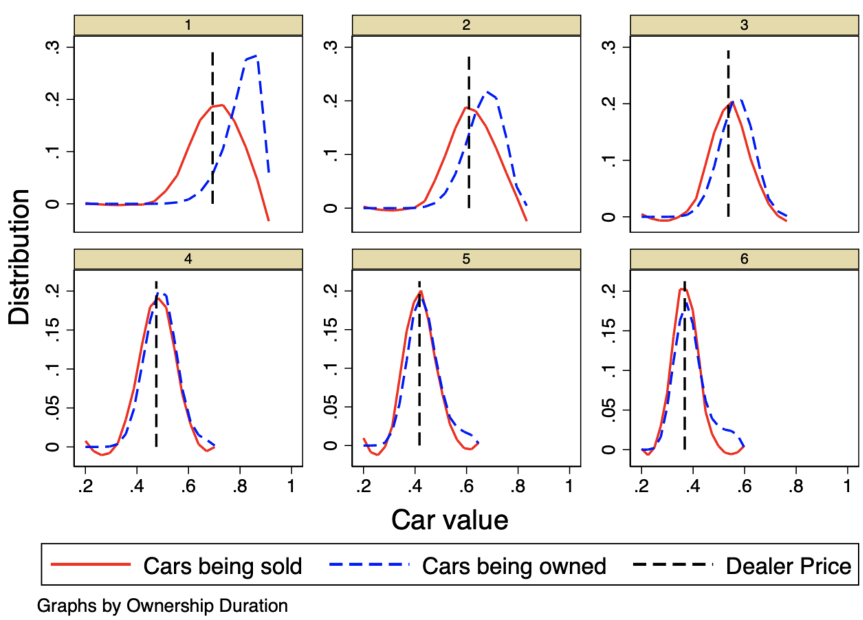
As the variance of income shocks increases, a higher percentage of cars are sold early on, and the lemons penalty declines. A greater number of car sales are driven by income shocks rather than

Figure 2: Price Declines by Ownership Duration



Notes: The figure plots, by duration of ownership, the average value of all owned cars and the dealer purchase price for cars that are sold.

Figure 3: Distribution of Value of Cars Sold and of Cars in the Population by Ownership Duration



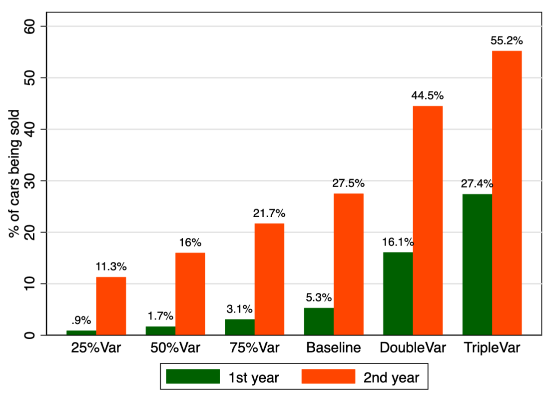
Notes: The figure plots for each level of ownership duration the distribution of car values in the population and among the sub-population of cars that are sold.

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%.

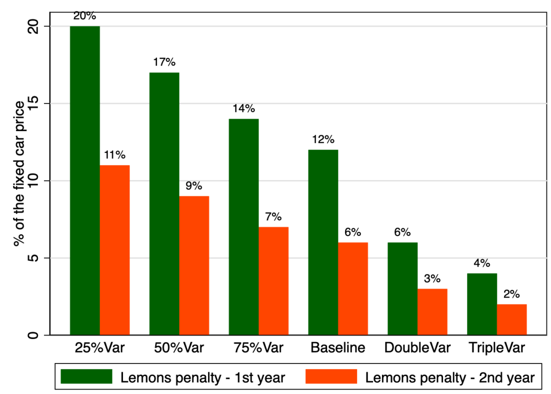
These results on the impact of changes in the variance of income speak to how we might expect the lemons penalty to change over the business cycle. There is now substantial evidence that the variance of permanent income shocks, σ_ϵ^2, increases in recessions (Storesletten et al., 2001; Blundell et al., 2013).[17] This counter-cyclical movement would imply that the lemons penalty is lower during economic downturns when cars are sold for reasons other than being of low quality.

Figure 4: Change the Variance of Permanent Income Shock

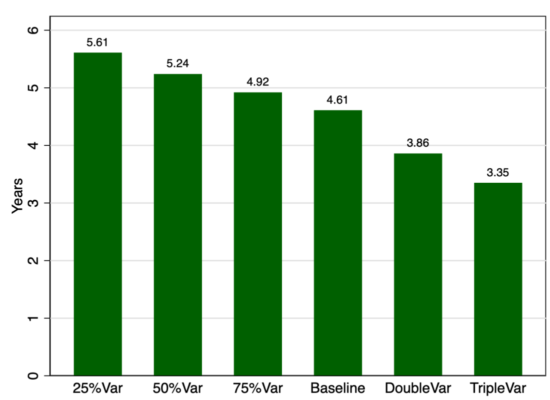
(a) Percentage of cars being sold



(b) Lemons penalty



(c) Ownership duration of cars



[17] Similarly, Guvenen et al. (2014) show that changes in labour income become left skewed in recessions.

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 5). Households can access this credit for purchasing cars. We reduce the fraction, ψ, of the car value that can be used as collateral and so reduce the amount of feasible borrowing:

$$a_{it+1} \geq -\psi p^d_{z_{it+1}} \tag{9}$$

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 5b 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 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 doesn't 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. 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 lemon penalty.[18]

6 Symmetric Information

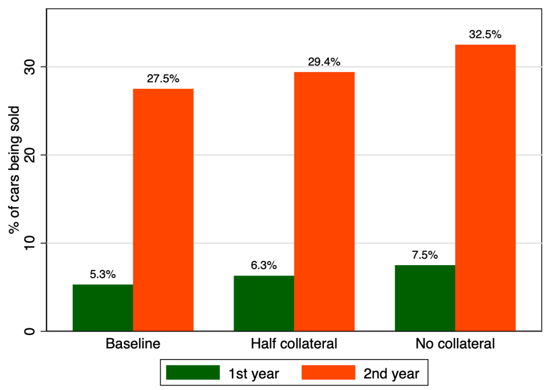
In our baseline model, shocks to car quality are private information. In this section, we compare this to a scenario where quality shocks are fully observable, meaning in formation is symmetric. We show the effects of information asymmetry on car transactions, turnover, and the average quality of cars brought to the 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

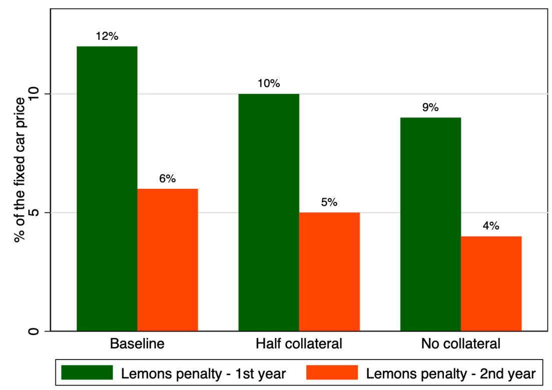
[18] We explore the impact of removing the ability of households to save (and borrow) to understand the importance of saving in our model. In this environment, the purchase of a car must be financed by giving up current consumption, and this further reduces ownership (see Appendix D.4). The resulting 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.

Figure 5: The Lemons Penalty and Borrowing Constraint

(a) Percentage of cars being sold



(b) Lemons penalty



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.[19] 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 high-quality cars being sold sooner, bringing the average quality sold to dealers closer to the population average. Figure 6 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 3, 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

[19] We re-estimate the symmetric information model in Section 7 to study the transaction responses to unemployment events.

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.

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	0.48	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%

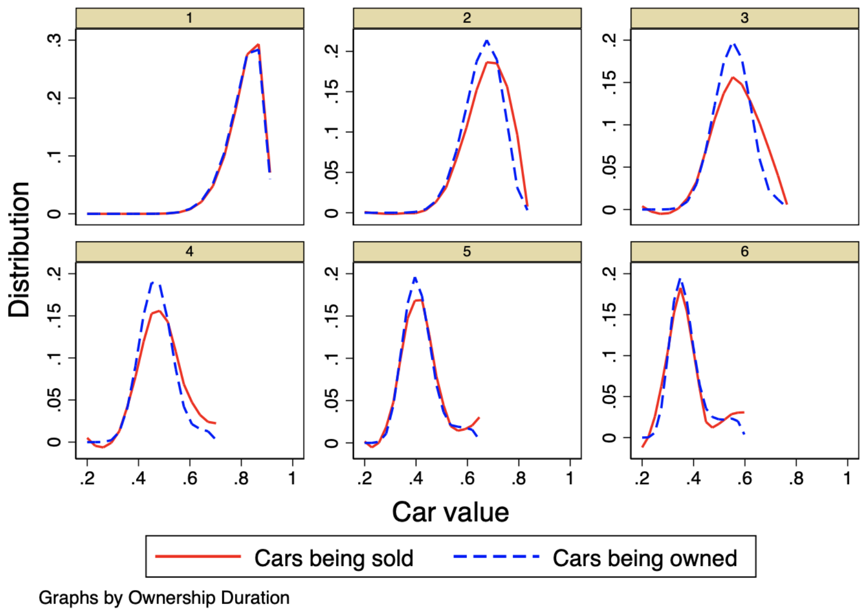
Notes: In an asymmetric information model, individual car quality is private information; In a symmetric information model, all shocks to car quality are observable.

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 accounted for by their car. By 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, i.e., the proportion of households that downgrade their cars among

Figure 6: Distribution of Value of Cars Sold and of Cars Owned: Symmetric Information



Notes: The figure plots for each level of ownership duration, the distribution of car quality in the population of cars owned and among the sub population of cars that are sold.

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, i.e. selling a car and either replacing it with a banger or not replacing it at all.

Comparison to the Data

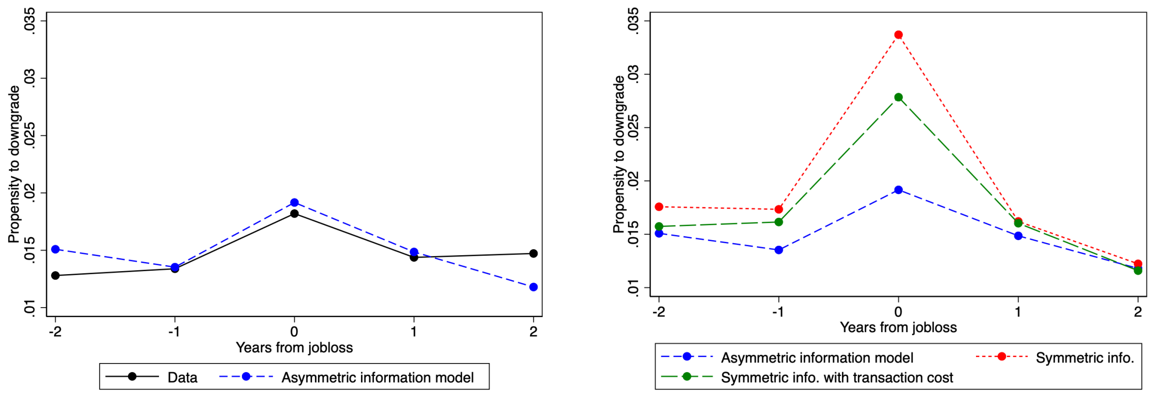
Evidence on how households respond to job loss was not used in the estimation procedure, and it thus provides some useful validation. We focus on the specific sample of job-losers and perform an event study for outcomes around the job loss. The event is defined to be the first job loss observed in the period 1999-2009. We include single adult households and couples.[20] Figure 7a 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.

[20]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 7: Downgrading after Job Loss. Data and Model Simulation

(a) Data and Asymmetric information

(b) Symmetric information



Notes: The event graphs are constructed by ordering observations according to the first year in the data period where households experience to be 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 $t-1$.

Adverse Income Shocks under Symmetric and Asymmetric Information

Figure 7b compares downgrading behaviour 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 re-estimating 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.

$$p^u - [q_i\, p^u + p^u\,(1-q_i)] = 0 \tag{10}$$

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.[21] In Table 12 and Table 13 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

[21]We estimate the unknown parameter values using the Method of Simulated Moments, maintaining all equilibrium conditions from Section 2.3.1.

contrast to the asymmetric information case, where the quality of cars sold is substantially lower than that in the population. [22]

Figure 7b shows that differing information assumptions impact a household's ability to use their car as a means of consumption-smoothing. We show downgrading behaviour following the job separation shock under symmetric information to compare to the model with asymmetric information. The blue line represents the asymmetric information 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. The lemons penalty reduces the liquidity of cars and the extent to which cars are used as insurance instruments against adverse income shocks.

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%

Notes: We introduce an exogenous transaction cost into the symmetric information model and re-estimate the model.

This difference in the average downgrading probabilities masks substantial differences in how cars of different ownership durations and of different quality are used. Figure 8 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 one-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

[22] We explore the impact of the lemons penalty on household borrowing by comparing the asymmetric information model to the symmetric information model. Average household borrowing in the asymmetric information model is 0.33, with a maximum collateral value of 0.69, compared to average household borrowing of 0.38, with a maximum collateral value of 0.81 under symmetric information. The lemons penalty restricts the collateral value of cars and limits borrowing opportunities.

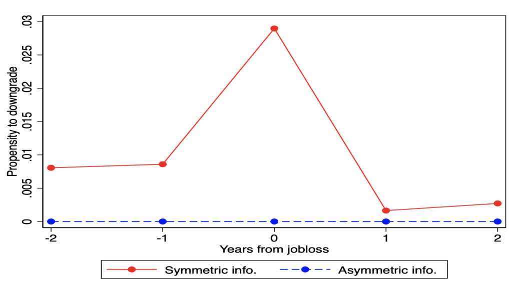
can be sold for a fair value but are rarely used when there is a lemons penalty. Under asymmetric information, it is older cars where there is less of a lemons penalty that are sold on job loss.

Even when conditioning on the length of car ownership, there are differences in which cars are being used for smoothing job separation shocks. Figure 9 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 9 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 smoothing, whereas under symmetric information, it is the very high quality cars which are being sold.

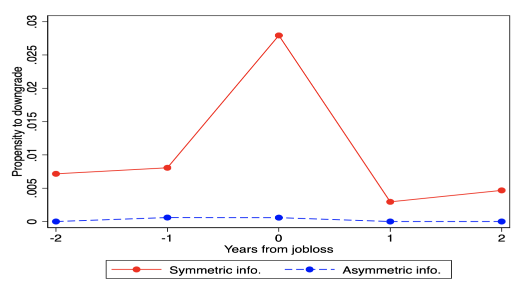
The message from Figure 9 is that the presence of asymmetric information introduces insurance against a car being of low quality: since dealers cannot condition the price on quality because it is unobservable, the owners of bad cars receive a price above the true quality of their car, whereas the owners 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.

Figure 8: Simulated Downgrading by Ownership Duration

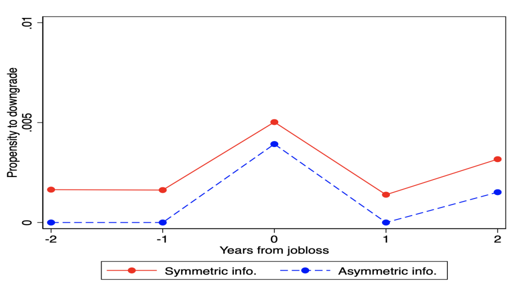
(a) Owned for 1-year



(b) Owned for 2-years



(c) Owned for 3-years



(d) Owned for 4-years

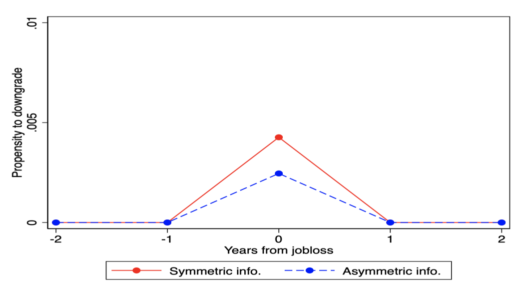
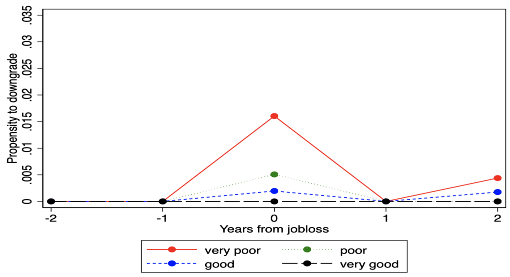
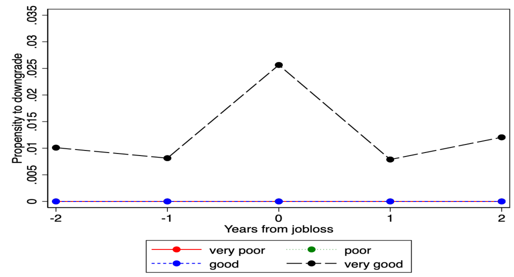


Figure 9: Simulated Downgrading by Car Quality

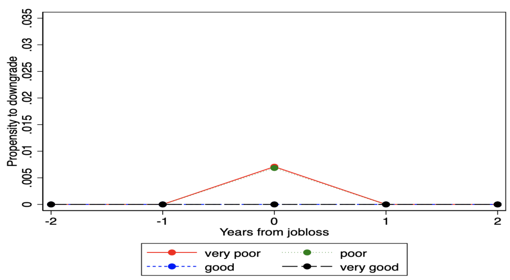
(a) Asymmetric info. (Owned for 3-years)



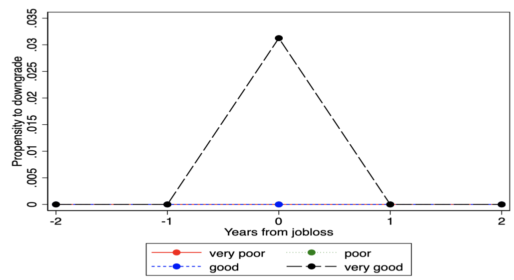
(b) Symmetric info. (Owned for 3-years)



(c) Asymmetric info. (Owned for 4-years)



(d) Symmetric info. (Owned for 4-years)



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).

8 Conclusions

In this paper, we assess the importance 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, i.e. 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 lemons penalty, and it 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 quantify 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 was 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 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 limit, 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, i.e. 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 are, 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 its 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 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 individuals, for whom the car makes up a large fraction of their wealth, are prevented from using this asset efficiently for income smoothing.

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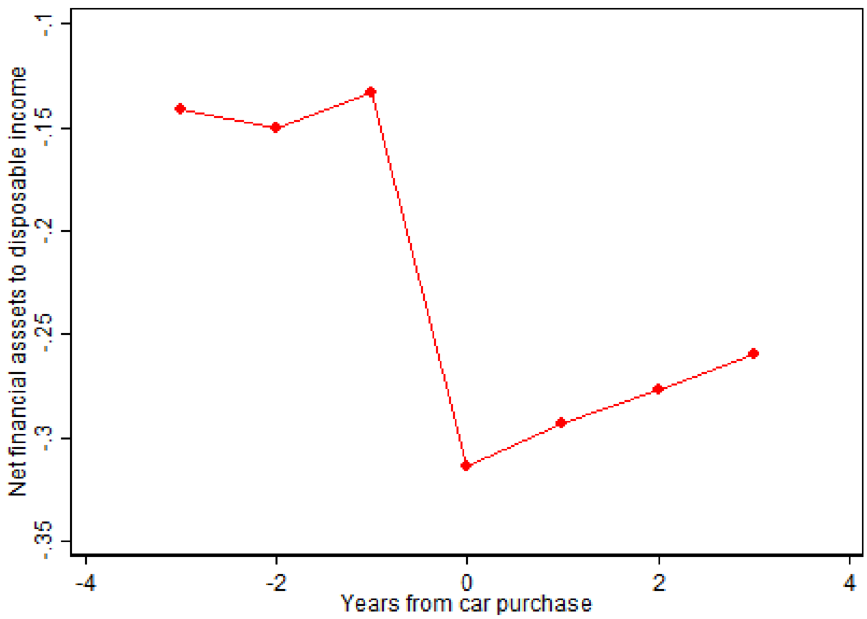
A Financial Assets around Time of Car Purchase

This appendix documents 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 non-mortgage debt. Net financial assets are measured relative to the average disposable income for the household across the years where the household enters the sample. The event is defined to be the first car purchase observed in the period 1999-2009.

Figure 10: Net Financial Assets Around Time of Car Purchase



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

Table 10 presents summary statistics for the full sample and for the sample of households who experience job loss, splitting by age group.

C Income Process

The estimated unconditional autocovariance up to order three is presented in Table 11 for the two education groups. Second- and higher order autocovariance is statistically significant, reflecting some persistence in the transitory component. Their size is however very small.[23]

[23] 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 10: Summary Statistics

	Full sample				Job loss sample			
Age group	30-40		41-60		30-40		41-60	
	Average	Median	Average	Median	Average	Median	Average	Median
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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	1,452,171		2,559,063		466,426		678,752	

Notes: A regular car is a car aged less than 15 years. All economic variables are CPI deflated to the level in 2000 and have been censored at 1st and 99th percentile 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 the debt variables, these variables can only be calculated for the years 1997-2009. The joblooser sample includes observations for individuals who have been affected by events during the period 1999-2009. An unemployment event is defined to take place if the household is exposed to three months of full-time unemployment over the year. For two-adult households, it is defined to take place if the couple jointly experience at least six months of unemployment within a calendar year. For confidentiality reasons, the medians are calculated as the average of 4 observations around the true median.

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 $\sigma_{\kappa}^2 = E\left(g_{it,eu}^2\right) - \sigma_{\epsilon}^2 - 2\sigma_{\nu}^2$, 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 $\rho_e^2 = \left[E\left(g_{it,ue}^2\right) - \sigma_{\epsilon}^2 - 2\sigma_{\nu}^2 - \sigma_{\kappa}^2\right]/\sigma_{\kappa}^2$, 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 occurs 50% of the time. κ_{1s} is positive, representing job a 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 is $\{0.181, -0.286\}$ 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.

Table 11: 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 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 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 constraint, and market outcomes.

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 re-estimation 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 $\lambda\, p_z^d$ 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 12 and Table 13, respectively. The estimated proportional transaction cost is small (0.9% of the sale price).

Upon examining the results, we found that the estimated lemons penalty, shown in the panel labelled "Asy Cost" of Table 14, 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 Re-estimation

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, i.e. 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 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"

Table 12: 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

of Table 12. The estimated proportional transaction cost is 5.6%. The fitted moments are in Column "Symmetric Info" of Table 13. 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 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 9. In the "Half collateral" column of Table 13, 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 13, 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

Table 13: 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%

Table 14: 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%

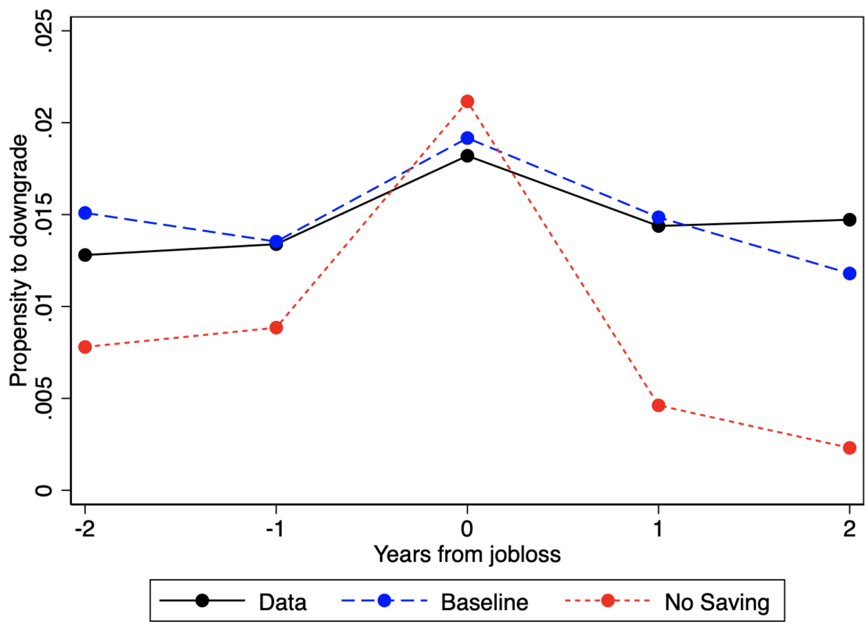
further substituting regular cars with bangers. We delve deeper into the impact of lending restrictions on the lemons penalty in Section 5.3.

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 re-estimate the model and report estimated parameter values and fitted moments in the column labelled "No Saving" of Table 12 and Table 13, 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 labelled "No Saving" of Table 14, 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 11 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.

Figure 11: Downgrading after Job Loss: No Saving



E Additional Computational Details

As described in Section 4, the computation of the model has three tiers: the inner is the dynamic programming problem of the household, the middle is the computation of the fixed point for equilibrium prices, and the outer is the optimisation 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 non-ownership) 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 maximise 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 C++ using 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 parallelised computer algorithm on 36 Xeon 6246 processors reduces 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 behaviour 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 close enough for all ownership duration, then we have found the fixed point. Otherwise, set $p^d_{old} = p^d_{new}$ and repeat until convergence.

Third, to estimate the model, we use the Method of Simulated Moments and minimise the relative distance between the data target and the model moment. We use an identity matrix as the weighting matrix. 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 endogenous parameter values. We 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. For parameter optimisation, we use the simplex algorithm from the NLopt library. After updating the endogenous parameter values, the process is repeated until convergence. The estimation takes about a week.

F The Impact of Varying Dealer Purchase Prices

Figure 12 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 single crossing ensures the existence and uniqueness of the equilibrium dealer purchase price.

To illustrate the single crossing property 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 13 presents the results. We also explored cross-derivatives of other price pairs, confirming the same outcomes.

In Figure 13a, we observed a negative correlation between the dealer purchase price and their profit, resulting in a single crossing between the profit curve and the zero-profit line. A single 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 single crossing occurs at a lower (higher) profit.

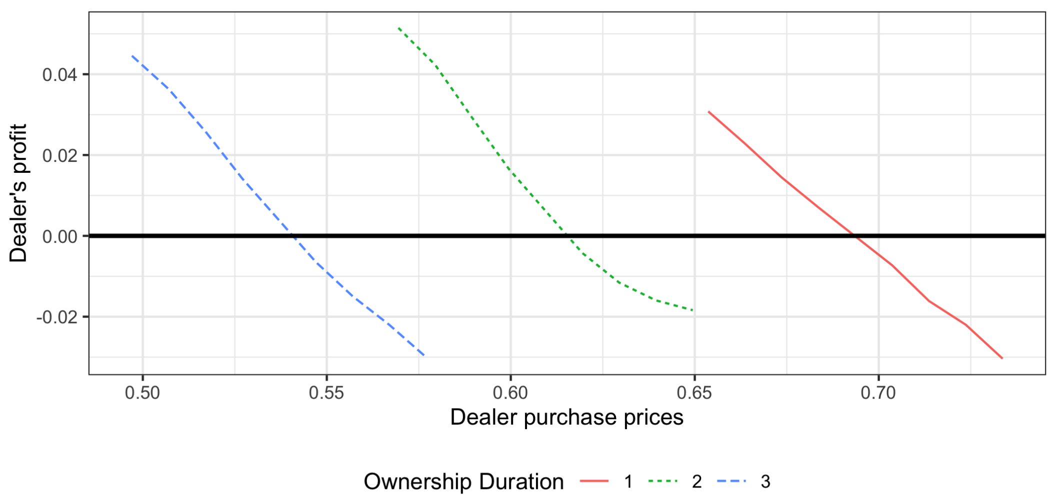
Figure 13b provides further insight into the negative correlation between price and profit. As the price paid by dealers for 1-year-old cars rises, the average profit per 1-year-old car decreases through a direct effect. This is offset by the increased quality of the cars that are sold to dealers. This 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 single crossing of the zero-profit line.

Furthermore, Figure 13c 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 linkage between different used car markets.

Finally, Figure 13d 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 rise in the 1-year-old car price, the overall profit exhibits a general downward trend.

Figure 12: The impact of varying dealer purchase prices on dealer profits

(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

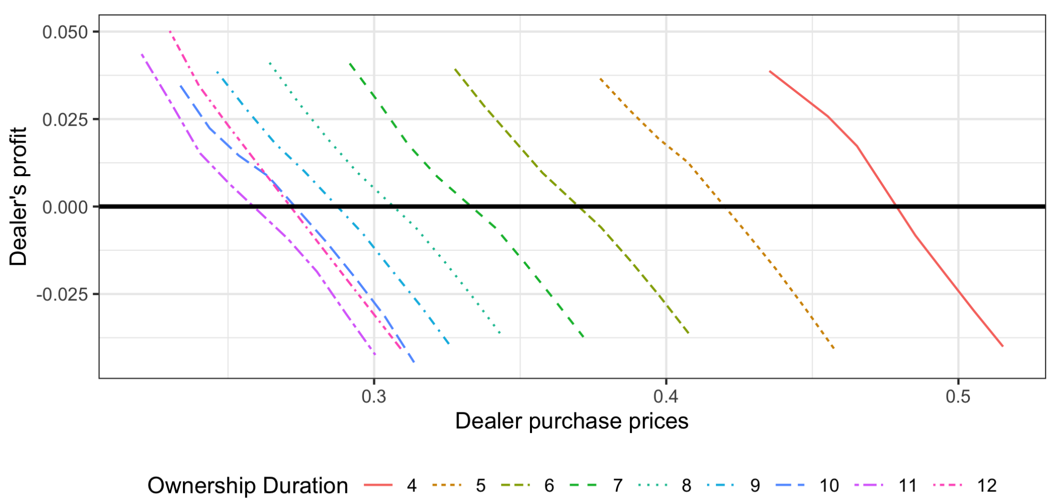
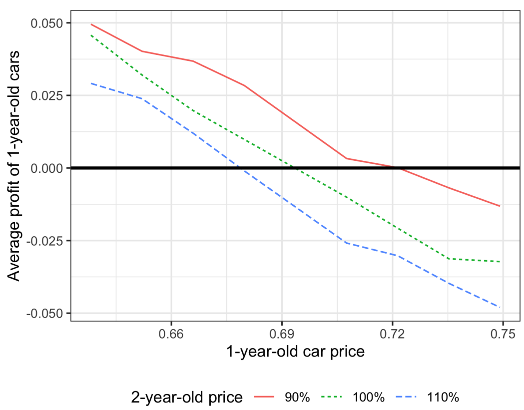
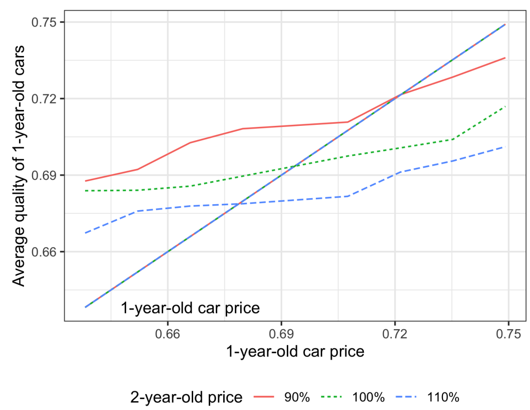


Figure 13: The impact of varying 1-year-old car price, setting 2-year-old price at different values

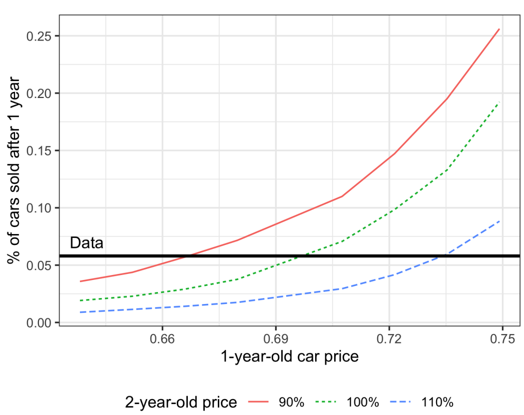
(a) Dealer's average profit for a 1-year-old car



(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