From Consumer Incomes to Car Ages: How the Distribution of Income Affects the Distribution of Vehicle Vintages

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May 2008

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Abstract

This paper studies the relationship between consumer incomes and ages of the durable goods consumed. At the household level, it presents evidence from the Consumer Expenditure Survey of a negative correlation between incomes and ages of the vehicles owned, controlling for the size of the vehicle stock. At the aggregate level, it constructs a dynamic, heterogeneous agents, discrete choice model with multiple vehicle ownership, to study the relationship between the distribution of consumer incomes and the distribution of vehicle vintages. Two versions of the model are solved, one with the restriction of at most one vehicle per agent and one with multiple vehicle ownership. For each version of the model, the parameters are calibrated to match vehicle ownership data for 2001. The moments of the income distribution are then varied to generate predictions for mean and median ages of vehicles and the results from the two versions of the model are compared. While these are mostly similar, some of the differences are quite illuminating.

Keywords: income distribution, motor vehicles, heterogeneous agents models, vertical differentiation

JEL classification: D11, D12, D91, E21

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*I am grateful to Russell Cooper, Dean Corbae, Maxim Nikitim, the anonymous referee, and participants in seminars at the University of Texas at Austin, the 2009 CEA meeting and the 2010 RES conference for helpful discussions, comments, and advice.

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1 Introduction

Expenditures on motor vehicles comprise the largest part of consumer expenditures on durable goods.[1] The durability property allows a vehicle to yield utility over a prolonged period of time, and potentially to more than one owner during its lifetime. This paper studies the role of consumer incomes in vehicle ownership decisions, such as the age of the vehicle at the time of purchase and the length of the ownership period, and the aggregate implications of these decisions for the distribution of vehicle vintages.

Understanding the determinants of the vehicle age distribution is important for the design and implementation of environmental and economic policies. The economic downturn of 2007 has induced the governments in the US, China, and many European countries to offer consumers monetary subsidies for the replacement of older fuel-inefficient vehicles with newer and efficient ones, with a double goal of improving environmental characteristics of the vehicle stock and helping the car industry by stimulating demand. Yet little is understood about the determinants of the demand for different vehicle vintages, including the new ones. This paper shows that income plays an important role in vehicle ownership decisions at the household level and constructs a dynamic model that explicitly maps consumer's income to the age of vehicle she chooses to buy and hold, if any. Thus, at the aggregate level, income distribution is a key factor determining the shape of the distribution of vehicle vintages and ownership rates. Policies that seek to affect sales and the distribution of vintages should take into account the endogeneity of the current distribution of vehicle vintages to the distribution of income.

The determinants of the vehicle age distribution are also of interest to the environmental scholars, since ages of vehicles are positively related to the emission levels. Environmental engineers in Miller et al. [12] study the relationship between per capita incomes and vehicle ages. The authors find a strong negative relationship

[1] Approximately 45% on average since the 1950s for the US.

between mean per capita incomes and median vehicle ages for counties in Tennessee, with correlation coefficients of -0.996 for passenger cars and -0.979 for light trucks. At the cross-country level, Storchmann [17] finds that car prices depreciate slower in developing countries than in industrialized countries, and that the economic life of automobiles is negatively related to real incomes. At the micro level, Adda and Cooper [1] use data on French household vehicle replacement decisions to find that higher-income households are more likely to replace their vehicles, controlling for the vehicle's age.[2]

This paper presents additional evidence from the Consumer Expenditure Survey on the importance of income in vehicle ownership decisions at the household level. Then, it develops a model and calibrates the parameters to match vehicle ownership data at the aggregate level. The calibrated model is used to study how the distribution of consumer incomes affects the distribution of vehicle vintages. The model is dynamic, with infinitely lived, heterogeneous in income agents. The agents are allowed to own multiple vehicles at a time, and can trade both new and used vehicles.

The vehicles of different vintages are vertically differentiated: younger vehicles are assumed to be superior to the older ones in terms of quality. The trade in used vehicle vintages is motivated by the heterogeneity in consumer incomes and the resulting differences in willingness to pay for quality. The equilibrium analysis in these markets is complicated, since the consumers are both buyers and sellers. To simplify the analysis, most models in this literature assume either a limited number of vintages and continuous distribution of consumer types or multiple vintages but a limited number of consumer types.[3] The model presented here has multiple types of consumers buying

[2]There is also a significant body of literature in transportation research on the determinants of automobile replacement. Gilbert [7] is one of the first to estimate the automobile replacement hazard functions for the US. The estimated replacement hazard is increasing in income. Chen and Neimeir [4] contains a review of this literature.

[3]For examples of the former, see Hendel and Lizzeri [10], Porter and Sattler [14], Stolyarov [16], and Chen, Esteban and Shum [5]. Except for Stolyarov [16], these models have only two vehicle vintages: new and used. Stolyarov's model assumes fifteen vehicle vintages and is used to investigate the equilibrium trade pattern in a car market with endogenous prices. He does not study the relationship between the distribution of types and vehicle ages.

and selling vehicles of different vintages. The equilibrium price for each vintage is computed as an approximation: the price is assumed to be decreasing with vehicle's age and the price function's parameter is calibrated within the model with market clearing condition. [4]

Allowing multiple vehicle ownership is important, since the evidence from Consumer Expenditure Survey indicates that vehicles of different ages are substitutes at the household level, so households with larger vehicle stocks tend to have older vehicles on average. The number of vehicles owned has a positive effect on the age of vehicle at the time of purchase and a negative effect on frequency of replacement. Survey evidence also indicates that currently in the US more than half of all households own two or more vehicles, and over twenty percent of households have at least three vehicles. To the author's knowledge, this is the first paper to model multiple vehicle ownership. Two versions of the model are solved and estimated, one with the restriction of at most one vehicle held at a time and one without this restriction, and the results and predictions from the two versions are compared. While these are mostly similar, some of the differences are quite enlightening.

In the model, the agent's decisions depend on her income and prices of vehicles. The incomes of different agent types are calibrated to match the empirical income distribution for the US in 2001.[5] Aggregation across individual agents determines demand for different vehicle vintages, and the resulting vehicle age distribution. For each version of the model, the single vehicle version and the multiple vehicles one, the model's parameters are calibrated to match vehicle ownership data for 2001. In both cases, the model generates a strong negative relationship between agents' incomes

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For example of the latter, see Licandro, Puch, and Sampayo [11].
Chen, Esteban and Shum [5] also contains a brief review of the current literature on the durable goods markets.

[4]The approach is similar to Adda and Cooper [2]; they, however, estimate the parameter of the price function outside the model with micro data and use the market clearing condition in the estimation of other parameters of the model as an additional moment.

[5]The year 2001 was chosen since it is the last year for which R.L. Polk & Co. provided the data on the distribution of motor vehicles by model year to the Ward's Automotive Yearbook. Thus, these are the most recent age distribution data that are publicly available.

and the ages of vehicles owned.

The estimated versions of the model are then used to study how changes in the underlying distribution of consumer incomes affect the aggregate vehicle ownership statistics, in particular, the mean and median ages of the vehicle stock. Surprisingly, while at the household level the relationship between income and the ages of vehicles owned is negative, the model predicts a non-monotone relationship between mean consumer incomes and mean age of the total vehicle stock. If the initial incomes are low, increasing mean income may actually lead to the aging of vehicles by encouraging entry of lower income consumers into vehicle ownership via purchases of older vehicles. This finding suggests the possibility of alternative explanation to the observed aging of the vehicle stock in the US from the 1960ies to the present. Both journalist and researchers ([9]) have hypothesized that the increase in the average ages of vehicles by more than 40% over this time period is either due to the increased durability of cars or improvements in the environment. The results of this analysis, however, indicate that higher consumer incomes and the resulting increase in vehicle ownership among lower-income consumers can also be part of the story.

When consumer incomes and the resulting vehicle ownership rates are sufficiently high, further increases in mean income lead to younger vehicle stocks according to both single and multiple vehicle ownership versions of the model. However, with multiple vehicle ownership there may be a reversal of this trend for the economies with high per capita incomes, if the majority of households uses their high incomes to increase the size of their vehicle stock, but consume older vehicles on average. Thus, even though at the household level the relationship between income and vehicle ages is positive, at the aggregate level it is non-monotone.

Both versions of the model predict that higher levels of income inequality lead to older vehicle stocks, with some divergence in the predictions of two models for the economies with very high levels of income inequality. For these economies, the multiple vehicles version of the model generates a negative relationship between the income inequality measure and ages of the vehicle stock. Multiple vehicle ownership results in a much larger weight assigned to the decisions of high income households, and even though the fraction of these households in the population declines with inequality, they choose to hold increasingly larger and younger vehicle stocks, shifting the mass of the aggregate age distribution towards younger vintages.

The layout of the paper is as follows. Section 2 presents micro level evidence of a negative relationship between incomes and holdings of vehicle vintages, using the Consumer Expenditure Survey data on household vehicle ownership for 2001. Section 3 describes the baseline model. Section 4 discusses the solution method for the single vehicle and the multiple vehicles versions of the model. Section 5 describes the estimation procedure and data used in the calibration, as well as the calibration results and the decision rules as functions of income. Section 6 presents the results of the model for the relationship between moments of the income distribution and aggregate vehicle ownership patterns, including the mean and median ages of the total vehicle stock. Section 7 concludes.

2 Evidence: Consumer Incomes and Vehicle Ownership Decisions

The data on vehicle ownership by households in the US for 2001 were obtained from the Consumer Expenditure Survey (CE) [3]. The survey is administered by the Bureau of Labor Statistics (BLS), and includes detailed information on expenditures for over $7,000$ households in the given year. The household characteristics and income data are part of the Interview Survey component of the CE; the data for this component are collected on a quarterly basis, with households in the sample interviewed every three months over a fifteen-month period. However, income questions are asked only in the first and fourth quarter. The data on household size, number of earners, geographic location and population, age of the reference person, and total income before taxes over the past twelve months were chosen for every household interviewed in the first quarter. The households with incomplete income responses were removed from the sample, resulting in the sample size of $6,381$ units.

The data on vehicles owned or leased by each of the households are reported in the Detailed Expenditure Files component of the survey. The survey asks detailed questions about every household vehicle, including its make and model year, the year it was purchased, and whether it was new or used at the time of purchase. The information on the vehicle's model year is particularly important for the purposes of this project, since it is used to compute the age of the vehicle. Unfortunately, the model year is recorded precisely only for the model years 1986 or newer, with the survey giving ranges for older vintages. Thus, the methods for censored data need to be used to perform the analysis.

The household decision on whether to own or lease a vehicle is modeled with a probit regression. The independent variables include the income and the squared income of the household, the household size, the number of earners, the dummy variables for geographic location and population size, and the age and the age squared of the reference person. The dependent variable is an indicator that equals one if the household owns or leases at least one vehicle. The results are presented in Column I of Table 1. They demonstrate that higher-income households are more likely to own or lease a vehicle, and that the effect is non-linear in income. Households with a larger number of earners are more likely to be vehicle-owners, possibly because they need this transport mode in order to get to work. Also, households in urban locations have greater excess to alternative means of transportation, such as public transport, and thus are less likely to have a vehicle. More expensive parking and maintenance may also discourage vehicle ownership in urban locations.

The tobit model for censored data was used to study the ages of vehicles owned by households. The results in Column II in Table 1 demonstrate that higher-income households tend to have younger vehicles. The results in Columns III and IV of

Table 1: **Modeling household vehicle ownership decisions**

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)
Number of earners	0.2062 (5.41)	−0.2253 (−2.92)	0.0856 (4.62)	−0.3536 (−2.71)
Urban location	−0.2258 (−2.09)	−0.1815 (−0.76)	−0.0126 (−0.21)	−0.1473 (−0.29)
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 parentheses.
2) Other controls include a constant, family size, geographic location and population dummies, origin of the vehicle (Domestic, European or Asian) and luxury vehicle dummies, truck indicator, age and age squared of the reference person.

Table 1 indicate that this is due to higher-income households being more likely to purchase a new vehicle instead of a used one, and hold on to this vehicle for a fewer number of years.[6] A positive and highly significant coefficient on the number of other vehicles owned or leased by the household shows that vehicles of different ages may be substitutes at the household level. The coefficient values for this variable in Columns III and IV of the table indicate that households with more vehicles are more likely to purchase a larger fraction of them used, and also tend to replace each of the vehicles less frequently.

The above analysis demonstrates that income plays an important role in vehicle ownership decisions at the level of the consumption unit, including the ages of vehicles

[6]The analysis for the number of years a vehicle is held was restricted to the vehicles that were new when purchased. The reason is that, in general, the number of years a vehicle is held depends on the age of the vehicle, so the sample was limited to control for this effect.

held. The next part of the paper presents a model that generates the relationships between income and vehicle ownership decisions of the same sign as the ones observed in the data. Since the number of vehicles owned is strongly correlated with vehicle ages, the model allows multiple vehicle ownership.

3 Model

The economy is populated with a finite number of infinitely lived heterogeneous agent types $j = 1, ..., N$. Each agent type j consists of a unit measure of identical consumers. The time period in the model is equal to one year. In every period t, agents of type j are endowed with income y_j, which is deterministic and constant over time. The agent types are ordered according to their income levels so that $y_1 < y_2 < ... < y_N$.[7]

In every period the agents decide on their consumption of non-durable and durable goods. The durable goods are $i = 1, ..., \overline{n}$ vehicles heterogeneous in ages $a_i = 0, ..., G+1$. Here $\overline{n}$ is the maximum number of vehicles an agent can simultaneously own and G is an upper bound on the vehicle's useful life. Thus, having a vehicle i of age $a_i > G$ is equivalent to having no vehicle.[8]

A vehicle i of age $a_i = 0$ is a new vehicle and its price $p(0)$ is exogenous in every period.[9]

The agents can trade both new and used vehicles. A used vehicle of age $a_i =$

[7]The model presented here is similar to Adda and Cooper [1], [2] with two key differences: 1) In Adda and Cooper income is stochastic, and heterogeneity of agents is due to the idiosyncratic income shocks. Here agents maintain their place in the income distribution with deterministic incomes. 2) Unlike Adda and Cooper, multiple vehicle ownership is allowed.

[8]An upper bound on vehicle's useful life is necessary for computational reasons. However, for G sufficiently large this assumption is not restrictive. According to the Ward's Automotive Yearbook [19], more than 16.6% of vehicles in the US where over 15 year of age in 2001. Unfortunately, more detailed data on the age distribution for older vehicles is not available. The results here were obtained for $G = 30$.

[9]As in Adda and Cooper ([1] and [2]), the supply of new vehicles is assumed to be 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.

$1,...,G$ is traded at price $p(a_i) = p(0)\exp(-\tau a_i)$, where τ parameterizes the rate of price depreciation.[10] The price of vehicle older than G is assumed to be zero, $p(a_i > G) = 0$.

In every period the agents derive utility from consuming non-durable goods c and vehicles of ages $A = (a_1, ..., a_{\overline{n}})$ according to the following utility function:

$$U(A, c) = v(A) + u(c), \tag{1}$$

where

$$u(c) = \frac{\left(\frac{c}{\lambda}\right)^{1-\gamma}}{1-\gamma}, \tag{2}$$

and

$$v(A) = n^{\alpha} \exp\left(-\eta\, m^2\right). \tag{3}$$

Here n is the number of vehicles agent owns and m is the mean age of the stock. Formally, $n = \sum_{i=1}^{\overline{n}} I_{a_i \leq G}$, $m = \frac{1}{n} \sum_{i=1}^{n} a_i$ and $I_{a_i \leq G}$ is an indicator that is equal to one when $a_i \leq G$.

The utility from vehicle ownership increases in the number of vehicles owned n when $\alpha > 0$, and the vehicles of different ages are assumed to be perfect substitutes, with consumer deriving utility from the average age of vehicles owned. For small values of η the utility declines slowly when consumer's vehicle stock is young on average, then picks up the pace as it ages, and slows down again when the vehicles are old. [11] The utility from the consumption of nondurables has a CRRA form with

[10] The exponential functional form has been found to provide the best fit for the French and the US used vehicle prices data by Adda and Cooper [2] with τ close to 0.2. I have also used the data kindly provided by Matthew Shum, (used previously in Esteban and Shum [6]), to verify that the functional form provides a good description of the price depreciation process in the data.

[11] The functional form for v is best motivated for the case of $n = 1$. Its shape looks similar to the percentage of total US vehicle stock remaining in use as a function of age. Greenspan and Cohen [8] use a similar functional form to estimate the scrappage of vehicles. They find that it fits the data well everywhere except for the higher ranges of vehicle ages, where it declines too fast resulting in

a scale factor λ.

Each agent of type j arrives in a period with vehicles of ages $A = (a_1, ..., a_{\overline{n}})$. In the beginning of the period, she decides whether to retain these vehicles or replace all or some of them with vehicles of vintages $A' = (a'_1, ..., a'_{\overline{n}})$. Whatever her decision, next period she starts with a vehicle stock that is one year older than the one she consumes in the current period. Formally, in every period each agent of type j solves:

$$V_j(A) = \max_{A'} \left\{ v(A') + u\left(y_j + \sum_{i=1}^{\overline{n}} \pi(a_i) - \sum_{i=1}^{\overline{n}} p(a'_i) \right) + \beta\ V_j(A'+1) \right\}, \tag{4}$$

where

$$\pi(a_i) = \begin{cases} p(a_i), & a_i = a'_i \\ \phi\ p(a_i), & otherwise,\ \phi < 1 \end{cases} \tag{5}$$

is the selling price of vehicle aged a_i, with ϕ parameterizing the fraction of value recovered by consumer from selling her current vehicle.

Trade in the secondary market is motivated by the differences in consumer incomes. The decisions of how many vehicles to have, which vintages to replace and which ones to hold on to depend on the prices of vehicle vintages. Ideally, these prices should be such that the markets clear for every vintage. However, this is a very difficult problem due to the linkages between markets for all vintages. Licandro, Puch and Sampayo [11] obtain analytical solution for the market-clearing price in a simpler model of a secondary market for vehicles with only two types of agents and at most one vehicle per agent. Other works, such as Hendel and Lizzeri [10], Porter and Sattler [14], and Stolyarov [16], have continuous distributions of consumer incomes but fewer vehicle vintages. These authors also assume that the agents can own at most one vehicle at a time.

The model presented here is more general, and the approach is to approximate

the tail that is not "thick" enough.

the equilibrium price function with an exponential function $p_a = p_0 \exp(-\tau a)$. The depreciation rate τ is estimated within the model with a moment condition that supply equals demand at given prices across vintages. The cost of this approach is that the prices and the decision rules obtained with it are not the equilibrium solutions, but rather their approximations.

4 Solving the Model

To solve the model means to find the price function parameter τ and the steady-state holdings of vehicle ages for each agent type, such that agents maximize lifetime utility taking prices as given, and markets clear for each vehicle vintage.

The numerical solution proceeds as follows. First, the optimization problem for every agent type $j = 1, ..., N$ is solved for a given value of the price function parameter τ. Then the decision rules are aggregated to find the steady-state distribution of vehicle ages in the economy. The steady state distribution determines the supply and demand for each vintage, conditional on prices of vintages. Finally, the differences between supply and demand are used to create a moment condition (average least squares) to find the value of τ that would bring the markets as close as possible to clearing.

For every agent type $j = 1, ..., N$ the decision rules $A' = q_j(A)$, where $q_j : \underbrace{[1, ..., G+2] \times ... \times [1, ..., G+2]}_{\overline{n}} \to \underbrace{[0, ..., G+1] \times ... \times [0, ..., G+1]}_{\overline{n}}$, can be solved for using the value function iteration method. These decision rules are then used to obtain the steady-state holdings of vehicles' ages $\widetilde{A}^j = [\widetilde{a}_1, \widetilde{a}_2, ..., \widetilde{a}_{\overline{n}}]$, where $\widetilde{a}_i$ is a vector of vehicle i's ages if vehicle i is held for several periods prior to replacement. The number of periods a vehicle is held depends on the agent's income level and the transaction cost of replacing a vehicle ϕ.[12]

Note that dimensionality of the problem grows exponentially in the maximum

[12]Without transaction costs ($\phi = 1$) the agent upgrades to her optimal vehicle vintage every period.

allowed number of vehicles $\overline{n}$. In fact, even with $\overline{n} = 2$ it takes a long time to compute the decision rules and estimate parameters of the model for a large value of G.

The approach adopted here is as follows. First, the model is solved for $\overline{n} = 1$, with the decision rules obtained via the value function iteration method. Second, additional assumptions are imposed on the model's decision rules so it can be solved for the multiple vehicles case. In what follows, these assumptions and the solution method are discussed.

Multiple vehicles model: Additional assumptions and solution

Several assumptions are imposed on the model in order to obtain its solution for the case when $\overline{n} > 1$. In the steady state, for agent type j,

- The number of vehicles owned $n_j \leq \overline{n}$ is constant.[13]
- Each vehicle $i = 1, ..., n_j$ is held for the same number of periods $h_j \in [1, G+1]$ prior to replacement.
- After h_j periods, each vehicle $i = 1, ..., n_j$ is replaced by a vehicle of age f_j.
- The agent prefers to replace her vehicles at equally spaced intervals if possible in order to smooth her consumption.

In other words, the agent has to buy all of her vehicles of the same age and hold them for the same number of periods prior to replacement. In order to smooth her consumption, she is assumed to make her replacements at equally spaced intervals, whenever possible.

For any agent type j, let $\mathbf{r} = (r_1, r_2, ..., r_h)$ be a vector comprised of the number of vehicles replaced in every period of the steady state decisions.[14] This vector $\mathbf{r}$

[13]The agent is considered to own vehicle i if its age $a_i \leq G$.

[14]Index j is suppressed for convenience.

depends on the number of vehicles n and the number of periods each vehicle is held h. It is constructed with the last assumption, that the agent prefers to replace her vehicles at equally spaced intervals if possible.[15]

The agent's problem can be reformulated as follows,

$$V_j = \max_{n,f,h} \left\{ \sum_{t=1}^{h} \beta^{t-1} \left(v\left(n, m_t\right) + u\left(y_j + r_t \left[\phi\, p\left(f+h\right) - p\left(f\right)\right]\right)\right) + \beta^h V_j \right\}$$

or

$$V_j = \max_{n,f,h} \left\{ \left[\sum_{t=1}^{h} \beta^{t-1} \left(v\left(n, m_t\right) + u\left(y_j + r_t \left[\phi\, p\left(f+h\right) - p\left(f\right)\right]\right)\right) \right] / \left(1 - \beta^h\right) \right\}, \tag{6}$$

where

$m_1 = \mu\left(f, n, h\right)$ and can be computed using $\mathbf{r}$, and for $t > 1$

$m_t = \left[n\left(m_{t-1} + 1\right) - r_t h\right] / n.$

Computationally the problem becomes one of iterating through different combinations of n, f, and h, and finding the one that gives the highest value of V_j for each agent type j.

As in the single vehicle ownership version of the model, the decision rules of the individual agents are aggregated to obtain the steady-state distribution of vehicle vintages.

[15] For example, if $n = 2$ and $h = 1$, then $\mathbf{r} = (2)$, that is, the agent has two vehicles and replaces both of them every period.

If $n = 2$ and $h = 2$, then $\mathbf{r} = (1, 1)$, so the agent replaces one of her two vehicles every period.

If $n = 2$ and $h = 3$, then $\mathbf{r} = (1, 1, 0)$. The agent owns two vehicles, each for three periods prior to replacement. She replaces one of her vehicles in each of the first two periods of the steady state rule, and none in the last period.

If $n = 2$ and $h = 4$, then $\mathbf{r} = (1, 0, 1, 0)$.

5 Calibration

The economic environment is characterized by a set of parameters. Parameters describing the income distribution and prices of new vehicles in 2001 $\left\{ \{y_j\}_{j=1,\ldots,N}\ ,\ p_0 \right\}$ are estimated from the data. For the multiple vehicle ownership version of the model the decision unit is a household. The single vehicle ownership version of the model is calibrated at the individual level, since ownership of at most one vehicle per household is a very strong restriction.[16]

The preference parameters $\{\eta, \gamma, \lambda, \alpha\}$ are chosen to match the data moments on the total number of vehicles registered per decision unit (per capita in the single vehicle version of the model and per household in the multiple vehicles ownership one), the new vehicle registrations per decision unit, the fraction of households owning at least one vehicle, and the mean age of vehicles, all for 2001. The single vehicle ownership version of the model does not allow to distinguish between the total number of vehicles registered per capita and the fraction of households owning at least one vehicle, so only the first moment is used for the calibration. Also, parameter α cannot be identified in the single vehicle setting, since it characterizes changes in utility from owning more than one vehicle. Thus, in the single vehicle version of the model three moments are used to identify three parameters.

The price depreciation parameter τ is estimated with a moment condition that supply should equal demand at given prices across vintages.

The remaining parameters are the number of agent types N, the upper bound on vehicle ages G, the fraction of the vehicle value recovered by the agent ϕ, the maximum number of vehicles an agent can own in the multiple vehicles version of the model $\overline{n}$, and the time discount rate β. Parameter values $N = 500$ and $G = 30$ are chosen to optimize on the computational time, while still resulting in meaningful predictions from the model. The maximum number of vehicles is $\overline{n} = 4$. According to the Consumer Expenditure Survey, in 2001 less than 3% of the US households had

[16] In the 2001 Consumer Expenditure Survey, over 60% of household own 2 or more vehicles.

a stock of more than four vehicles, so this choice is hardly restrictive. The annual discount rate $\beta = 0.96$ is chosen to match previous studies. In the price data from Kelley Blue Book and Edmunds.com, the wedge between the trade-in and retail values is anywhere from 5% to 10%. Here I assume that it is 10%, and set parameter $\phi = 0.9$.

Next I describe the procedure and data used to assign values to $\left\{ \{y_j\}_{j=1,\ldots,N},\ p_0,\ \eta, \gamma, \lambda, \alpha \right\}$.

5.1 Parameters calibrated outside the model

The income distribution in 2001 is approximated with a lognormal density function, with parameters μ and σ calibrated to match two moments from the data, the mean household income and the Gini coefficient in 2001. These data were obtained from the Historical Income Tables compiled by the US Census Bureau from the Annual Social and Economics Supplements to the Current Population Survey. The estimated lognormal distribution function was used to calculate the mean household incomes for each of the 500 agent types. The number of people per household is positively correlated with income. Thus, to account for these differences in household size by income groups, the mean incomes of households were computed in per capita terms. The average number of people over the age of 16 by income percentiles was obtained from the Consumer Expenditure Survey and extrapolated to the 500 types. These estimates were used to calculate the mean incomes per person over the age of 16 for each of the agent types $\{y_j\}_{j=1,\ldots,500}$. The single vehicle ownership version of the model is estimated at the per capita level using these income values. The multiple vehicles version of the model is evaluated at the household level, so these income estimates are multiplied by the average number of people per household for the US in 2001 to obtain the mean household income for each agent type.

The price of a new vehicle, p_0, comes from the Ward's Automotive Yearbook [19]. The estimate used is the average expenditure per new car in 2001.

5.2 Parameters calibrated within the model

In the single vehicle version of the model, the values of preference parameters η, γ, and λ are chosen to bring the model's aggregate predictions as close as possible to the data on the total number of vehicles per capita, the new vehicle registrations per capita, and the mean ages of vehicles in 2001. In the multiple vehicles ownership setting, the first two moments are taken at the household level, an additional preference parameter α is calibrated, and an extra moment on the fraction of households owning at least one vehicle is added to the procedure.

The data on the size of the vehicle stock, the sales of new vehicles and the mean age of vehicles in the US are published by the Ward's Automotive Yearbook [19], and the original source of the data is R.L. Polk & Co. The Consumer Expenditure Survey (2001) is used to approximate the fraction of households owning at least one vehicle.

The data in the Ward's Automotive Yearbook are presented separately for cars and trucks. For the purposes of this project, the numbers of cars and trucks were added to obtain aggregate statistics. For the single vehicle version of the model, the total number of vehicles and the new vehicle registrations were divided by the civilian noninstitutional population over sixteen years of age acquired from the Bureau of Labor Statistics, to obtain per capita values of these data moments. For the multiple vehicles version of the model, these values were divided by the total number of households in the US, available from the same source. The data on the mean age of vehicles are also presented separately for cars and trucks. The mean age of the total vehicle stock was computed as the weighted average of the mean ages of cars and trucks, with fractions of each vehicle type as weights.

The calibration procedure seeks to minimize the distance between the data and the model's predictions in the least squares sense. The criterion used is a weighted sum of the distances between actual and predicted moments, with each component weighted by the empirical inverse of the moment's variance from the trend over a 35 year period (1967-2001) for the total number of vehicles, new vehicle sales, and the mean age of vehicles, and a 27 year period (1979-2001) for the fraction of households owning at least one vehicle.

The moment for the market clearing conditions across vehicle ages was also added to the criterion. The moment used to estimate τ is the distance between supply and demand, averaged over vehicle vintages. The final criterion was minimized via the simplex algorithm due to Nelder and Mead [13].

5.3 Calibration results: Parameter values and decision rules

This section presents the calibration results and decision rules for two versions of the model and compares the models' predictions to several additional moments from the data.

5.3.1 Single vehicle version of the model

The calibrated parameter values and moments from both model and data are presented in Table 2. With the assumption of at most one vehicle per person, the model cannot generate more than 1 vehicle per capita. The calibrated model predicts 0.996 vehicles per capita, versus 1.0074 vehicles per capita observed in the data.[17] The model does well matching two other data moments, the new vehicle registrations per capita and the average age of vehicles.

The estimated rate of price depreciation τ is equal to 0.1906.[18] At this value of the parameter, 8.7% off all vehicles are misallocated, meaning that they are either in excess supply or demand. This is a measure of distance from the equilibrium, and it is arguably not too large.[19]

[17]The data on the total vehicle stock in the US obtained from the Ward's Automotive Yearbook includes all motor vehicles, including heavy trucks and buses. The data on the number of passenger cars and light trucks only would be more suitable for the purposes of this project; however, this data is not publicly available. The estimate obtained from the Consumer Expenditure Survey for 2001 puts the number of vehicles per person over the age of 16 at around 0.9. This is likely to be a lower estimate, since the survey tends to oversample from the lower income part of the population.

[18]For comparison, Cooper and Adda [2] estimate $\tau = 0.2$ using the Kelley Blue Book Data.

[19]The model assumes no international trade in used vehicles and no vehicle destruction in traffic

Table 2: Calibration results: Single vehicle, per capita level

Parameter	Estimate	Moment (2001)	Model	Data
λ	$15,441$	Total veh., PC	0.9960	1.0074
η	0.0006	New veh., PC	0.0780	0.0813
γ	3.5994	Mean age of veh.	8.5211	8.6
			Least sq. dist.	**% misall.**
τ	0.1906	Market clearing	$1.2911e-005$	8.6957

Figure 1: Average age of vehicles owned and Decision rules by agent types: Single vehicle

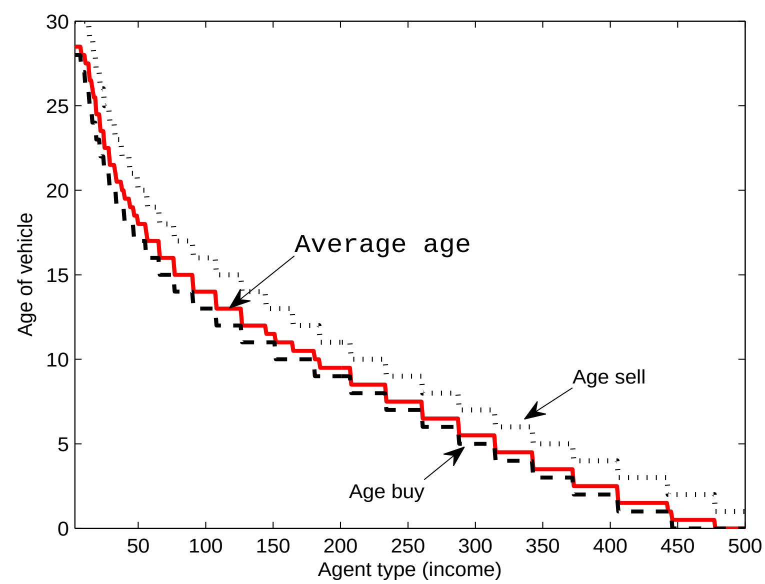


Figure 1 plots the decision rules and the resulting average ages of vehicles owned by income types, from lowest to highest. The model predicts a strong negative relationship between income and ages of vehicles. The predicted average ages of vehicles are the outcome of two decisions: what vehicle vintage to buy and how long to keep this vehicle prior to replacement or, equivalently, what vehicle vintage to sell. Figure

accidents.

1 shows that higher-income consumers choose to purchase younger vehicles. The ages of vehicles sold also decline with income. For each agent type, the difference between the age of vehicle sold and the vehicle's age when it is purchased is the number of years the vehicle is held prior to replacement. This difference declines with income.[20]

5.3.2 Multiple vehicles version of the model

This section presents the calibration results for the multiple vehicles version of the model with households as decision units. The agents are allowed to own up to 4 vehicles. Table 3 presents the calibrated parameter values and moments from both model and data. There is an additional parameter α that was missing from the single vehicle version of the model, and it captures the increase in household's utility from the higher number of vehicles owned. Another moment is also added to the estimation procedure - the fraction of households that own at least one vehicle.

The model does well matching the data moments. The price depreciation rate τ is equal to 0.0871, a much lower value than the single vehicle version's 0.1906. Lower values of τ make older vehicles relatively more expensive, so households demand newer vehicles when prices are slow to depreciate. In the multiple vehicles setting, wealthier households buy more new or slightly used vehicles, increasing the supply of younger vintages. Thus, a smaller value of τ is needed to match supply with demand when households can own more cars. At this parameter value, the percentage of vehicles that is in either excess demand or excess supply by vintage is 10.8.

Figure 2 depicts the decision rules and the resulting average ages of vehicles by income types predicted by the model. Notice that the relationship between the average age of the stock and the household's income is no longer monotonically decreasing. Households with higher income may obtain higher utility from vehicle ownership by

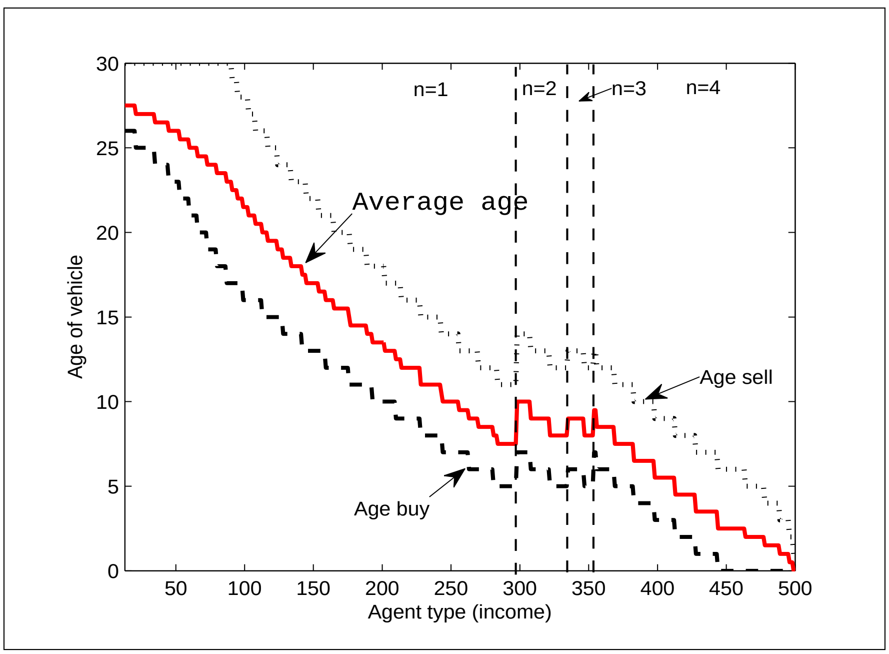
[20] Due to an upper bound on the possible vehicle's age, agents at the very bottom of the income distribution are "forced" to replace their vehicles more frequently. The maximum number of years a vehicle is held is five (income type $j = 16$. It decreases to annual replacement for agent types $j \geq 478$.

increasing the size of their vehicle stock, even if those vehicles are older on average. The dashed vertical lines in Figure 2 separate households with different numbers of vehicles. Observe that the number of vehicles owned increases with income, and that for households with the same number of vehicles the average age of vehicles owned declines with income.

Table 3: Calibration results: Multiple vehicles, HH level

Parameter	Estimate	Moment (2001)	Model	Data
λ	$45,111$	Total veh., per HH	2.0080	2.0024
γ	3.2997	Fract. owners	0.8633	0.8705
η	0.0002	New veh., per HH	0.1177	0.1618
α	0.0328	Mean age of veh.	8.5867	8.6
			Least sq. dist.	**% misall.**
τ	0.0871	Market clearing	$1.2313e-004$	10.7841

Figure 2: Average age of vehicles owned and Decision rules by agent types: Multiple vehicles



For a given size of the vehicle stock, the age of vehicles at the time of purchase is lower for higher income households. Similar relationship holds for the ages of vehicles sold and household income types. The difference between the age of vehicle sold and the vehicle's age at the time of purchase is the number of years a vehicle is held prior to replacement. Note that this difference is larger on average relative to that in the single-vehicle case, that is, the vehicles tend to be replaced less frequently. The number of years a vehicle is owned declines with income.[21]

6 Results: Distribution of Income and Distribution of Vehicle Vintages

This part of the paper studies how changes in the distribution of consumer incomes affect aggregate vehicle ownership patterns, with particular interest in the predictions for the mean age of the total vehicle stock. Subsection 6.1 considers the effect of changing the mean household income relative to the 2001 benchmark, holding the level of income inequality and the price of a new vehicle fixed at their US in 2001 levels. In Subsection 6.2, the mean household income and a new vehicle's price are the same as in 2001, and it is the level of income inequality that is allowed to vary. Both subsections compare predictions of the single vehicle and the multiple vehicles versions of the model.

In both subsections, the values of preference parameters η, γ, λ, and α are as estimated in the corresponding versions of the model. The price depreciation parameter τ, however, is reestimated in both versions for every change in the income distribution with a moment condition that demand should equal supply across vehicle vintages. Thus, the implicit assumption is that the price of a new vehicle is set globally, while the trade in used vehicles is limited to the boundaries of a given economy.

[21]For households with only one vehicle the relationship is non-monotone due to the upper bound on the possible vehicle's age.

6.1 Mean Household Income and Vehicle Ownership

This subsection studies how changes in mean household income affect the model's predictions for the total number of vehicles owned per capita, the fraction of households owning at least one vehicle, the new vehicle sales per capita, and the mean and median ages of vehicles. The household level predictions obtained from the multiple vehicles version of the model are normalized by the average number of people per household in the US in 2001, to enable comparison of results from two versions of the model at per capita levels.

The mean household income is allowed to vary relative to the 2001 benchmark, from 25% of the 2001 level, to 200%. The parameters of the lognormal density function were reestimated to match each level of mean household income and the same value for the Gini coefficient as in 2001. The estimated distribution functions were used to calculate mean per capita incomes for each of the 500 agent types via the same procedure as described in Section 5.1.

In both single vehicle and multiple vehicles versions of the model, for each value of the mean household income, the price depreciation parameter τ is reestimated using the average of market clearing conditions across vehicle vintages. Figure 3 shows how price depreciation rates vary with mean household income in both versions of the model. Notice, that though the scale is different, with smaller estimated values of τ in the multiple vehicles version of the model, the trend is similar. The model predicts that prices depreciate faster in higher-income economies, a result consistent with the findings of Storchmann [17].

The uneven shape of the lines is the outcome of a discrete number of agent types (500), and only a fraction of them making buying and selling decisions in every economy. The low-income economies have the majority of consumers with very low incomes. If prices were to depreciate faster, these consumers would purchase very old vehicles. However, there would not be a sufficient number of higher-income consumers purchasing younger vehicles and supplying the older ones, so the value of the market clearing moment would be large. A lower value is obtained when the price depreciation rate is small, and the lower-income consumers choose to not own a vehicle. As incomes grow, prices depreciate faster to stimulate demand for older vintages.

Figure 3: Price depreciation rate τ and Mean household income

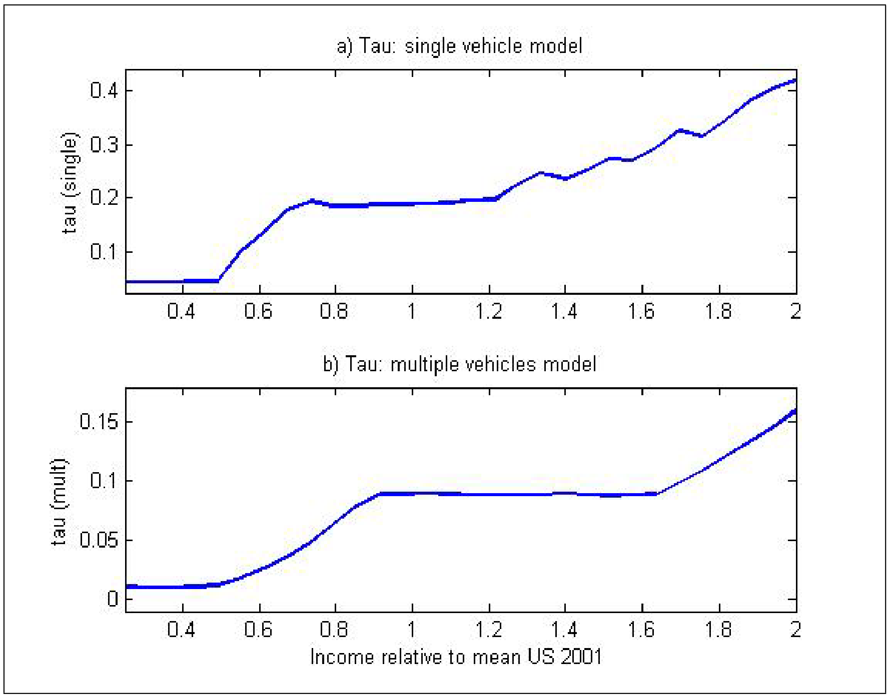
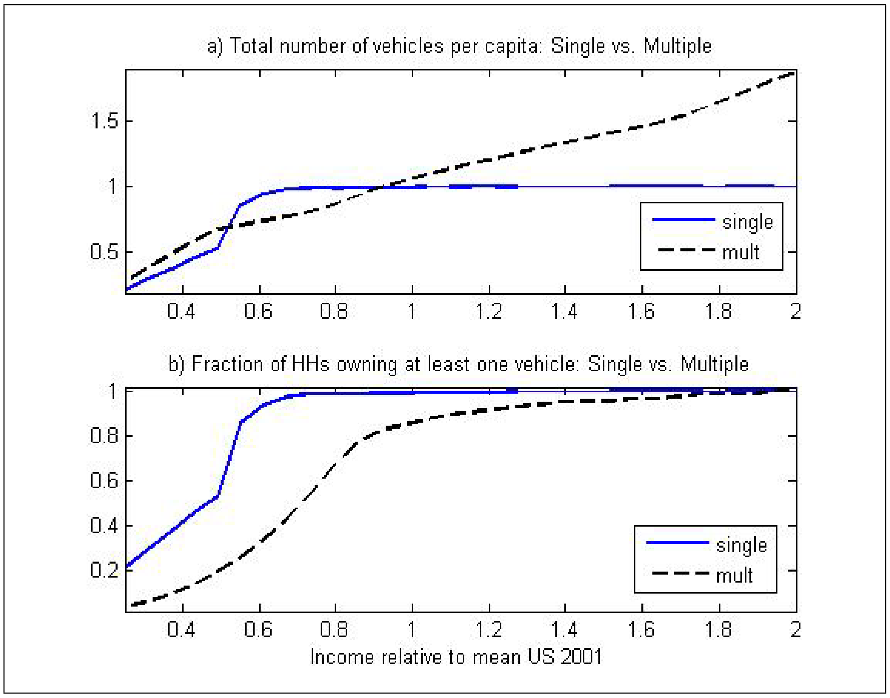


Figure 4a shows a significant increase in per capita vehicle ownership over this range of relative mean income values. The increase in the total number of vehicles per capita is much stronger in the multiple vehicles version of the model, since the single vehicle version limits the maximum number of vehicles held per capita to one. Figure 4b shows a similar pattern for the fraction of households owning at least one vehicle. For the single vehicle version of the model, of course, the total number of vehicles per capita and the fraction of households owning at least one vehicle are the same.

Figure 5 shows the relationship between mean household incomes and the new vehicle sales per capita. Overall, higher income economies tend to sell more new vehicles per capita, but there are two notable exceptions. Both versions of the model

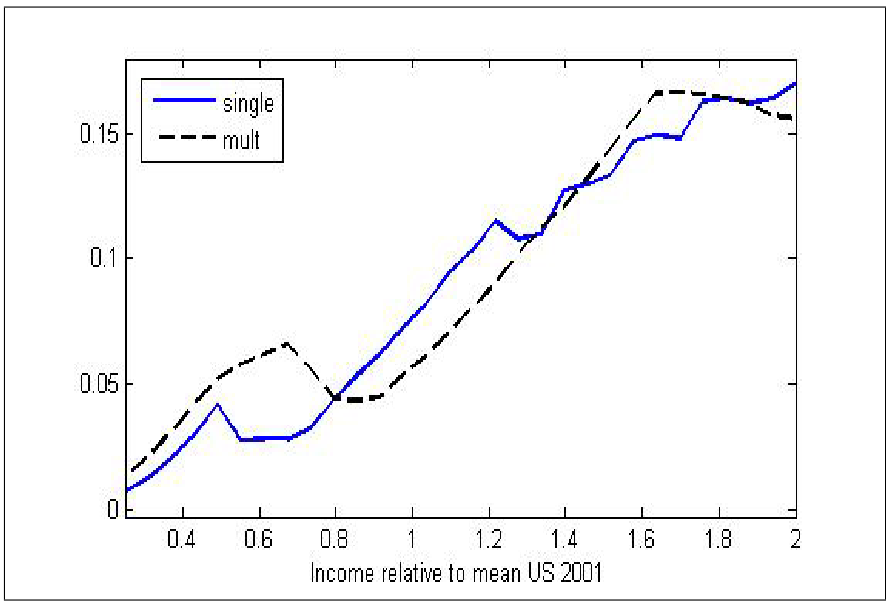
Figure 4: Vehicle ownership and Mean household income



show a decline in sales around the value of 50% of the 2001 US mean household income. Notice that around this mean income value the price depreciation rate increases sharply due to the increase in the fraction of vehicle owners. At lower values of τ, the excess supply of older vehicles becomes too large, so better market clearing is achieved with a higher price depreciation rate and resulting increased demand for older vintages. Thus, small differences in mean household incomes result in large differences in price depreciation rates and relative attractiveness of older vehicles. This produces a pronounced decline in new vehicle sales.

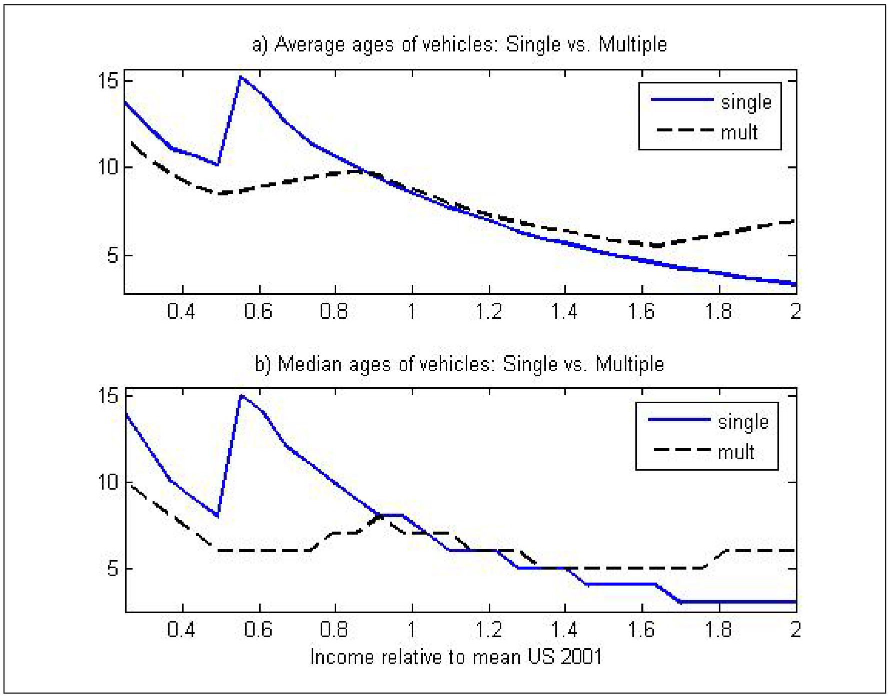
The second exception to the 'higher mean income - more new vehicle sales' rule is more interesting, since it is observed only in the multiple vehicles version of the model. Around the value of 160% of the 2001 US mean household income there is another large increase in the price depreciation rate in the multiple vehicles version of the model. At this high income levels, almost all households own at least one vehicle and the average number of vehicles per household (not per person over sixteen years of age, as in the graph) is 2.8. At these high ownership rates, lower values of price depreciation rate would result in high demand for newer vehicles and, therefore, large excess supply of older ones. Smaller values of the market clearing moment are obtained with larger τ. As a result, increases in mean income translate into increases in utility from vehicle ownership through further enlargement of the average size of the household's vehicle stock, a larger share of which is purchased used. This trend is likely to be reversed at very high income levels, much higher than the 200% of the 2001 US mean household income. Eventually, every household would be so wealthy that it would hold the maximum possible number of vehicles and purchase all of them new.

Figure 5: New vehicle sales per capita and Mean household income



Finally, Figure 6 shows that the mean and median ages of vehicles are non-monotone in mean household income for both versions of the model. This is a very interesting result, since the model produces a negative relationship between income and vehicle ages at the household level, yet, at the aggregate level, this is no longer the case. In low-income economies, increases in mean income may lead to the aging

Figure 6: Mean and median ages of vehicles and Mean household income



of the vehicle stock. This is due to the lower-income consumers choosing to become vehicle owners for the first time as their incomes increase. These consumers choose to hold older vehicles, so their decisions shift the mass of the age distribution towards older vintages. The jagged nature of the predicted average and median ages in low-income economies in the single vehicle model is due to a small total number of vehicles held by agents in the model.

For the economies with the mean income above a certain level, and with the majority of consumers owning at least one vehicle, there is, again, a divergence in the predictions of two versions of the model. The single vehicle version predicts that additional increases in income result in the younger vehicle stock. Thus, the mean and median ages of vehicles decline in mean income, when the mean income is above some low threshold value. The multiple vehicles version of the model also shows the initial decline in vehicle ages after the threshold mean income value, however, this trend is reversed for the economies with mean household income of approximately

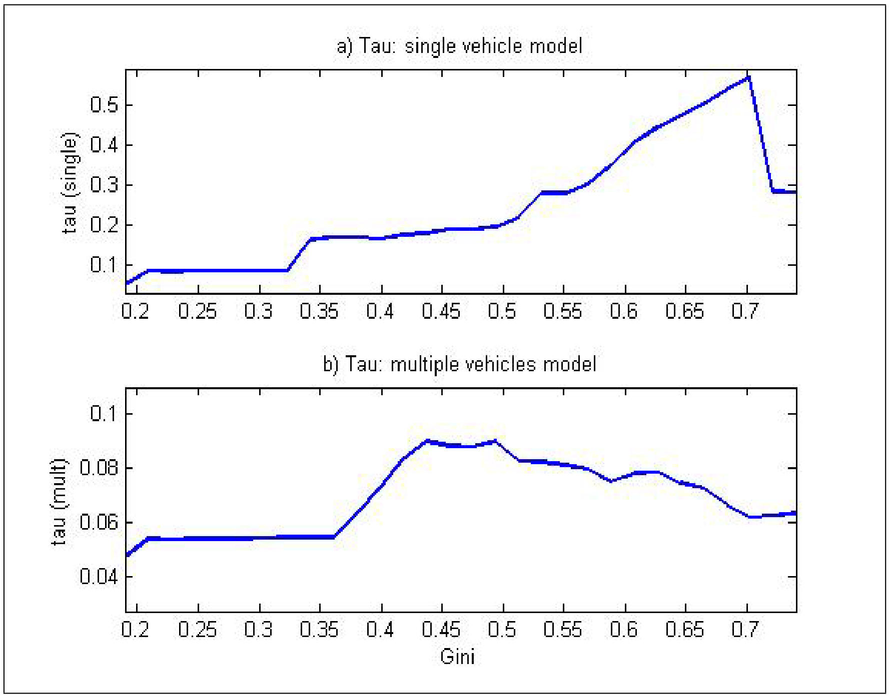
160% of that in the US in 2001 and higher. The explanation is the same as in the case of new vehicle sales. At high income levels, increases in income lead to larger vehicle stocks for households and these are comprised of on average older vehicles. Eventually this trend is likely to be reversed, and at extremely high income levels every household would own the maximum possible number of vehicles, all of them new.

There is currently one empirical study of the relationship between mean incomes and median ages of vehicles. Miller et al. [12] provide evidence of a strong negative relationship between these variables for counties in Tennessee. There are two ways to reconcile their findings with the results of the models. First, the relative mean incomes of counties in Tennessee are likely to be concentrated around one. In this neighborhood, both models predict the decline in mean and median ages of vehicles with income. Second, the predictions have been obtained with the assumption of no trade in used vehicles between economies with different relative mean incomes. It is very likely that this assumption is exceedingly strong at the county level in Tennessee, and the price depreciation rates do not vary much, if at all, by county. For a constant price depreciation rate, both versions of the model would predict monotone relationships between mean household income and vehicle ownership statistics: a positive one for total number of vehicles per capita, fraction of households owning at least one vehicle, new vehicle sales, and a negative one for the mean and median ages of vehicles.

6.2 Income Inequality and Vehicle Ownership

In this subsection, the mean household income and the price of a new vehicle are the same as in the benchmark model, and the Gini coefficient is allowed to vary from 0.19 to 0.74, which corresponds to the largest range of values for this coefficient measured across countries.[22] As before, the incomes of agent types $j = 1, ..., 100$ for each value of the Gini coefficient were computed using the estimates for the lognormal distribution function.

Figure 7: Price depreciation rate τ and Income inequality



Figures 7a and 7b show the predicted price depreciation rates τ from the single vehicle and the multiple vehicles versions of the model respectively. Note that the smallest values of the price depreciation rate are observed in the economies with the lowest degree of income inequality. When the value of the Gini coefficient is low, the income distribution is more concentrated around the mean. Low degree of income heterogeneity means that consumers are more similar to each other. Thus, they make similar vehicle ownership decisions and the resulting vehicle age distribution is also concentrated. Higher values of the price depreciation parameter τ would lead to the majority of consumers wanting to purchase older vehicles. However, the supply

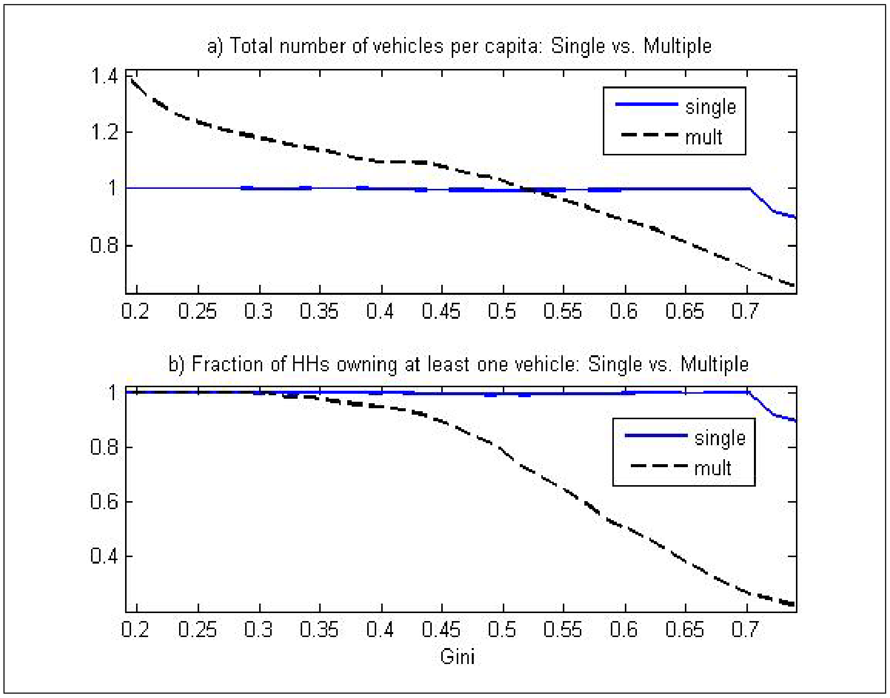
[22]See the United Nations Development Programme's "Human Development Report" for 2006, 2007/2008, and 2009 [18].

of these vehicles would be low, due to a much smaller number of consumers with incomes above the mean. Therefore, in the economies with low degree of income heterogeneity, price depreciation rate needs to be low in order to induce purchases of newer vehicles. Figure 9 shows that the per capita new vehicle sales tend to be higher in the economies with very low levels of income inequality, though the relationship itself is very uneven due to the typically small sample size for households purchasing new vehicles.

Both versions of the model also predict a positive relationship between income inequality and price depreciation rate for the economies with Gini coefficients below some threshold value. Thus, higher variability in incomes results in higher variability in prices of vehicles, through larger values of the price depreciation parameter τ. More dispersed income distributions lead to greater heterogeneity in vehicle age holdings. However, for the single vehicle version of the model, Figure 7a shows that at very high levels of income inequality there is a sharp decline in the price depreciation rate. In these economies almost all income is held by a small fraction of very wealthy households. At higher values of τ, even these households would choose to purchase older vehicles, yet there would not be enough households to supply them. Thus, smaller price depreciation rates induce demand for newer vehicles, which can in turn be supplied to the increased number of below average income households once these vehicles age. In the single vehicle version of the model, this leads to a pronounced decline in ownership rates (see Figure 8a), increase in per capita sales of new vehicles (Figure 9a), and an abrupt increase in the mean and median ages of vehicles (Figures 10a and 10b) at very high levels of income inequality.

The multiple vehicles version of the model produces a different, somewhat bell-shaped relationship between income inequality and price depreciation. The price depreciation rate peaks at the value of the Gini coefficient around 0.45. There is a negative relationship between income inequality and price depreciation rates in the economies with income inequality measure above this threshold value. This very

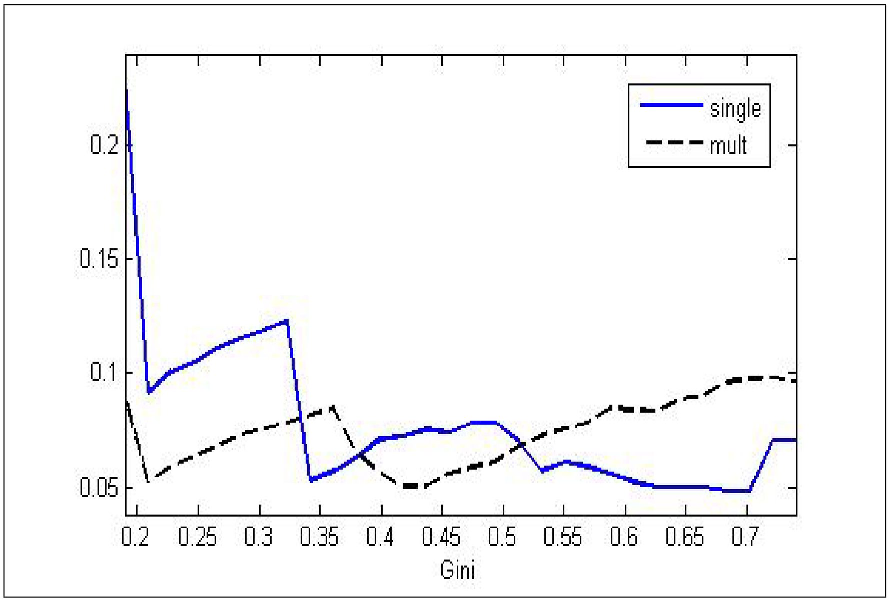
Figure 8: Vehicle ownership and Income inequality



interesting result is due to most of the wealth getting concentrated in the hands of the increasingly smaller share of households, who then hold the increasingly larger share of the vehicle stock due to multiple vehicles ownership. The substitutability of vehicles of different ages in household's consumption means that households with similar income and larger vehicle stocks tend to consume, on average, older vehicles. To rebalance the demand towards newer vehicles, the price depreciation rate needs to be lower in the economies with very high levels of income inequality. Figure 9 shows a positive relationship between income inequality and per capita sales of new vehicles for the economies with high levels of income inequality, even though the total vehicle ownership rates in Figures 8a and 8b decline steadily as an increasingly larger fraction of the population becomes too poor to own any vehicles.

Figures 10a and 10b show the predictions of both versions of the model for the mean and median ages of vehicles. The single vehicle version predicts that the vehicle stocks should be older in the economies with higher levels of income inequality. As

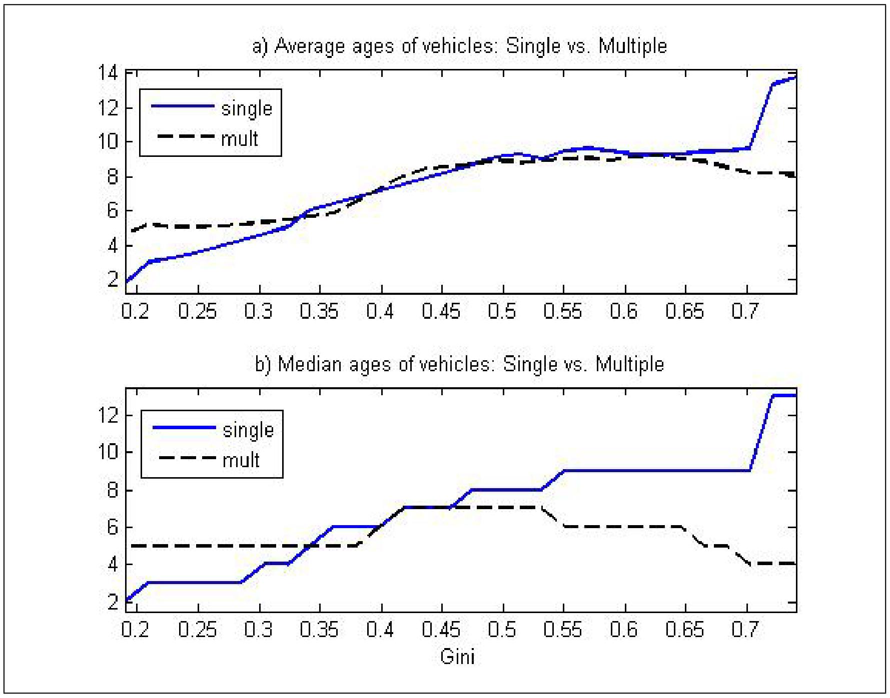
Figure 9: New vehicle sales per capita and Income inequality



income inequality increases, the mass of the income distribution shifts to the left, so the majority of the population becomes relatively more poor. Their decisions cause the mean and median ages of vehicles to increase. That it is not the case in the multiple vehicles model for very high levels of income inequality. The high-income fraction of the population is shrinking, but these household also have more income on average, and thus hold increasingly larger vehicle stocks. Their decisions play the key role in determining the age of the aggregate vehicle stock, and since these households tend to hold newer vehicles, the stock is younger in the economies with very unequal income distributions.

The model assumes that vehicles of the same age are homogeneous in quality. If high income households had other means of increasing their utility from vehicle ownership, say, by purchasing luxury brands, the negative relationship between household's income and the average age of its vehicle stock would be weaker. At the aggregate level, when income inequality is very high, the positive relationship between income inequality and new vehicle sales and the negative relationship between income in-

Figure 10: Mean and median ages of vehicles and Income inequality



equality and ages of vehicles would then become weaker or even disappear. The predictions of two versions of the model would become more similar.[23]

7 Conclusion

The goal of this paper was to study the relationship between the consumer's income and her vehicle ownership decisions, and to analyze the implications of these decisions for the moments of the vehicle age distribution by aggregating over consumers with different income levels. For these purposes, a model of a vertically differentiated market with durable goods and multiple goods ownership was constructed and calibrated to the US data on incomes and vehicle ownership. The assumption of mul-

[23]The empirical relationship between income inequality and moments of the vehicle age distribution is difficult to establish due to the unavailability of data. For the US, the data on income inequality at the state or the MSA levels are available from the US Census Bureau. However, the data on the vehicle age distribution at those levels of disaggregation are not publicly available.

tiple vehicle ownership is important, since evidence from the Consumer Expenditure Survey indicates that vehicles of different ages are substitutes at the household level, and households with larger vehicle stocks tend to own older vehicles on average. The equilibrium prices of used vehicle vintages are approximated with an exponentially decreasing function, and the depreciation rate is endogenous.

The model predicts that income inequality and average incomes play an important role in determining the size of the vehicle stock and the distribution of vehicle vintages in the economy. Some of the model's predictions have been verified by earlier studies, such as a negative relationship between per capita incomes and median ages of vehicles (Miller et al. [12]) and higher price depreciation rates in higher-income economies (Storchmann [17]). Other predictions would benefit from testing and further research.

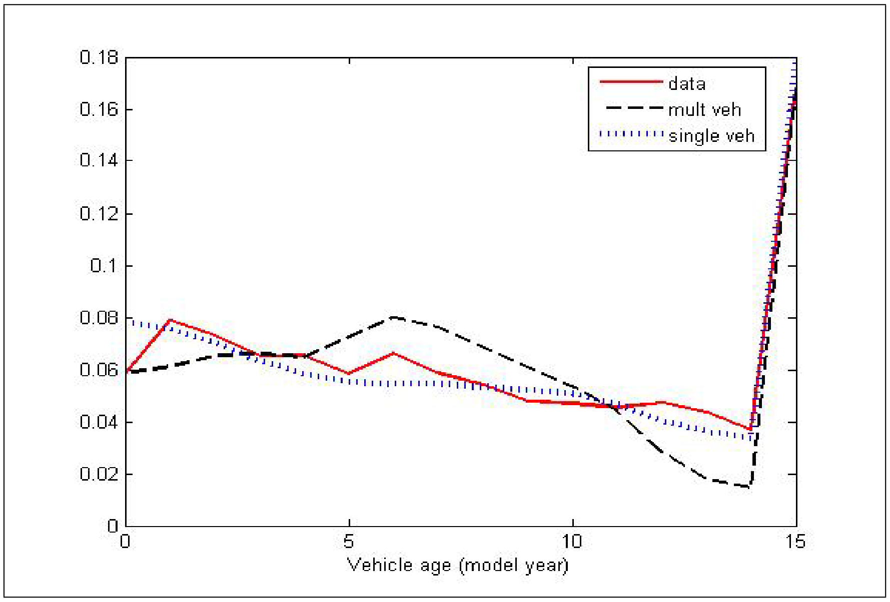
Overall, this paper makes an important step in studying the relationships between consumer incomes and the ages of durable goods consumed, at both the individual and the aggregate levels.

A Additional statistics: Model and data

This section computes and compares additional statistics from both versions of the model and from the data. These statistics were not used in the calibration of the model. Figure 11 plots the age distribution of vehicles in 2001. The data on the distribution of vehicles in use by model year have been obtained from the Ward's Automotive Yearbook. All of the vehicles 15 years of age and older are grouped together in the data, so the same aggregation was done for the vehicle ages generated by each version of the model. The three distributions look similar, but the distribution obtained from the single vehicle version of the model is closer to the empirical one. The conclusion is that the model does well matching the distribution of vehicle vintages in the US in 2001.

On the other hand, the model generates a much stronger negative relationship between consumer incomes and ages of vehicles held than the one observed in the data. Figure 12 plots the average ages of vehicles owned by income percentiles from the two versions of the model and data. The data come from the Consumer Expenditure Survey for 2001. Note that the multiple vehicles version of the model does better matching the ages of vehicles held by the upper fifty percentiles of the income distribution, while the single vehicle version generates somewhat better predictions

Figure 11: Age distribution of vehicles: models and data



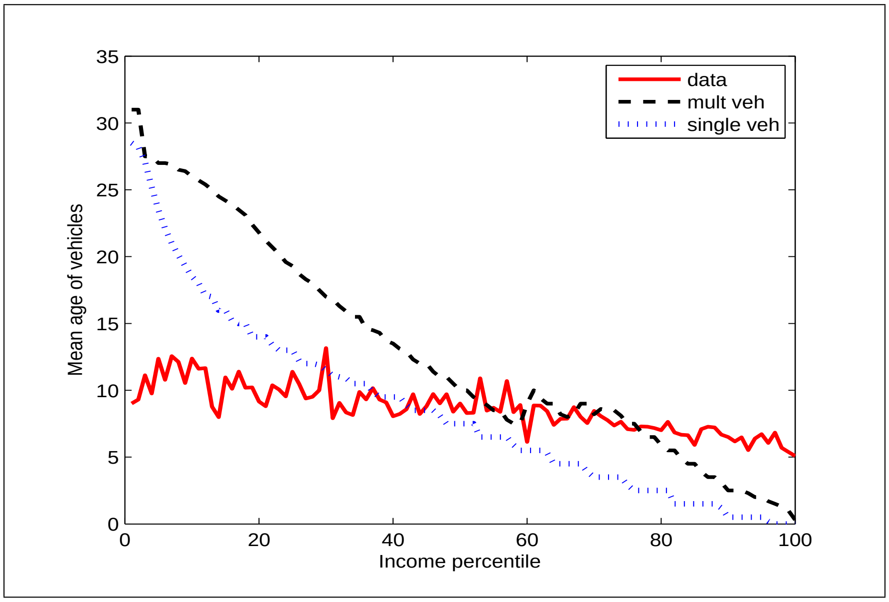
for the households in the lower income half of the distribution. However, the predicted relationship between household incomes and average ages of vehicles held is still too strong, especially for the lower income percentiles. This is due to two factors. First, the Consumer Expenditure Survey reports the exact model year only for vehicles made in 1986 and after, thus the estimated average ages from the data are biased downwards. And second, the utility function from vehicle ownership belongs to the one parameter family, which makes it convenient for the estimation; however, for older vehicles this function generates a rapid decline in utility. As a result, for low income households small differences in income may translate in significant differences in the ages of vehicles held.

The model also underpredicts the average expected number of years a new vehicle has been held, 1.3 in the single vehicle version of the model and 2.8 in the multiple vehicles one versus 4.8 in the data. Notice that in the multiple vehicles version of the model the agents replace their vehicles less frequently. This is consistent with the results from the cross sectional reduced form analysis in Section 2.

The number of years a vehicle is held positively depends on the size of transaction costs of replacing a vehicle. A modification of the model with larger monetary and/or utility costs to replacing a vehicle would result in a higher value for the average number of years a vehicle is held, as well as a less dramatic relationship between incomes and ages of vehicles owned.[24] However, higher monetary replacement costs

[24]Schiraldi [15] finds significant transaction costs of automobile replacement. The estimated transaction costs (both monetary and disutility) for most car models and vintages are between 10% and

Figure 12: Average age of vehicles by income percentiles: models and data



are not consistent with the data, and adding utility costs to replacing a vehicle would increase the number of parameters to be calibrated, which is computationally costly. The latter is also true of relaxing another assumption, that all vehicles of the same vintage are homogeneous in quality.

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80% of the respective price levels, with the peak of distribution at 20% to 40%.

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