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CREDIT SHOCKS AND EQUILIBRIUM DYNAMICS IN CONSUMER DURABLE GOODS MARKETS

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JEL Classification: E21, E32, L62

Keywords: Durable goods, credit constraints

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Credit Shocks and Equilibrium Dynamics in Consumer Durable Goods Markets*

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1 Introduction

Expenditures on consumer durable goods are a large, highly volatile, and procyclical component of GDP. Car markets around the Great Recession are a stark example of this volatility: Figure 1 shows that new-car registrations in the U.S. dropped from approximately 20 million in 2007 to 12 million in 2009 and recovered to 20 million by 2013. This sharp decline accounted for over half of the total reduction in consumer expenditures on durable goods, implying that understanding this component of consumer spending is critical in accounting for household dynamics in the Great Recession.[1]

The objective of this paper is to study the equilibrium dynamics of consumer durable goods markets in response to macroeconomic shocks, with a special focus on car markets. A key contribution of our analysis is to uncover and quantify a new mechanism that transmits aggregate credit shocks to purchases of new durable goods through equilibrium price changes in secondary markets.

We begin our analysis by examining different data sources in order to gain a broad picture of household vehicle holdings and equilibrium dynamics in car markets. These data reveal several interesting patterns that complement the drop in new-car sales during the Great Recession displayed in Figure 1. Most notably, (1) vehicle scrappage declined from 2007 to 2009; (2) the cost of replacing a used car with a new one increased from 2007 to 2009, as used-car prices dropped and new-car prices remained stable; and (3) the fraction of households that replaced a used vehicle with a new one bottomed out during the Great Recession.

These facts motivate us to develop a macroeconomic model of durable consumption that features a notion of endogenous illiquidity, stemming from equilibrium dynamics in secondary markets. We use this novel framework to analyze the transmission mechanism of macroeconomic shocks to durable-goods purchases. The model includes the key elements needed to study this transmission: It allows for borrowing constraints that may affect households' vehicle holdings; it incorporates transaction costs that may trigger household

[1]Household expenditures on motor vehicles declined by approximately 100 billion U.S. dollars between 2007 and 2009. On average, this component accounts for approximately 35 percent of total consumer expenditures on durable goods. Moreover, the motor vehicle industry plays an important role in U.S. business cycles, because of its key position in the network structure of production (e.g., Atalay, 2017). Employment in this industry declined by approximately 35 percent during the Great Recession, leading to direct government interventions in the form of bailouts and stimulus to car purchases.

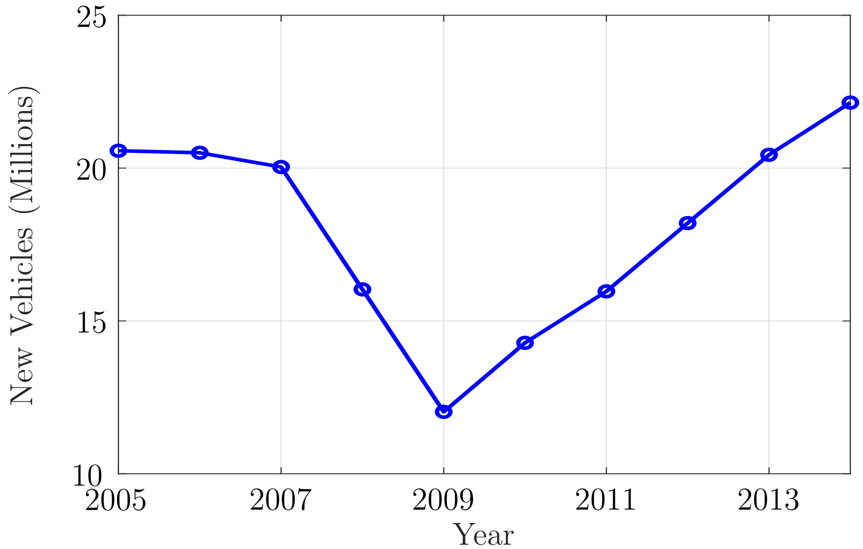

Figure 1: New-vehicle registrations from 2005 to 2014, in millions.

inertia; and it is set in general equilibrium, because households' car purchases depend on both interest rates and car prices, which displayed large fluctuations in the Great Recession.

Our model is an incomplete-markets framework with uninsurable income shocks and durable adjustment. Durable goods feature two additional characteristics that are important in accounting for their equilibrium dynamics. First, the model features a quality ladder for durable goods: Cars differ in quality because of depreciation. Thus, because of indivisibility, cars of different qualities are imperfect substitutes.[2] Second, households choose when to replace their cars by trading them at market-clearing prices on secondary markets or scrapping them.

We parameterize the model to match several aggregate statistics for car markets and household-level cross-sectional moments on car ownership in the U.S., as well as empirical targets for household income and wealth. Our economy features a negative correlation between wealth and car age, consistent with evidence that Gavazza, Lizzeri, and Roketskiy (2014) report. Wealthier households tend to own new, high-quality cars; when the quality of these cars depreciates over time, wealthy households sell them and replace them with newer,

[2]The large majority of households own a vehicle that is an imperfect substitute for a new vehicle, because of indivisibility. Specifically, our transaction data described in Section 3 show that the 10th percentile of the distribution of new-vehicle prices in 2007 equals $16,239, whereas Table 1 of Jacobsen and van Benthem (2015) reports that the average price of a 3-year-old car in the U.S. equals approximately $16,400 (in 2009 dollars). Moreover, the average lifetime of vehicles may exceed 15 years, depending on the model. All these facts together make it apparent that the large majority of households own a vehicle whose value is well below that of a cheap new car, and thus is an imperfect substitute for a new vehicle.

higher-quality ones. Low-wealth households tend to own old, low-quality cars, scrapping them when their quality deteriorates further and replacing them with mid-quality, used cars. Thus, secondary markets play the fundamental role of reallocating used cars from higher-income households to lower-income ones.

In this setting, we consider a shock that permanently tightens credit limits, as in other recent papers that propose this shock as a plausible exogenous source of macroeconomic dynamics consistent with the experience of the Great Recession (e.g., Guerrieri and Lorenzoni, 2017; Huo and Ríos-Rull, 2016). As in these papers, a tighter borrowing constraint motivates all households to increase their savings, leading to a sharp decline in the equilibrium real interest rate. Importantly, in our model, low-wealth households—for whom the borrowing constraints become tighter—decide to postpone scrapping their old, low-quality vehicles. Because these low-wealth households are natural buyers of mid-quality, used cars, their decision to postpone scrappage leads to a decrease in the demand for these mid-quality cars, thereby lowering their price. Hence, high-wealth households, who normally trade in moderately used cars to replace them with new, high-quality ones, suffer an increase in the replacement cost of their vehicles and decide to delay their replacement. Thus, even though the change in the borrowing limit does not directly affect these wealthy households, the equilibrium dynamics in secondary markets prompt them to postpone their new-car purchases. In our calibration, this negative feedback effect of secondary markets on the primary market quantitatively dominates the positive effect of low interest rates on purchases of new durable goods. Hence, the model predicts a large decrease in new-car sales, as well as in scrappage and used prices, consistent with the empirical evidence we document.

The distinctive feature of our model is the endogenous illiquidity of durable goods, arising from the equilibrium dynamics in secondary markets. In our framework, the price of used durables falls in response to a credit tightening—that is, when the marginal value of liquidity is highest. This equilibrium effect renders durable goods a poor store of value and amplifies their cyclical dynamics. Critically, this mechanism is crucial in accounting for the large drop in new-car sales, as well as the positive comovement of scrappage and new sales observed in the data. We perform a rich series of decompositions and counterfactual analyses to show that this implication of our model is in stark contrast to the implications of models that do not account for secondary-market equilibrium.

We further enrich our model to study several interactions between durable goods markets and the macroeconomy, which allows us to quantify the importance of equilibrium dynamics in durable goods markets during the Great Recession. Specifically, we consider aggregate income shocks, endogenous changes in the marginal cost of new durable goods, and borrowing constraints that depend on the value of households' durable holdings—that is, collateral constraints. These features improve the quantitative performance of the model against the data. Most notably, a combination of credit tightening and an aggregate income decline accounts for almost the entire drop in new-car sales.

Finally, we use our model to evaluate the effects of targeted fiscal stimulus, in the form of car-replacement subsidies, similar to the "Cash for Clunkers" program implemented in the U.S. in 2009. We show that secondary markets play an important role in the transmission of these policy interventions. Specifically, we find that general-equilibrium effects dampen the stimulus of these subsidies on the demand for new cars, by depressing the trading and prices of used-car markets. Hence, these subsidies are less effective than models that do not consider general-equilibrium effects would predict.

The rest of the paper is organized as follows. Section 2 highlights our contribution to the literature. Section 3 documents the key empirical patterns for vehicle prices and households' vehicle replacement during the Great Recession. Section 4 introduces our model, which we parameterize in Section 5. Section 6 considers the effects of macroeconomic shocks, such as an aggregate tightening of the borrowing limit and a negative aggregate income shock. Section 7 studies durable-replacement subsidies, and Section 8 concludes. The appendices collect additional results.

2 Related Literature

This paper contributes to several strands of literature. First, since at least Mankiw (1982) and Bernanke (1985), understanding the dynamics of expenditures on durable goods has been an important question in macroeconomics. In their seminal paper, Grossman and Laroque (1990) develop a model of durables adjustment subject to transaction costs, proportional to the value of the current durable stock, motivating this assumption with the idea of indivisibility: In order to increase the utility flow for durables, a household must trade its current durable good and replace it with a new one. Consistent with this notion, several papers focus on models of lumpy durables adjustment (see, among others, Caballero, 1993; Eberly, 1994). Among these contributions, Leahy and Zeira (2005) is particularly related to our paper, as they study the cyclical effects of the timing of lumpy durable goods purchases in general equilibrium. Recently, Kaplan and Violante (2014); Berger and Vavra (2015); and Guerrieri and Lorenzoni (2017) embed households' fixed adjustment costs in a Bewley (1986)–Huggett (1993)–Aiyagari (1994) general-equilibrium framework with uninsurable idiosyncratic risk.[3] We enrich this framework with a quality ladder for durables, which households can trade at market-clearing prices on secondary markets (or scrap).[4] We obtain that the illiquidity of durable goods is an equilibrium outcome that varies with the aggregate state of the economy, rather than a fixed parameter.[5] Moreover, we show that this endogenous illiquidity is essential in accounting for the positive comovement of car scrappage and new-car sales observed during the Great Recession.[6]

Second, because of our assumption of indivisibility, our mechanism shares some features with other papers in which agents are simultaneously buying and selling assets. Stein (1995) builds a housing-market model in which households' down-payment constraints amplify shocks to house prices, thereby reducing housing demand. Anenberg and Bayer (2020) show that the cost of simultaneously holding two homes varies endogenously over the cycle, driving fluctuations in trade volume. Garriga and Hedlund (2020) study housing markets in the Great Recession, using an incomplete-markets model with search frictions that render housing illiquid. Our paper differs from these contributions in that our equilibrium notion

[3] Relatedly, Huo and Ríos-Rull (2016) and Favilukis, Ludvigson, and Van Nieuwerburgh (2017) study the effects of financial shocks in models of housing with incomplete markets.

[4] Caplin and Leahy (2006) develop a tractable equilibrium model of durable goods markets with fixed adjustment costs by approximating the distribution of durable goods holdings.

[5] We use the term "illiquidity" to relate our framework to the early contribution of Grossman and Laroque (1990), as well as the more recent literature on two-asset incomplete-markets models, such as Kaplan and Violante (2014). In these models, households solve a portfolio problem between a standard asset and an "illiquid" asset—i.e., an asset subject to transaction costs. These papers do not feature illiquidity in the sense of search frictions and related time to sell. Also in our framework, there are no search frictions. However, the cost of adjusting the stock of durable goods is determined by equilibrium prices in a competitive secondary market, as well as standard transaction costs. Prices vary in response to aggregate shocks, because durable goods of different qualities are imperfect substitutes.

[6] Our paper is also related to Adda and Cooper (2006), who empirically study the aggregate dynamics of car sales; Oh (2019), who studies durable replacement and second-hand markets in a representative-agent business-cycle model; Rampini (2019), who analyzes how durability affects durable-goods financing in a model with collateral constraints; and Chafwehé (2017), who considers secondary markets for durables in a stationary partial-equilibrium model with incomplete markets.

of illiquidity stems from the imperfect substitutability across durables of different qualities that trade at market-clearing prices. Vehicles represent an ideal setting to measure relative price movements across goods of different qualities. However, the main insights from our analysis should also apply to housing markets, as households move up and down a "property ladder." Relatedly, Ortalo-Magné and Rady (2006) show how housing market dynamics depend on the ability of young buyers to afford the down payment on a house and Landvoigt, Piazzesi, and Schneider (2015) emphasize spillover effects across partially segmented housing markets during the 2000-2005 housing boom.

Third, the literature on consumer durable goods has investigated the role of secondary markets in allocating new and used goods (see, among others, Rust, 1985; Anderson and Ginsburgh, 1994). Most closely related are the empirical/quantitative papers of Adda and Cooper (2000), who study how government subsidies for the replacement of old cars with new ones in France affect the time-series of new-vehicle sales; Stolyarov (2002), who investigates resale rates across different car vintages; and Gavazza, Lizzeri, and Roketskiy (2014), who provide a quantitative welfare analysis of secondary markets.[7] We contribute to this literature by introducing (other) incomplete asset markets and macroeconomic shocks, and thus study the interactions between markets for durables and the rest of the economy.

The paper also contributes to the literature that studies capital replacement and, more generally, markets for capital goods. Among other papers, Cooper and Haltiwanger (1993) show that the replacement of depreciated machines can create endogenous fluctuations in the productivity and output of a single producer; Cooper, Haltiwanger, and Power (1999) explore aggregate investment fluctuations due to plants' discrete replacement of their capital stock. However, none of these papers consider equilibrium in the market for used capital in the presence of aggregate dynamics and, thus, fluctuations due to endogenous changes in the resale price of capital. Hence, our paper complements the recent work of Lanteri (2018), who studies capital reallocation in an equilibrium model of firm dynamics with endogenous resale price of capital, whereas we focus on consumer durables. A key novelty of our framework is that because households simultaneously buy higher-quality, new durable goods and sell lower-quality, used goods, price dynamics in the secondary market affect the timing of household purchases in the primary market.

[7] Chen, Esteban, and Shum (2013) study the effects of the secondary market for automobiles on manufacturers' incentives in the primary market.

Finally, our mechanism of delayed upgrading of durable goods during the Great Recession is consistent with the concurrent analysis of Dupor, Li, Mehkari, and Tsai (2018), who study the effect of households' income expectations on their car purchases during the Great Recession, and with the evidence of Jaimovich, Rebelo, and Wong (2019), who show that households also traded down in the quality of their nondurable consumption in that period.

3 Empirical Patterns

The goal of this section is to document key empirical facts on households' adjustment of their vehicle stock and on vehicle prices during the Great Recession. Appendix A describes our data and methodology in more detail, and provides additional patterns that complement those that we report in this section.

(1) Vehicle scrappage decreased.

We obtain the yearly aggregate stock of registered vehicles in the U.S. from the Federal Highway Administration (FHWA), the yearly inflow of sales of new vehicles from the U.S. Bureau of Economic Analysis, and the yearly inflow of new-vehicle leases from the National Automobile Dealers Association (NADA). We combine these sources to construct the yearly outflow of vehicle scrappage using the accounting identity:

$$\textsc{Scrappage}_t = \textsc{Stock}_t - \textsc{Stock}_{t-1} + \textsc{New Sales}_t + \textsc{New Leases}_t.$$

Figure 2 displays the resulting series of vehicles scrapped in the U.S. for the period 2005-2014, and shows that vehicle scrappage bottomed out during the Great Recession, declining by approximately 16 percent in 2009 relative to 2007. Together, Figures 1 and 2 imply that the total stock of vehicles remained approximately constant during the period, whereas the age of the stock increased during the recession, as we document in Appendix A.

(2) The cost of replacing a used vehicle with a new one increased.

We use data on new-vehicle transaction prices obtained from Dominion Dealer Solutions and used-vehicle prices obtained from the National Automobile Dealers Association

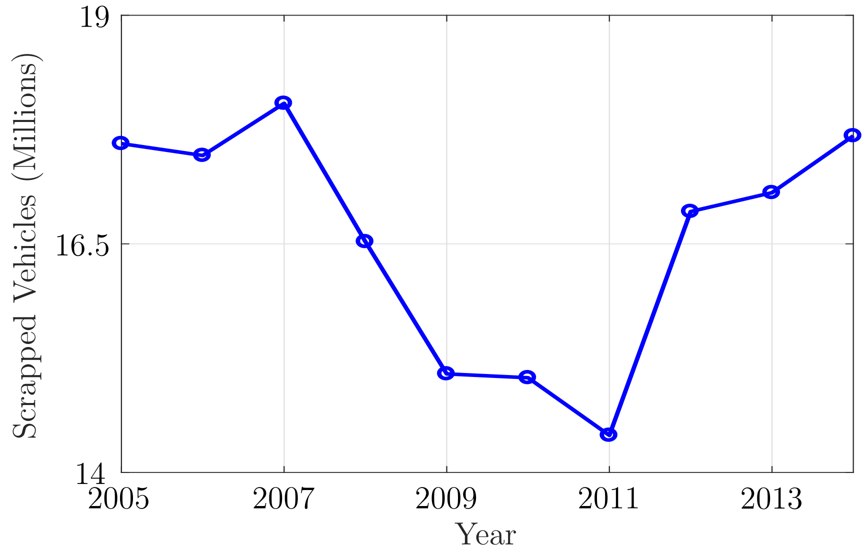

Figure 2: Number of vehicles scrapped during 2005-2014.

(NADA) to compute the replacement cost of new vehicles, calculated as the difference between the transaction price of a new (i.e., age-0) vehicle model and the 4-year-old trade-in price of the same vehicle model. The four panels of Figure 3 display these replacement costs. The top-left panel displays an index of replacement costs, which we construct by pooling all vehicles in the Dominion and NADA datasets, normalized to equal 100 in 2007; the other panels portray it for three popular vehicles in the U.S.: the Honda Civic (top-right panel), the Toyota Camry (bottom-left panel), and the Honda Accord (bottom-right panel). All of these panels show that the cost of replacing a used vehicle with a new one spiked during the Great Recession, increasing in 2009 by approximately 20 percent relative to pre-recession years.[8]

Figure 4 highlights the main reason why the cost of replacement increased during the Great Recession. The top-left panel displays its two components: the average price of a new and that of a 4-year-old vehicle in our datasets, both normalized to equal 100 in 2007. This panel shows that while new-vehicle prices displayed a modest average decline of approximately 2 to 3 percent during the Great Recession, used-vehicle prices were substantially more volatile, dropping by slightly more than 20 percent during those years. The other

[8]As we explain in Appendix A, the NADA dataset reports used-vehicle prices recorded in July of each year (hence, 2008 prices do not incorporate the events of Fall 2008 following the bankruptcy of Lehman Brothers). For consistency, we performed a robustness check that uses new-vehicle transactions that occurred during July of each year only, and the results are very similar to those reported in Figures 3 and 4.

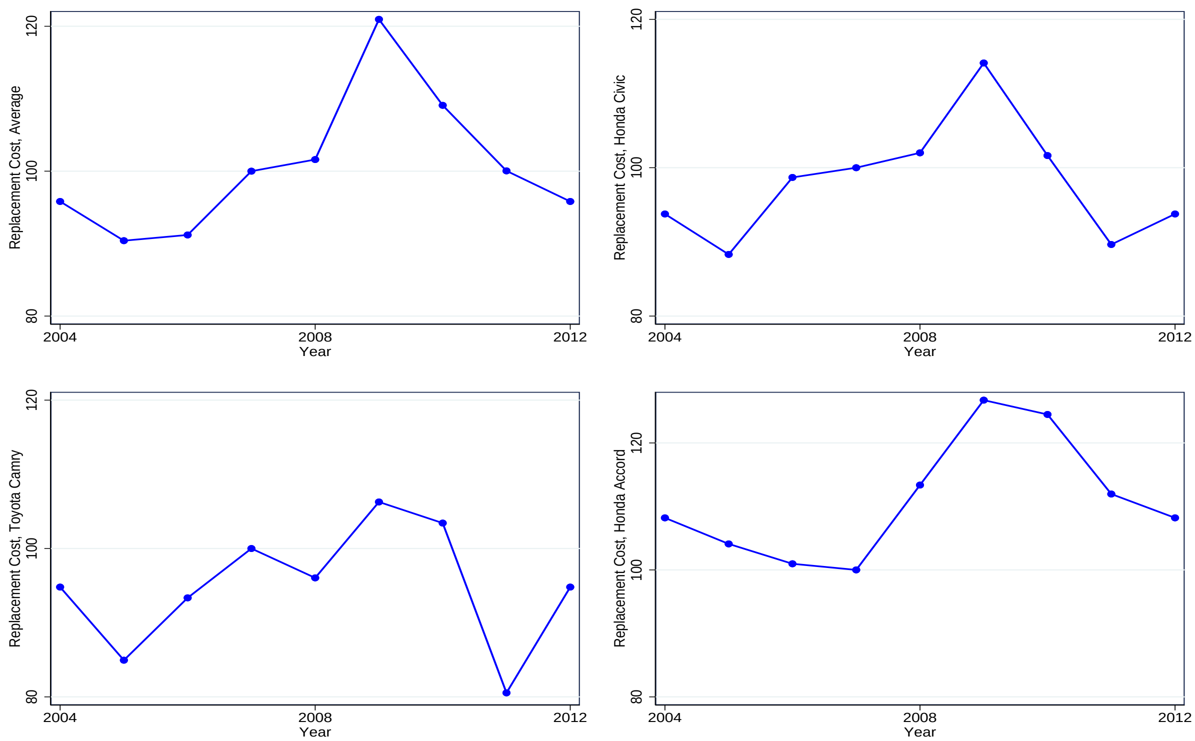

Figure 3: The figure displays the linearly detrended (=year 2004) cost of replacing a 4-year old vehicle with a new one of the same model during the period 2004-2012. The top-left panel displays the average cost computed using all vehicles in the Dominion and NADA datasets. The other panels display the costs of replacing three popular models: the Honda Civic (top-right panel), the Toyota Camry (bottom-left panel), and the Honda Accord (bottom-right panel). All series are normalized to equal 100 in 2007.

three panels portray the price of a new and that of a 4-year-old vehicle for the same models for which Figure 3 displayed the costs of replacement. These panels reveal that new-vehicle price declines were heterogeneous across models, since the prices of a new Honda Civic and a new Toyota Camry exhibit larger reductions than that of a new Honda Accord during the Great Recession. However, all of these models exhibit larger declines in used-vehicle prices than in new-vehicle prices.[9]

In Appendix A we report on two complementary patterns. First, we verify that the Consumer Price Index (CPI) for new- and used-vehicle prices display patterns similar to those in Figures 3 and 4.[10] Second, we analyze financing incentives (i.e., cash rebates)

[9]Our data suggest that cheaper vehicles experienced larger percentage increases in their replacement cost than expensive vehicles during the Great Recession.

[10]We also verified that the starting point of our empirical analysis, i.e., the pre-recession years, were not

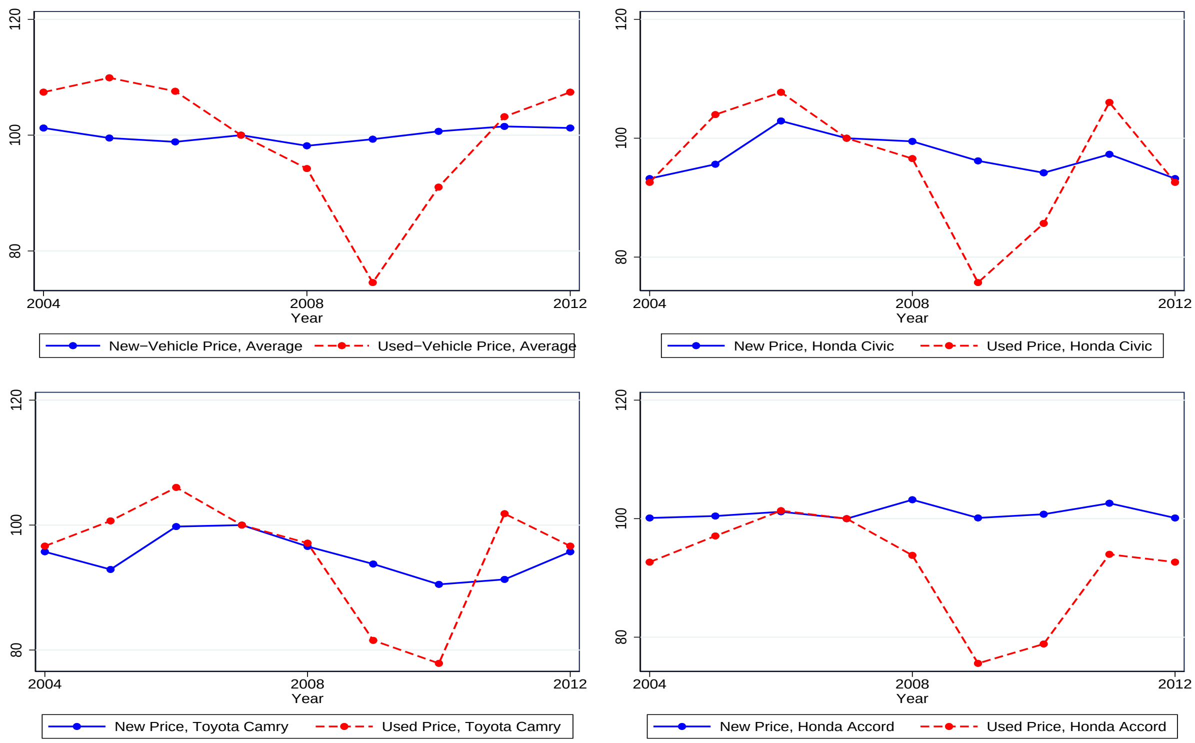

Figure 4: The figure displays linearly detrended (=year 2004) prices of new and used (i.e., 4-year old) vehicles during the period 2004-2012. The top-left panel displays the average new price and the average used price computed using all vehicles in the Dominion and NADA datasets, respectively. The other panels display new and used prices of three popular models: the Honda Civic (top-right panel), the Toyota Camry (bottom-left panel), and the Honda Accord (bottom-right panel). All series are normalized to equal 100 in 2007.

available to consumers published in the magazine *Ward's AutoWorld*, showing that they did not increase substantially during the Great Recession. While we do acknowledge that our evidence on financing incentives is limited, we should point out that several papers assert that auto-financing terms did not improve during 2008-2009. Most notably, Benmelech, Meisenzahl, and Ramcharan (2017) and Ramcharan, Verani, and Van den Heuvel (2016) show that disruptions in asset-backed securities (ABS) markets led to a deterioration of auto-financing terms for households. Similarly, Gertler and Gilchrist (2018) and Bernanke (2018), among others, review the evidence on financial factors during the Great Recession and maintain that the costs of auto loans increased during those years.[11]

unusual years for car markets. In particular, both aggregate sales and the CPI price indices for vehicles do not display significant deviations from their long-run trends.

[11]Furthermore, the CPI of leased cars and trucks increased during the Great Recession. This additional evidence bolsters the argument that the replacement cost increased and suggests that financing terms

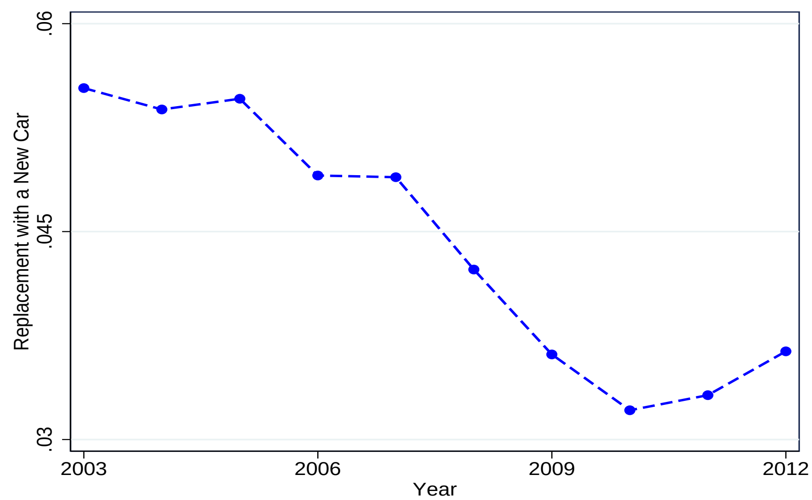

Figure 5: Share of households that replaced at least one used vehicle with a new one during 2003-2012.

(3) Vehicle replacement decreased.

We use the Consumer Expenditure Survey (CEX) to measure households' vehicle replacement. CEX data are well suited for this purpose, because they report information about households' vehicles, including their acquisition date and whether they were acquired new or used.

We use these data for two main purposes. First, we seek to understand the quantitative importance of replacement for new-vehicle sales by calculating the share of households that replaced used vehicles with new ones, among all households that acquired new vehicles. This share equals approximately 50 percent (in Appendix A we explain that this estimate is likely a lower bound of the actual share), and thereby suggests that a decline in replacement can have a first-order effect on new-vehicle sales. Second, we compute the share of households that replaced a used vehicle with a new one. Figure 5 displays this share for each year during 2003-2012, showing that it bottomed out during the Great Recession—and thus

did not improve in those years, for two main reasons: (1) Lease rates should be closely related to the replacement cost index that we construct above and display in Figure 3. Specifically, in a frictionless market, the lease rate $l_{i,t,s}$ of vehicle i at time t and duration s should equal $l_{i,t,s} = p_{i,t} - \frac{1}{(1+r)^s} E_t\left(p_{i,t+s}\right)$, where $p_{i,t}$ is the price of vehicle i in period t, r is the interest rate, and $E_t\left(p_{i,t+s}\right)$ is the expected resale value at the end of the lease in period $t+s$ (Gavazza, 2010). (2) Car leasing is a popular form of car financing. More generally, the financing of car leases is very similar to that of auto loans, as both are mostly financed through ABS.

exactly when the cost of replacement spiked—and recovered thereafter.[12]

Overall, these empirical patterns seem to suggest the following narrative for the decline in new-vehicle sales during the Great Recession: Households delayed scrapping their (old) cars, thereby decreasing the demand for used cars and depressing their price; in turn, the decline in used-car prices increased the cost of replacing used cars with new ones, thereby reducing the demand for new cars.[13] In the next section we formalize this idea in an incomplete-markets economy in which households can acquire durable goods of different qualities, subject to a borrowing constraint. We show that a tightening of the borrowing limit induces a larger fraction of constrained, lower-income households to decrease their demand for used cars, thereby triggering a decrease in secondary-market prices; this decrease leads to an increase in the cost for higher-income households to replace their used cars with new ones, and thus decreases new-car sales.[14]

4 Model

We build a framework to study households' durable adjustment when their durables depreciate over time and they face uninsurable, idiosyncratic income risk. Households derive utility from a nondurable consumption good and a durable good (i.e., a car). The key features of our framework are: (i) Durable goods are indivisible and vertically differentiated in their quality, stochastically moving down a quality ladder because of depreciation; (ii) Used cars trade on quality-specific secondary markets at equilibrium prices, and cars of sufficiently low quality are endogenously scrapped.

[12] Gradual technological progress makes vehicles more durable over time, also inducing a lower-frequency downward trend in the frequency of replacement, as well as positive growth in average vehicle age, as we show in Appendix A.

[13] A further test of this mechanism would exploit cross-sectional heterogeneity in changes in used-car prices across households to estimate how individual households' probabilities of replacing their used cars with new ones depend on the replacement cost. Richer datasets that combine household information on income and wealth with more detailed information about car ownership may allow this analysis to be performed in the future.

[14] Appendix A reports that households substituted to cheaper new vehicles during the Great Recession. However, the magnitude of this substitution across new cars seems small, most notably when we compare it with the drop in the quantity of new cars sold and the drop in used prices. Hence, this comparison between magnitudes seems to support our choice to focus on the bigger margin of adjustment, namely, whether to acquire a new car and sell/scrap the current depreciated one, in the presence of active secondary markets for used cars.

In this section, we describe the stationary equilibrium of the model, in which all aggregates and prices are constant over time; in Section 5 we calibrate the model and describe its key quantitative properties; in Section 6 we consider the effects of aggregate shocks.

4.1 Environment

Preferences. A continuum of unit-mass of infinitely lived households, indexed by i, has preferences represented by a utility function defined over infinite sequences of nondurable consumption c_{it} and durable consumption (i.e., car services) d_{it}:

$$\mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t u(c_{it}, d_{it}), \tag{1}$$

where E_0 is the expectation operator, $\beta \in (0,1)$ is the discount factor, and $u(c_{it}, d_{it})$ is the per-period utility function.

Durable Goods. We consider a finite number N of different car qualities q_n, with $q_1 > q_2 > ... > q_N$. New cars are of quality q_1 and cars depreciate stochastically over time. Specifically, a car of quality q_n, for $n = 1, ..., N-1$, becomes a car of quality q_{n+1} in the following period with probability π_n. Because we assume that cars of quality q_N are useless, our model features positive correlation between car quality and car durability.[15]

Cars are indivisible and each household owns at most one car.[16] Hence, $N+1$ possible car ownership statuses exist, with the first N corresponding to the N car qualities; we refer to the $N+1th$ as the status of a household without a car. In period t, household i enjoys

[15] A stochastic process for car depreciation, with a discrete quality ladder, has several advantages over a deterministic process. First, it separates car age and car quality, thereby allowing heterogeneous car qualities across households conditional on identical car ages, while maintaining a negative correlation between the two in the economy. Second, it smooths the aggregation of household replacement decisions. Third, it reduces the number of markets to clear, which reduces the computational burden, while at the same time still allowing for long-lived durables.

[16] We abstract from explicitly modeling horizontal differentiation of new-car qualities, because our main focus is the timing of replacement of used cars and its equilibrium response to aggregate shocks. Moreover, computational tractability prompts us to abstract from the possibility of owning multiple vehicles. Although many U.S. households own more than one vehicle, multiple vehicles do not seem to affect the main mechanism we focus on: delayed replacement.

utility from its durable d_{it} according to

$$d_{it} = d(n, \theta_i) \equiv \begin{cases} q_n & \text{if household } i \text{ owns a car of quality } q_n \\ \theta_i & \text{if household } i \text{ does not own a car,} \end{cases} \tag{2}$$

where θ_i is a household-specific type, constant over time, drawn from a distribution $F_\theta(\theta)$, that determines household i's relative preference for living without a car. Hence, we allow for ex ante heterogeneity in households' net utility enjoyed from a car—for example, because of the heterogeneous distance of households' residence from their workplaces or heterogeneous quality of public transport in the cities where they live, which we take as exogenous.

Income. In every period t, each household i receives idiosyncratic stochastic income w_{it} (denominated in units of the nondurable good), which evolves over time according to a Markov process with transition $F_w(w_{it}, w_{i,t+1})$.

Technology. New cars are produced by perfectly competitive firms using a linear technology with the nondurable good as the only input. Let p_1 be the constant marginal cost of new cars in terms of nondurables. Perfectly competitive firms operate a scrappage technology that gives p_N units of the nondurable good for each scrapped car, regardless of its quality. A car of quality q_N must be exogenously scrapped in the current period.

Markets. Households can trade cars at equilibrium prices p_n. Households that sell their cars of quality q_n incur transaction costs $\lambda(p_n)$. Technology determines p_1 and p_N, whereas cars of quality q_n trade at their market-clearing prices p_n, $n = 2, ..., N-1$. For notational convenience, we let $p_{N+1} = 0$.

Households can borrow and save by trading one-period noncontingent bonds $b_{i,t+1}$ at their equilibrium price p_b, subject to a borrowing constraint

$$b_{i,t+1} \geq \phi, \tag{3}$$

where $\phi \leq 0$ is the debt limit.

Government. The government issues a constant level of noncontingent bonds b_G and imposes lump-sum taxes τ on all households to finance interest payments on its debt.

Hence, the budget constraint of the government is

$$b_G(1 - p_b) = \tau. \tag{4}$$

In Section 7, we study a deficit-financed stimulus policy that subsidizes households' car replacement.

Timing. At the beginning of each period, households receive their income and observe the depreciation shock to their durables. Next, they make trading, production, consumption, and saving decisions. The nondurable good is the numeraire of our economy.

4.2 Household Problem

We now describe households' problem in recursive form. Let $V(b, w, n; \theta)$ be the value function of a household of type θ with bond holdings b, income w, and car quality q_n. This function satisfies the following Bellman equation:

$$V(b, w, n; \theta) = \max_{c, b', \tilde{n}} u(c, d(\tilde{n}, \theta)) + \beta \mathrm{E}\left[V(b', w', n'; \theta) | \tilde{n}, w\right], \tag{5}$$

subject to stochastic transitions for income and car quality, the borrowing constraint (3), and the budget constraint:

$$c + p_{\tilde{n}} + p_b b' + \tau = w + p_n - \lambda\left(p_n\right) \mathcal{I}\left(\tilde{n} \neq n\right) + b, \tag{6}$$

where the indicator function $\mathcal{I}\left(\tilde{n} \neq n\right)$ equals one when households trade cars and zero otherwise. The left-hand side of the budget equation (6) reports household expenditures: nondurable expenditures c, durable expenditures $p_{\tilde{n}}$ on car $\tilde{n}$, bond purchases $p_b b'$, and lump-sum taxes τ. The right-hand side reports household resources: income w; the proceeds p_n of the sale of car n, net of transaction costs $\lambda\left(p_n\right)$; and bond holdings b.

The Bellman equation (5) makes it explicit that household preferences for durables depend on their type θ. Similarly, our notation highlights the fact that the car $\tilde{n}$ households choose could differ from the car n' they own at the beginning of the following period, because of depreciation.

The policy functions $b' = g_b(b, w, n; \theta)$ and $\tilde{n} = g_n(b, w, n; \theta)$ for future bond holdings and car choice, respectively, solve the dynamic program (5).

4.3 Stationary Competitive Equilibrium

We now define the stationary competitive equilibrium of this economy. Clearing in the bond market requires

$$\int g_b(b,w,n;\theta)dm(b,w,n;\theta) = b_G, \tag{7}$$

where $m(b,w,n;\theta)$ is the beginning-of-period stationary cumulative distribution of households over individual states (i.e., bond holdings b, income w, and car quality q_n) and type θ. The left hand-side is the aggregate net demand for bonds from households, whereas the right-hand side is the level of government debt.

Clearing in the market for cars of quality q_1 requires

$$\int \mathcal{I}(g_n(b,w,n;\theta)=1)dm(b,w,n;\theta) = \int dm(b,w,n=1;\theta) + x, \tag{8}$$

where x is the endogenous aggregate production of new cars. The left-hand side is the aggregate demand for cars of quality q_1, which comes from all households whose policy function is to hold a car of quality equal to q_1 (thus the indicator function $\mathcal{I}$ for their choices). The right-hand side is the aggregate supply of cars of quality q_1, which is the sum of the equilibrium flow of new production x and of the stock of existing cars of quality q_1 that did not depreciate from the previous period.

Clearing in the market for cars of a given quality $q_{\bar{n}}$, for $\bar{n} = 2, ..N-1$, requires

$$\int \mathcal{I}(g_n(b,w,n;\theta)=\bar{n})dm(b,w,n;\theta) \leq \int dm(b,w,\bar{n};\theta). \tag{9}$$

The left-hand side is the aggregate demand for cars of a given quality $q_{\bar{n}}$, which comes from all households whose policy function is to hold a car of quality $q_{\bar{n}}$ (thus, the indicator function $\mathcal{I}$ for their choices). The right-hand side is the aggregate supply of cars of quality $q_{\bar{n}}$. If households do not scrap any car of quality $q_{\bar{n}}$ in equilibrium, equation (9) holds with equality; if households scrap some cars of quality $q_{\bar{n}}$ in equilibrium, equation (9) holds with strict inequality, and $p_{\bar{n}} = p_N$; that is, $q_{\bar{n}}$-cars trade at the scrappage value.

Definition 1 *A* ***Recursive Stationary Competitive Equilibrium*** *is (i) a value function $V(b,w,n;\theta)$ and associated policy functions $g_b(b,w,n;\theta)$ and $g_n(b,w,n;\theta)$; (ii) a stationary distribution $m(b,w,n;\theta)$; and (iii) a vector of prices $(p_b, p_2, ..., p_{N-1})$, such that*

1. *$V(b,w,n;\theta)$ satisfies the Bellman equation (5);*
2. *The stationary distribution $m(b,w,n;\theta)$ is consistent with the type distribution $F_\theta(\theta)$, the exogenous income and car depreciation shocks, and with household policy functions $g_b(b,w,n;\theta)$ and $g_n(b,w,n;\theta)$;*
3. *The bond market clears—i.e., equation (7) holds;*
4. *Car markets clear—i.e., equation (8) determines the flow x of production of new cars, and equation (9) holds.*

5 Calibration

We now describe our choices of functional forms and parameter values for preferences, income process, credit market, car production, and trading costs. Table 1 reports the numerical values of the parameters.

Preferences. We follow Berger and Vavra (2015) and choose the following per-period utility function: $u(c_{it}, d_{it}) = \frac{\left(c_{it}^{\alpha} d_{it}^{1-\alpha}\right)^{1-\gamma}}{1-\gamma}$. We set $\alpha = 0.95$ to match the expenditure share on vehicles, which equals approximately 5 percent, according to Personal Consumption Expenditure data from the U.S. Bureau of Economic Analysis. We set the curvature of the per-period utility $\gamma = 2$, which is within the range Aiyagari (1994) considers.

A period in the model coincides with a year, consistent with the frequency of our data. Hence, we set $\beta = 0.945$, which, along with the calibrated degree of idiosyncratic risk discussed below, results in a real interest rate of approximately 2.5 percent, thereby matching its 2007 value.

Income. We assume that income follows an AR(1) process in logs: $\log(w_{i,t+1}) = \rho \log(w_{i,t}) + \epsilon_{i,t+1}$. We set the persistence of the process to $\rho = 0.9$. The innovations $\epsilon_{i,t+1}$ are i.i.d. across households and over time, normally distributed with mean $-0.5\sigma_w^2$ and standard deviation $\sigma_\epsilon = 0.2$, following the estimates of Flodén and Lindé (2001) in PSID data. These parameters imply that mean income equals one—that is, a normalization—and the cross-sectional

Table 1: Parameter Values

Parameter	Value	Target/Source
α	0.95	Vehicles expenditure share
β	0.945	Interest rate
γ	2	Literature
ρ	0.9	Literature (PSID)
σ_ϵ	0.2	Literature (PSID)
ϕ	-1	Fraction of constrained agents
b_G	1.5	Liquid assets/GDP
π_1	1/3	Trade frequency on used market
π_2	0.1	Average vehicle life
π_3	0.5	Scrappage frequency
q_1	1	Normalization
q_2	0.3	Price depreciation
q_3	0.1	Scrappage of q_3-cars
θ	$\in \{0, 1\}$	Household with car/no car
$Pr(\theta = 1)$	0.1	Fraction of households with no car
p_1	0.45	New vehicle price/income
p_4	0.036	Price depreciation
λ_0	0.03	Estimate in NADA dataset
λ_1	0.15	Estimate in NADA dataset

standard deviation σ_w of the log of income equals $\frac{\sigma_\epsilon}{\sqrt{1-\rho^2}} = 0.63$. We further discretize this process with a three-valued Markov chain, using the method of Rouwenhorst (1995).

Bond Market. We follow Guerrieri and Lorenzoni (2017) and set the level of government debt to match the ratio of liquid assets to GDP, which equals 1.78 in 2006. Moreover, we set the borrowing constraint ϕ to target a fraction of constrained households approximately equal to 10 percent, consistent with the fraction Kaplan and Violante (2014) report. The resulting value of $\phi = -1$ implies that households can borrow up to the average annual income.

Cars. A large number of car qualities (and thus a large number of endogenous prices) renders computation cumbersome, because our model features rich household heterogeneity as well as aggregate dynamics. Hence, we choose a parsimonious structure for car qualities by setting $N = 4$.

We set the values of the depreciation probabilities and of the car qualities to match statistics related to the average lifetime of cars and their average price depreciation reported in Jacobsen and van Benthem (2015), which we briefly report now. Specifically, we set the depreciation probabilities as follows: $\pi_1 = 1/3$, which implies that on average, high-quality cars depreciate after 3 years. Accordingly, we refer to the market for quality-q_2 car as the used market. We set $\pi_2 = 1/10$, which implies that on average, cars are of medium quality for 10 years; $\pi_3 = 1/2$. These depreciation parameters allow our model to closely match two statistics: the average lifetime of cars, which is approximately equal to 15 years, and the average scrappage rate of 15-year-old cars, which is approximately equal to 10 percent.

We normalize $q_1 = 1$ and set $q_2 = 0.3$ and $q_3 = 0.1$ (we do not need to specify a value for q_4, as households scrap these cars). These quality levels, along with the aforementioned depreciation probabilities, allow the model to closely match the price decline of a 3-year-old car and, thus, are consistent with average replacement costs in our car-price dataset. We set the marginal cost p_1 of producing new cars equal to 0.45 in order to match the ratio of average new-car prices to household income. We set the scrappage value p_N to 0.036 to match the average residual value of cars older than 15 years. Given these values for q_3 and p_N, some households scrap cars of quality q_3 in the stationary equilibrium of our model, consistent with the evidence on scrappage rates for old cars. This scrappage of quality-q_3 cars implies that their price equals p_N.

Moreover, we parameterize the type distribution that determines the utility of not owning any car to a two-type distribution, with values $\theta_i \in \{0, 1\}$. Thus, households with $\theta_i = 1$ choose not to own a car, whereas households with $\theta_i = 0$ choose to own one. We set the probability distribution over types to match the empirical share of households with no car, which equals approximately 10 percent in the 2000-2010 American Community Survey.

Transaction Costs. We specify the transaction-cost function to include a fixed cost and a cost proportional to the car value—that is, $\lambda_0 + \lambda_1 p_n$. We use NADA prices to calibrate these parameters to match the difference between retail and trade-in prices across cars of different vintages, implying that empirical retail prices map into the prices paid by buyers in the model and trade-in values map into the prices obtained by sellers. We obtain $\lambda_0 = 0.03$ and $\lambda_1 = 0.15$.[17]

5.1 Properties of the Stationary Equilibrium

We now describe the main features of the stationary equilibrium of the calibrated model, with a greater focus on durable goods.

Because the utility function displays complementarity between nondurable consumption and durable consumption, households enjoy both a higher level of nondurable consumption and higher-quality cars as their liquid wealth (i.e., bonds b_{it}) and income increase. Thus, the correlation between nondurable consumption and car values is positive: It equals 0.51. Similarly, the correlation between liquid wealth and car values equals 0.49. The presence of transaction costs and the discreteness of the set of car qualities induce inaction in durables adjustment, thereby reducing these correlations relative to their values in models in which households can freely adjust their durable stock.[18] These correlations are also lower than the correlation between bond holdings b_{it} and nondurable consumption c_{it}, both of which households can adjust at no cost, and which equals 0.83. Moreover, the correlation between income w_{it} and beginning-of-period car values is 0.38, whereas the correlation between income and the value of the car chosen for the same period ($p_{\tilde{n}}$) is higher and equals 0.56. This difference reflects the fact that income shocks are persistent, and thus provide information about future wealth and consumption, inducing durable adjustment. The correlation between income and nondurable consumption, which is freely adjustable, is 0.88.

Figure 6 displays households' main replacement policies as a function of their bond holdings (on the vertical axis) and income (on the horizontal axis): The dashed line is the threshold for replacing cars of quality q_2, and the solid line is the threshold for replacing cars of quality q_3. These thresholds represent the minimum level of bond holdings that triggers households with a given level of income to upgrade their car. For instance, households with a q_2-car (q_3-car) upgrade to a higher-quality q_1 car (q_2 or q_1 car) if their bond holdings and

[17] This procedure abstracts from other potential sources of trading costs, such as time and search costs, which unfortunately we cannot measure in our data.

[18] In Section 6.2, we compute the stationary equilibrium of the economy without transaction costs. This allows us to isolate the separate roles of quality discreteness and transaction costs for the correlation between nondurable consumption and car qualities.

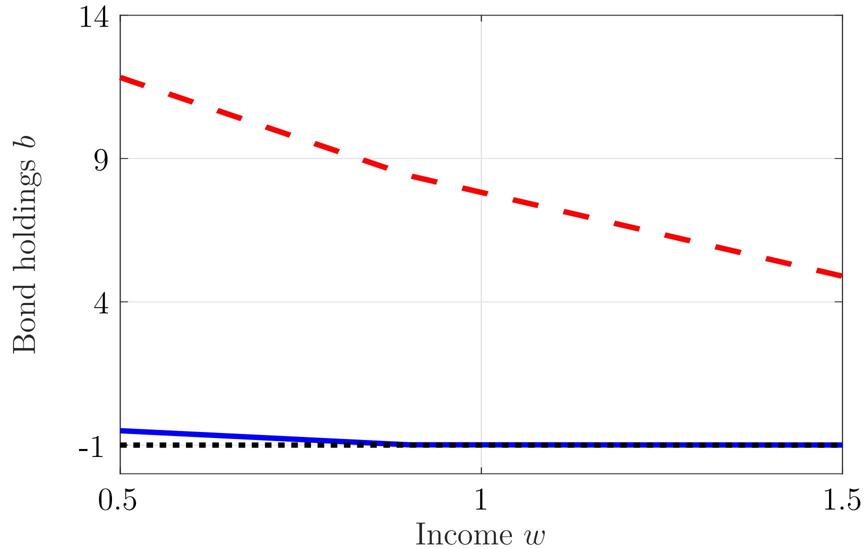

Figure 6: Thresholds for car replacement. The solid line represents the threshold for upgrading from quality q_3 to quality q_2 (or q_1, in the case of households with the highest income realization). The dashed line represents the threshold for upgrading from quality q_2 to q_1. The dotted line corresponds to the borrowing limit ϕ.

income lie above the dashed (solid) line, whereas they keep their current car if their bond holdings and their income lie below the dashed line.

The figure identifies three sets of households. The first, above the dashed line, comprises the richest households, who replace their cars as soon as they depreciate from q_1 to q_2. In the stationary equilibrium of our economy, approximately 4 percent of households upgrade from q_2 to q_1 in each period. This moment is close to the empirical fraction of households upgrading from a used car to a new one displayed in Figure 5, even though this is not a calibration target. The second set, between the solid line and the dashed line, comprises mid-wealth households. The majority of these mid-wealth households replace cars of quality q_3 (or q_4), and buy cars of quality q_2 from the richest households. The minority of mid-wealth households—that is, those with low liquid wealth and high income—replace their cars of quality q_3 with cars of quality q_1: Because the persistence of income shocks is high, these households expect their wealth and nondurable consumption to increase in the near future; thus, they choose to avoid paying the transaction costs multiple times and upgrade directly to cars of the highest quality. In the stationary equilibrium, approximately 2 percent of households upgrade directly from a car of quality q_3 to a car of quality q_1. The figure shows that the solid threshold for upgrading from q_3 to a higher-quality car (either q_2 or q_1) coincides with the borrowing limit (i.e., the horizontal dotted line at $\phi = -1$)

for households with sufficiently high income. The third set, the one above the dotted line of the borrowing limit $\phi = -1$ and below the solid line, comprises households with low income and high debt. These households keep their low-quality cars and will upgrade only after they deleverage and move away from the borrowing constraint. We recall that in our stationary equilibrium, 10 percent of households are borrowing-constrained (this fraction is a calibration target). The vast majority of these constrained households—approximately 85 percent—have a low income realization and thus are in this third region.

Finally, the stationary equilibrium of the economy features no household that downgrades to lower-quality durables: All households, including those that own cars of quality q_1, either hold on to their cars or upgrade to higher-quality cars.

6 Macroeconomic Shocks

In this section we study the effects of macroeconomic shocks, such as an aggregate tightening of the borrowing limit and a negative aggregate income shock. Specifically, we compute the transitional dynamics of our model economy that starts from the steady state characterized in Section 5.1, receives unexpected aggregate shocks (described in more detail in the following sections), and reaches a new steady state over time, thereby following several recent papers that assume households did not foresee the aggregate shocks of the Great Recession (e.g., Guerrieri and Lorenzoni, 2017; Huo and Ríos-Rull, 2016). Along the transition path, we assume that households have perfect foresight about aggregate variables.

When the economy is out of steady state, the value function, the distribution of households over individual states, and the equilibrium prices for bonds and cars change over time. Hence, we solve for the sequences $\{V_t\}_{t=0}^{T}$, $\{m_t\}_{t=0}^{T}$, $\{p_{b,t}, p_{2,t}, ..., p_{N-1,t}\}_{t=0}^{T}$, consistent with household optimization and market clearing, where $t = 0$ is the period in which shocks hit and households learn about them, and T is the period in which the economy reaches its new steady state. Appendix C describes the numerical algorithm, explaining a novel, widely applicable method we develop to overcome the challenge of clearing multiple markets when heterogeneous agents make discrete choices.

We start by considering the effects of a credit shock that tightens households' borrowing limit. In our view, this case allows us to illustrate in the cleanest way the main economic mechanisms that lead to declines in new-car sales, scrappage, and used-car prices.

Moreover, we show that it can quantitatively account for a sizable fraction of the declines observed in the data. We will further enrich the model to include additional realistic features of the Great Recession, such as aggregate income shocks and a borrowing constraint that depends on the value of households' durable holdings—that is, a collateral constraint. These richer versions of the model improve the quantitative performance of the calibrated model.

6.1 Credit Shock

We now analyze the aggregate dynamics of our economy following a tightening of the borrowing limit for all households.[19] We model this credit tightening as an unexpected shock that hits the economy in its stationary equilibrium; when the shock hits, households learn about current and future credit limits.

We parameterize the path of the borrowing limit to match the sharp decline in the real interest rate during the Great Recession, which dropped from 2.5 percent in 2007 to -2 percent in 2010 (we measure the real interest rate as the difference between the annualized return on 3-month Treasury bills and the growth of the GDP-deflator). In practice, we match this decline by gradually decreasing the credit limit from $\phi = -1$ in the pre-shock stationary equilibrium at $t = -1$ to $\phi_t = -0.4$ at $t = 2$, thus changing by 0.2 in each period $t = 0, 1, 2$. After the shock the credit limit stays permanently at its new, tighter level, as in Guerrieri and Lorenzoni (2017).[20]

Figure 7 displays the sharp decline in the interest rate (right panel) as the tighter borrowing limit (left panel) changes all households' consumption-saving trade-off. Specifically, the shock forces low-wealth households, whose debt is close to the old borrowing constraint, to reduce their debt to satisfy the new, tighter borrowing limits. Simultaneously, wealthier households seek to increase their precautionary savings, foreseeing that they will face tighter credit conditions in the future should their income decrease. Because the aggregate demand for savings increases, the top-right panel shows that the real interest rate $r_t \equiv 1/p_{b,t} - 1$ falls to clear the bond market. The drop in the interest rate is particularly swift when

[19] Benmelech, Meisenzahl, and Ramcharan (2017) and Guerrieri and Iacoviello (2017) emphasize the empirical relevance of aggregate credit-market conditions for vehicle sales.

[20] We also consider a persistent, but not permanent, credit shock in Appendix B and obtain similar results.

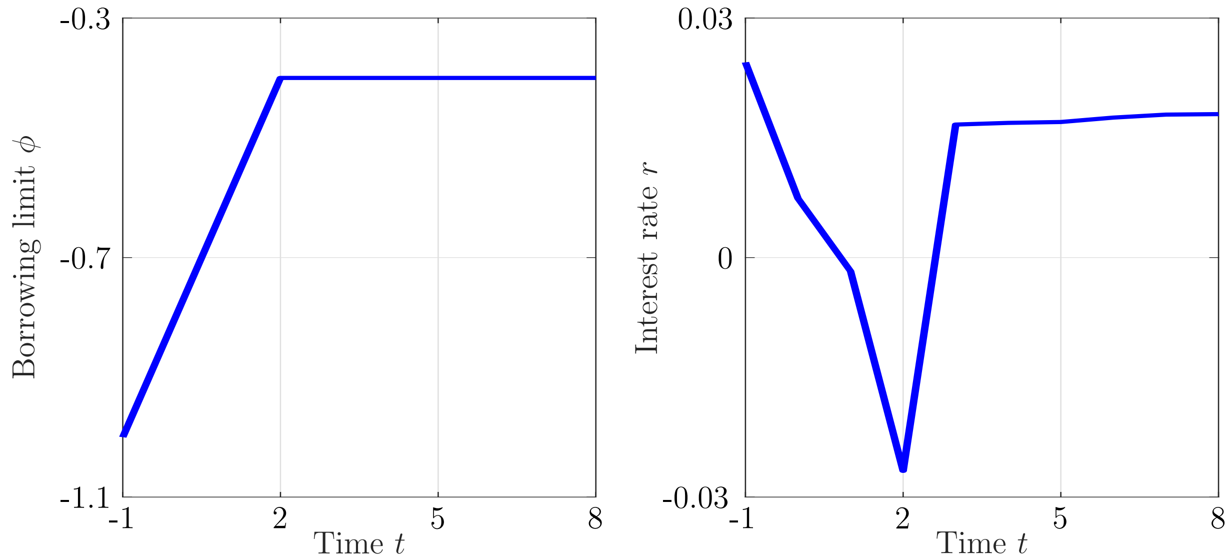

Figure 7: The left panel displays the dynamics of the borrowing constraint and the right panel displays the dynamics of the interest rate. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit at $t = 0$. The horizontal axis displays time t.

the borrowing limit changes in periods $t = 0, 1, 2$ because households need to satisfy the increasingly tighter borrowing constraints; the interest rate then stabilizes around its new steady state level of 1.9 percent—that is, 60 basis point lower than its value of 2.5 percent in the old steady state—when the borrowing limit stays at its new long-run level.

Figure 8 displays striking patterns in car markets, most notably while the borrowing limit becomes increasingly tighter in $t = 0, 1, 2$. The credit tightening motivates all households to postpone expenditures on durable goods, thereby holding on to their current cars and delaying their replacement. These incentives are stronger for low-wealth households, as their initial debt was close to the old borrowing limit. Because these households usually own cars of quality q_3 and postpone their replacement, scrappage falls (top-left panel) and the demand for used cars of quality q_2 falls as well.[21] The lower demand for cars of quality q_2 induces a decrease in their trading volume (top-right panel) and equilibrium price (bottom-left panel).

This softening of used-car markets also spurs wealthy households to postpone the replacement of their cars. These households usually own cars of quality q_2 and would upgrade to new ones in normal times—that is, in the pre-shock stationary equilibrium. However,

[21] The credit shock also leads to a fall in demand for cars of quality q_1 from households with low wealth and high income that upgrade directly from q_3 to q_1 in the stationary equilibrium.

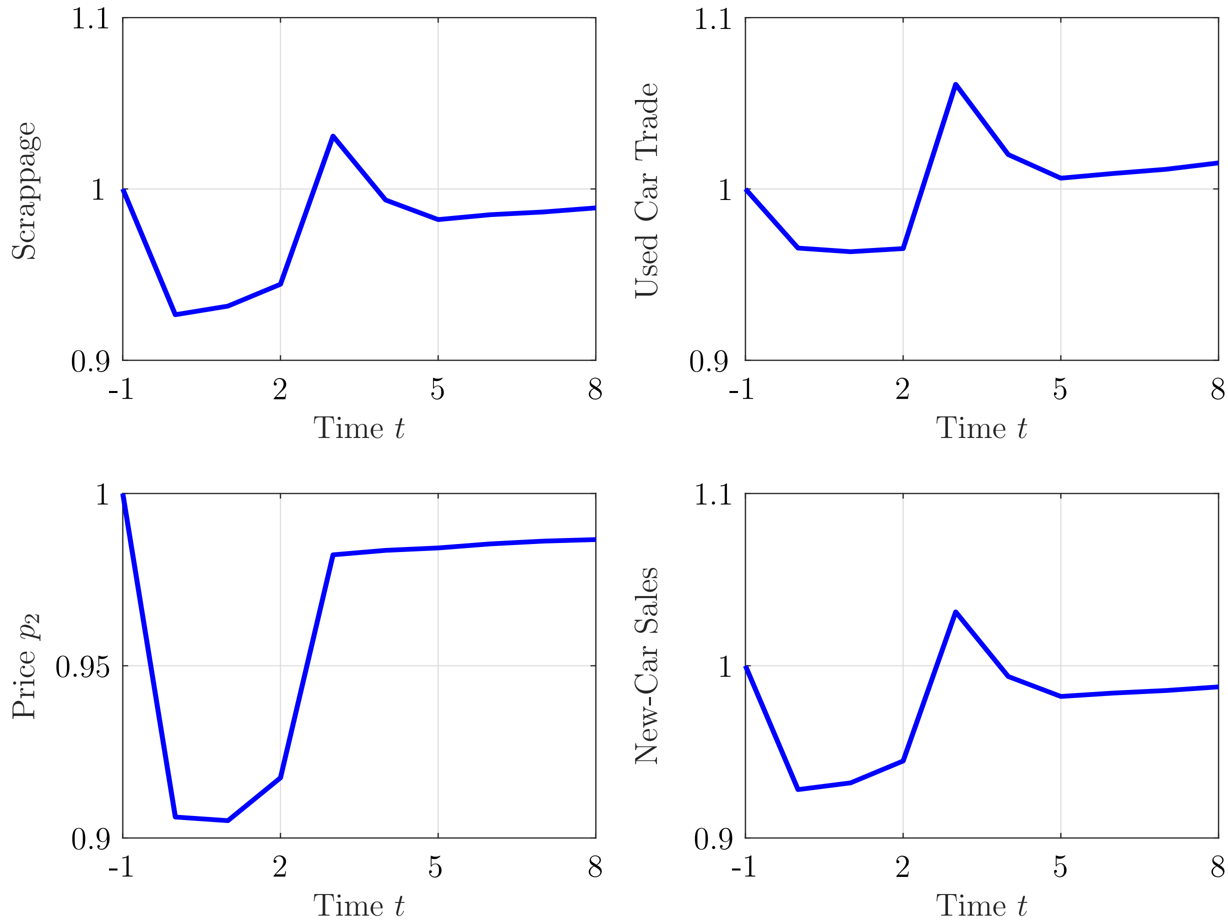

Figure 8: Dynamics of the credit shock. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars.

these wealthy households now face a high replacement cost, because they can trade in their q_2-cars only at fire-sale prices; moreover, they anticipate that used-car values will recover after the economy adjusts to the new credit conditions. Hence, new-car sales decline on impact at $t = 0$ (bottom-right panel). This finding is striking, because (i) the tighter credit limits are not binding for new-car buyers and (ii) the real interest rate falls sharply, which makes durable-goods purchases attractive for unconstrained households.

Quantitatively, the credit shock accounts for declines in new-car sales and in scrappage of approximately 7 percentage points, and in used prices of approximately 10 percentage points relative to their respective values in the stationary equilibrium at $t = -1$. Hence, our quantitative analysis suggests that a credit tightening, disciplined to match the dynamics of the interest rate observed in the data, can account for approximately 20 percent of the decline in new car sales and for approximately 50 percent of the increase in the replacement cost of used cars that we documented in Sections 1 and 3, respectively. In the following sections, we will show that introducing further realistic features to our model, such as an aggregate income decline, brings the key outcomes of our model economy quantitatively closer to their empirical counterparts.

When the economy recovers from the credit shock, the protracted delay in car replacement prompts a spike in scrappage, used trade, and new sales at $t = 3$. In Section 6.5, we will show that these spikes become more muted once we introduce additional features of credit markets, such as collateral constraints.[22] From $t = 4$, car markets gradually adjust to the new stationary equilibrium.[23]

6.2 Inspecting the Mechanism: Endogenous Illiquidity of Durable Goods

A distinctive feature of our model is the endogenous illiquidity of durable goods, which implies that the volume of trade in secondary markets and used-car prices drop as credit constraints tighten. As we recount in Section 2, this endogenous illiquidity is in contrast to a large literature that assumes constant transaction costs, implying that the interest rate is the key price signal for durable purchases. The goal of this subsection is to highlight the differences between our framework and that prevailing in the literature. To do so, we now analyze the equilibrium effects of the credit shock in a series of counterfactual scenarios to disentangle the separate roles of changes in the borrowing limit, equilibrium price changes, and exogenous transaction costs.

[22] Moreover, car durability has been increasing steadily over time, thanks to long-run technological improvements, lengthening the expected life of vehicles, as we report in footnote 12 and Appendix A. While it is challenging to model this trend in a tractable way in our framework, accounting for this long-run trend would likely dampen the spike in new-car sales driven by pent-up demand for replacement.

[23] An implication of our assumption of stochastic quality depreciation is that the echo effects of aggregate shocks are quantitatively less important, relative to models of durables replacement with deterministic quality (or age) transitions.

6.2.1 The Role of Equilibrium Prices

In this subsection, we provide three sets of counterfactuals that highlight the contribution of equilibrium prices. First, we decompose the results of Figure 8 into the individual contributions of the credit shock, the interest rate, and the price of used cars. Second, we consider a counterfactual scenario in which the credit shock hits the economy and bond markets clear, but used-car prices do not change. Finally, we consider a counterfactual scenario in which the credit shock hits the economy and used-car markets clear, but the interest rate does not change—i.e., a small open economy.

Decomposition: Credit Limit vs. Prices. We aim to decompose the direct effects of the credit shock and the equilibrium effects due to price changes by computing the transitional dynamics of scrappage and new-car sales in three different cases, in which we only change: (1) the borrowing limit, (2) the interest rate, and (3) the price of used cars. Figure 9 displays car-market outcomes in these three cases.

Specifically, in the first case (solid line), we feed into the household problem the path of the borrowing limit only—that is, without clearing the bond market through the endogenous interest rate and without clearing the used-car market through the endogenous used-car price. In this case, the economy experiences a massive decline in scrappage, by approximately 50 percent, and a smaller decline in new-car sales, by approximately 12 percent.

In the second case (dashed line), we feed into the household problem the path of the interest rate only. In this case, the economy experiences a boom in new-car sales, temporarily doubling, as the decline in the interest rate corresponds to a decline in the user cost of new cars; thus, many households find it optimal to substitute away from bonds and toward high-quality durables.[24]

In the third case (dashed-dotted line), we feed into the household problem the equilibrium path of the price of quality-q_2 cars only. In this case, the economy experiences an increase in scrappage and a large decline in new-car sales, by approximately 50 percent, since low-wealth households scrap their low-quality cars and upgrade to intermediate-quality cars, whereas high-wealth households face a sharp increase in the cost of replacing their q_2

[24]In Appendix B we explicitly relate our mechanism to the notion of user cost of a durable good.

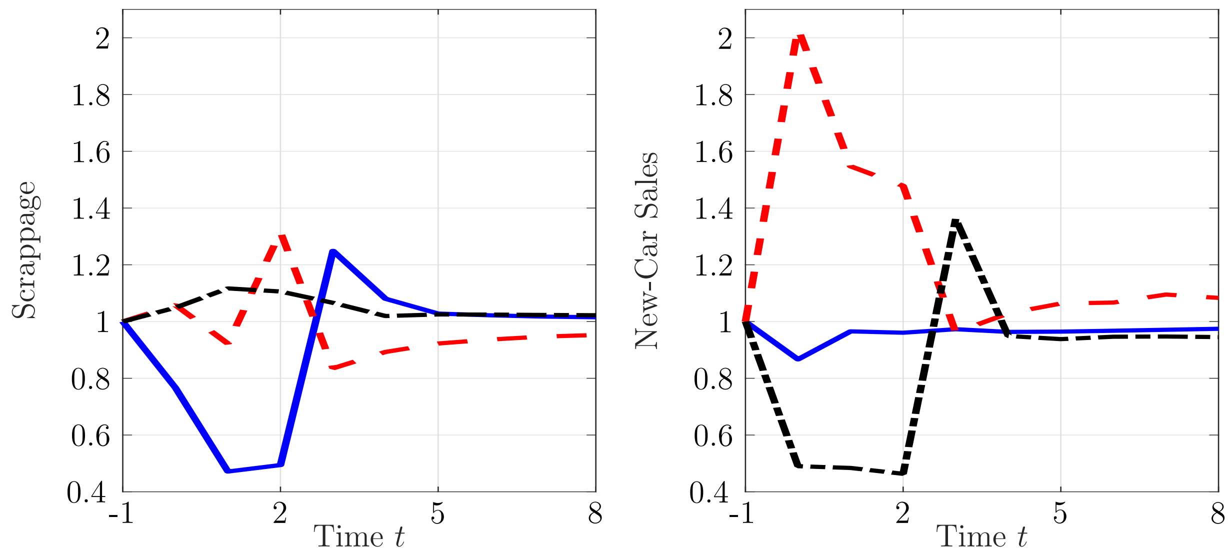

Figure 9: Decomposition of the individual effects of credit shock and price changes. The left panel displays scrappage and the right panel sales of new cars. The solid line refers to the effects of changes in the borrowing limit; the dashed line to the effects of equilibrium interest rate dynamics; the dashed-dotted line to the effects of equilibrium used-car price dynamics.

cars with higher-quality, new ones.[25]

This decomposition sheds further light on the general-equilibrium dynamics displayed in Figure 8. Overall, it suggests that the credit shock plays a key role for scrappage, as it directly affects low-wealth households' choices; the secondary-market equilibrium transmits the shock from low-wealth households' scrappage decisions to high-wealth households' upgrades of their durable goods. This equilibrium feedback from the used-car market to the new-car market dominates the effect of the decline in the interest rate on new-car purchases, which instead makes car replacement more desirable by reducing the user cost of new vehicles.

No Equilibrium in Secondary Markets. To further highlight the role of secondary markets, we now consider the following partial-equilibrium counterfactual scenario. We assume that the credit limit tightens and the bond market clears; however, durable-goods

[25] Because we consider a permanent credit shock, each item of this decomposition has a terminal condition that differs from the initial condition. For instance, when we change the borrowing limit only, the terminal household value function depends on the initial stationary-equilibrium prices and on the final stationary-equilibrium borrowing limit, thereby combining short-run effects and long-run differences. In order to isolate the short-run effects, in Appendix B we also consider a temporary, but highly persistent, credit shock, since the temporary shock removes the effects of long-run differences in steady-state values. We find that our key results are robust to this change. Notably, secondary markets account for the entirety of the decline in new-car sales in this alternative scenario.

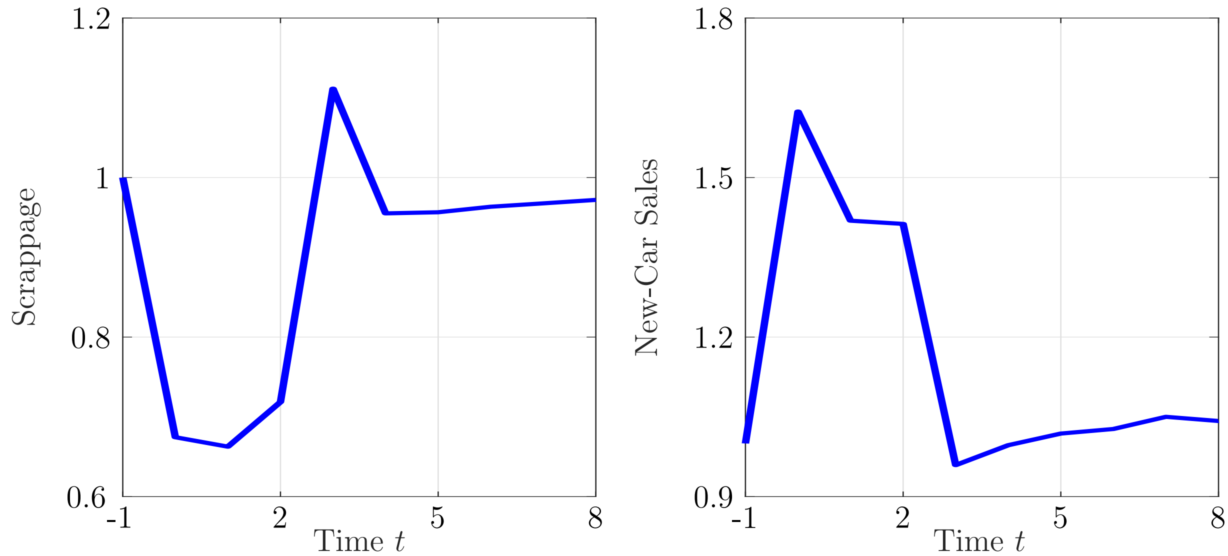

Figure 10: The effect of the credit shock on car markets in the absence of used-car market clearing. The economy is hit by the same credit shock as in Figure 8. The bond market clears. However, the market for used cars does not clear—that is, cars can be re-transformed into non-durable consumption at the prices prevailing in the initial stationary equilibrium. The left panel displays scrappage and the right panel displays sales of new cars.

prices do not adjust. Specifically, we assume that households can transform durable goods into nondurable goods (and vice versa) at constant rates of transformation, equal to the prices prevailing in the initial stationary equilibrium. Hence, while the interest rate adjusts to clear the bond market after the credit tightening, the price p_2 of used cars is constant along the transition.

The left panel of Figure 10 displays the path of car scrappage and the right panel displays the path of new-car sales in this partial-equilibrium case. In the absence of the endogenous response of used-car prices, the economy features a strong negative comovement between scrappage and new-car purchases. This comovement arises because borrowing-constrained households still decide to postpone scrappage of their low-quality cars, as the left panel shows. Their demand for used cars falls, but in the absence of secondary-market clearing, this shift in demand does not translate into a lower price for used cars; hence, wealthy households experience no change in the cost of replacing their used q_2 cars with higher-quality ones. In addition, the decrease in the real interest rate stimulates their car-replacement activity, inducing a large increase in new-car sales—approximately equal to 60 percent—relative to their value in the initial stationary equilibrium, as the right panel shows.[26]

This counterfactual case indicates that equilibrium in secondary markets plays a key role in generating a decline in purchases of new durables and a positive comovement of scrappage and new sales, consistent with the U.S. data during the Great Recession we reported in Sections 1 and 3.

We now further investigate the dynamics of the aggregate stock of cars in this counterfactual experiment. Because many wealthy households respond to the interest-rate decline by upgrading to cars of quality q_1, whereas many poorer households tend to hold on to cars of quality q_3, instead of upgrading to q_2, because of the tighter credit limit, there are effects of opposite signs on the average quality of cars. Thus, we compute the aggregate quality of the stock of cars as follows: $Q_t \equiv \sum_{n=1}^{N} m_{nt} q_n$, where m_{nt} is the fraction of households who own a car of quality n at the beginning of period t, which we obtain by integrating the distribution of households over wealth and income. As we display in Figure 11, aggregate durables quality Q_t increases in response to the credit shock. This result clarifies that the effects of precautionary savings and interest-rate changes on the production of new cars dominate the effects of the decisions of poorer households and the associated decline in transitions to quality q_2.[27]

In this counterfactual analysis we have assumed that a technology allows to transform durable goods into nondurables at constant rates equal to stationary-equilibrium prices, thus removing the effects of imperfect substitutability of durable goods on endogenous price changes. In Appendix B.2, we also investigate an alternative assumption that makes durable goods of different qualities perfect substitutes by changing household preferences. Specifically, we remove the assumption of indivisibility and let households purchase any positive amounts of durable goods of different qualities.

Consistent with our baseline model with indivisibility, we find that poorer household demand lower-quality cars. Hence, credit shocks affect demand for used cars and market-clearing in the secondary market plays an important role in transmitting them to the production of new cars. Different from the counterfactual experiment with a re-transformation

[26] The increase in purchases of durable goods in response to a credit tightening is consistent with some of the findings of Guerrieri and Lorenzoni (2017), most notably their Figure 15.

[27] The variable Q_t is the relevant counterpart of the aggregate stock of durables in models that do not explicitly distinguish between heterogeneity in quality or quantity. For completeness, we also verified that the aggregate value of the stock of cars in terms of nondurable goods increases, thus using stationary equilibrium prices p_n (a monotone, but nonlinear, function of qualities) instead of qualities.

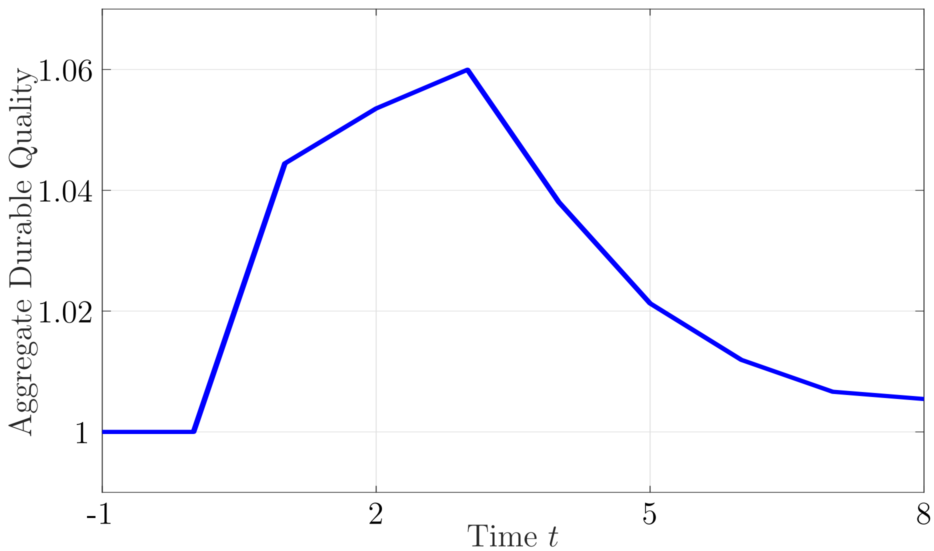

Figure 11: The effect of the credit shock on aggregate quality of the car stock in the absence of used-car market clearing. The economy is hit by the same credit shock as in Figure 8. The bond market clears. However, the market for used cars does not clear—that is, cars can be re-transformed into non-durable consumption at the prices prevailing in the initial stationary equilibrium. The figure displays the aggregate quality of the stock of cars, $Q_t \equiv \sum_{n=1}^{N} m_{nt} q_n$, where m_{nt} is the fraction of households who own a car of quality n at the beginning of period t.

technology for durables, we find that perfect substitution in preferences does not necessarily imply that relative prices of durables of different qualities are constant. Durable goods prices depend both on quality, which affects the utility flow, and on discounted residual value, and thus are jointly determined with the equilibrium interest rate.

Small Open Economy. We now analyze the interaction between the endogenous real interest rate and our mechanism of endogenous illiquidity based on equilibrium in the secondary market. To this end, we consider a small-open-economy version of our model that keeps the interest rate exogenously constant at its initial stationary-equilibrium value. We hit the economy with the same credit shock as in the baseline case and impose equilibrium in used-car markets only. We then compare the small-open-economy outcome with the general-equilibrium outcome—that is, the case in which both interest rates and car prices adjust to clear their respective markets.

Figure 12 displays this comparison: The solid lines refer to the general-equilibrium model and the dashed lines to the small open economy. We find that our mechanism linking the credit shock to new-car sales through used-car prices is highly powerful in the small open economy: A 4-percent decline in used prices leads to a drop in new sales of

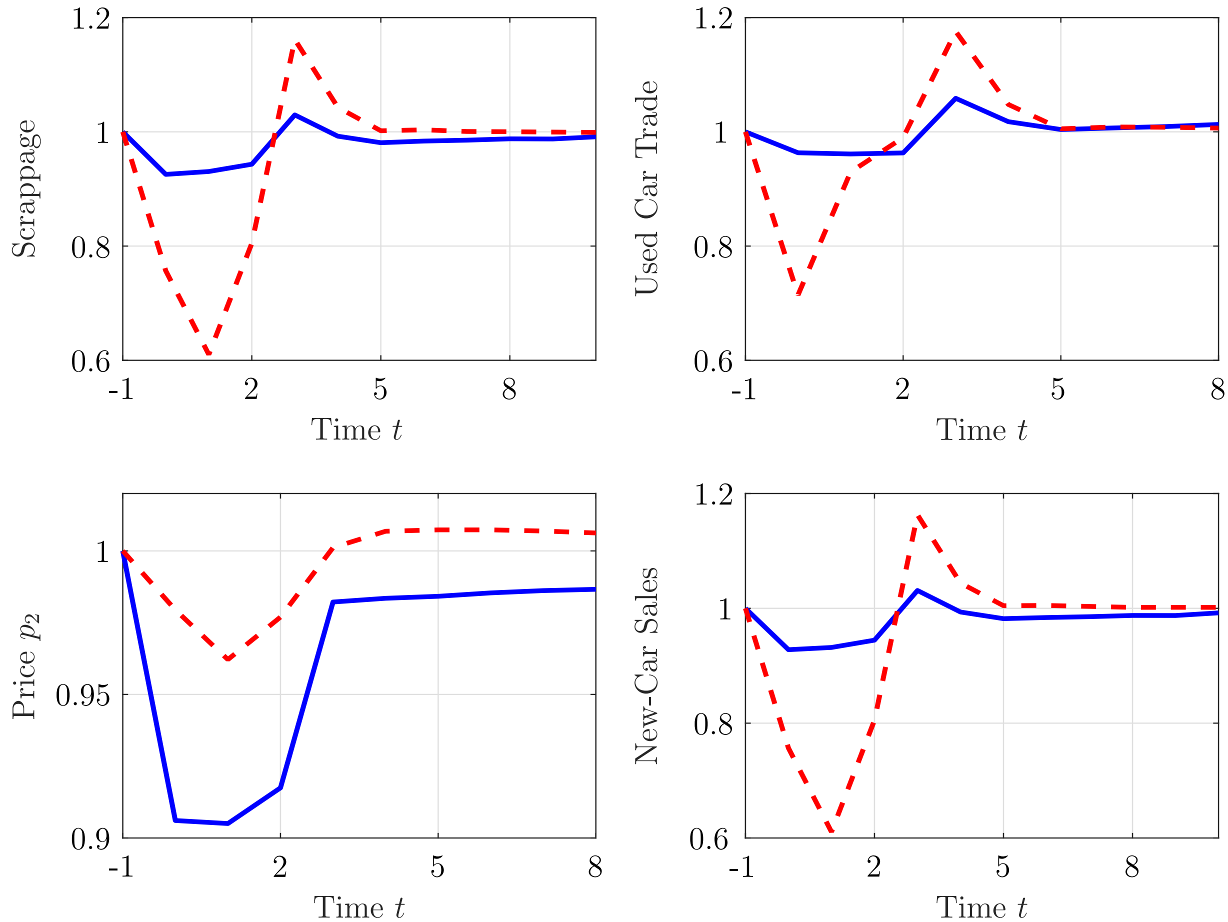

Figure 12: Dynamics of the credit shock in a small open economy. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the general-equilibrium case—i.e., market clearing in bond market and car markets. The dashed line displays the small-open-economy case—i.e., market clearing only in car markets.

approximately 40 percent. The decline in new sales is similar to its empirical counterpart, whereas the decline in used-car prices in the small-open-economy model is five times smaller than its empirical counterpart of 20 percent.

Relative to these small-open-economy dynamics, the endogenous decline in the interest rate adds two key effects. First, a temporarily low real rate stimulates durable upgrading for high-wealth households, that face a portfolio decision between bonds and durable goods. Because of this decline in the interest rate, the decline in new-car sales in response to the credit shock is more moderate in the general-equilibrium case than in the small-open-economy case. Second, new-car purchases triggered by a low interest rate represent an outward shift in the supply of used cars, as new-car buyers trade in their used cars. This outward supply shift creates additional downward pressure on used-car prices. Hence, we find that the magnitude of the decline in p_2 is twice as large in the general-equilibrium case as in the small-open-economy case, and closer to the magnitude observed in the data.

The comparison displayed in Figure 12 suggests that endogenous changes in the real interest rate likely played a consequential role in the large decline in used-car prices during the Great Recession, while attenuating the elasticity of new-car sales to used-car prices. These cross-market equilibrium effects are a novel feature of our framework, and they highlight the importance of modeling durable-goods dynamics in general equilibrium.

In Appendix B.3 we leverage the small-open-economy version of our model to implement two alternative calibration strategies of the credit shock that target household debt statistics reported by the Consumer Financial Protection Bureau, rather than targeting the dynamics of the real interest rate, as in our baseline calibration. Specifically, in one alternative calibration, we target outstanding auto loans; in the other calibration, we target overall household debt. We find that our mechanism plays a key role in both alternative calibrations. Quantitatively, the effects of the shock on new-car sales are large and similar to those of our baseline case when we match auto loans, but weaker when we consider overall household debt. This difference arises because outstanding mortgages declined gradually in the data, calling for a small and gradual credit shock in the model.

6.2.2 The Role of Transaction Costs

A large literature emphasizes the role of transaction costs in explaining consumer inertia in durable-goods markets (e.g., Caballero, 1993; Attanasio, 2000; Berger and Vavra, 2015). We now study how transaction costs affect our economy and its response to the credit shock. To this end, we remove transaction costs by setting $\lambda_0 = \lambda_1 = 0$. We first describe the key patterns of car replacement in the stationary equilibrium to facilitate comparison with the stationary equilibrium of the economy with transaction costs of Section 5.1; we then discuss the response of this economy to the credit shock.

As we recount in Section 5.1, the stationary equilibrium of the economy with transaction costs features no households downgrading the quality of their cars, and approximately 4 percent of households replacing cars of quality q_2 with cars of quality q_1. These patterns

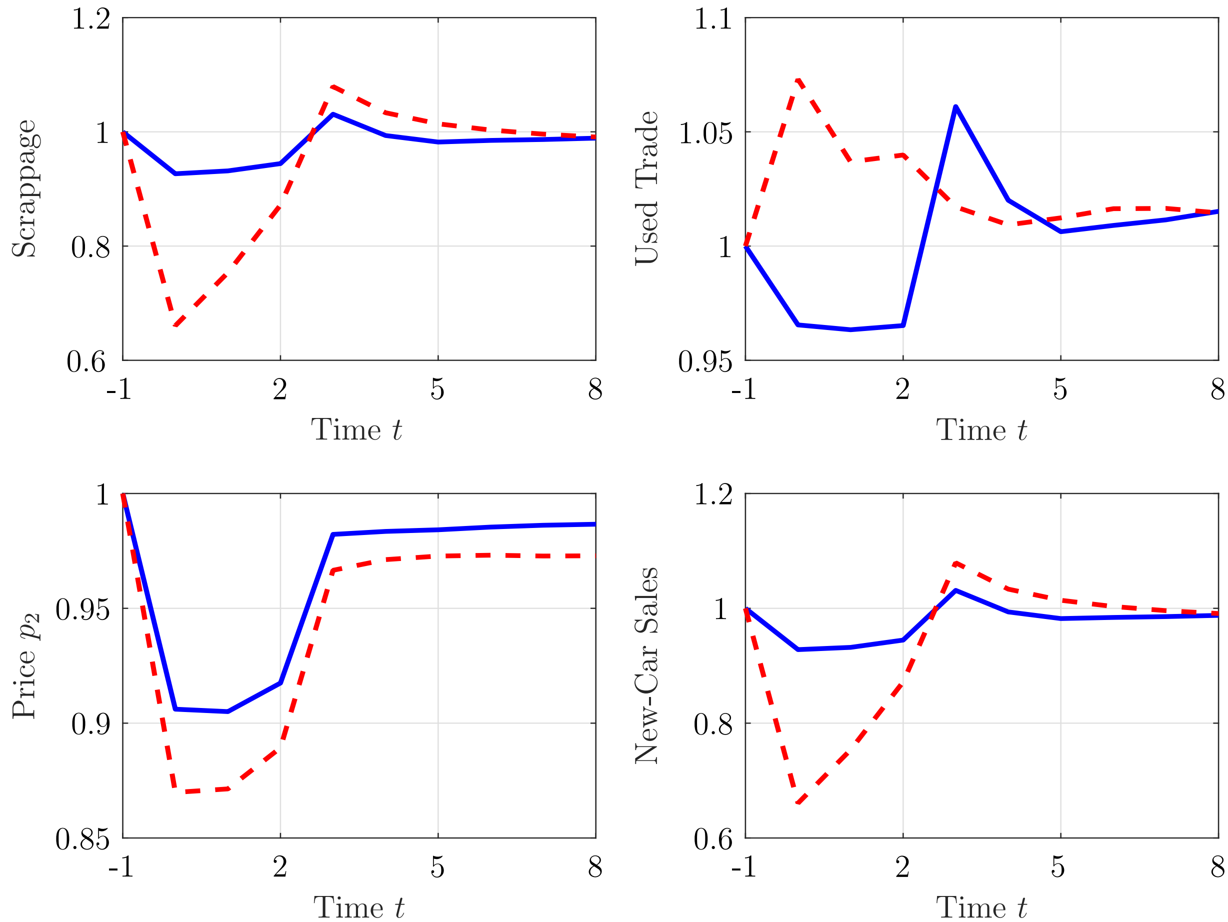

Figure 13: Credit shock in the absence of transaction costs. The economy is in stationary equilibrium at $t = -1$. Households learn about the new path of the borrowing limit $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the baseline case and the dashed line displays the case without transaction costs ($\lambda_0 = \lambda_1 = 0$).

change significantly in an economy with no transaction costs. First, 1 percent of households downgrade from q_1 to q_2. Second, 0.3 percent of households downgrade from q_2 to q_3. Third, the volume of trade of used cars is higher: More than 7 percent of households replace a car of quality q_2 with a car of quality q_1. Overall, these patterns of trading increase the correlation between nondurable consumption and car values: This correlation coefficient equals 0.64, versus 0.49 in the economy with transaction costs.

The absence of transaction costs implies that quality downgrading plays an important role in the economy's response to the credit shock. Figure 13 illustrates how the economy without transaction costs (dashed lines) behaves in response to this aggregate shock, and compares it with that of our baseline case with transaction costs (solid lines). Without transaction costs, the shock leads to a substantially larger decline in scrappage, used-car prices, and new-car sales relative to those of the baseline case; however, the volume of trade of used cars increases above its initial level, whereas it drops in the economy with transaction costs (as in the data). The key reason for these equilibrium dynamics is that in order to increase their liquid assets, many middle- and low-wealth households who own cars of quality q_2 respond to the credit shock by selling them and temporarily downgrading to cars of quality q_3. This force leads to an increase in supply (and thus in trading volume) of used cars of quality q_2, driving their price down further. This downgrading effect is so strong that cars of quality q_3 are in excess demand at the scrappage value p_N; thus, they temporarily trade at a higher price than p_N while the economy adjusts to the shock.

By contrast, the volume of downgrading the aggregate shock induces is quantitatively small in our baseline calibration with transaction costs, because households anticipate that downgrading implies that they will incur transaction costs twice: First, when they downgrade; and second, when they re-upgrade their car in the near future, once the economy stabilizes toward its long-run stationary equilibrium.

Overall, this counterfactual case suggests that by preventing larger downgrading of durable goods than that observed in the data, transaction costs play an important role in dampening the effect of the shocks on secondary-market prices, and thus on new-car sales.

6.3 Aggregate Income Shock

We now further enrich our model by considering the joint effect of a tightening of the credit limit and of a negative aggregate income shock. Thus, this case includes additional realistic features of the Great Recession, during which both credit conditions and household incomes deteriorated. We parameterize the credit shock in the same way as in our baseline case of Section 6.1. Moreover, we approximate the output decline induced by the Great Recession by assuming that all households receive an exogenous negative shock equal to 2 percent of their income for 2 years, which in our calibration coincide with 2008 and 2009.[28]

[28] A decline in aggregate output allows us to account for a decline in both nondurable consumption and durable purchases. By adding an explicit modeling of the production of nondurable goods and assuming price rigidities or other frictions, our framework may be able to endogenously generate a decline in aggregate output in response to the credit shock. However, these additional features are beyond the scope of our

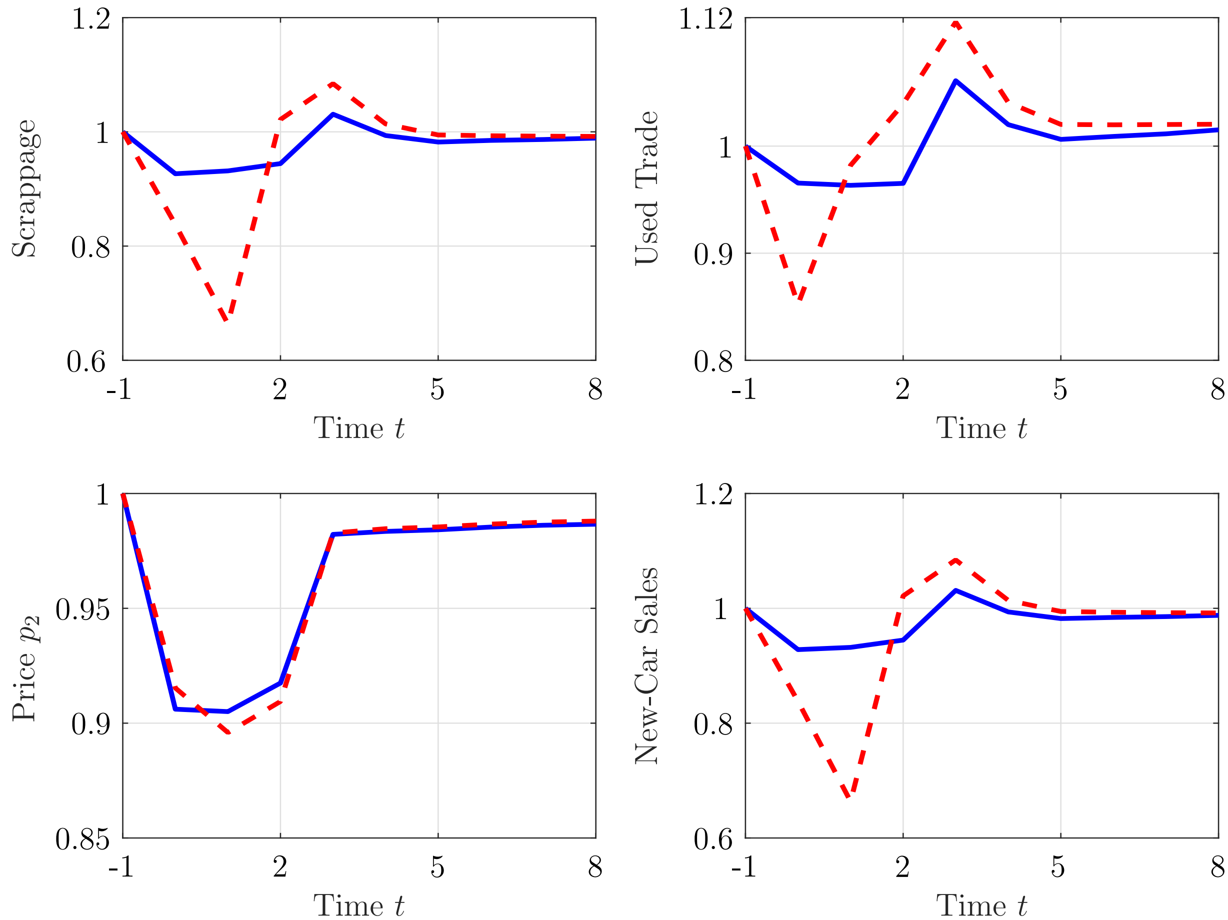

Figure 14: Credit and income shocks. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit and income at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the baseline case with a credit shock only; the dashed line displays the case with credit and income shocks.

Figure 14 displays the transitional dynamics of our main variables of interest. The aggregate income shock amplifies the effects of the credit shock on car markets. Relative to the baseline case with the credit shock only, it leads to larger declines in scrappage and new-car purchases, which drop by approximately 35 percent relative to their initial values in the stationary equilibrium. Hence, through a combination of aggregate credit and income shocks, our model successfully accounts for a large fraction of the empirical decrease in car sales during the Great Recession displayed in Figure 1.

paper, given our focus on durable goods markets. For models that endogenously generate output declines following similar financial shocks, see, for instance, Guerrieri and Lorenzoni (2017) and Huo and Ríos-Rull (2016).

The income decline affects the patterns of car replacement through two channels. First, it directly amplifies our mechanism of delayed quality upgrade by making financial conditions even tighter for poor households close to the scrappage threshold. Second, it induces wealthier households to postpone their car replacement, regardless of feedback from the secondary market: They hold on to their intermediate-quality cars until after the recession. Hence, both demand and supply in the used-car market drop on impact, inducing a sizable decline in the volume of cars traded.

In Appendix B.4, we perform an analysis of the separate roles of secondary-market prices and transaction costs, similar to that of Section 6.2, but in this case with both credit and aggregate income shocks hitting the economy. The results are consistent with those of the baseline case with only a credit shock. Notably, this decomposition confirms that accounting for equilibrium in secondary markets is important in explaining the decline in new-car sales observed during the Great Recession.

We also study an aggregate income shock in the absence of credit tightening, under two alternative specifications. First, we consider a shock that hits all households symmetrically (as in the case analyzed above). Whereas the income shock acts as a powerful amplifier for the credit tightening, we find that an aggregate income decline alone cannot account for the empirical patterns described in Section 3. When the borrowing limit does not change, the income shock induces price effects that do not match those observed in the data: In our flexible-price environment, the combination of low current income and expectations of higher future income lead to an increase in the real interest rate; moreover, the decrease in both demand and supply of used cars implies that the income shock alone cannot generate a sizable drop in used-car prices. For these reasons, our model suggests that a quantitatively successful explanation of the dynamics described in Section 3 involves a combination of tighter credit conditions and an income decline.

Second, inspired by the empirical literature on the skewed effects of recessions (e.g., Guvenen, Ozkan, and Song, 2014), in Appendix B.5, we explore the effects of an income shock that hits low-income households only.[29] We find that a temporary income loss for low-income households leads to qualitative effects similar to the credit tightening, which suggests that our main mechanism for delayed scrappage and replacement is general and

[29] The skewed income shock increases income uncertainty, as well.

may apply to several empirically relevant cases in which aggregate shocks affect the income-wealth distribution asymmetrically. Quantitatively, however, this version of the income shock, in isolation, also seems less powerful than the combination of credit shock and aggregate income shock illustrated in Figure 14.

6.4 Endogenous Price of New Durables

So far, we have assumed that the marginal cost of producing new durables p_1 is an exogenous constant. To account for the modest decline in new-car prices in the Great Recession reported in Section 3, we now generalize our production technology for new durable goods, by assuming that the marginal cost (in terms of output good) is a function of the aggregate quantity produced. This experiment allows us to address the following question: What are the effects of a new-car price decline on used-car prices and new-car sales?

Specifically, we assume that the marginal cost of new durables at time t equals

$$p_{1,t} = c_0 + c_1(x_t - \bar{x}), \tag{10}$$

where c_0 and c_1 are positive coefficients, x_t is aggregate production of quality-q_1 durables at time t, and $\bar{x}$ is the level of production in stationary equilibrium.

This linear "supply function" is consistent with curvature in the production function for new durables; specifically, with a quadratic total cost function. Durable producers are perfectly competitive: They take the path of the aggregate marginal cost as given, and set the output price equal to the marginal cost in each period.[30] The baseline version of the model is the special case in which $c_1 = 0$.

To assess the quantitative role of endogenous new-price changes in the Great Recession, we focus on the version of the model with both a credit and an aggregate income shock. We calibrate $c_1 = 0.75$ to approximately match a three percent peak-to-trough decline in new-car prices, in line with the evidence based on the Dominion dataset and the CPI data reported in Section 3 and Appendix A, respectively.

Figure 15 portrays the results of this analysis. As demand for durables of all qualities

[30] For simplicity, and because of our focus on aggregate outcomes, we abstract from a more detailed modeling of the micro-structure of production, such as non-constant returns to scale at the firm level, entry, and exit.

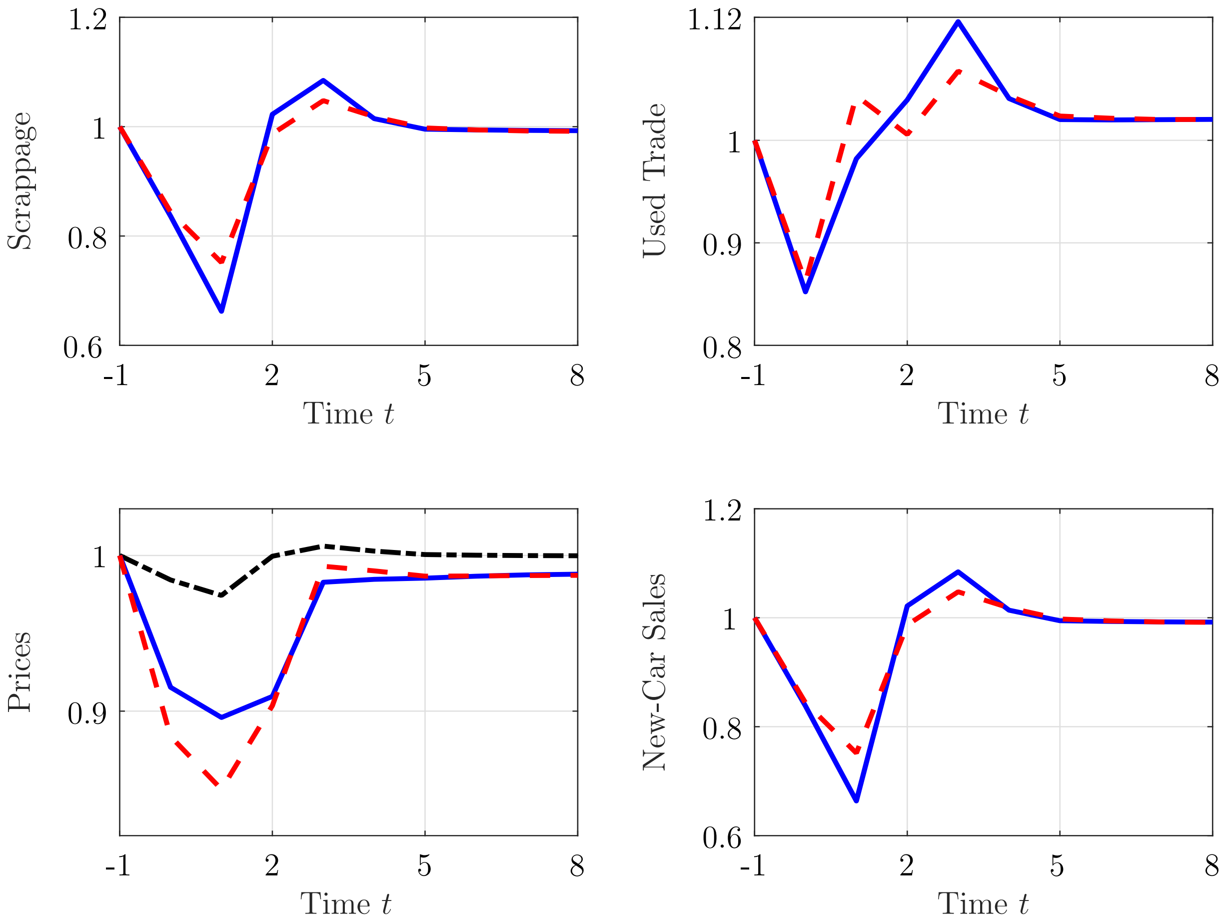

Figure 15: Credit and income shocks with endogenous new-car price. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit and income at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the case with constant p_1; the dashed line displays the case with endogenous p_1. The dashed-dotted line displays the path of p_1 in the endogenous case.

declines in the recession, new prices endogenously decline before recovering as the economy adjusts to the shock. We highlight two key equilibrium effects of the endogenous marginal cost of durables. First, because new and used cars are partially substitutable, the decline in new-car prices in the recession puts additional downward pressure on used-car prices, further deepening their drop (overall, approximately 15 percent) relative to the baseline model with constant marginal cost. This effect improves the degree of success of our model in matching the empirical dynamics of used prices.

Second, the key price signal for households' replacement decisions from quality q_2 to quality q_1—i.e., the main driver of new sales—is their *relative* price. Although new cars are cheaper in the recession, the fact that q_2 cars lose even more value implies that the dampening effect of the new-price decline on the drop in new sales is limited. Quantitatively, the model with endogenous p_1 predicts a 25 percent decline in new-car sales.

Overall, we find that our main insights on the importance of secondary-market equilibrium for durable purchases are robust to the inclusion of curvature in the production of new cars. Consistent with our empirical analysis, the cost of replacing used cars with new ones still rises substantially during the crisis, thereby discouraging new sales; this is similar to our baseline result with exogenous new prices.

6.5 Durables as Collateral

Our baseline case considers a constant credit limit ϕ that applies to all households, independent of their durable holdings. We now study a specification of the model in which household borrowing limits depend on the expected resale value of their durables—that is, a collateral constraint. This analysis encompasses the case of car loans, although it applies more generally. We show that this modification reinforces the main mechanism of our model, which links a credit tightening to a drop in new durables purchase through a drop in resale prices. Moreover, this modification smooths the recovery of durable goods markets once the borrowing limit stays at its new long-run value.

To introduce a role for durables as collateral, we replace equation (3) with the following constraint:

$$b_{i,t+1} \geq \phi_t \left(\chi_0 + \chi_1 \mathrm{E}_t \left[p_{n_{i,t+1}} | \tilde{n}_{it}\right]\right), \tag{11}$$

where the term ϕ_t denotes the exogenously time-varying level of the credit limit. This collateral constraint allows for both uncollateralized debt, through the term χ_0, and collateralized car loans, through the term $\chi_1 \mathrm{E}_t \left[p_{n_{i,t+1}} | \tilde{n}_{it}\right]$. The aggregate shock ϕ_t affects both components of the credit limit. Equation (11) highlights the fact that the expected collateral value depends on the chosen car quality $\tilde{n}_{it}$. Higher quality implies a higher expected equilibrium resale value, and thus a larger borrowing capacity.

We set $\chi_1 = 0.85$, an intermediate value in the empirical range of loan-to-value ratios for auto loans.[31] We then set $\chi_0 = 0.8$ to make total household debt close to its counterpart

[31] For instance, aggregate data on auto loans from the Federal Reserve Board of Governors report loan-to-value ratios around 90 percent, and data from NADA suggest an average value slightly below 80 percent.

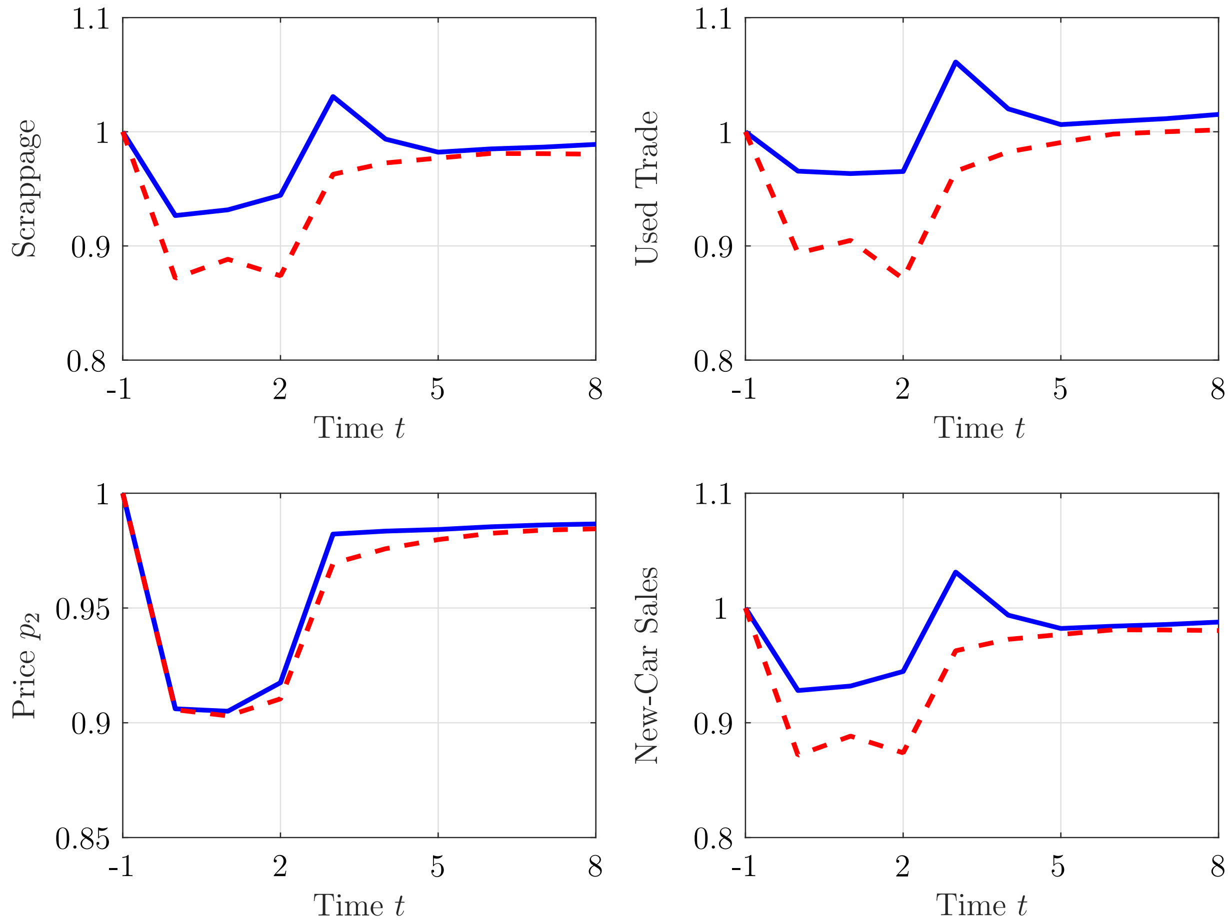

Figure 16: Shock to the collateral constraint. The economy is in stationary equilibrium at $t = -1$. Households learn about the new path of the borrowing limit $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used car; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the baseline case and the dashed line displays the case with collateral constraint.

in the economy without collateral, i.e., the baseline model, for comparison purposes. As in our baseline case, we consider a shock that changes ϕ_t from a steady-state value of -1 to a new steady-state value of $-0.4.$, which induces a path for the interest rate close to its empirical counterpart. To isolate the role of collateral, in this analysis we abstract from aggregate income changes and endogenous new-durables prices.

Figure 16 illustrates the transitional dynamics of our variables of interest. Qualitatively, the collateral constraint does not change the outcomes relative to the baseline shock. Quantitatively, we observe a substantially larger decline in scrappage and new-car sales than in the baseline case, whereas the dynamics of used-car prices are broadly similar. Most notably, the drop in new-car sales (bottom-right panel) is almost twice as large as that obtained in the baseline case, thereby accounting for approximately half of the decline in new-car sales displayed in Figure 1. The reason for this larger drop is that the presence of resale values in the credit constraints induces an amplification effect: Expected low resale prices for used cars further tighten credit limits for new-car buyers after the aggregate shock hits.

This amplification effect is closely related to a standard financial accelerator effect à la Kiyotaki and Moore (1997), with one important difference. In our model, there is a clear distinction between new-durable prices and resale values, in contrast to most of the literature. While resale values drop in bad times, new prices do not. This difference makes new purchases particularly unattractive during downturns, which induces a stronger amplification mechanism than in models with a single price of durable (or capital) goods.

7 Policy Evaluation: Durable-Replacement Subsidies

We now use our framework to study the effects of a fiscal intervention aimed at stimulating household spending on durable goods during a credit crunch, similar to the car-replacement stimulus implemented in the U.S. in 2009 (the Cars Allowance Rebate System, commonly referred to as "Cash for Clunkers"). Similar subsidies are common across countries and across several recession episodes (e.g., Adda and Cooper, 2000, provide a structural evaluation of two interventions in France in the 1990s).

In our framework, secondary markets play an important role in the transmission of these policy interventions. Thus, we introduce a durable-replacement subsidy immediately after the credit-supply shock discussed in Section 6.1 hits the economy. Specifically, in the first year in which the credit shock hits, the government offers a subsidy equal to 10 percent of the price of a new car to owners of cars of quality q_3 who choose to scrap their cars and replace them with a new car (i.e., of quality q_1) in that year.[32] We assume the

[32] The Car Allowance Rebate System offered subsidies between $3,500 and $4,500, depending on car models; that is, approximately 10 percent of the average new car price. However, these subsidies were only available during the months of July and August 2009, and thus our yearly calibration does not allow us to exactly match the timing aspect of the policy. Moreover, the Car Allowance Rebate System did not involve a minimum age requirement in order for scrapped vehicles to qualify for the subsidy (this aspect differs from the related French policies studied by Adda and Cooper, 2000). Eligibility depended largely on fuel efficiency and on other attributes that our model abstracts from. In practice, however, most scrapped cars

government initially finances this policy by running a deficit; after 10 years, the government raises lump-sum taxes in order to gradually reduce the debt to its initial steady-state value. Formally, taxes equal:

$$\tau_t = \begin{cases} \tau_t^* & \text{if} \quad t < 10, \\ \tau_t^* + \psi(b_{Gt} - b_G^*) & \text{if} \quad t \geq 10, \end{cases}$$

where τ_t^* and b_G^* are taxes and government debt in the baseline case analyzed in Section 6.1; we set $\psi = 0.06$ to achieve convergence of government debt to its steady-state value within 30 years from the policy implementation.

In Figure 17, we compare the dynamics of the key variables of interest under the policy (dashed line) with those obtained in the baseline case with no subsidies (solid line). The direct effect of the policy is to attenuate the fall in scrappage and new-car sales while the subsidies are available. However, general-equilibrium effects dampen the stimulus of these subsidies. Most notably, the policy induces a further decline in the price of used cars (quality q_2) and a larger fall in the volume of trade, relative to the baseline case, because in the baseline case, most households that scrap their q_3-cars replace them with q_2-cars rather than new q_1-ones. However, the stimulus leads households to substitute away from cars of quality q_2 and toward cars of quality q_1. As a result, demand for cars of quality q_2 falls, triggering a drop in their price and their volume of trade. In turn, the fire-sales p_2 prices urge wealthy households—who, in the absence of the policy, would trade in their q_2 cars for q_1 cars—to delay these replacement purchases. Hence, the subsidies are less effective than models that do not include general-equilibrium effects would predict.

Overall, this analysis highlights that these subsidies generate two types of substitution: (1) substitution from q_2-cars to q_1-cars, which seems broadly consistent with the results of Hoekstra, Puller, and West (2017), who find that households tended to purchase less expensive and smaller new vehicles during the period of the Car Allowance Rebate System, and (2) intertemporal substitution in scrappage and demand for new cars only from the near future, which is consistent with the empirical evidence of Mian and Sufi (2012) and Hoekstra, Puller, and West (2017). Both of these substitution channels limit the effectiveness of the policy in terms of stimulating current expenditures on durables.[33]

were relatively old. For simplicity, we focus on an eligibility criterion based on our notion of car quality, but given the size of the subsidy, extending eligibility to higher-quality cars would not affect the results.

[33]Because we do not model explicitly the production of nondurable goods and do not assume nominal

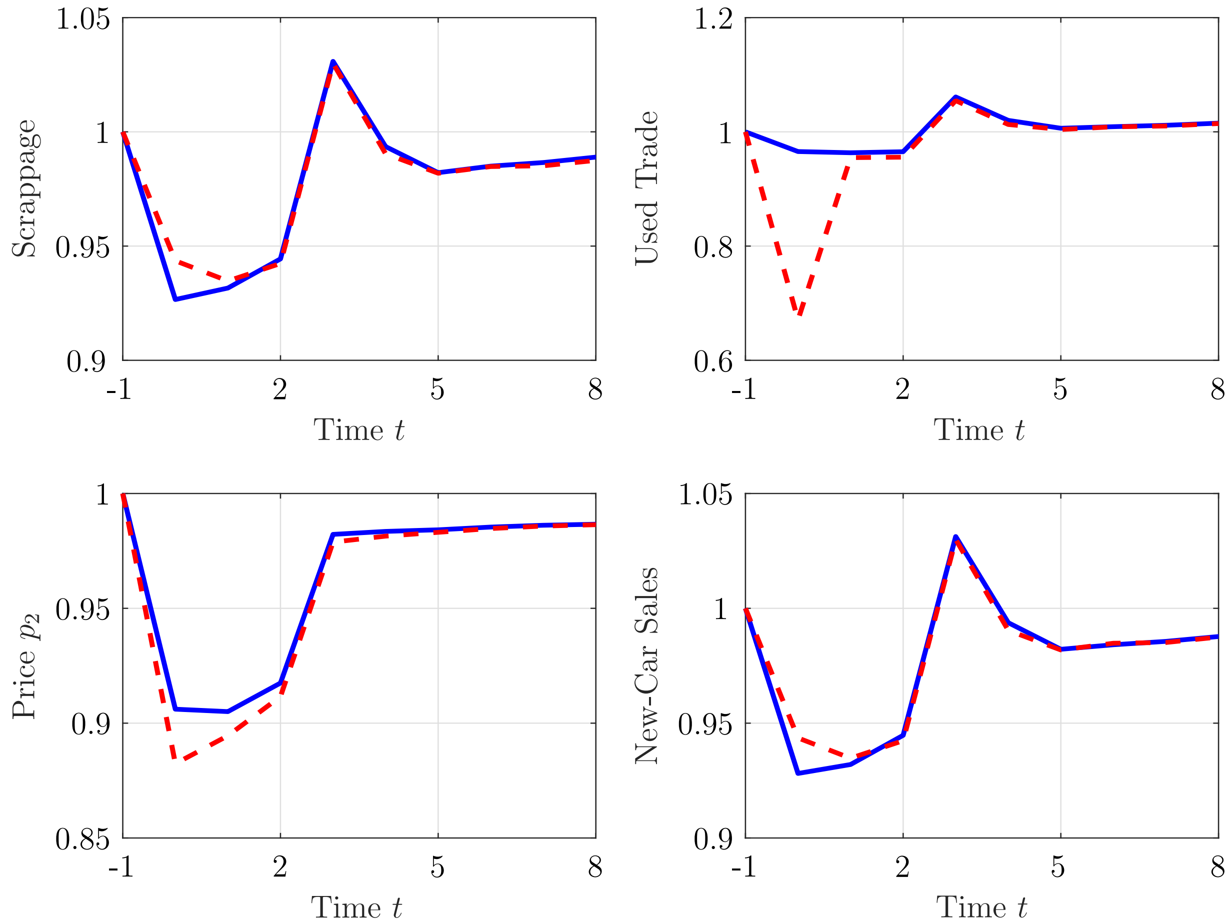

Figure 17: Credit shock and durable-replacement subsidy. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit and policy at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the baseline case; the dashed line the case with replacement subsidies.

8 Conclusion

In this paper, we propose a novel general-equilibrium model of endogenous illiquidity of consumer durable goods to account for the aggregate dynamics of durable expenditures. Our equilibrium notion of illiquidity stems from the imperfect substitutability across durables of different qualities, which trade at market-clearing prices. Aggregate shocks lead to changes

rigidities, labor-market frictions, or other sources of inefficiency that might give rise to aggregate-demand externalities, our framework is not designed to quantify the desirability of this type of fiscal stimulus. Hence, in terms of welfare, our model implies that the policy has effects of negligible magnitude. A richer model that combines our equilibrium mechanism with other macroeconomic frictions may allow us to study normative questions on the optimal design of replacement subsidies in response to aggregate shocks.

in the relative prices of durables of different qualities, affecting the replacement cost of higher-quality goods. We show that our model matches several striking patterns of U.S. car markets during the Great Recession.

We believe that car markets represent an ideal setting in which to study our mechanism, since we can measure relative price movements across goods of different qualities quite accurately. Nevertheless, in future research we hope to apply the key insights of our mechanism to housing markets as well, in which households climb a "property ladder" as their income increases.

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APPENDICES

A Data and Additional Empirical Patterns

In this appendix, we describe in more detail the datasets used in Section 3; we explain the methodology to construct our new- and used-car price indices; we provide additional empirical patterns that complement those of Section 3; and we report some robustness checks about the dynamics of new-car prices.

A.1 Data Sources

In addition to the aggregate data used to construct the annual number of scrapped cars displayed in Figure 2, we use three data sources in Section 3. The first two are rich datasets on new- and used-car prices obtained from Dominion Dealer Solutions and NADA, respectively. The third is the Consumer Expenditure Survey. We now describe these datasets in more detail.

New-car Prices. This dataset reports the universe of new-vehicle transactions in five states—Colorado, Idaho, North Dakota, Ohio, and Texas—for the period 2004-2012, including sales to consumers, leases, and fleet sales. Critically, the dataset reports the transaction price,[34] the month of the transaction, and the make, model, body, and trim of each vehicle. The dataset includes more than 18 million vehicle transactions.[35]

Used-car Prices. This dataset is an unbalanced panel, reporting historic values of different vintages of vehicle models. It includes two price series, retail and trade-in, for 10 U.S. geographic regions—California, Central, Desert, Eastern, Midwest, Mountain, New England, Northwest, Southeast, and Southwest.[36] Retail prices represent the "typical selling price" of a transaction between a dealer (as a seller) and a user (as a buyer) for a used vehicle, based on clean conditions; trade-in prices represent the "typical price for a vehicle at trade-in"—that is, a transaction in which a buyer sells an older model to a dealer, using

[34] For North Dakota, transaction prices are reported for 2008-2012 only

[35] We have verified that the number of new-vehicle transactions in the Dominion dataset tracks the aggregate number of new-vehicle sales we plot in Figure 1. This similarity seems to suggest that the Dominion dataset is representative of the entire U.S. market.

[36] The states included in each region are available at the following link: http://www.nada.com/b2b/Portals/0/assets/pdf/NADA_Regions%20Datasheet_2013.pdf.

the proceeds as partial payment on a new purchase. NADA updates these used-car prices monthly, based on transaction records at dealerships. We obtained used-car price data for the month of July for every year from 2003 to 2012.

CEX. The CEX is a quarterly survey of U.S. households that, among other things, reports information about households' vehicles at the time of the interview, such as the model, its age, whether it is owned or leased, the acquisition date (although this is often missing), and whether it was acquired new or used.

We use these data from 2003 to 2012 (for comparability with the NADA prices) to compute some aggregate statistics on households' vehicle holdings and transactions. More specifically, the CEX surveys are quarterly, with most households interviewed for four quarters. We define a vehicle replacement when we observe that a household disposes of a vehicle it previously possessed (either owned or leased) and acquires another vehicle, even if these two events happen in different quarters. This definition mechanically implies that households surveyed for fewer quarters are less likely to replace a vehicle than households surveyed for all four quarters. Hence, we restrict our analysis to households surveyed for at least three quarters and compute our statistics at the annual level.

Although the CEX data are useful for understanding households' decisions regarding their vehicles, we should point out that their use poses some challenges. Most importantly, the sample size of each CEX survey is not large; on average, approximately 7,000 households are surveyed each quarter. Because we further restrict our analysis to households surveyed for at least three quarters, we have approximately 5,600 households per year. Moreover, households trade their vehicles infrequently, which implies that the aggregate statistics we construct based on CEX data are noisy.[37]

A.2 Construction of New- and Used-vehicle Price Indices

We construct a new-vehicle price index using the Dominion dataset, dropping fleet sales (unfortunately, the price is missing in many of these transactions), and thus exploiting approximately 15.5 million observations on new-vehicle transactions. We estimate the

[37]Households' vehicle sales most likely follow vehicle purchases, rather than vice versa. Hence, our procedure could miss households' replacement when households purchase a vehicle in the last quarter in which they are surveyed (because the subsequent sales are not recorded).

following regression with these data:

$$p^n_{ijst} = \alpha^n_{y(t)} + \beta^n(Year_t - 2004) + \gamma^n_{js} + \epsilon^n_{ijst}, \tag{A1}$$

where the dependent variable p^n_{ijst} is the transaction price of individual vehicle i of make-model-body j (e.g., Toyota Corolla 4L) in state s and month t; $\alpha^n_{y(t)}$ are fixed effects for the year y of the transactions; $(Year_t - 2004)$ is a linear annual trend; γ^n_{js} are fixed effects at the make-model-body j and state s level (e.g., Toyota Corolla 4L in Texas); and ϵ^n_{ijst} are unobservable components of prices. Our new-vehicle price index for year y equals the estimate of $\alpha^n_{y(t)} + \bar{\gamma}^n_{js}$ in equation (A1), i.e., the sum of the year fixed effect and the population-averaged make-model-body-state fixed effects. Hence, our new-vehicle price index holds fixed all car amenities that are common across all vehicles of the same make-model-body-state, thereby varying exclusively due to the year fixed effects $\alpha^n_{y(t)}$ that capture any variation over time within each make-model-body-state and not due to composition changes by which vehicles are sold over time. As a result of our methodology, although we do not have data on repeat sales of the same vehicle i over time and, thus, we cannot exactly replicate the construction of the Case-Shiller Price index, our price index shares some desirable properties with the Case-Shiller Price index of the housing market.

Similarly, we construct a used-vehicle price index using the NADA dataset. We estimate the following regression on these data:

$$p^u_{ijry} = \alpha^u_y + \beta^u(Year_y - 2004) + \gamma^u_{jr} + \epsilon^u_{ijry}, \tag{A2}$$

where the dependent variable p^u_{ijry} is the NADA trade-in price of a 4-year-old vehicle of trim i of model-model-body j (e.g., Toyota Corolla 4L) in Census region r and year y; α^u_y are fixed effects for the year y of the transactions (we have NADA used prices for the month of July of each year only); $(Year_y - 2004)$ is a linear annual trend; γ^u_{jr} are fixed effects at the make-model-body j and Census region r level (e.g., Toyota Corolla 4L in the Southwestern Region); and ϵ^u_{ijry} are unobservable components of prices. Our used-vehicle price index for year y equals the estimate of $\alpha^u_y + \bar{\gamma}^u_{jr}$ in equation (A2), i.e., the sum of the year fixed effect and the population-averaged make-model-body-region fixed effects. As for the new-vehicle price index, the used-vehicle price index varies over time exclusively due to

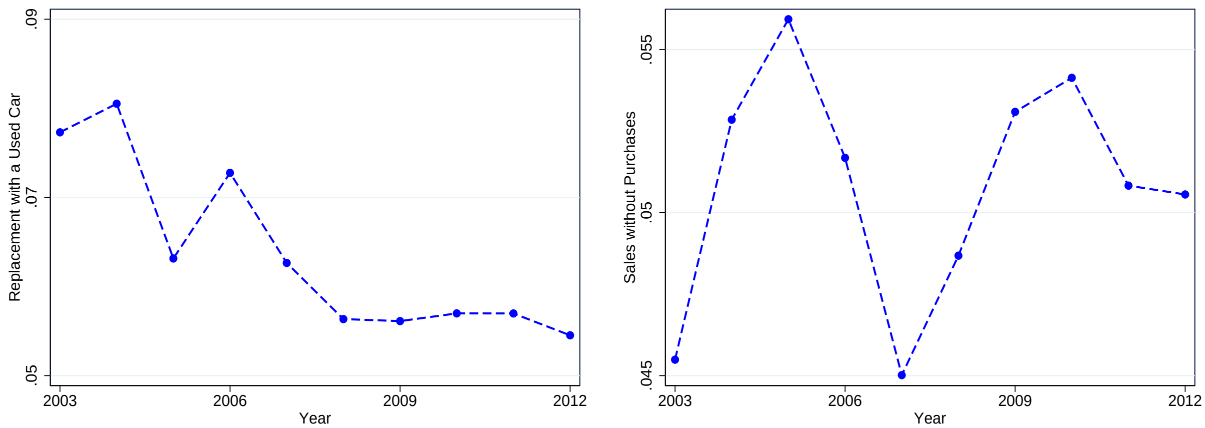

Figure A1: The left panel displays the fraction of households with cars that replaced at least one used vehicle with another used one during 2003-2012. The right panel displays the fraction of households with cars that disposed of a used vehicle without acquiring another one during 2003-2012.

the year fixed effects α_y^u, and not due to composition changes by which used vehicles trade over time.

Based on the new-vehicle and used-vehicle price indices, we construct a replacement cost index as their difference $\left(\alpha_{y(t)}^n + \bar{\gamma}_{js}^n\right) - \left(\alpha_y^u + \bar{\gamma}_{jr}^u\right)$.

Moreover, we estimate equations (A1) and (A2) separately for three popular models—Toyota Corolla, Honda Civic, and Honda Accord—and construct model-specific new-vehicle, used-vehicle, and replacement cost indices.

Figure 3 displays these replacement costs, normalized to equal 100 in 2007. Figure 4 displays its two components: the new-vehicle price index $\alpha_{y(t)}^n + \bar{\gamma}_{js}^n$ and the used-vehicle price index $\alpha_y^u + \bar{\gamma}_{jr}^u$, normalized to equal 100 in 2007.

A.3 Additional Empirical Patterns

(4) The decline in used-car prices was due to a decline in their demand.

We use the CEX data to investigate the behavior of households in secondary car markets, which can shed light on the decline in used-car prices documented in Figure 4. To this end, we calculate the fraction of households that replaced a used, old car with another used, but younger, car. The left panel of Figure A1 shows that this fraction *declined* during the

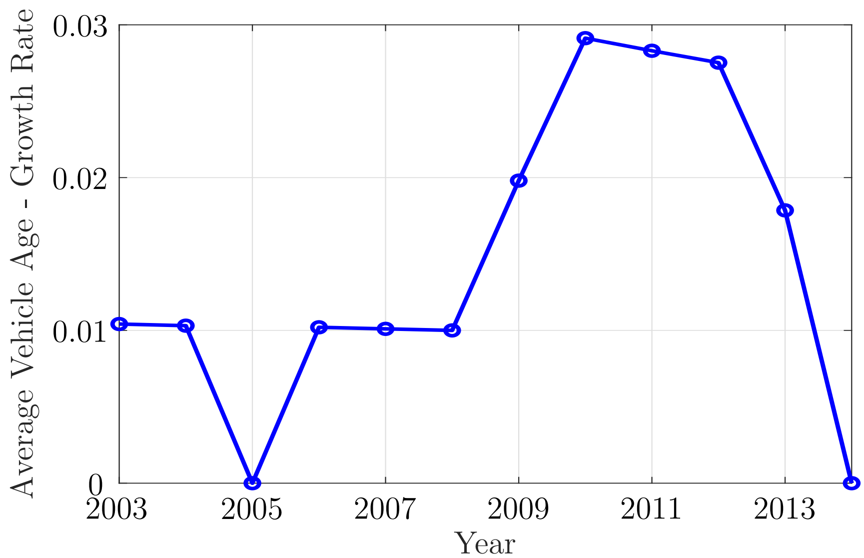

Figure A2: Growth rate of the average age of registered vehicles in the U.S., between 2003 and 2014.

Great Recession, thereby suggesting that a decline in the demand for used cars was the main reason for the decline in used-car prices, rather than an increase in their supply.[38] The right panel of Figure A1 further reinforces the idea that the increase in the supply of used cars during the Great Recession was likely modest, by displaying the fraction of households that sold cars but did not simultaneously purchase another one. Although this fraction increased during the Great Recession, the magnitude of the overall increase from 2007 to 2010 was modest (approximately 0.9 percentage points), and thus it is smaller than the decline in replacement purchases documented in the left panel of Figure A1; more generally, the level it reached during those years was lower than the level it reached pre-2008, whereas replacement purchases clearly bottomed out during the Great Recession.

(5) The average age of registered vehicles increased during the Great Recession.

Consistent with the decline in scrappage and new-vehicle registrations we document, we also observe a steep increase in the average age of the stock of registered vehicles. Figure A2 shows the time series of the growth rate of the average age of all light vehicles in operation. The source of these data is the R.L. Polk Co.

Before the Great Recession, the average age of vehicles was increasing by approximately 1 percent per year, largely because of the effects of technological progress on vehicle dura-

[38]Figure 5 and the left panel of Figure A1 together suggest that the decline in used-car prices did not trigger a substitution from new cars to lightly used (i.e., pre-owned) vehicles.

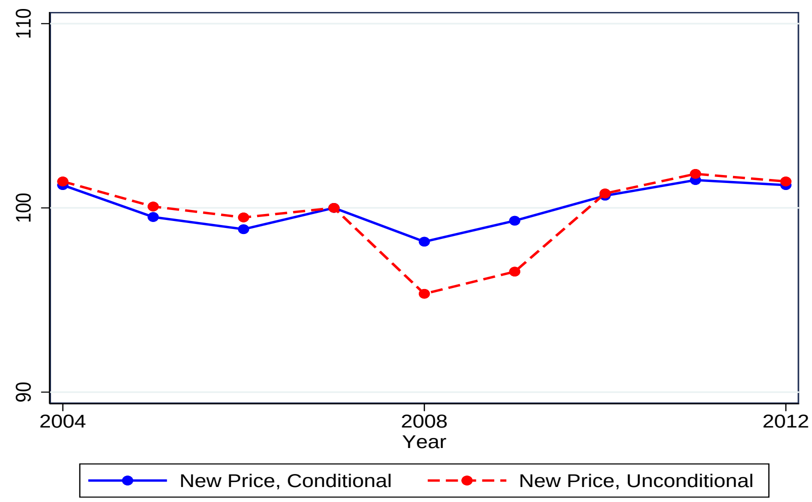

Figure A3: The figure displays new-vehicle price indices: The one represented by the solid line holds compositional changes in new-vehicle purchases constant; the dashed line allows for compositional changes in new-vehicle purchases. Both series are normalized to equal 100 in 2007.

bility. In response to the Great Recession, the average age of the vehicle stock increases more rapidly, by approximately 3 percent per year, reflecting the endogenous postponement of new sales and scrappage.

6) Consumer substitution to cheaper new vehicles was limited.

A natural question is to what extent households substituted to cheaper new vehicles during the Great Recession. Our new-car data are well suited for this purpose. To do so, we use these new-vehicle prices to perform a regression similar to (A1), but we include a set of fixed effects γ_s^n at the state s level only rather than the richer set of fixed effects γ_{js}^n at the make-model-body j and state s level. Based on this regression, we construct a different annual new-vehicle price index from the one obtained above: By not including the fixed effects at the make-model-body level, this index does vary over time also because of composition changes by which vehicles are purchased over time.

Figure A3 compares the new-vehicle price index (solid line) portrayed in the top-left panel of Figure 4 with the different new-vehicle price index that also accounts for compositional changes (dashed line). The comparison between the two indices suggests that households substituted to cheaper vehicles during the Great Recession, consistent with the evidence from nondurable goods and services in Jaimovich, Rebelo, and Wong (2019).

Table A1: Oaxaca-Blinder Decomposition

$\bar{p}^n_{2007}$	26,426
$\bar{p}^n_{2008}$	25,114
$\psi^n_{js,2007}\left(\mathbb{1}_{ijs,2007}\left(js\right) - \mathbb{1}_{ijs,2007}\left(js\right)\right)$	828
$\left(\psi^n_{js,2007} - \psi^n_{js,2008}\right)\mathbb{1}_{ijs,2008}\left(js\right)$	484

Notes: This table reports the values of the Oaxaca-Blinder decomposition of the difference between the average new-car transaction price $\bar{p}^n_{2007}$ in 2007 and $\bar{p}^n_{2008}$ in 2008. The term $\psi^n_{js,2007}\left(\mathbb{1}_{ijs,2007}(js) - \mathbb{1}_{ijs,2008}(js)\right)$ is the explained component; the term $\left(\psi^n_{js,2007} - \psi^n_{js,2008}\right)\mathbb{1}_{ijs,2008}(js)$ is the unexplained component.

Alternatively, we can perform an Oaxaca-Blinder decomposition of new-car prices to understand the extent of consumer substitution towards cheaper new vehicles during the Financial Crisis (Blinder, 1973; Oaxaca, 1973). Specifically, we use our data on new-car transaction prices, we detrend them using a linear trend (as in regression (A1)), and run the following regression separately in the baseline year $t = 2007$ and in the recession year $t = 2008$:

$$p^n_{ijst} = \psi^n_{js,t}\mathbb{1}_{ijst}(js) + \epsilon^n_{ijst}, \tag{A3}$$

where p^n_{ijst} is the detrended (=year 2004) transaction price of individual vehicle i of make-model-body j (e.g., Honda Accord Sedan 4D) in state s and year t; $\mathbb{1}_{ijst}(js)$ are indicator variables equal to one if vehicle i is of make-model-body j and the transaction is in state s, and zero otherwise; $\psi^n_{js,t}$ are the coefficients (i.e., fixed effects at the make-model-body j and state s estimated in year t); and ϵ^n_{ijst} are unobservable components of prices.

Based on these two regressions for the baseline year $t = 2007$ and for the recession year $t = 2008$, the Oaxaca-Blinder decomposition equals:

$$\begin{aligned}\bar{p}^n_{2007} - \bar{p}^n_{2008} = \quad & \psi^n_{js,2007}\left(\mathbb{1}_{ijs,2007}(js) - \mathbb{1}_{ijs,2008}(js)\right) \\ & + \left(\psi^n_{js,2007} - \psi^n_{js,2008}\right)\mathbb{1}_{ijs,2008}(js),\end{aligned}$$

where the first term after the equality equals the explained component and the second term equals the unexplained component.

Table A1 reports the numerical values. The overall difference $\bar{p}^n_{2007} - \bar{p}^n_{2008}$ equals approximately $\$1,300$, or about five percent of 2007 prices. The explained component is

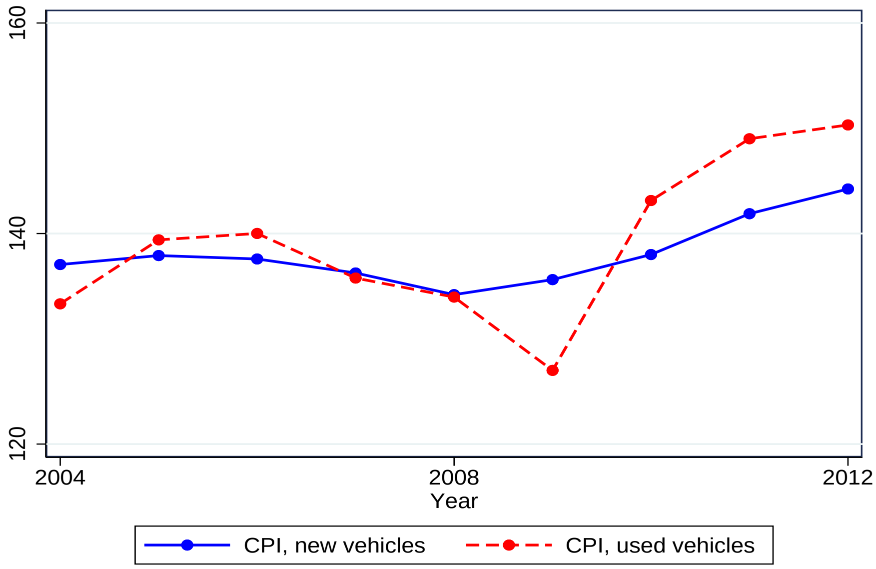

Figure A4: Monthly CPI of new and used vehicles computed by the Bureau of Labor Statistics during 2004-2012.

due to compositional changes in the car purchased and it equals \$848, or approximately three percent of 2007 prices; the unexplained component equals \$484, or approximately two percent of 2007 prices.

Hence, the Oaxaca-Blinder decomposition reports magnitudes almost identical to those displayed in Figure A3, which corroborates that our methodology above yields reliable price indices.

(7) The Consumer Price Index confirms our price patterns.

Figure A4 verifies that the monthly Consumer Price Index (CPI) of new and used vehicles follows patterns similar to those reported in Section A. It shows that the used-vehicle price deflator declined substantially more than the new-vehicle price deflator during 2007-2009.

We should point out that the CPI indices do not allow for clean comparisons at the vehicle level, thus possibly confounding interpretation of the differences between the dynamics of the new and used series. With this important caveat, we can also investigate the dynamics of used-car prices in previous business cycles, which we cannot rely on our transaction data for. We find that in the 2001 recession no drop in used prices occurred, consistent with the notion that the 2001 recession was less associated with a household credit crunch. Going further back in time, we use the whole 1953-2018 BLS sample, and, in the interest of a comparison with the analysis in our micro data, we analyze the data at annual frequency. We thus HP-filter the price indices using a smoothing parameter $\lambda = 6.25$. Consistent with our key empirical findings, the price index for used vehicles is substantially more volatile than the price index for new vehicles. The standard deviation of the cyclical component of used prices equals 0.037, whereas the standard deviation of the cyclical component of new prices equals 0.012.

(8) Manufacturers' cash rebates were limited during the Great Recession.

We complement our analysis of new-car prices with a dataset on cash rebates offered by car manufacturers on purchases of new vehicles. These rebates were advertised in the specialized magazine *Ward's AutoWorld*.[39] We find that despite some fluctuations over time, these rebates did not increase substantially during the Great Recession.

Specifically, Figure A5 displays the average manufacturer rebate on a new Toyota Camry, one of the popular car models we analyzed in Section 3, during the period 2006-2011. We focus on the Toyota Camry because we have consistent and large availability of data on rebates over time.[40] The figure shows that the rebate exhibits limited variation over time. While the rebate is larger in 2009 than in 2007, rebates were even larger in both 2006 and 2011—i.e., 2 years of economic expansion. Moreover, the overall variation in the rebates shown in the figure is small relatively to the price of a new Toyota Camry—i.e., between 1 and 3 percentage points of the overall price—and substantially smaller than the volatility of used transaction prices discussed in Section 3.

While these data on manufacturer rebates seem to confirm the robustness of our finding that new-car prices did not change as much as used-car prices during the Great Recession, we should acknowledge that we do not have data on dealer incentives, such as "free gas" or satellite radio membership. The value of these dealer incentives is often quite limited compared to the magnitude of the decline in used-car prices, but we cannot rule out that dealers added such amenities during the financial crisis to a greater extent than in non-recession years. Therefore, the next subsection reports on robustness checks that hone in

[39] We are grateful to Charles Murry for graciously sharing these data with us.

[40] We construct the series in the figure by averaging over geographic locations and model trims. We find a similar pattern if we focus on single trims of this car.

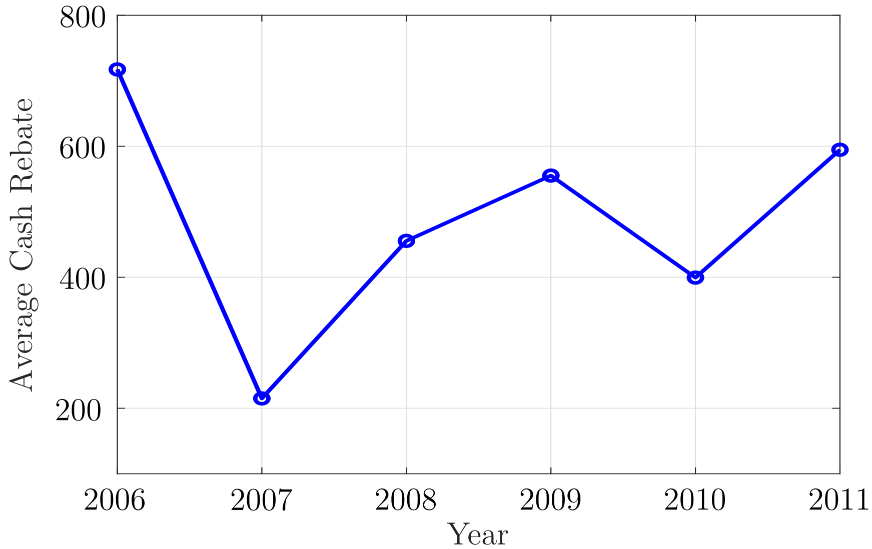

Figure A5: Average cash rebate (in dollars) offered by Toyota on the purchase of a new Toyota Camry between 2006 and 2011.

on these unobservable car amenities.

A.4 Robustness Checks: New-Car Price Index

The goal of this subsection is to report on some robustness checks about our new-car price index. Although our new-car transaction data described above are rich, we acknowledge that they do not report all car characteristics, including dealer incentives. Nevertheless, we can use these data to assess the importance of unobservable car amenities and their variation over the years. Our analysis leverages the key insight of the influential paper by Altonji, Elder, and Taber (2005), which points out that the amount of selection on the observed explanatory variables provides a guide to the amount of selection on the unobservables.

More specifically, we perform several regressions in which the dependent variable is the new-vehicle price, and we gradually increase the set of explanatory variables. Comparing the R^2 of these regressions allows us to assess how much these observable characteristics account for the observed variation of prices. More critically, comparing the resulting year fixed effects based on these regressions helps us understand how selection due to compositional changes of car sales over the years affect our new-car index.

Table A2 reports the R^2 and the estimates of the year fixed effects of these regressions.

Table A2: New-Car Prices

	(1)	(2)	(3)	(4)
Time Trend	608.838	579.694	533.569	515.224
	(0.816)	(0.972)	(1.179)	(1.200)
Year 2005		-454.512	-457.708	-413.368
		(6.197)	(6.089)	(5.749)
Year 2006		-628.303	-588.280	-479.761
		(6.072)	(6.224)	(5.959)
Year 2007		-324.621	-478.320	-402.151
		(6.023)	(6.410)	(6.186)
Year 2008		-806.102	-981.379	-905.051
		(6.338)	(6.881)	(6.654)
Year 2009		-507.351	-690.261	-672.646
		(7.076)	(7.495)	(7.187)
Year 2010		-150.990	-295.855	-316.485
		(6.870)	(7.094)	(6.771)
Year 2011		71.780	-73.062	-93.225
		(6.709)	(6.665)	(6.275)
Constant	26165.708	26583.467	26835.983	26872.597
	(3.511)	(5.021)	(5.541)	(5.507)
Make-Model-Body-State FE	Yes	Yes	No	No
Make-Model-Body-Trim-State FE	No	No	Yes	No
Make-Model-Body-Trim-Dealer-State FE	No	No	No	Yes
R^2	0.8068	0.8071	0.8269	0.8689
Observations	15,750,272	15,750,272	15,750,272	15,750,272

Notes: The dependent variable is the transaction price of a new car. Specification (2) corresponds to equation (A1).

Column (1) documents that the time trend and fixed effects at the make-model-body-state capture approximately 80 percent of the overall sample variation of prices. Specification (2) adds year fixed effects (our main regression equation (A1)), but the R^2 barely changes, suggesting that cyclical variation in prices is minimal. Specification (3) includes fixed effects at the make-model-body-trim-state level, which add two percent to the R^2. Specification (4) includes fixed effects at the make-model-body-trim-dealer-state level, which further increase the R^2 by approximately four percent.

The estimates of the year fixed effects are very similar across specifications (2)-(4). To further appreciate the differences, Figure A6 displays the estimates of the new-price

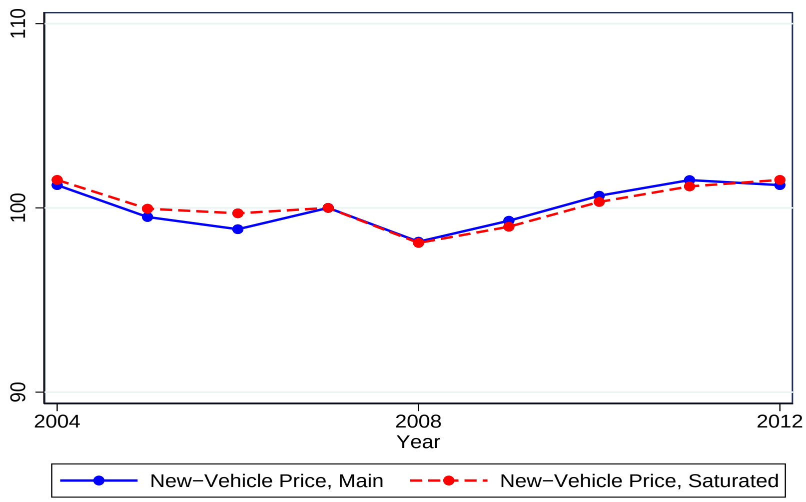

Figure A6: The figure displays new-vehicle price indices: The one represented by the solid line is our main index, based on specification (2) of Table A2; the dashed line is based on specification (4) of Table A2. Both series are normalized to equal 100 in 2007.

indices based on these regressions: the solid line is our main new-car price index based on specification (2), displayed in Figure 4; the dashed line is based on specification (4). The solid and the dashed lines are almost identical.

The regressions of Table A2 underscore two main points: 1) Specification (3) controls for trim characteristics, in addition to make-model-body-state fixed effects of specification (2). However, we note that the increase in the R^2 from column (2) to (3) is small. The monetary values of different trims within make-body-model tend to be larger than the monetary values of dealer incentives, which offer vehicle accessories that can be installed at the dealership. Critically, the addition of these trim controls does not affect the estimates of the year fixed effects, implying that selection due to variation in the composition of trims sold over the business cycle does not affect our new-car price index. 2) Specifications (3) and (4) show that further controlling for dealer fixed effects captures some variation in prices, because the R^2 increases by approximately four percent, but this increase is limited as well. However, strikingly, this variation is orthogonal to the year fixed effects because it does not affect their estimates. Hence, selection due to the composition of sales across dealers over the business cycle does not affect our new-car price index.

To summarize, selection due to compositional changes of sales across trims and across dealers over the years does not affect our new-car price indices, as Figure A6 shows. Hence, if selection on these observed explanatory variables provides a guide to the amount of selection on unobservable dealer incentives, as Altonji, Elder, and Taber (2005) postulate, the variation of dealer incentives across years seems unlikely to overturn our key finding that the drop in new-car prices was smaller than the drop in used-car prices during the Great Recession.

B Additional Model Results

In this appendix, we report additional results from our model. First, we derive a general notion of user cost of durable goods in our model. Second, we generalize our framework to consider the case of perfect substitutability in preferences for durable goods. These derivations provide further intuition on key aspects of our mechanism. Third, we consider three alternative formulations of the credit shock, thereby complementing the results of Sections 6.1 and 6.2. Fourth, we decompose the role of equilibrium in secondary markets and the role of transaction costs in the model with both credit and aggregate income shocks of Section 6.3. Finally, we show that the key mechanism highlighted in the paper does not stem from credit-supply shocks only, but, more generally, from shocks that affect the wealth-income distribution asymmetrically.

B.1 User Cost

We now discuss a user-cost interpretation of our results. The user cost of a durable good is the cost associated with enjoying an additional unit of a durable good for only one period. In models that abstract from changes in the prices of durable goods, the user cost is simply the sum of the interest rate (or opportunity cost of capital) and the depreciation rate. In our model, we can similarly define the user cost of an upgrade from a car of quality q_2 to a car of quality q_1 as the replacement cost paid in the current period, net of the discounted revenue from doing the opposite trade (downgrade from q_1 to q_2) in the following period.

With our notation, and focusing for simplicity only on proportional transaction costs (λ), the user cost υ of upgrading from q_2 to q_1 is

$$\upsilon \equiv p_1 - p_2(1-\lambda) - \frac{1}{1+r}\left[(1-\pi_1)p_1(1-\lambda) + \pi_1 p_2'(1-\lambda) - p_2'\right] \tag{B1}$$

where we use primes to denote future-period variables. The formula shows that the user cost can increase because of an increase in the interest rate, as in standard models, or because of a decline in the price p_2. Thus, we can use the formula to quantify the importance of a decline in used-car prices, expressing it in terms of an equivalent change in the interest rate, using our calibrated parameter values and equilibrium prices.

Specifically, we now compute the counterfactual increase in r that would give the same increase in υ in two alternative scenarios. First, we consider a permanent 1-percent decline in p_2. This decline has the same effect on the user cost as a 37-basis-points increase in the interest rate. Second, we consider a 1-percent decline in p_2, but no change in p_2'. In this case, the temporary decline in the used-car price is equivalent (in terms of its effect on the user cost) to a 212-basis-point increase in the interest rate. This analysis provides an alternative interpretation of our key results, by showing that a current decline in used-car prices, combined with expectations of a recovery, has a large effect on the user cost, which induces households to postpone replacement.

B.2 Perfect Substitutability in Preferences

We now investigate the generality of our results in a model with perfect substitutability between durable goods of different qualities, and without indivisibility. This version of the model allows for a first-order condition, or "asset-pricing" equation, for durable goods.

We generalize the household problem in our model to add a continuous choice over durable size, on top of the discrete choice over durable quality, and assume different qualities are perfect substitutes. Moreover, we abstract from transaction costs. For simplicity, we also abstract from ex ante heterogeneity in preferences, i.e., types θ, as well as government debt and taxes, but these features can be included easily. We consider both a small-open-economy and a general-equilibrium version of this model.

Parts of this analysis build on, and adapt to our context, some insights that Rampini (2019) obtains in a model with financially constrained entrepreneurs and new and used capital, assumed to be perfect substitutes in production.

Environment and Household Problem. Households have preferences represented by the following utility function:

$$\mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t u(c_{it}, d_{it}), \tag{B2}$$

with

$$d_{it} \equiv \sum_{n=1}^{N} q_n \tilde{s}_{n,it}, \tag{B3}$$

where q_n is durable-good quality, in a discrete set $n = 1, .., N$, and $\tilde{s}_{n,it} \in S_n \subseteq \mathbb{R}_{\geq 0}$ is durable-good quantity or size (or any other continuous attribute) chosen for the current period.

The household budget constraint in stationary equilibrium reads

$$c_{it} + p_b b_{i,t+1} + \sum_{n=1}^{N} p_n \tilde{s}_{n,it} = w_{it} + b_{it} + \sum_{n=1}^{N} p_n s_{n,it}. \tag{B4}$$

where $s_{n,it}$ are beginning-of-period durables quantities.

We impose the following constraints on durable size: $S_n \equiv \mathbb{R}_{\geq 0}$ for all n, and denote by $\nu_{n,it}$ the Lagrange multiplier on the non-negativity constraint for durables of quality n. Our baseline model with indivisibility is a special case of the general formulation above, under alternative restrictions on the choice sets S_n; specifically, $S_n \equiv \{0, 1\}$, and if $\tilde{s}_{m,it} = 1$, then $\tilde{s}_{n,it} = 0$ for $n \neq m$.

As in our baseline model, the borrowing limit is $b_{i,t+1} \geq \phi$, and we denote by $\nu_{b,it}$ the associated Lagrange multiplier.

By taking the first-order conditions of the household problem, we obtain the following "asset-pricing" optimality condition for durables of quality n:

$$p_n u_{ct} = q_n u_{dt} + \beta \left[(1 - \pi_n) p_n + \pi_n p_{n+1}\right] \mathrm{E}_t u_{c,t+1} + \nu_{nt}, \tag{B5}$$

where we drop the dependence of allocations on i to simplify notation, and use u_{ct} and u_{dt} as shorthand notation for the marginal utility from nondurable and durable goods, respectively, at time t.

Equation (B5) explicitly highlights some key features of our theory: (i) heterogeneous durable-good quality affects the "dividend" term from enjoying the durable good; and (ii) expectations about equilibrium resale prices play an important role in the decision to purchase durable goods.[41]

The first-order condition with respect to bonds is

$$p_b u_{ct} = \beta \mathrm{E}_t u_{c,t+1} + \nu_{bt} \tag{B6}$$

We now make some additional simplifying assumptions in order to obtain a transparent analytical characterization. Specifically, we assume that only two qualities of cars are useful, i.e., $q_1 > q_2 > 0$. We refer to quality-q_1 cars as new cars and quality-q_2 as used cars. New cars are produced with a linear technology with constant marginal cost p_1 using nondurable goods and become used (q_2) in the next period with certainty. Used cars become worthless scrap ($q_3 = p_3 = 0$) in the following period with certainty. Thus, durable goods are useful for two periods, as new and then as used.

In this case, we can express equation (B5) as follows for qualities q_1 and q_2, respectively:

$$p_1 u_{ct} = q_1 u_{dt} + \beta p_2 \mathrm{E}_t u_{c,t+1} + \nu_{1t}, \tag{B7}$$

$$p_2 u_{ct} = q_2 u_{dt} + \nu_{2t}. \tag{B8}$$

Importantly, these optimality conditions highlight the fact that durables differ not only in their quality, or current utility flow, but also in their future residual value, or durability. In particular, quality and durability are positively correlated.

Equilibrium Definition and Characterization. The state variables of a household are its level of wealth $a_t \equiv b_t + p_2 s_{2t}$ (the sum of bonds and durable goods holdings, because of the absence of transaction costs) and its income w_t. We use the notation $g_n(a, w)$ to denote the size $\tilde{s}_n$ of a durable good of quality n demanded by a household with states (a, w). As in the rest of the paper, we use g_b to denote the policy function for bonds.

The definition of stationary equilibrium is standard: (i) household decision rules for consumption, durable quality and size, and bonds, as a function of the state, (ii) a distribution of households $m(a, w)$, (iii) prices p_b and p_2, such that household decisions satisfy the optimality conditions above, the distribution of households perpetuates itself, and markets

[41] For convenience, we assume that each infinitesimal unit of durable good of quality n depreciates with probability π_n. Thus, by the law of large numbers, households know with certainty what fraction of their continuous amount of each quality $\tilde{s}_{nt}$ is going to depreciate. This feature is different from our baseline model with indivisibility, where depreciation is necessarily stochastic.

clear.

Specifically, in the small-open-economy case, we take p_b as exogenous and only impose the market-clearing condition for used cars:

$$\int g_2(a,w)dm(a,w) = \int g_1(a,w)dm(a,w), \tag{B9}$$

where the left-hand side reports total demand for used cars and the right-hand side reports total supply of used cars, which equals the total amount of new cars depreciated from the previous period.

In the general-equilibrium case, we also impose market clearing in the bond market:

$$\int g_b(a,w)dm(a,w) = 0. \tag{B10}$$

We emphasize that equation (B9) crucially distinguishes this model from models with a homogeneous durable good, which would instead feature the bond market-clearing condition (B10) only or, equivalently, a joint resource constraint for durables and nondurables.

Consider the case in which the marginal household, indifferent between new and used cars ($\nu_{1t} = \nu_{2t} = 0$), is unconstrained in its borrowing ($\nu_{bt} = 0$) (we focus on this case for simplicity; if the marginal household is constrained, our findings discussed below, in particular the endogeneity of prices with respect to the borrowing limit, are even more relevant). The Euler equations above become

$$\frac{p_1}{q_1} = \frac{u_d}{u_c} + p_b \frac{p_2}{q_1}, \tag{B11}$$

$$\frac{p_2}{q_2} = \frac{u_d}{u_c}. \tag{B12}$$

By substituting out the marginal rate of substitution between nondurable and durable consumption, we obtain

$$\frac{p_1}{p_2} = \frac{q_1}{q_2} + p_b. \tag{B13}$$

Equation (B13) showcases that the relative price of new versus used cars depends both on their relative quality and on their relative durability and thus on the interest rate.

At this relative price, all unconstrained households are indifferent between new and used cars. A marginal increase in purchases of used cars and the associated decrease in purchases of new cars can be exactly offset by increasing savings in bonds, leaving the household problem unchanged.[42]

We now consider the choice of borrowing-constrained households. Combining equations (B7) and (B8), we can write

$$\frac{p_1}{q_1} - \frac{p_2}{q_2} = \beta \frac{p_2}{q_1} \frac{\mathrm{E} u_c'}{u_c} + \frac{\nu_1}{q_1 u_c} - \frac{\nu_2}{q_2 u_c}. \tag{B14}$$

Equations (B11) and (B12) jointly imply

$$\frac{p_1}{q_1} - \frac{p_2}{q_2} = p_b \frac{p_2}{q_1}. \tag{B15}$$

Hence, the left-hand side of (B14) is positive. Moreover, for a constrained household, $\beta \frac{p_2}{q_1} \frac{\mathrm{E} u_c'}{u_c} < p_b \frac{p_2}{q_1}$. Thus, we conclude that $\nu_1 > 0$; that is, constrained households only purchase used cars, because they discount the future resale value of new cars at a higher rate than the market interest rate.

Consistent with our baseline model, we obtain that low-wealth households demand cars of lower quality. Furthermore, if the utility function is Cobb-Douglas in nondurables and durables, as in our model parameterization, constrained households demand nondurable goods and used cars in fixed proportions, implying positive comovement between their available resources (income and debt issuance) and their demand for used cars.

We now discuss the extent to which preferences with perfect substitutability pin down equilibrium prices for durable goods. Equation (B13) suggests that in a small open economy (i.e., with an exogenous bond price p_b), the price of used cars is indeed independent of the distribution of households, as long as the marginal household is unconstrained.

In general equilibrium, however, any aggregate change that affects the equilibrium bond price, such as a change in the borrowing limit, also implies a change in the relative price of used cars. The reason is that despite "static" perfect substitutability in utility, new and used cars differ in their durability, with new cars featuring higher durability than used cars (as well as quality). Hence, new cars act as a savings device because they have a

[42]Equation (B13) also gives the lower bound for the relative price of used cars in a stationary equilibrium. At a lower p_2, all households would prefer used cars, which is inconsistent with market clearing. In a related model, Rampini (2019) also characterizes equilibria in which used durables trade at a premium, and the marginal buyer is constrained.

positive residual value, whereas used cars have no future resale value.[43] Thus, no-arbitrage conditions between bonds, new cars, and used cars imply that changes in the price of used cars must offset any changes in the interest rate to ensure that unconstrained households are indifferent between new and used cars, and the market for used cars clears.

Credit Shocks and Durable Goods Markets. We now analyze the transmission of shocks that affect demand for used durables to production of new durables. Consider an economy in stationary equilibrium, and assume that an unexpected shock hits a positive measure of constrained households, by tightening their borrowing limit, only for one period. For simplicity, future borrowing limits are unchanged for all households. Thus, the optimization problem of unconstrained households is unchanged, unless prices change.

Households hit by this temporary credit shock decrease their demand for both non-durable and durable goods (in equal proportions if utility is Cobb-Douglas). Because these households purchase used cars only, total demand for used cars falls.

The transmission mechanism of this shock to other households depends on whether the interest rate is exogenously fixed or endogenously determined. In the small-open-economy version of the model, the bond price is unaffected. Clearly, total supply of used cars is predetermined. Thus, unconstrained households, who are indifferent between new and used cars, partly substitute away from new cars and toward used cars to make up for the demand shortfall, without changing their overall consumption of durables or their total savings. This substitution toward used cars ensures that the used-car market clears (at the same initial price). Overall, the demand shock in the used-car market translates directly to the production of new cars, which must decrease. However, this small-open-economy model cannot account for our empirical findings on the relative price of new and used cars, different from our baseline model.

Moreover, this substitution away from new cars on the part of wealthy households also implies that they increase their bond holdings to maintain the same level of savings. Hence, in the general-equilibrium version of the model, the interest rate needs to fall to clear the bond market. In turn, this interest-rate change implies that the price of used cars must also decrease relative to the initial equilibrium, in order to restore indifference for unconstrained

[43] With the general stochastic depreciation structure of our baseline model, used cars also have a positive residual value. Nevertheless, the relative price of used cars still depends on the equilibrium interest rate, because of different expected durability of new and used cars.

households and ensure market clearing for used cars.

Thus, this model features a version of our novel transmission mechanism: Credit-constrained households decrease their demand for used cars; used-car prices endogenously decline; an increase in the relative price of new cars (relative to used ones) reduces the desirability of new cars for wealthy households.

To highlight the importance of imposing market clearing in the used-car market for this result, consider a counterfactual in which used cars can be re-transformed into nondurables at constant rate p_2^{-1}, as in our counterfactual with fixed prices of Section 6.2. Now, starting from the same initial allocation described above, when the credit shock induces a decline in the interest rate to clear the bond market, the discounted resale value of new cars increases, and all unconstrained households strictly prefer new cars to used cars, thus hitting the non-negativity constraint for used cars, $\nu_{2t>0}$. As all households decrease their demand for used cars, this violates equation (B9), and some used cars are indeed re-transformed into nondurables.

Summary of Results. To summarize this analysis, a version of our model with perfect substitutability in preferences is consistent with several of our findings. In particular, an equilibrium assignment of lower-quality cars to poorer households occurs. As a consequence, a credit tightening manifests itself as a negative demand shock for used cars, and secondary markets transmit this shock to new-car purchases.

In a small-open-economy version of the model, the shock is transmitted directly to wealthy households, but it does not generate endogenous price changes, such as those observed in the data. In general-equilibrium, the model features a version of our novel transmission mechanism through endogenous price changes.

We find that this model does not feature exogenously constant prices for durables, because it imposes market clearing for used cars. Hence, this model does not collapse to the homogenous-durable-good model that is typically analyzed in the literature.

B.3 Alternative Parameterizations of the Credit Shock

We now consider three alternative parameterizations of the credit shock and investigate the sensitivity of our main results. First, we assume the shock is not fully permanent. Second, we consider two alternative calibrations of the shock, matching different credit variables

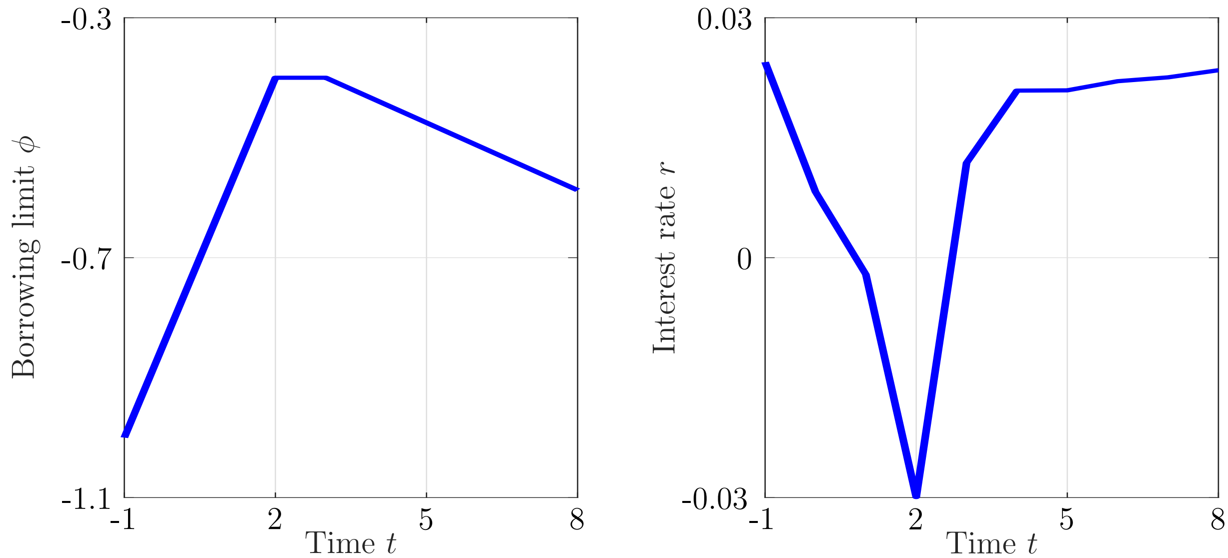

Figure B1: Credit variables with a persistent, but not permanent, shock. The left panel displays the dynamics of the borrowing constraint and the right panel the dynamics of the interest rate. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit at $t = 0$. The borrowing limit reverts to its initial value following a linear path between $t = 4$ and $t = 19$. The horizontal axis displays time t.

rather than the real interest rate: In one calibration, we match the dynamics of auto loans around the Great Recession; in the other, we match the dynamics of overall household debt.

A persistent, but not permanent, credit shock. Our baseline credit shock is permanent, as in Guerrieri and Lorenzoni (2017). As a consequence, our counterfactuals of Section 6.2 feature different terminal conditions for each path considered, depending on which aggregate series is fed into the household problem or which market clears. We now show that our results are robust to a change in the assumption on the long-run value of the borrowing limit. To this end, we assume that the borrowing limit eventually reverts to its initial value. We then use this version of our model to follow two alternative calibration strategies.

We assume that the credit shock follows the same path as in our baseline until $t = 3$. Afterward, the shock linearly reverts back to the initial stationary-equilibrium value, reaching it after 15 periods. Thus, the credit tightening is not permanent, but it is highly persistent. In Figures B1 and B2, we report the dynamics of credit-market variables and durable-good market variables, respectively. The equilibrium dynamics induced by this shock are remarkably similar to those of the baseline case considered in Section 6.2. In Figure B3, we

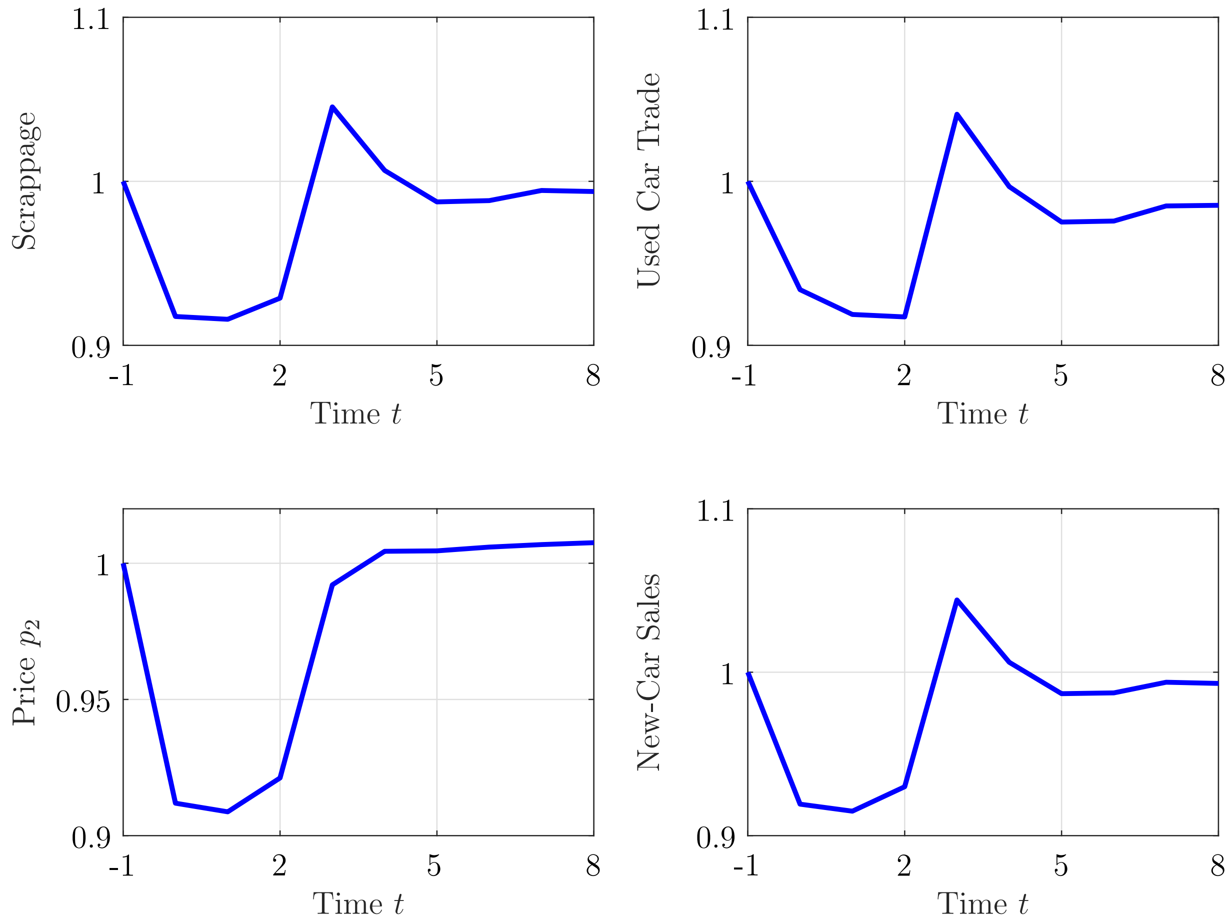

Figure B2: Equilibrium dynamics with a persistent, but not permanent, credit shock. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new path of the borrowing limit at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars.

repeat the key decomposition of Figure 9 by feeding the dynamics of borrowing limit, interest rate, and used-car price, one at a time, into the household problem. In this case, each series converges to the same stationary equilibrium—that is, the initial one—as shocks and prices eventually return to their initial equilibrium value. Thus, different long-run terminal conditions do not affect short-run differences. We find that our main insights are robust to this modification. Moreover, when the shock is not permanent, the credit tightening would not, *by itself*, trigger a decline in new-car sales. Thus, secondary markets account for the entirety of the decline in new-car sales, making our mechanism even more powerful than in the baseline case.[44]

[44]We also considered a credit shock that reverts to its initial value more quickly. Small changes in the

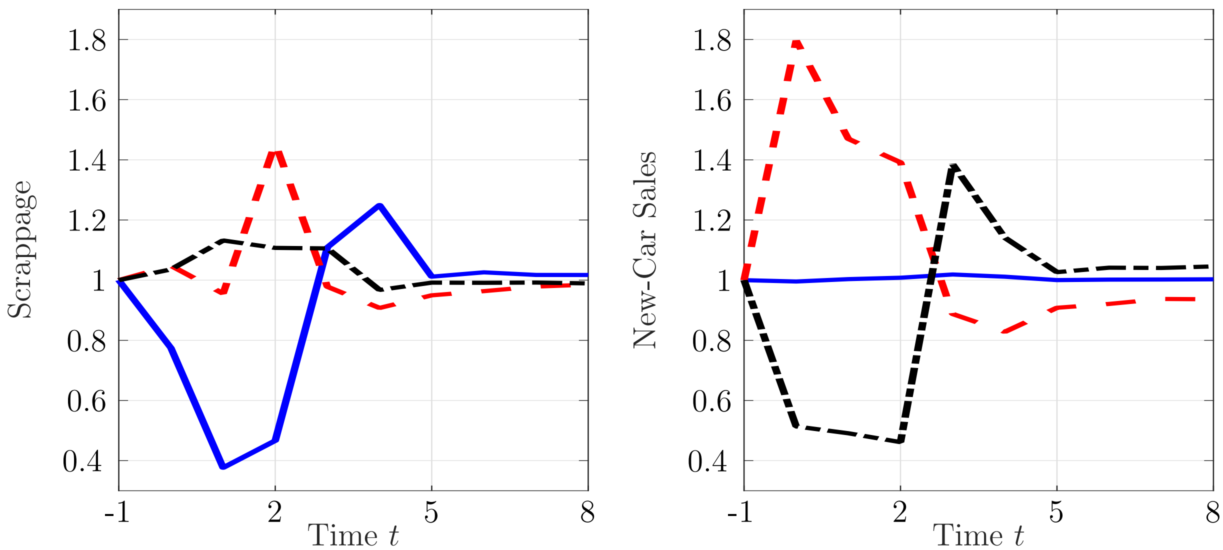

Figure B3: Decomposition with a persistent, but not permanent shock. The left panel displays scrappage and the right panel sales of new cars. The solid line refers to the effects of changes in the borrowing limit; the dashed line to the effects of equilibrium interest rate dynamics; the dashed-dotted line to the effects of equilibrium used-car price dynamics.

Alternative calibration 1: Matching auto loans. Our baseline calibration target for the credit shock is the real interest rate. We now consider an alternative approach by targeting credit quantities. First, we use the small-open-economy version of our model and parameterize the credit shock to match the dynamics of auto loans, thus abstracting from interest-rate changes. Specifically, the Consumer Financial Protection Bureau reports data on the number and total volume of auto loans originated in each month from 2005. We compute the peak-to-trough decline in these two series during the Great Recession and find that both of them declined by approximately 40 percent. Next, we parameterize the credit shock in our small-open-economy model to match this target, interpreting all debt in our model as auto loans (we discuss an alternative interpretation below). This calls for a slightly smaller tightening than our baseline, namely from $\phi = -1$ to $\phi = -.5$ over 3 years, after which we assume the shock slowly reverts back over 15 years. Under this calibration, the shock induces a 25-percent decline in new-car sales and a 4-percent decline in used-car prices. We see this as further evidence that our key mechanism is also empirically important in the context of a small open economy, with a narrow focus on car markets.

speed of reversion do not affect our results. When the reversion is very fast, however, we find that the real interest rate features strong nonmonotone dynamics while reverting to its initial value, which appears inconsistent with the fact that the real interest rate has remained low since the Great Recession.

Alternative calibration 2: Matching total household debt. We now consider an alternative notion of credit quantity by mapping debt in our model to a broad notion of household debt in the data. Specifically, we exploit data reported by the Federal Reserve Bank of New York on outstanding household debt between 2003 and 2018 and calculate that the (linearly detrended) stock of household debt declined by approximately 20 percent between 2008 (peak) and 2015 (trough). Accordingly, we target these deleveraging dynamics in our small-open-economy model. This target calls for both a smaller and a more gradual shock in our model. Specifically, the credit limit goes from $\phi = -1$ to $\phi = -.77$ over 7 years, before gradually reverting back over a period of 15 years.

Qualitatively, the results are consistent with the main mechanism of the paper. Scrappage, used prices, and new sales all decline. Quantitatively, however, we find that the gradualism of this shock induces smaller, although more persistent, changes in both prices (approximately 0.5 percent) and quantities (approximately 5 percent). We do not see this version of the model as the most promising to quantitatively account for the main facts on car markets, because we believe that the Great Recession hit car markets more suddenly than what the overall process of household deleveraging over several years implies. This is especially true in the context of a model with perfect foresight, in which most agents can easily plan their response to this projected path of the debt limit. Moreover, we restrict attention to one-period debt in the model. Hence, it is likely that the same target for the reduction in the stock of debt implies a significantly smaller shock on the flow of debt than what would be consistent with the prevalence of longer maturities, as in the data. Thus, we see this as a highly conservative lower bound on the importance of our mechanism. To further corroborate this view, we solved this version of the model in general equilibrium and found that the interest rate decline implied by this shock equals only 0.5 percent.

B.4 Credit and Income Shocks: Inspecting the Mechanism

We study the separate roles of used durable prices and transaction costs in the economy hit by a credit tightening and an aggregate income shock, as in Section 6.3. The results of this decomposition are very similar to our findings in the presence of a credit shock only (Section 6.2), thereby emphasizing that accounting for equilibrium in secondary markets is crucial even in the presence of aggregate income changes.

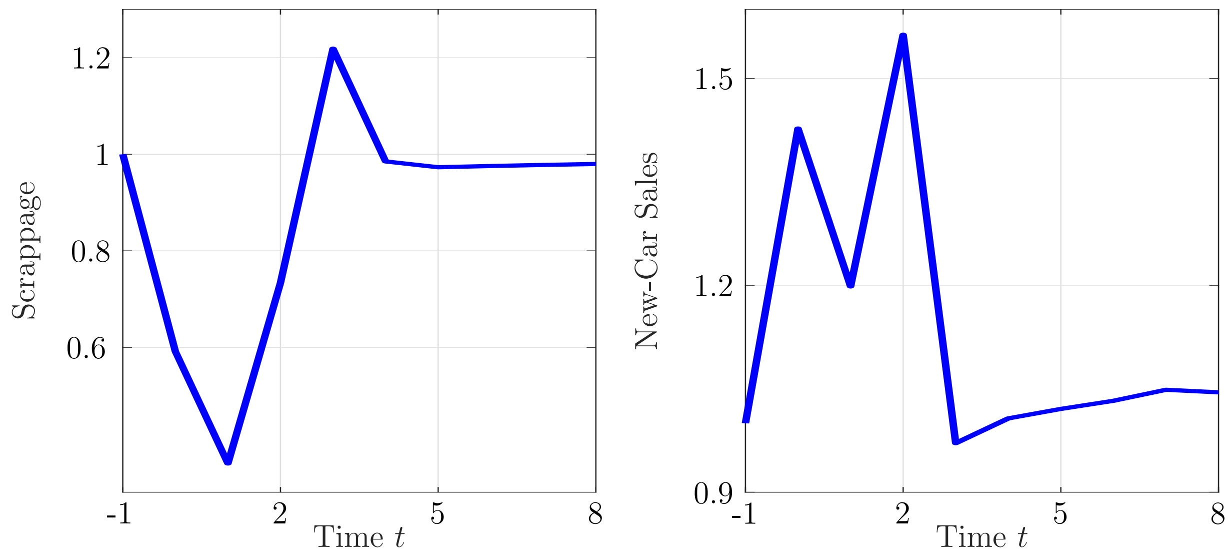

Figure B4: Credit and income shocks in the absence of secondary-market clearing. The economy is hit by the same credit and income shock as in Figure 14. The bond market clears. However, the market for used cars does not clear—that is, cars can be traded with the rest of the world at the prices prevailing in the initial stationary equilibrium. The left panel displays scrappage and the right panel the sales of new cars.

First, we recompute the transitional dynamics assuming that the secondary market does not clear, and cars trade at their initial prices. Figure B4 displays the resulting equilibrium dynamics. As we found in the case of a credit shock only, scrappage declines substantially and new-car production increases in response to the shocks. Hence, equilibrium in the secondary market is necessary to induce a fall in new car sales, consistent with the evidence from the Great Recession. Relative to Figure 10, the aggregate income shock further decreases scrappage and dampens the initial increase in car sales, which peak 3 years after the initial shocks at over 50 percent above the steady-state value.

Second, we recompute the transitional dynamics with the aggregate credit shock and the aggregate income shock, clearing both credit and car markets, but setting the transaction costs equal to zero, as we did in Figure 13 for the baseline case without aggregate income shocks. Figure B5 displays these results. The dashed line represents the dynamics without transaction costs, and the solid line reproduces the dynamics obtained in Figure 14 with transaction costs. Similar to our findings of Section 6.2, the absence of transaction costs induces a spike in downgrading activity in the recession, leading to a temporary increase in the trading volume of used cars, a more sizable decline in used prices, and a larger fall in scrappage and new production, compared with the economy with transaction costs.

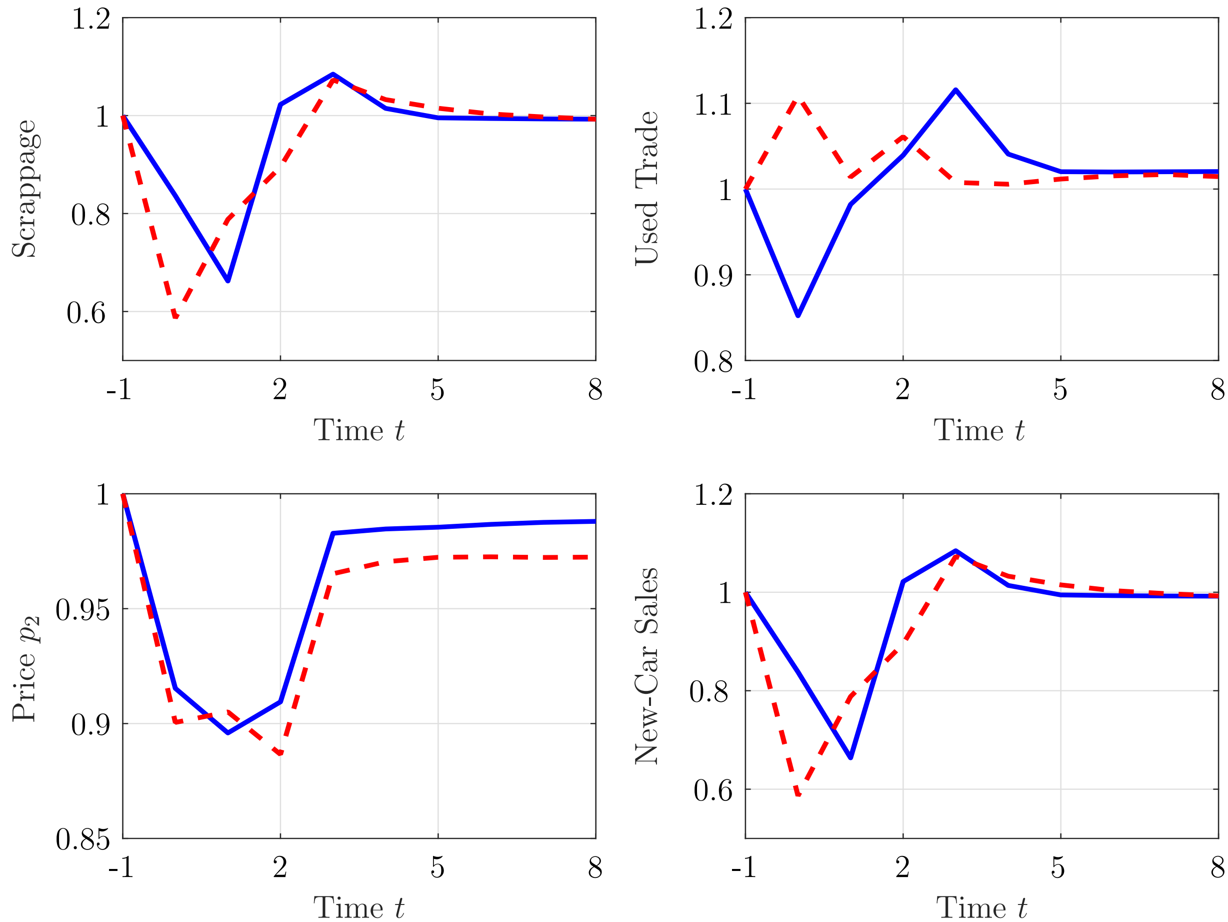

Figure B5: Credit and income shocks in the absence of transaction costs. The economy is in stationary equilibrium at $t = -1$. Households learn about the new path of the borrowing limit and income at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the case with calibrated transaction costs and the dashed line the case without transaction costs ($\lambda_0 = \lambda_1 = 0$).

B.5 Skewed Income Shock

We now show that the main mechanism highlighted in the paper also arises in the presence of skewed income shocks, even without shocks to the credit supply. The empirical literature on the skewed effects of business cycles (e.g., Guvenen, Ozkan, and Song, 2014) motivates us to study the effects of a shock that decreases the income of low-income households only over a period of 2 years. We assume the income realization of low-income households (i.e., households whose income is the lowest point in our grid) decreases by 10 percent for 2 years. The persistence of the shock over 2 years implies that this shock affects the income process of all households, either directly because of its current realization or indirectly because of

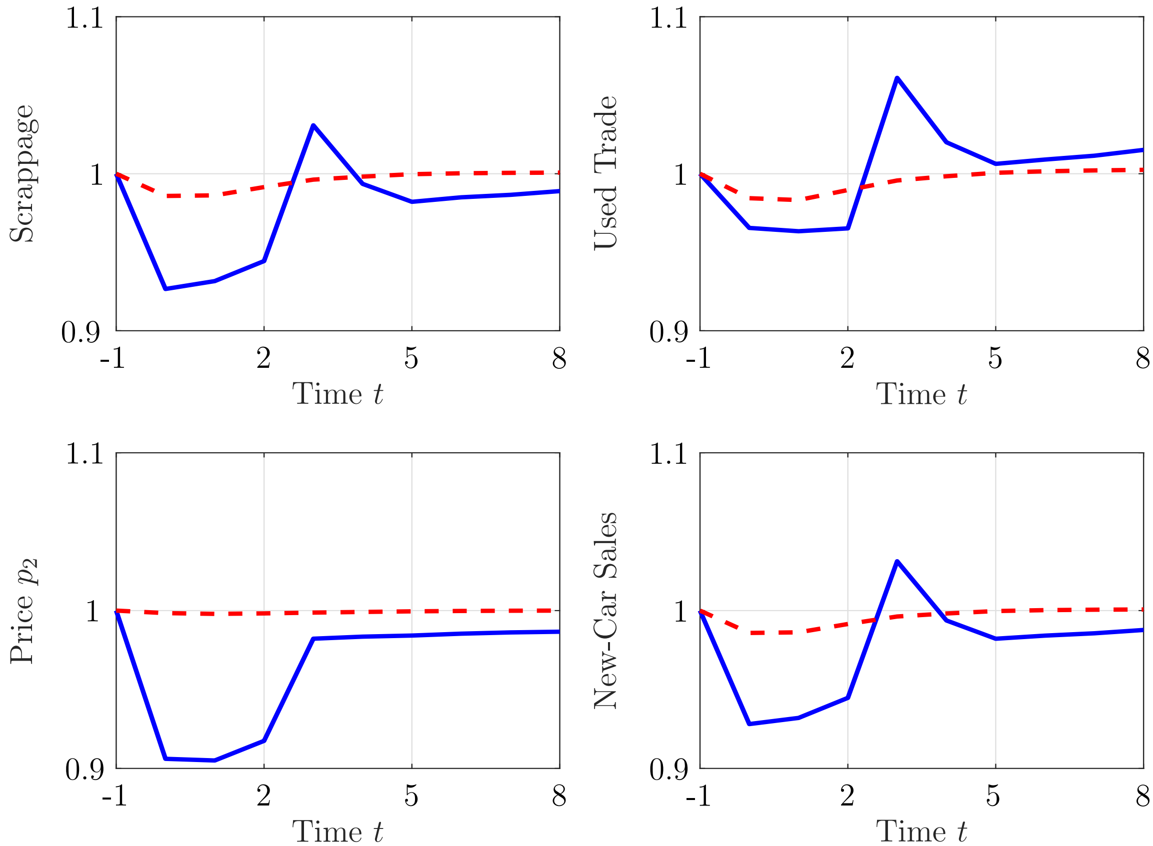

Figure B6: An income shock to low-income households. The economy is in the stationary equilibrium at $t = -1$, and households learn about the new income path at $t = 0$. The horizontal axis displays time t. The top-left panel displays scrappage; the top-right panel the volume of trade of used cars; the bottom-left panel the price p_2 of quality-q_2 cars; and the bottom-right panel the sales of new cars. The solid line displays the baseline case (credit shock), and the dashed line the case of an income shock to low-income households.

the possibility of a transition to the low-income shock in the second period. For simplicity, we focus on the equilibrium in the car market and abstract from bond-market clearing, but the results are robust to general-equilibrium effects from the interest rate.

Figure B6 illustrates the effects of this shock to low-income households on the outcomes of interest. The qualitative effects are similar to those arising after the credit tightening analyzed in Section 6: Low-income households, which are temporarily hit by the income shock, choose to postpone the scrappage of their low-quality cars, inducing a decline in used-car prices and the volume of used-car trade; in turn, this equilibrium effect induces higher-income households to postpone the replacement of their intermediate-quality cars, leading to a decrease in new-car sales. However, the equilibrium dynamics are quantitatively smaller than those reported in Section 6: The drop in new-car sales is less than 2 percent.

Hence, this analysis suggests that skewed income shocks may have contributed to the empirical patterns described in Section 3, but they are unlikely to be their main driver. Nevertheless, they could be potentially relevant to account for the dynamics of durable-goods purchases during other business-cycle episodes in which credit markets were not as affected as during the Great Recession.

C Solution Algorithm

In this appendix, we describe our algorithm to solve for the stationary equilibrium and the transitional dynamics following unexpected aggregate shocks. We emphasize our novel method to find market-clearing prices in the presence of heterogeneous agents making discrete choices, which seems applicable to a large class of models. We use this method to solve for the stationary equilibrium and the transitional dynamics of our model.

C.1 Stationary Equilibrium

We now provide the main steps in solving for the stationary equilibrium of the model (see Definition 1 in Section 4.3).

1. We discretize the set of possible states for bonds b (using a fine grid with $N_b = 600$ nodes) and income w, using the method in Rouwenhorst (1995) with three nodes.

2. We guess a bond price p_b and car prices p_n for $n = 2, ..., N-1$.

3. We solve for the value function V on the discretized state-space by iterating on the Bellman equation (5). We let households choose bonds on a continuum by interpolating the continuation value. We obtain the policy functions g_b and g_n.

4. We compute the stationary distribution m on the discretized state-space using a non-stochastic simulation: We start from an initial distribution and then iterate on the law of motion of the distribution implied by the policy functions and the transition probabilities of the income and depreciation shocks. We allocate households to grid points for bonds according to the distance between their desired level of bonds and the two closest grid points, following the method of Young (2010).

5. We compute excess demand for bonds and cars, and update prices using a quasi-Newton method until all markets clear. We describe the details of the market-clearing procedure in subsection C.3.

C.2 Transitional Dynamics

We now provide the main steps in solving for the transitional dynamics, assuming the economy is initially in the stationary equilibrium and households learn about the new aggregate conditions at $t = 0$. To compute the equilibrium dynamics, we need to solve for sequences of prices $\{p_{b,t}, p_{n,t}\}_{t=0}^{T-1}$, policy functions $\{g_{b,t}, g_{n,t}\}_{t=0}^{T-1}$, and household distributions $\{m_t\}_{t=1}^{T-1}$ such that households maximize utility, all markets clear in each period, and the distribution evolves according to households' policy functions, to the transition probabilities of the idiosyncratic income, and to the depreciation shocks. We apply a sequential solution algorithm as described by Ríos-Rull (1998).

1. We compute both the initial and final stationary equilibria using the algorithm described above.

2. We set the number of periods (years), $T = 30$, by which we assume the economy converges to the final stationary equilibrium.

3. We guess a sequence of bond prices and car prices $\{p_{b,t}, p_{n,t}\}_{t=0}^{T-1}$ for $n = 2, ..., N - 1$.

4. We initialize the algorithm parameter $S = 0$ that we use in the following steps.

5. We obtain a sequence of policy functions $\{g_{b,t}, g_{n,t}\}_{t=S+1}^{T-1}$, by iterating backward in time from $t = T - 1$ to $t = S + 1$ and solving the household maximization problem in each period, using interpolation of the continuation value. Notice that at $t = T - 1$, the continuation value is simply given by the value function V associated with the final stationary equilibrium.

6. Taking as given all prices, decision rules, and value functions from $t = S + 1$ onward, we look for the prices $p_{b,S}$ and $p_{n,S}$ and associated decision rules $g_{b,S}$ and $g_{n,S}$ such that all markets clear at $t = S$, given the distribution of households m_S. We look for market-clearing prices using a quasi-Newton method, described in more detail in subsection C.3.

7. We update the distribution of households using the obtained policy functions and compute m_{S+1}, using a nonstochastic simulation. We allocate households to grid points for bonds according to the distance between their desired level of bonds and the two closest grid points, following Young (2010).

8. We iterate on steps 4-7 by sequentially setting $S = 1, ..., T-1$, hence clearing markets one period at a time and obtaining a new sequence of prices.

9. We compute a convex combination of the guessed price sequence and the newly obtained price sequence and restart from step 4. We continue this procedure until convergence of the price sequence.

C.3 Market-clearing Method

Our model features heterogeneous agents making a discrete choice over car quality. The discreteness of the policy functions generates a challenge in clearing markets: The excess demand function for a given car quality is a step function, leading to either inaccuracy or failure of standard root-finding methods.

To explain this problem and our proposed solution, we now use a simplified version of our model in stationary equilibrium, in which only two car qualities exist, $n = 1, 2$. Thus, we only need solve for the relative price of cars of quality q_2, $p \equiv p_2/p_1$. Car scrappage is exogenous, and so is the bond price. Moreover, let us restrict attention to heterogeneity in income w and wealth b, by assuming that all households have the same no-car utility type θ. Thus, we consider the discretized space for the state (b, w, n).

First, we introduce some convenient notation. Let us consider all households with a given income realization $\bar{w}$ that own cars of a given quality $\bar{n}$. These households differ in their wealth b, which we discretized on a grid $\{b_j\}$ for $j = 1, ..., N_b$, where j denotes a grid point.

Let $m_j(\bar{w}, \bar{n})$ be the fraction of households at grid point j at the beginning of the period. Let $b^*(\bar{w}, \bar{n}; p) \in [\phi, b_{N_b}]$ be the threshold for wealth such that only households with wealth above $b^*(\bar{w}, \bar{n}; p)$ choose a car of quality q_1, given a relative price p; that is,

$$g_n(b, \bar{w}, \bar{n}) = \begin{cases} 2 & \text{if} \quad b \leq b^*(\bar{w}, \bar{n}; p) \\ 1 & \text{if} \quad b > b^*(\bar{w}, \bar{n}; p). \end{cases} \tag{C1}$$

Notice that in general, $b^*(\bar{w}, \bar{n}; p)$ does not coincide with any grid point for b. Let b_J and b_{J+1} be the two neighboring grid points, such that $b_J < b^* < b_{J+1}$.[45]

Total demand for cars of quality 2 coming from households with income $\bar{w}$ and car $\bar{n}$ equals $\sum_{j=1}^{J} m_j(\bar{w}, \bar{n})$; that is, the mass of households whose wealth is below the threshold. Under standard continuity properties of the value function V, the threshold is a continuous function of the price p. Hence, for small changes in p, the threshold $b^*(\bar{w}, \bar{n}; p)$ is still between the same grid points. Accordingly, no change occurs in the total quantity demanded by households with income $\bar{w}$ and car $\bar{n}$. A sufficiently large price change, instead, implies that the threshold crosses one of the closest grid points, either b_J or b_{J+1}, leading to a discrete change in the quantity demanded. This point shows that total demand conditional on a given realization of income and car quality is a step function.

Aggregate demand for cars of quality q_2 is the sum of demands from all discrete income and car-quality values. Because the sum of multiple step functions is also a step function, aggregate demand is a step function. Moreover, the total amount of cars of quality q_2 is fixed at the beginning of the period. Hence, total excess demand (demand minus supply) is also a step function with respect to the price.

Finding a zero of a step function is problematic for numerical nonlinear equation solvers. Moreover, the simple approach of stopping at a price that gives the minimum absolute excess demand can be quite inaccurate, even with a large number of grid points.[46]

We propose an intuitive, efficient, and easily applicable solution to obtain a continuous excess demand function and achieve accuracy in market clearing. The key idea is that

[45] In the interest of simplifying notation, we avoid explicitly expressing J as a function of $(\bar{w}, \bar{n})$, but it is understood that each income and car-quality state has associated thresholds and neighboring grid points.

[46] In our model, this approach does not achieve a market-clearing error below 10^{-3}, even with 1,000 grid points for bonds. Furthermore, this issue cannot be easily solved by using Monte Carlo simulation instead of a nonstochastic simulation. One can use similar arguments to show that a Monte Carlo simulation also leads to an excess demand that takes the shape of a step function. Moreover, the size of the market-clearing error guaranteed by this approach equals the inverse of the number of agents used in the simulation. This relation leads to a substantially higher computational cost than our proposed method, for a given desired level of accuracy.

continuity can be achieved by making the distribution of households close to the threshold depend on the distance between the threshold and the neighboring grid points.

Specifically, we compute the threshold associated with a given guessed price. Next, we take the beginning-of-period distribution m and we move a fraction of agents from grid point J to $J+1$, proportionally to the distance between the threshold and grid point b_{J+1}:

$$m_{J\to J+1} = \frac{b_{J+1} - b^*(\bar{w}, \bar{n}; p)}{b_{J+1} - b_{J-1}} m_J. \tag{C2}$$

We rationalize this choice as follows. We interpret each mass point m_J as a discrete approximation of the true distribution of households with a level of wealth in a neighborhood of grid point b_J. We propose an alternative, continuous approximation of this distribution, which we construct by distributing households at grid point b_J over the interval $[b_{J-1}, b_{J+1}]$. If we distribute these households using a uniform distribution, a fraction $\frac{b_{J+1}-b^*(\bar{w},\bar{n};p)}{b_{J+1}-b_{J-1}}$ of households are at grid point b_J according to the discrete approximation of the distribution, but are instead to the right of the threshold $b^*(\bar{w}, \bar{n}; p)$ under the uniform approximating distribution.[47] Hence, they should make the same car-quality choice as households at grid point b_{J+1}.

Symmetrically, we move a fraction of agents from grid point $J+1$ to J as follows:

$$m_{J+1\to J} = \frac{b^*(\bar{w}, \bar{n}; p) - b_J}{b_{J+2} - b_J} m_{J+1}. \tag{C3}$$

We get a new distribution $\tilde{m}$, which coincides with m, except at the grid points that are closest to the thresholds; in particular, $\tilde{m}_J = m_J + m_{J+1\to J}$ and $\tilde{m}_{J+1} = m_{J+1} + m_{J\to J+1}$. Next, we use the modified distribution to evaluate aggregate demand for car quality q_2. Thanks to the continuity of b^* with respect to the price, it is easy to prove that the expression $\sum_{j=1}^{J} \tilde{m}_j(\bar{w}, \bar{n})$ is a continuous function of p. Hence, total excess demand is a continuous function of the price, allowing us to find a zero with arbitrary accuracy with standard nonlinear solvers.

In the interest of consistency in the treatment of all of the markets, we also use $\tilde{m}$ to clear the bond market. Moving agents to close grid points for bonds is similar to of we deal

[47] Alternative closed-form expressions for the mass of agents who move between grid points can be found by assuming other approximating distributions; for instance, a truncated normal. This alternative assumption leads to quantitatively negligible differences in the solution.

with the discreteness of the grid and continuity of the bond policy function g_b, following the simulation method Young (2010) proposed.

Although we referred to a simplified model, the method generalizes to the richer model of Section 4. In practice, our algorithm to clear markets for both the stationary equilibrium and the transitional dynamics works as follows:

1. We guess prices for bonds and car qualities.

2. We solve the household problem and compute all of the thresholds for wealth such that households are indifferent between any two car qualities chosen in equilibrium, for each level of income, car quality, and type.

3. We transform the distribution by shifting households close to the thresholds proportionally to the distance between the thresholds and the neighboring grid points, as in equations (C2) and (C3).

4. We use the transformed distribution to evaluate excess demand for bonds and car qualities.

5. We update prices using a quasi-Newton method until markets clear.

6. We use the obtained policy functions and transition probabilities of the idiosyncratic shocks to update the transformed distribution associated with equilibrium prices and obtain the next beginning-of-period distribution.