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Abstract

The average age of vehicles in the US has increased by more than 40 percent since the early 1960s. Over the same time period, consumer incomes on average have been growing faster than prices of new vehicles. This paper asks whether greater affordability of vehicles and the resulting increase in vehicle ownership among lower-income consumers can explain some of the aging of vehicles in the US. Consumers with lower incomes are more likely to purchase used vehicles and hold on to them longer, so their decisions affect the age composition of the vehicle population.

I evaluate this hypothesis using a dynamic, non-stationary, heterogeneous agents model, with consumer incomes and prices of new vehicles growing over time at the rates calibrated from the data. The agents in the model buy and sell both new and used vehicles. These vehicles are differentiated by age-dependent quality (high, medium and low), with the assumption that older vehicles are more likely to be of poorer quality. The prices of used vehicles depend on their quality level and are allowed to change over time at endogenous rates.

The estimated model predicts a significant increase in the average age of vehicles from 1967 to 2001. The conclusion is that consumer incomes are an important factor in vehicle ownership decisions, including the ages of vehicles held, and changes in incomes have contributed to the aging of the vehicle stock in the US.

Keywords: motor vehicles, heterogeneous agents models, intertemporal consumer choice, discrete choice

JEL classification: D12, D91, E21

1 Introduction

The average age of motor vehicles in the US has increased by over 40 percent since the mid-1960s. A similar trend is observed for the median age of vehicles, which has increased by 39 percent from 1967 to 2001. Both of these trends are depicted in Figure 1 below. The aging of the vehicle stock has occurred at the same time as the rapid increase in vehicle ownership, from 0.67 vehicles per person of driving age in 1967 to more than one vehicle per person almost forty years later (Figure 2a). As the data on new vehicle registrations show, this increase has not been the outcome of higher rates of purchase for new vehicles, but the result of the difference between registrations of new vehicles and scrappage of the previously owned ones. Thus, over this time period, both the total number of vehicles and the fraction of used vehicles have increased, producing the observed trend of aging for the vehicle stock.

Figure 1: Mean and median ages of vehicles in the US

Source: Motor Vehicle Facts and Figures [7] and Ward's Automotive Yearbook [10]

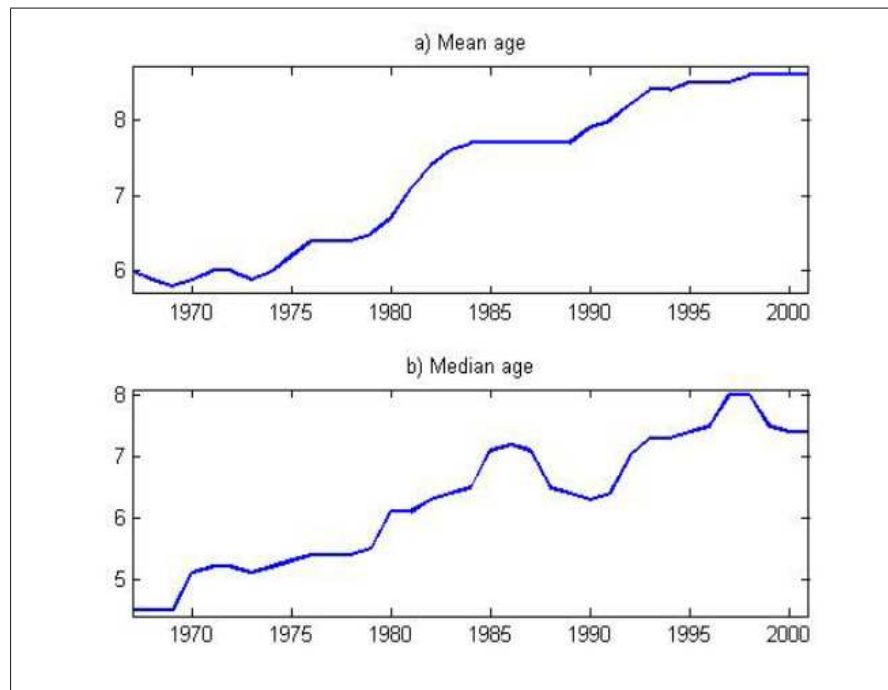
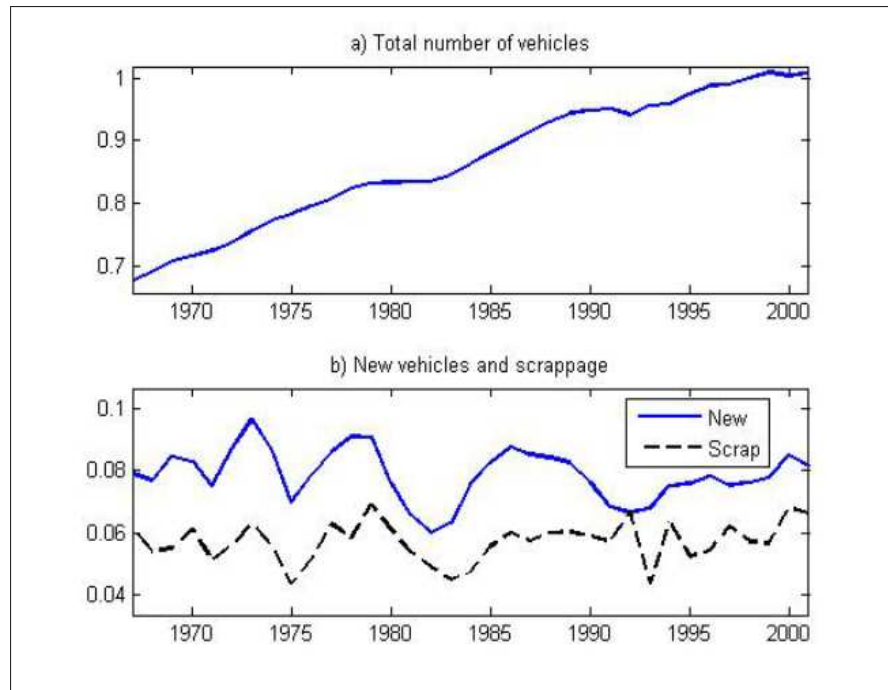


Figure 2: Number of vehicles per capita, using civilian noninstitutional population over 16 years of age

Source: Ward's Automotive Yearbook [10]



Motor vehicles are the largest component of consumer durables, so understanding what factors determine the ages of the goods consumed, and how changes in these factors affect this aspect of consumption is an important economic undertaking. Another reason to study the causes of aging of motor vehicles in the US is that it has a negative impact on the environment, since older vehicle stocks are associated with higher levels of emissions.¹

This paper analyzes the effect of demand factors on vehicle ownership decisions. It asks whether increases in real consumer incomes can explain some of the aging of vehicles, through their effect on these decisions. The hypothesis is that income growth has enabled lower-income consumers to become vehicle owners for the first time via purchases of used, older vehicles. Their choices have led to both the growth

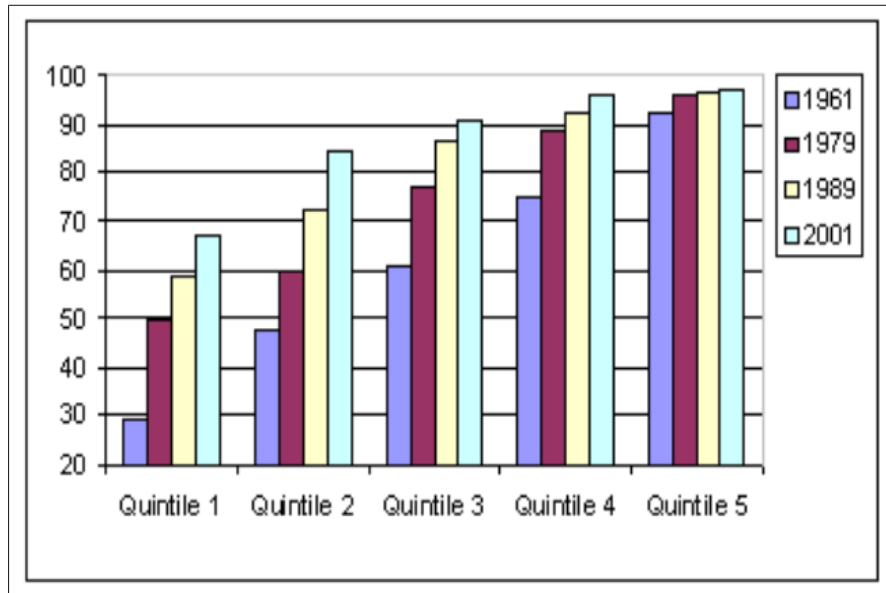
¹The US Environmental Protection Agency uses a computer model MOBILE that correlates emission toxicity directly with ages of vehicles to guide its policy decisions.

of the vehicle stock and the increase in the average age of vehicles.

Figure 3 shows that vehicle ownership rates have increased over the past forty years, with most of the increase occurring among households in the lower income quintiles. These households are less likely to own a vehicle; when they do, their vehicles tend to be older on average. Table 1 presents summary statistics to illustrate these differences in consumption of vehicles. Lower-income households tend to own older vehicles, both because they are more likely to buy them used and because they hold on to them longer.²

Figure 3: Percentage of households that own or lease one or more vehicles by income quintiles

Source: Consumer Expenditure Survey [3]



To evaluate the effect of changes in consumer incomes and prices of vehicles on vehicle ownership decisions, I use a dynamic, non-stationary, heterogeneous agents model, with consumer incomes and prices of new vehicles growing over time at the rates observed in the data. Figure 4 shows that the prices of new vehicles have been

²The statistics on the number of years a vehicle is held is presented only for vehicles that were new at the time of purchase. In general the number of years a vehicle is owned depends on vehicle's age, so this subset of vehicles was chosen in order to control for the effect of age.

Table 1: Vehicle ownership by income quintiles

Income group: Quintiles	Fraction of HHs that own or lease at least 1 vehicle			Age of vehicles owned or leased			Fraction new, 1979-2001	Years held (new only), 1979-2001
	1979-2001	1979	2001	1979-2001	1979	2001		
Quint. 1 (low)	0.64	0.60	0.70	10.02	8.20	10.46	0.32	7.28
Quint. 2	0.88	0.85	0.88	8.88	7.25	9.55	0.36	5.95
Quint. 3	0.94	0.93	0.95	8.18	7.06	8.74	0.41	5.38
Quint. 4	0.96	0.96	0.97	7.60	6.42	7.74	0.46	5.03
Quint. 5 (high)	0.97	0.98	0.97	6.67	5.87	6.55	0.58	4.79

Source: Consumer Expenditure Survey [3]

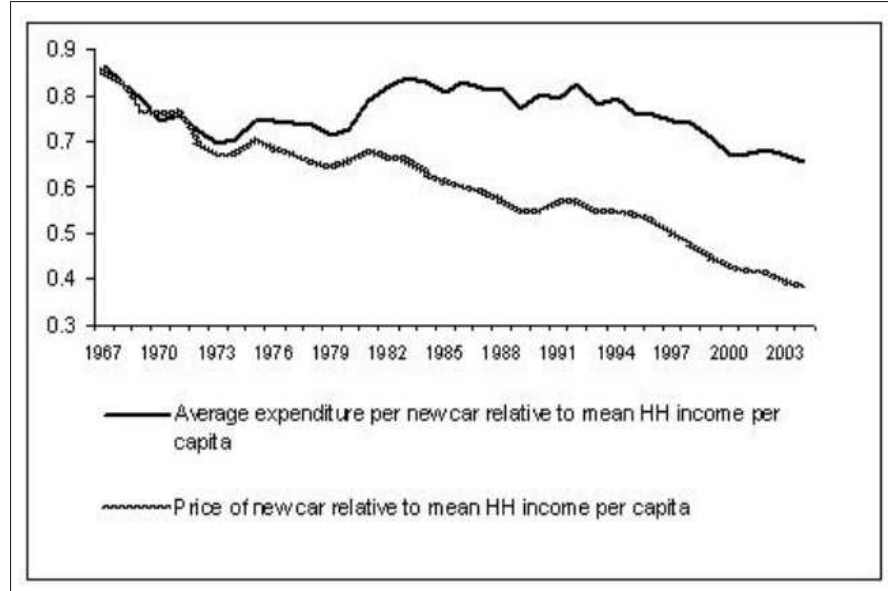
declining relative to the mean incomes of households.³ The consumers in the model are allowed to own up to one vehicle at a time, and can trade both new and used vehicles. The vehicles are differentiated by quality which depends on vehicle's age via the assumption that older vehicles are more likely to be of poorer quality. The prices of used vehicles depend on their quality level and are allowed to change over time at endogenous rates.

The estimated model is able to replicate both the increase in vehicle ownership and the stationarity of new vehicle registrations over the 1967-2001 period. It predicts a significant increase in the average age of vehicles (39.3%) over this time period due to the entry of lower-income consumers into vehicle ownership and their decisions to own older vehicles. Thus, this simple model demonstrates that demand factors have a strong influence on vehicle ownership decisions, including the ages of vehicles held, and changes in these factors have contributed to the overall trend of aging and increased longevity of the vehicle stock in the US over the 1967-2001 period.

Hamilton and Macauley [5] make the first attempt at understanding the causes

³Ward's Automotive Yearbook [10] publishes average expenditure per new car and an estimated average new car price for a 1967 "comparable car". The data on mean incomes are from the Historical Income Tables compiled from the Annual Demographic Supplements to the Current Population Survey.

Figure 4: Price of new car and average expenditure per new car relative to mean household income
 Sources: Ward's Automotive Yearbook [10] and the US Census Bureau



of increased longevity and aging of vehicles in the US. The authors ask whether improvements in durability could account for increased longevity of cars. The reduced form analysis on the automobile death rates leads them to conclude that increased longevity of cars has nothing to do with improvements in durability, and is due entirely to changes in some external factors. They hypothesize that these factors may include declining maintenance costs, lower accident rates, improved roads, or any other forces that cause consumers to take better care of their cars and maintain them into older age. While changes in these factors could have potentially contributed to the aging of vehicles, as well as to some of the increase in vehicle ownership, they would not be able to account for non-declining sales of new vehicles and the increase in vehicle ownership as dramatic as the one observed in the data.

The remainder of the paper is organized as follows: Section 2 describes the model and Section 3 discusses the solution algorithm. Section 4 describes the estimation procedure. The results are presented in Section 5. Section 6 concludes with summary

and possible extensions. Appendix A contains a detailed description of the data, and Appendix B presents additional motivating evidence.

2 Model

The economy is populated with a finite number of infinitely lived agents $j = 1, \dots, N$, heterogeneous in incomes. In every period t agent j is endowed with income y_t^j , with $y_t^1 < y_t^2 < \dots < y_t^N \forall t$. The natural logarithm of agent j 's income grows every period at a constant rate g_y^j , that is, $\ln(y_{t+1}^j) = (1 + g_y^j) \ln(y_t^j)$, $j = 1, \dots, N$.

In every period the agents decide on their consumption of non-durable and durable goods. The durable goods are vehicles heterogeneous in quality.⁴ Let $q \in \{H, M, L, N\}$ be the vehicle's quality level, where $q = H$ if vehicle's quality is high, $q = M$ if it is medium, $q = L$ if it is low, and $q = N$ if no vehicle is owned. In every period t , the vehicles of all quality levels can be traded at respective prices $p_t(H)$, $p_t(M)$, and $p_t(L)$. The outside option of not owning a vehicle is available to the agent at price $p_t(N) = 0 \forall t$.

Agent j in period t derives utility from consuming non-durable goods c_t^j and vehicle qualities q_t^j according to the following utility function:

$$U(q_t^j, c_t^j) = v(q_t^j) + u(c_t^j), \quad (1)$$

where

$$v(q_t^j) = \begin{cases} 1, & \text{if } q_t^j = H \\ \eta, & \text{if } q_t^j = M \\ \eta^2, & \text{if } q_t^j = L \\ 0, & \text{if } q_t^j = N \end{cases} \quad \text{and} \quad u(c_t^j) = \frac{\left(\frac{c_t^j}{\lambda}\right)^{1-\gamma}}{1-\gamma}.$$

⁴The quality of the vehicle depends on its age; however, the vehicle's age does not enter the decision problem directly.

The utility from vehicle ownership is increasing in vehicle's quality due to the assumption of $\eta < 1$. The utility from the consumption of nondurables has a CRRA form with a scale factor λ .

Agent j arrives in period t with a vehicle of quality q .⁵ In the beginning of the period, he chooses the vehicle's quality to consume in the current period, \tilde{q} . The option of keeping a vehicle is equivalent to choosing $\tilde{q} = q$. Prior to entering period $t + 1$, the agent realizes a random shock to vehicle's quality. The distribution of the shock depends on current quality level \tilde{q} , and its realized value q' is the quality of the vehicle in the beginning of next period, $t + 1$. Formally, in every period t agent j solves:

$$V_t^j(q) = \max_{\tilde{q}=H,M,L,N} \{v(\tilde{q}) + u(y_t^j + p_t(q) - p_t(\tilde{q})) + \beta E_{q'/\tilde{q}} V_{t+1}^j(q')\}, \quad (2)$$

The transition probability matrix from today's quality level \tilde{q} to tomorrow's q' is

$$\Pi(\tilde{q}, q') = \begin{bmatrix} \pi_{HH} & 1 - \pi_{HH} & 0 & 0 \\ 0 & \pi_{MM} & 1 - \pi_{MM} & 0 \\ 0 & 0 & \pi_{LL} & 1 - \pi_{LL} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3)$$

It is assumed that vehicle's quality cannot improve as a result of the shock or go down more than one step on the quality ladder in a single period. These assumptions are made in order to have a straightforward mapping between vehicle's quality and age. As a vehicle ages, its quality stochastically deteriorates from high to low, until it is destroyed. Note that $\Pi(\tilde{q}, q')$ is not indexed by time, reflecting the assumption of constant physical durability.

Agent's decisions in period t are affected by current and future prices of vehicle qualities $\{p_\tau(H), p_\tau(M), p_\tau(L)\}_{\tau=t, \dots, \infty}$. Assume that a high quality vehicle can only be purchased new, therefore, its price $p_t(H)$ is the price of a new vehicle. The new

⁵The indices j and t on vehicle's qualities are suppressed to simplify exposition.

vehicle's price $p_t(H)$ in every period is exogenous.⁶ The natural logarithm of $p_t(H)$ is assumed to grow at a constant rate g_p , so that $\ln(p_{t+1}(H)) = (1 + g_p) \ln(p_t(H)) \forall t$.

A non-stationary equilibrium for a series of new vehicle prices is a collection of type-specific value and policy functions, and prices of used vehicles, such that individuals optimize and markets for vehicle qualities M and L clear in every period $t = 0, \dots, \infty$. Solving for the equilibrium involves finding market-clearing prices $\{p_t(M), p_t(L)\}_{t=0, \dots, \infty}$. This is a very difficult task due to its high dimensionality and feedbacks between qualities and time periods. To reduce dimensionality of the problem, assume that $p_t(M) = \alpha_t^M p_t(H)$ and $p_t(L) = \alpha_t^L p_t(M)$ with $\alpha_t^M, \alpha_t^L \in [0, 1]$ in every period t . The parameters α_t^M and α_t^L are allowed to grow or decline over time at respective rates g_M and g_L , so that $\alpha_{t+1}^M = (1 + g_M) \alpha_t^M$ and $\alpha_{t+1}^L = (1 + g_L) \alpha_t^L$.⁷ The initial values α_0^M and α_0^L and growth rates g_M and g_L are estimated within the model with a moment condition that supply equals demand at given prices across qualities and time. Thus, instead of estimating potentially thousands of individual prices, the problem is reduced to finding the values for four parameters. The cost of this approach is that the prices and the decision rules obtained with it are not the equilibrium solutions, but their approximations.

The model makes strong assumptions on the processes for consumer incomes and new vehicle prices. Even though incomes have on average been growing faster than prices over the past forty years, there is no reason to believe that this trend should continue indefinitely into the future. The best way to deal with this issue would be to

⁶Adda and Cooper ([1] and [2]) study household demand for cars using a dynamic stationary discrete choice model. They make the same assumption about the production side of the market for new cars. The supply of new vehicles is characterized by a constant returns to scale production function. Together with the assumption of constant mark-ups, this implies that the price of a new vehicle is independent of the demand for new vehicles. This assumption of the exogenous new vehicle's price greatly simplifies the analysis. However, it may be too strong, since the time-series analysis shows that moments of the distribution of vehicle vintages significantly predict future prices of new vehicles.

⁷The restriction $\alpha_t^M, \alpha_t^L \in [0, 1] \forall t$ means that actually $\alpha_{t+1}^M = \max\{\min\{(1 + g_M) \alpha_t^M, 1\}, 0\}$ and $\alpha_{t+1}^L = \max\{\min\{(1 + g_L) \alpha_t^L, 1\}, 0\}$.

have a model of supply for new vehicles. However, given the imperfectly competitive structure of the industry and the dynamic nature of the model's environment, this is a very complicated task that is beyond the scope of this project.⁸ Short of endogenizing the price of new vehicles, would be imposing a time period on the model after which prices and incomes grow at the same rate. This would require making an assumption on when this growth rate equality would occur.

The model also assumes that consumers cannot borrow to finance a purchase of a vehicle. Relaxing this assumption may facilitate the entry of lower-income agents into vehicle ownership. This would substantially increase the computational complexity of the model. However, its qualitative implications should remain unaltered, since in any given time period ownership rates would be a declining function of income, and among vehicle owners consumers with lower incomes would hold lower quality, older vehicles. Similarly, relaxing the assumptions of deterministic processes for incomes and prices of vehicles, and no transitions between income groups, would affect the quantitative, but not the qualitative implications of the model.

3 Solving the Model

3.1 Agent's Decision Problem

The model is non-stationary with several growth rates $\{g_y^j\}_{j=1,\dots,N}$, g_p , g_M , and g_L , where g_y^j is the growth rate for income of agent j , g_p is the growth rate for the price of a new vehicle $p_t(H)$, and g_M and g_L are those of price depreciation parameters α_t^M and α_t^L for prices of used vehicle qualities M and L respectively. The non-stationarity of the model does not allow it to be solved using the value function iteration method, because the value function changes over time. The solution can still be obtained, though, because for every type of agent there exists a future time period after which his decision is trivial. If the agent's income grows faster than the price of a new vehicle

⁸See Shum and Esteban [4] for a dynamic oligopoly model of the automobile industry.

($g_y^j > g_p$), he will eventually be wealthy enough to only hold a high quality vehicle in every period. That is, after some period $T(j)$, for any initial state $q \in \{H, M, L, N\}$ the agent will choose $\tilde{q} = H$. Therefore, for agents with $g_y^j > g_p$, the solution algorithm consists of finding period $T(j)$ and solving for the agent's optimal quality choices backwards from this period to period zero.

For agents with $g_y^j < g_p$, there also will be a time period in the future after which the decision is trivial. This decision depends on prices of other vehicle qualities, described by parameters α_t^M and α_t^L , and their respective growth rates g_M and g_L . An agent whose income grows slower than the price of a new, high quality vehicle eventually will not be able to afford such a vehicle. However, he may purchase a vehicle of different quality level depending on its price. If $g_M, g_L \geq 0$, vehicles of all qualities are getting less affordable, and the agent will eventually choose to exit the market. If the price of a medium quality vehicle grows slower than the agent's income, that is, $g_M < 0$, eventually both medium and low quality vehicles will be available at zero prices, and consumers with $g_y^j < g_p$ will be purchasing medium quality vehicles. Finally, if $g_M \geq 0$ and $g_L < 0$, eventually the agent will not be able to afford either high or medium quality vehicles, and will be holding low quality vehicles in every period. Therefore, for any values of g_M and g_L there will be a time period $T(j)$ after which agent's decision is trivial, and the optimal vehicle quality holdings can be solved for by backwards induction.

Using the method outline above, the policy functions from $t = 0$ to $t = T(j)$ are obtained for every agent type $j = 1, \dots, N$. The Q series of shocks to quality are generated for every type of agent, and the policy functions are used to find optimal choices in every period and map them to vehicle ownership decisions and vehicle ages held, if any.

3.2 From Qualities to Ages

Agent's decisions are based on vehicle's quality. To infer vehicle's age from these decisions, two pieces of information are required: the age of the vehicle at the time of purchase, and the number of periods it has been held by the agent. Since a period in the model is equal to one year, the knowledge of these two factors is sufficient.

Every vehicle starts its life at the age of zero at the high quality level. Over its lifetime, it receives annual shocks to quality that may lead to its depreciation, until it is destroyed or there is no longer an agent that is willing to hold it at its current quality level and price. The shocks to quality are drawn from the distribution functions given in rows of matrix $\Pi(\tilde{q}, q')$ (3). The choice of matrix $\Pi(\tilde{q}, q')$ implies that, on average, a high quality vehicle will transition to medium quality after a certain number of years, which depends on the value of π_{HH} . Similarly, the number of years it takes for a typical medium quality vehicle to transition to low quality will depend on the value of π_{MM} , and π_{LL} determines the physical life expectancy of a vehicle.

The values for π_{HH} and π_{MM} have been chosen so that, on average, a high quality vehicle becomes a medium quality one after three years, and a medium quality vehicle transitions to low quality after an additional six years. The choice of the threshold values is guided by Stolyarov's [9] study on the resale rates of used automobiles. He finds that the resale rates are non-monotonic in age, with two spikes at approximately four and ten years of age. To find π_{LL} , I assume that it takes, on average, another eleven years for a vehicle to be destroyed, so that the physical life expectancy of a vehicle is twenty years of age.⁹

⁹The assumption of $\pi_{LL} < 1$ is made so that low income agents may not own a lower quality vehicle indefinitely, without any loss to utility from vehicle ownership occurring over time. Higher values of π_{LL} make it easier to produce the result that the average age of vehicles rises as poorer agents become vehicle owners, since they would be less likely to replace their vehicles. The choice of twenty as the average age of destruction seems like a reasonable compromise.

It is important to emphasize that the transition probabilities are not time-dependent, and thus vehicle's durability characteristics remain constant over time. Even though the physical life expectancy is constant, the economic one is not, since it depends on agents' decisions.

For simplicity, I assume throughout the model that every agent demanding a vehicle of particular quality gets one. If this quality is not supplied, the agent will receive a four year old vehicle if he demands a medium quality vehicle, and a ten year old vehicle if a low quality one is his optimal choice.¹⁰ This is especially true in period $t = 0$, since by assumption every agent begins his life with no vehicle, so there is no supply of used vehicles. In all subsequent periods, however, demanders are matched with suppliers whenever possible.

If markets for used vehicles clear in every period after the initial one, every vehicle in the model can be traced from the beginning of its life to its end, as it changes owners according to the supply and demand decisions of agents. The age of each of the vehicles in every period can be easily obtained, and the vehicle age distribution computed. However, given that the market clearing conditions for used vehicles do not hold exactly in many of the periods, there will be time periods with excess supply or demand for particular vehicle quality. Thus, there will be used vehicles that disappear into nowhere or appear from nowhere. This is an unfortunate consequence of the model's simplifying assumption on the prices of used vehicles, and the goal is to minimize the discrepancies between supply and demand, making the fraction of such vehicles as small as possible.

4 Estimation

Solving the model requires the assignment of particular values to its parameters. Parameters describing preferences and prices of used vehicles $\{\eta, \gamma, \lambda, \alpha_0^M, \alpha_0^L, g_M, g_L\}$ are estimated within the model via a combination of simulated method of moments and nonlinear least squares approaches. The incomes of agents and the price of a new vehicle in 1967, as well as their growth rates, $\left\{ \{y_{1967}^j, g_y^j\}_{j=1, \dots, N}, p_{1967}(H), g_p \right\}$, are estimated outside the model. The number of agent types $N = 100$ and the num-

¹⁰If a used vehicle of these qualities is not supplied domestically, suppose he orders one from Europe or Asia.

ber of generated series for the shocks to quality for every type of agent $Q = 100$ are chosen so as to optimize on the computational time, while still resulting in meaningful predictions from the model. The annual discount rate $\beta = 0.96$ is chosen so as to match previous studies.

An additional piece of information is required in order for the model to be solved, and that is the distribution of vehicle vintages among agents' types in the first year of interest, 1967. Since there is no data available to estimate it, the procedure steps back an additional 20 years to the year 1947, and assumes it to be the model's initial time period.¹¹ In this initial period, the agents of every type j start out without a vehicle, and make decisions from that period forward on whether to own a vehicle and if so, of what quality. This way, the agents' preferences and changes in incomes and prices determine optimal vintage holdings in the first year of interest from the data, 1967.

Below I describe the estimation procedure and data used to estimate specific parameters of the model. A more detailed description of the data is provided in Appendix A.

4.1 Parameters estimated outside the model

The initial incomes of agents $\{y_{1967}^j\}_{j=1,\dots,N}$ and their growth rates $\{g_y^j\}_{j=1,\dots,N}$ are estimated using the data on mean household income and the measure of income inequality, the Gini coefficient, from the Annual Demographic Supplements to the Current Population Survey (CPS). The income distribution was approximated with a lognormal pdf, with its parameters estimated so as to match the mean household income and the Gini coefficient in every year from 1967 to 2005. Then, the mean incomes for each of the 100 percentiles were computed using the estimated lognormal density function. Household size tends to vary among different income groups, with

¹¹Number 20 was picked since it is the physical life expectancy of a vehicle, and the effect of the initial age distribution, if any, would "wear off" by the year 1967.

households in lower income percentiles on average having fewer people. To take this into account, the mean incomes of households were computed in per capita terms. The average number of people per household over the age of 16 was obtained from the CPS, and the Consumer Expenditure Survey [3] was used to obtain the ratios between household sizes in different income percentiles.¹² Using these data, the estimates for the mean incomes per person over the age of 16 were obtained for each of the income percentiles. These estimates were deflated by the Personal Consumption Expenditures (PCE) price index. The growth rates $\{g_y^j\}_{j=1,\dots,N}$ for the natural logarithm of mean household income per person 16 years old and older in every percentile were estimated using thus generated data for the 1967-2005 period.

The estimates for the average price of a new vehicle in 1967, $p_{1967}(H)$, and the growth rate of its natural logarithm, g_p , were obtained using the data on the average expenditure per new car published in the Ward's Automotive Yearbook [10] for the years 1967-2005. Prior to the estimation, the price data were also adjusted by the PCE.

The estimated growth rate for the price $g_p = 0.001$. The income growth rates $\{g_y^j\}_{j=1,\dots,N}$ monotonly increase from percentile 1 to 100. This corresponds to the observed increases in income inequality. The incomes of agents in percentiles $j = 1, \dots, 8$ grow slower than the price of a new vehicle, that is, $g_y^j < g_p$. Wealthier percentiles grow at higher rates with $g_y^j > g_p$ for $j = 9, \dots, 100$.

4.2 Parameters estimated within the model

The preference parameters η , γ , and λ , the initial price depreciation parameters α_0^M and α_0^L , and their respective growth rates g_M and g_L are estimated using a combination of simulated method of moments and nonlinear least squares approaches. The data used in the estimation are the total number of vehicles per capita, the new ve-

¹²This ratio is stationary over the twenty year period in the Consumer Expenditure Survey [3], even though the average household size is declining.

hicle registrations per capita, and the mean ages of vehicles. The data on registered vehicles in the US were compiled from the Ward Automotive Yearbook [10]. The per capita numbers were obtained by dividing the aggregate number of vehicles and the new vehicle registrations by the civilian noninstitutional population over sixteen years of age acquired from the Bureau of Labor Statistics.

The parameter values were chosen so as to minimize the distance between the observed data and the predictions from the model in the least squares sense. The minimized criterion is a weighted sum of three components: 1) the average distance between actual and simulated new vehicle registrations per capita over the 1967-2001 period, 2) the average distance between actual and predicted total number of vehicles registered per capita over the same time period, and 3) the difference between the average age of vehicles in the model and data in 1967. Each of the component criteria was weighted by the empirical inverse of the moment's variance from the trend. Note that the procedure aims to match the average age of vehicles only in 1967. The model seeks to explain the increase in the average age of vehicles over the 1967-2001 period, so the choice of the whole path as a moment would strongly bias the estimation procedure towards producing the desired result.

The model's predictions for the number of new vehicle registrations per capita are affected by the realizations of shocks to quality. Thus, minimizing the distance between the observed data and the average predicted variable would produce inconsistent estimates for a fixed number of simulations Q . The nonlinear least square objective function was corrected for this inconsistency bias using the method introduced in Laffont, Ossard, and Vuong [6]. They propose a modification of the criterion that includes a second-order correction term for the bias; with $Q = 100$ the value of this term is negligible.

The moments for the market clearing conditions across vehicle qualities and time were also added to the criterion. The prices of used vehicle qualities $p_t(M)$ and $p_t(L)$ in every period t can be obtained for any given values of $\{\alpha_0^M, \alpha_0^L, g_M, g_L\}$. These

parameters are chosen so as to minimize the average distance between supply and demand for each quality in every period.

The final criterion was minimized via the simplex algorithm due to Nelder and Mead [8].

5 Results

5.1 Estimated Parameters and Moment Values

Table 2 presents the estimated parameter values, and Figure 5 plots two data series used in the estimation, the total number of vehicles per capita and the new vehicle registrations per capita, both over the 1967-2001 period. Overall, predictions generated by the model are close to the data, with agents in the model entering the market for vehicles and purchasing new vehicles at rates similar to those observed in the real world. Also, the average age of vehicles in 1967 generated by the model is 5.9989, versus 6.0 in the data.

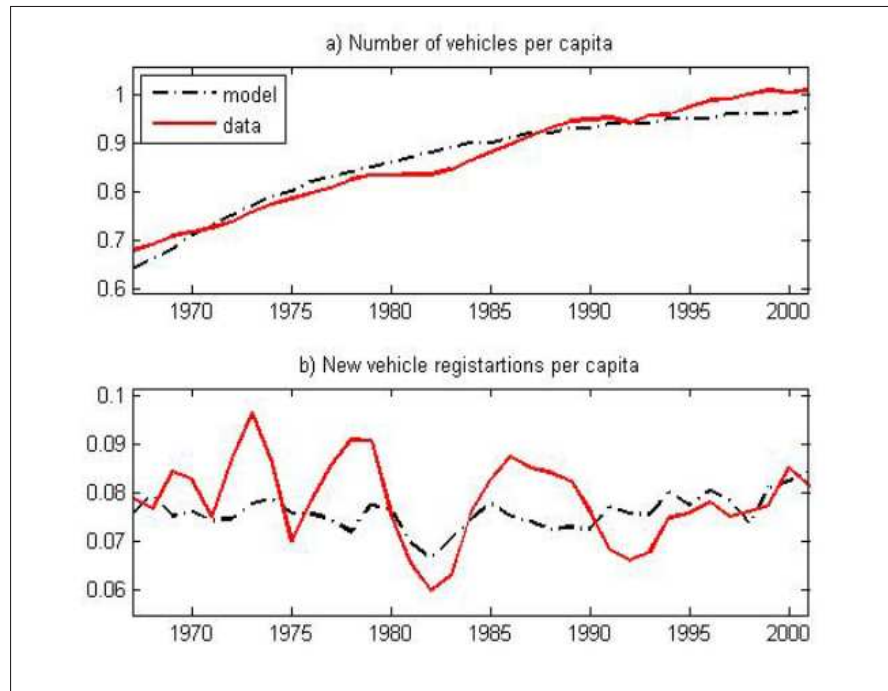
The model slightly under predicts the total number of vehicles per capita at the end of the sample period. The low rates of income growth in the bottom three income percentiles are not sufficient to induce their entry prior to 2001 even with declining prices of low quality vehicles. For the new vehicle registrations per capita, the series generated by the model is not as volatile as the one from the data. The model does not have any income or price shocks; the only source of volatility for the predicted new vehicle registrations series is shocks to quality. Overall, the model is capable of generating both the non-stationary number of vehicles per capita and the stationary new vehicle registrations per capita patterns observed in the data.

Table 2: Parameter Estimates

Parameter	Estimate	Standard Error
λ	15,501	5.8903
γ	2.8125	$6.8859e - 004$
η	0.6042	$1.9590e - 004$
α_0^M	0.8021	$2.4097e - 004$
g_M	-0.0248	$8.0812e - 006$
α_0^L	0.6480	$1.7249e - 004$
g_L	-0.0199	$1.0617e - 005$

Note: Standard errors are computed from 100 Monte Carlo replications.

Figure 5: Total number of vehicles per capita and new vehicle registrations per capita: model versus data



With prices of new vehicles growing at a rate lower than the average rate of income growth, high quality vehicles are becoming relatively more affordable to increasingly larger fraction of the population, leading to greater potential supply of medium as well as lower quality vehicles. The model implies that the prices of used vehicles

should decline over time, that is, $g_M < 0$. In the limit, as $t \rightarrow \infty$, $p_t(M) \rightarrow 0$ and $p_t(L) \rightarrow 0$. If that was not the case and $g_M > 0$, eventually medium quality vehicles would cost as much as the new, high quality ones. If $g_M = 0$ and $\alpha_0^M > 0$, the price of a medium quality vehicle grows at rate g_p . Thus, for any $g_M \geq 0$, the bottom eight income percentiles with $g_y^j < g_p$ would eventually not be able to afford medium quality vehicles. At the same time, income percentiles nine through one hundred would be demanding high quality vehicles and supplying medium quality ones at positive prices. However, the demand for medium quality vehicles would be equal to zero, and the market clearing condition would not hold. If $g_M < 0$, income types nine through one hundred would eventually be buying high quality vehicles, and would be indifferent between selling and scrapping their vehicles once the transition to medium quality has occurred. Agent types one through eight would be purchasing medium quality vehicles at zero prices, and the extra medium quality vehicles supplied would get scrapped. The market for low quality vehicles would disappear entirely.

The estimates for the parameters describing the prices of medium and high quality vehicles and their evolution over time $\{\alpha_0^M, \alpha_0^L, g_M, g_L\}$ are presented in Table 2. At these parameter values the average fraction of the total vehicle stock that is either in excess demand or supply is equal to 0.0555. This means that on average around 5.6% of the total vehicle stock appear from nowhere and/or vanish in every period.¹³ The estimation procedure aims to bring this fraction as close to zero as possible, so this is a measure of closeness to the equilibrium. The actual criterion used is the squared distance between per capita supply and demand, averaged over time periods and used vehicle qualities. The value of the criterion at the estimated values for the parameters is $9.5789e - 004$.

¹³Thus, the undesirable feature of the model is that it generates imports and exports of used vehicles.

5.2 Average Age of Vehicles, 1967-2001

Figure 6 plots the average ages of vehicles over the 1967 – 2001 period from model and data. The model predicts a substantial increase in the average age of vehicles due to the entry of lower income consumers into vehicle ownership. The predicted average age increases from 5.9989 in 1967 to 8.3567 in 2001, a 39.3 percent increase in the model versus the 43.3 percent increase in the data.

The shape of the predicted average age increase, however, does not match the one from the data. The model implies that eventually, as incomes grow relative to prices of vehicles, the majority of consumers will be holding high quality vehicles, with the rest owning medium quality ones. In the limit, the average age of vehicles will be low at 3.48.¹⁴ Thus, initial aging of the vehicle stock will be followed by future decline in the average age, as income growth causes increasingly larger fraction of consumers to choose younger and better quality vehicles. The predicted average age sequence, therefore, is of the inverse U- shape. The model also does not have any shocks to aggregate income or prices of vehicles, so any generated sequence for the average age would be characterized by a steady increase, followed by a steady decline.

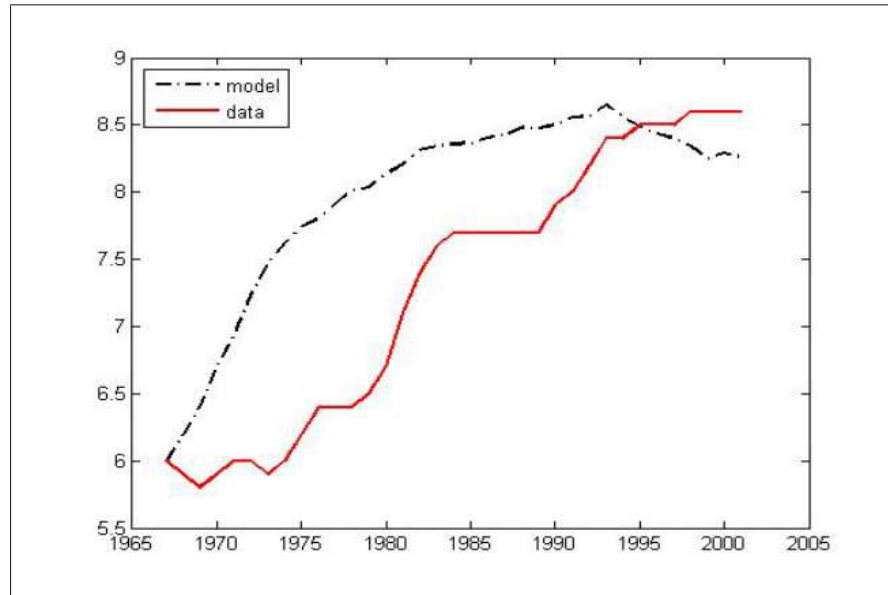
This paper asks whether some of the increase in the average age of vehicles in the US over the 1967-2001 period could have been due to the increases in consumer incomes and the ensuing entry of lower-income consumers into vehicle ownership. The estimated model produces a positive answer to this question. Even though it predicts that eventually the vehicle stock will be getting younger and the used vehicle market will be very small, over the time period in question the market for used vehicles is growing and the vehicle stock is aging.¹⁵ The satiation begins to occur around the year 1993, after which the average age starts to decline.

The agents in the model have two means for improving their well-being in re-

¹⁴It is on average 3 for the top 9 through 100 income groups, and 9 for the bottom 1 through 8 ones.

¹⁵The model predicts that the average age of vehicles will fall below the 1967 level of 6.0 around the year 2078.

Figure 6: Average age of vehicles: model versus data



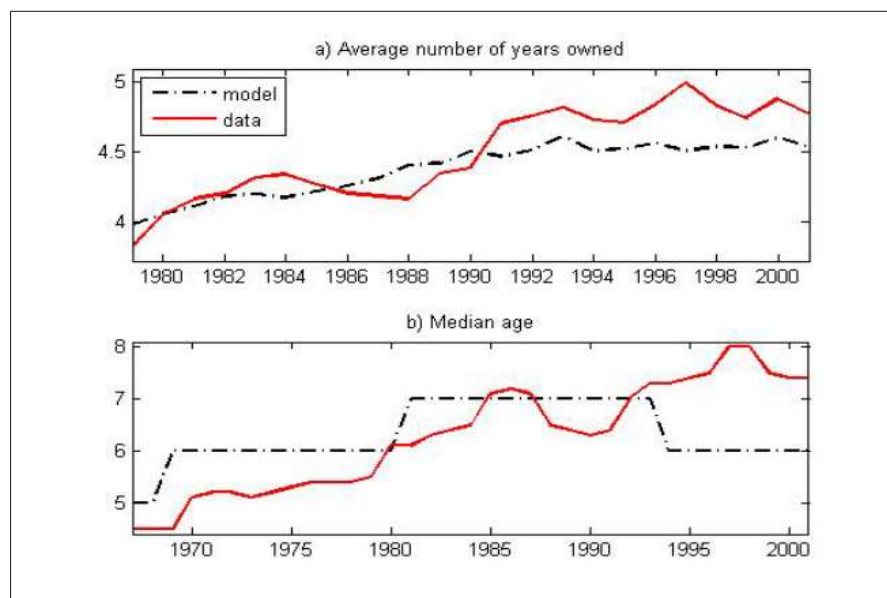
sponse to growth in incomes, depending on their vehicle ownership status. Non-vehicle owners can use additional income to acquire their first vehicle. Vehicle owners can purchase a higher quality, newer vehicle. The decline in the average age begins to occur when most of the consumers have become vehicle owners, and as such can only respond to further increases in income by choosing to hold higher quality, younger vehicles. There are two assumptions that bias the model towards this intensive margin: unit demands and single vehicle type. Introducing another type of a vehicle, a luxury one with a higher value of parameter η , would weaken this intensive margin. Another option is to allow the agents to own more than one vehicle. Appendix B presents some evidence from the Consumer Expenditure Survey that relaxing the assumption of unit demands may be important. At the household level, vehicles of different ages appear to be substitutes, as households with more vehicles tend to purchase a larger fraction of them used and hold on to each of their vehicles longer. As the result, the average age of vehicles is higher in households with larger vehicle stocks. We also observe an increase in the average number of vehicles owned by households over

time.¹⁶ With these assumptions relaxed, the model would imply a more prolonged increase in the average age of the vehicle stock. This is an interesting extension of the model that is left for future research.

5.3 Additional moments

To evaluate the fit of the model, consider two additional statistics calculated from both model and data in Figure 7. The data on the average number of years a vehicle is held come from the Consumer Expenditure Survey, 1980-2002. The data on the median ages of vehicles are from Ward Automotive Yearbook. The predictions from the model appear to be in approximately the same range. The model begins to under predict both the average number of years a vehicle is owned and the median age of vehicles starting around 1993, the same year the average age of vehicles in the model also begins to decline.

Figure 7: Average number of years owned and median age: model and data



¹⁶Evidence from the Consumer Expenditure Survey shows a steady increase in the average number of vehicles per person over the age of 16 in household that own or lease at least one vehicle, from 0.94 in 1979 to 1.06 in 2001.

Next subsection analyzes agents' behavior to see what decisions generate the results presented above.

5.4 Agents' Decisions

Agents in the model decide in every period whether to own a vehicle, and if so, of what quality. These decisions evolve over time in response to changes in income and prices of vehicles. All of the agent types can be sorted into several groups according to how these decisions on ownership and vehicle quality change over time. Every agent in the estimated model falls into one of the following seven groups:

1. No vehicle is owned over the whole sample period;
2. The agent does not own a vehicle at first, and owns a low quality vehicle by the end of the sample period;
3. The agent does not own a vehicle in the beginning of the sample period, and transitions to a medium quality vehicle by the end of the period;
4. The quality of the agent's vehicle stock increases from low to medium over the sample period;
5. The agent owns a medium quality vehicle over the whole sample period;
6. The agent starts out with a medium quality vehicle and updates its quality to the high level at some point prior to the end of the period;
7. A high quality vehicle is always held.

Figure 8 illustrates these categories and sorts the agents accordingly.

Note that the groups are ordered by income, from lowest to highest, and vehicle ownership and vehicle quality consumption are strictly increasing in income. Consumption of vehicle ages, however, is not strictly monotone in income. To illustrate,

suppose that agent *A* has a slightly lower income than agent *B*. As the result of the income difference, agent *B* chooses to become a vehicle owner via a purchase of a low quality vehicle one period before agent *A* does. If both agents purchase a low quality vehicle of an average selling age for these vehicles, which is 10, and the vehicle of agent *B* survives to the next period, then agent *B* owns an 11 year old vehicle at the same time as lower-income agent *A* owns a 10 year old one.

Figure 8: Agent types according to vehicle ownership and quality decisions

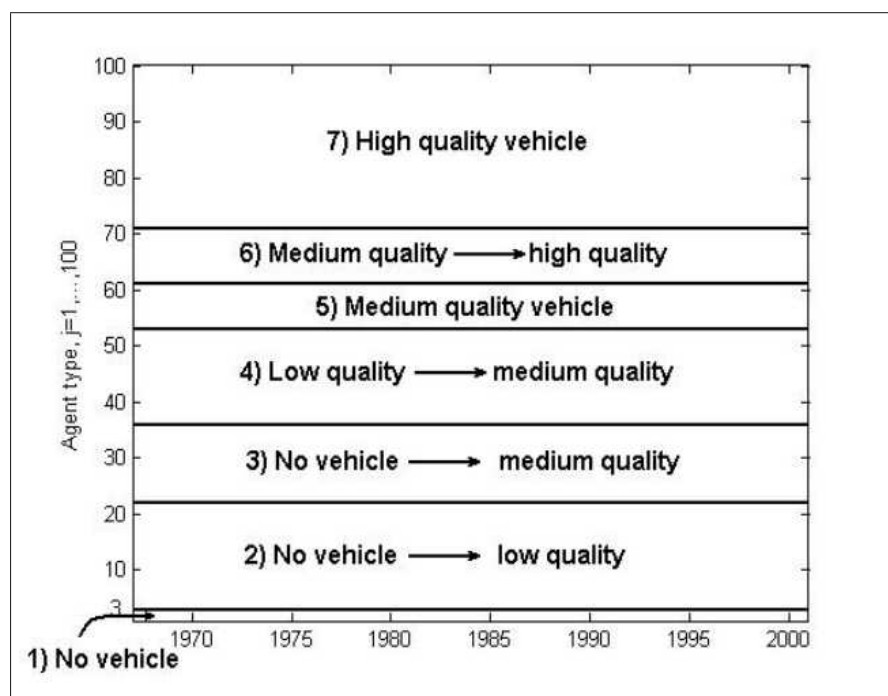
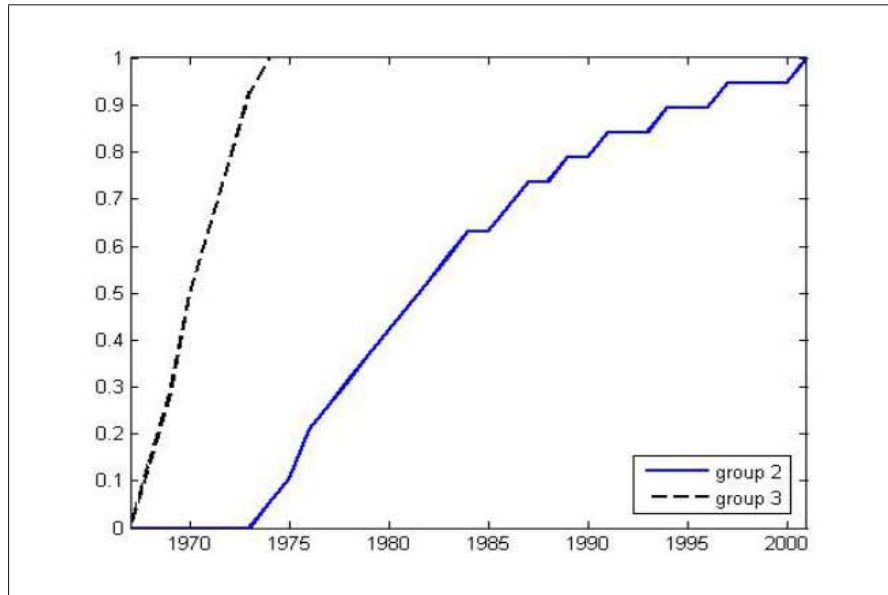


Figure 10 illustrates the average ages held by agents in different groups via pairwise comparisons. Agents in Group 1 do not own a vehicle over the whole sample period, so Figure 10a shows only the average ages of vehicles owned by agents in Group 2. The stock of vehicles held by the agents in this group experiences a steady increase in the average age over the sample period. The agents in Group 3 are wealthier than the ones in Group 2. However, Figure 10b shows that for the first half of the sample period they own on average older vehicles. This is due to them entering into vehicle

Figure 9: Fraction of vehicle owners in Groups 2 and 3

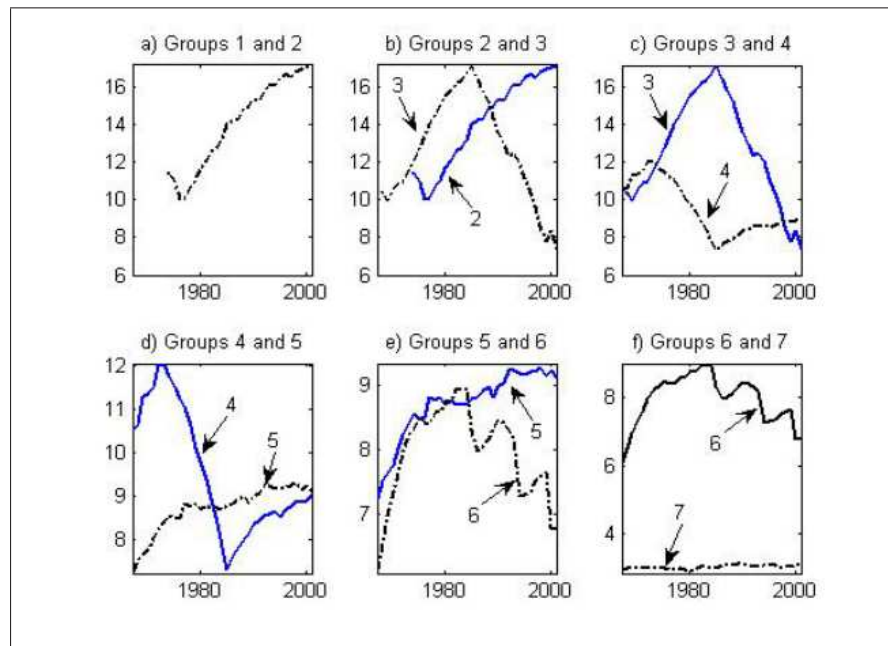


ownership sooner, and thus holding their vehicles for several periods prior to the entry of their lower-income counterparts, similar to the example above with agents *A* and *B*. The agents in Group 3 eventually switch to holding medium quality, younger vehicles, so the average age of their vehicle stock begins to decline. Figure 10c shows that the agents in Group 4 transition to the ownership of medium quality vehicles sooner than most of the agents in Group 3, thus, on average, their vehicles are younger than those held by the lower-income types. Agents in Group 5 own medium quality vehicles over the whole sample period. Figure 10d shows that their vehicles tend to be younger than those held by the agents in Group 4 over the first half of the sample period. The relationship changes as more agents from Group 4 become owners of medium quality vehicles for the first time. Figure 10d depicts the average ages of vehicles held by Groups 5 and 6, and shows that as agents in Group 6 switch to the ownership of high quality vehicles, their vehicle stock becomes younger. Finally, in Figure 10f agents from Group 7 always hold the youngest vehicles on average.

The relationship between incomes and the ages of vehicles owned is not strictly monotone, however, as Figure 11 illustrates, the model still produces an overall pat-

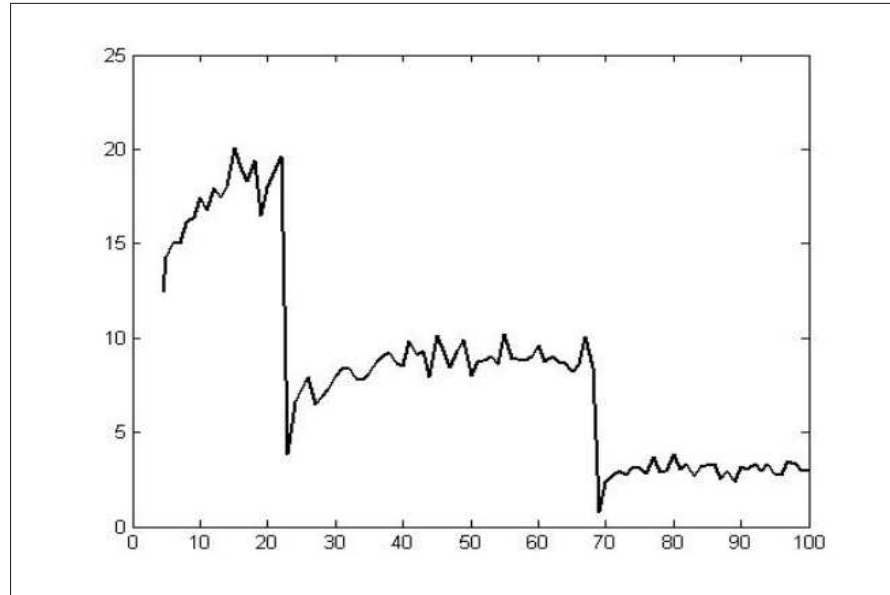
tern of inverse relationship between vehicle ages and incomes. The model generates three distinct groups of agents with large differences in the mean ages of vehicles held, which is due to the assumption of only three age-dependent quality levels for vehicles, high, medium, and low. Similar pictures can be generated for other years in the sample period.

Figure 10: Average ages of vehicles by ownership and quality decision groups



The overall increase in the average age of vehicles predicted by the model is mostly due to the decisions of agents in Groups 2 and 3. As these agents choose to become vehicle owners for the first time with low quality, older vehicles, the mass of the age distribution shifts towards older vintages. Figure 9 illustrates the entry rates of agents in these two groups. Eventually, the model predicts a decline in the average age of the vehicle stock as agents respond to income increases by updating the quality of their vehicle. The average ages of vehicles held by agents in Groups 3, 4, 5, and 6 experience this decline over the sample period.

Figure 11: Average ages of vehicles owned by income percentiles, 2001



6 Conclusion

This paper developed a dynamic, non-stationary, discrete choice, heterogeneous agents model, to study the increased vehicle ownership among lower-income consumers and its effect on aggregate demand for vehicle vintages. The agents have different incomes, and their incomes grow over time at the rates calibrated from the data. They can choose to own up to one vehicle at a time, and can trade both new and used vehicles. The vehicles are differentiated by age-dependent quality, with the assumption that older vehicles are more likely to be of poorer quality. The price of a new, high quality vehicle is exogenous, and its growth rate is estimated from the data. The prices of used vehicles depend on their quality level and are allowed to change over time at endogenous rates.

The model is able to replicate both the increase in per capita vehicle ownership over the 1967-2001 period, as well as the stationarity of the per capita new vehicle registrations series. It predicts a significant increase in the average age of vehicles over this time period, due to the entry of lower-income consumers into vehicle ownership

via the purchase of low quality, older vehicles.

The model restricts the agents to owning at most one vehicle. Evidence from the Consumer Expenditure Survey indicates that vehicles of different vintages are substitutes at the household level. Households with more vehicles tend to purchase a larger fraction of them used and hold on to each of their vehicles longer, so their vehicle stocks tend to be older. The data also show an increase in the number of vehicles per household over the time period of interest. Thus, increases in real consumer incomes may affect both the vehicle ownership rates and the age distribution of vehicles not only through the entry of lower-income consumers into vehicle ownership, but also by making the ownership of more than one vehicle affordable to an increasingly larger fraction of the population. Allowing multiple vehicle ownership and/or adding another dimension to vehicle differentiation would also prolong the period of aging of the vehicle stock, and postpone the eventual decline in the average age of vehicles predicted by the model. These extensions of the model are left for future research.

Overall, this paper makes an important step in studying the non-stationarity of durable consumption with a dynamic discrete choice model, that is both relatively simple and capable of replicating some of the important features of the data. It shows that demand factors have a strong influence on vehicle ownership decisions, including the ages of vehicles held, and changes in these factors have contributed to the aging of the vehicle stock in the US.

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A Data Description

A.1 The US Motor Vehicle Stock

The annual data on the total number of cars and trucks, the number of new vehicles registered, the distribution of vehicles by model year, and the prices of new cars come from the Ward's Automotive Yearbook [10]. The publication has been produced by Ward's Communications since 1938, and is a comprehensive annual report on the state of the US automotive industry. In every issue, the selected statistics are reported for the given year and several previous years, so the numbers for the years prior to 1982 could be obtained from the more recent issues.

R.L. Polk & Co. is the original source for the data on the total number vehicles in use, new vehicle registrations, and the distribution of vehicle vintages. In every year, the statistics are presented separately for cars and trucks. For the purposes of this project, the numbers for cars and trucks were added to obtain aggregate statistics. The mean age data are also provided separately for cars and trucks. In every year, the mean age of all vehicles was calculated as the weighted average of the mean ages of cars and trucks.

The Ward's Automotive Yearbook also publishes the average expenditure per new car in every year. The editors obtain these data from the US Department of Commerce, Bureau of Economic Analysis, as the average transaction price per new car. They also compute an estimate of the average new car price for a 1967 "comparable car", by adding the value of safety and emissions equipment as determined by the US Bureau of Labor Statistics (BLS) to the 1967 average transaction price, and inflating this sum to current dollars using the BLS "New Car Consumer Price Index - All Urban Consumers."

A.2 Household Income

The data on the mean income of households and the Gini ratios for the years 1967-2001 were obtained from the Historical Income Tables compiled by the US Census Bureau from the Annual Social and Economic Supplements to the Current Population Survey (CPS).

A.3 Households and vehicles

The data on vehicle ownership by households were obtained from the Consumer Expenditure Survey (CE) [3]. The survey is administered by the Bureau of Labor Statistics (BLS). The Interview Survey component of the CE is collected on a quarterly basis, with households in the sample interviewed every three months over a fifteen-month period.¹⁷ However, income questions are asked only in the first and fourth quarter. For every survey year in the sample, the data on size, location, and total income before taxes over the past twelve months were chosen for every household interviewed in the first quarter. The income data were used to sort the households by income groups, the bounds for which were computed using the CPS data. The incomplete income respondents were excluded from the sample. The average size of the final sample for the 1980 – 2002 surveys is 7,760 households in every year.

The data on vehicles are reported in the Detailed Expenditure Files component of the survey. For every household in the sample, the BLS collects the information on vehicles owned by the household. The survey asks detailed questions about every vehicle owned by the household, including its make and model year, the year it was purchased, and whether it was new or used at the time of purchase. Starting in 1991, similar questions about leased vehicles were added to the survey. The information on the vehicle’s model year is particularly important for the purposes of this project,

¹⁷The unit of observation in the CE is a consumer unit, which is comprised of all persons in the household that share expenditures on housing, food, and other living expenses. Although there is a difference between households as defined by the US Census Bureau and the consumer units of CE, it is small, and for the purposes of this project these are assumed to be the same units.

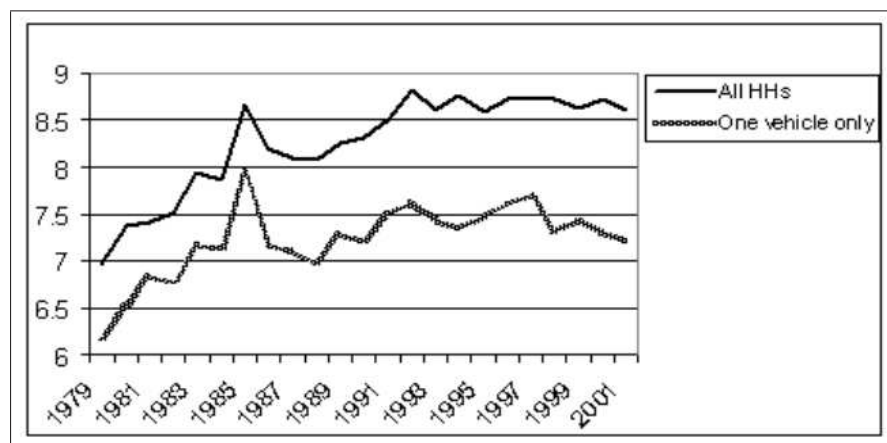
since it is used to compute the age of the vehicle. Unfortunately, for some of the model years, the CE reports ranges instead of actual years. For example, in 2002, the model year is recorded precisely for models produced after 1987. The survey gives ranges for older vintages. For the 1990 issue this "cut-off" year is 1986. Thus, computing the vehicle age statistic is more problematic in the earlier issues of the survey. However, it is still possible to establish the motivating pattern of poorer households on average owning older vehicles.

For the regressions in Table B.1, the income in every year was deflated by the Personal Consumption Expenditures (PCE) price index provided by the Bureau of Economic Analysis.

B Multiple Vehicle Ownership

This appendix provides some evidence that vehicles of different vintages are substitutes at the household level.

Figure B.1: Average age of vehicles among households



The summary statistics in Figure B.1 were also computed separately for households in the top income decile, so as to control for the effect of income. The regression analysis indicates that household size is an important factor in vehicle ownership decisions, so the sample was also limited to households with two persons over the age

Table B.1: Determinants of vehicle ownership and ages of vehicles owned

Source: Consumer Expenditure Survey [3]

Independent variable	I. Probit: Own a vehicle	II. Tobit: Vehicle's age	III. Probit: Purchased used	IV. OLS: Number of years own (new)
Income, \$1000	0.0203 (15.86)	-0.0525 (-18.8)	-0.0140 (-20.27)	-0.0115 (-2.51)
Income squared	-0.00004 (-12.18)	0.00011 (11.47)	0.00003 (13.55)	0.00003 (1.71)
Luxury vehicle		0.0692 (0.25)	0.1997 (2.98)	-0.6086 (-1.44)
Num. of other vehicles		1.0606 (20.93)	0.1359 (11)	0.5280 (4.42)
R^2	0.1899	0.0203	0.0975	0.0824
Number of obs.	6,381	10,334	10,283	3,757

1) t-statistics are given in parenthesis.

2) Other controls include a constant, family size, number of earners, geographic location, population, origin of the vehicle (Domestic, European, Asian), truck indicator, age and age squared of the reference person.

of sixteen. The location of the household was controlled for as well, through the exclusion of rural households from the sample. In this subsample, the average age of vehicles in households with more than one vehicle is also always higher than the average age of vehicles in households with one vehicle only.

Table B.1 shows that the number of other vehicles owned has a positive and strongly significant effect on the age of the vehicle held. This seems to be due to households with more vehicles purchasing or leasing a larger fraction of them used, and holding on to them longer.