Leasing and Selling in Durable Goods Oligopoly*

Wanjia Zhu†

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Abstract

This paper examines how leasing affects the profitability and market power of durable goods oligopolists. By leasing some new products in addition to selling, oligopolists can earn profits from attracting consumers with high preferences for leasing, alleviating self-competition by controlling the secondary markets, and mitigating the Coase effect they suffer due to the lack of commitment. However, leased products depreciate faster than sold products, which reduces the value of off-lease products to oligopolists. To understand the various interrelated effects of leasing, I develop a dynamic equilibrium model of durable goods oligopoly with leasing, selling, and secondary markets. I calibrate the model to aggregate data from the US heavy-duty truck industry and obtain a good fit. In counterfactuals, I quantify different effects of leasing and assess how quality depreciation and market structure affect these effects. Results show that eliminating leasing decreases truck manufacturers' profits by 83.2% and markups by 31.6%. Manufacturers benefit more from leasing when leased trucks depreciate slower and when there is more competition.

Keywords: Lease, secondary markets, durable goods, heavy-duty trucks
JEL codes: L13, L14, L25, L62

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†Department of Economics, University of Wisconsin-Madison. E-mail: wanjia.zhu@wisc.edu.

1 Introduction

A lease is a contractual agreement where a user, the lessee, makes regular payments to an asset owner, the lessor, in return for the right to use the asset for a limited time. Throughout the world, lease is the most common legal form of holding assets other than ownership (Merrill, 2020). From household goods and passenger cars to healthcare equipment, heavy-duty trucks, and aircraft, leasing is extensively used in durable goods industries. For instance, about one-third of the aircraft operated by major carriers are under an operating lease (Gavazza, 2011); in the late 2000s, around 25% of new cars were leased in both the US and Europe (Johnson, Schneider, and Waldman, 2014).

With the widespread use of leasing, one natural question to ask is: How much does leasing benefit durable goods producers? There is a large theoretic literature on the benefits of leasing, but empirical works are still limited. How much leasing benefits firms is ultimately an empirical question because the answer depends on underlying features of industries. For instance, a common assumption made in theoretic works is a monopoly market. But most durable goods industries are oligopolistic, in which the benefits from leasing can be different from those under monopoly.

In this paper, I build and calibrate a dynamic equilibrium model of durable goods oligopoly with leasing, selling, and secondary markets. The demand model features a heterogeneous consumer population. The supply model is a dynamic game where oligopolistic producers make concurrent leasing and selling decisions, and are involved in simultaneous move quantity competition every period. Prices are determined in a Markov Perfect Equilibrium. I use the model to examine how leasing affects the profitability and market power of durable goods oligopolists in an empirical setting. I also assess how the effects of leasing depend on underlying market features including quality depreciation and market structure.

My model allows durable goods producers to benefit from leasing through three interrelated channels. These three effects of leasing are all documented in the durable goods literature, but this paper is among the first ones to incorporate them into an empirical framework.

First, there is a market expansion effect. By offering leases, durable goods producers can attract consumers with high preferences for leasing who would otherwise buy from the secondary markets or not buy any goods at all. This expansion in market brings profits to producers. Furthermore, when there are leasing options, those who buy new trucks are consumers with higher preferences for buying. Producers can extract a larger surplus from these consumers and get a higher markup.

Second, there is a market control effect. Since durable goods producers retain the ownership of leased products, they in essence control a part of the secondary markets. Producers are able to reduce the availability of used goods by scrapping some or all of the off-lease products they own. In this way, they reduce the competition with their past selves in the secondary markets.

The alleviation of self-competition can increase the profits and markups of producers.[1]

Third, there is a time consistency effect. The resale value of durable goods depend on future prices. Durable goods producers can raise this resale value and thus their current profits if they can commit to restricting future outputs and keeping future prices high. However, in the absence of the ability to commit, producers are time inconsistent: once the future comes, they increase outputs. The profit loss from this overproduction is called the Coase effect.[2] There is no Coase effect on leased products because they are owned by producers and do not have resale values. In other words, leasing benefits producers by mitigating the Coase effect.

One disadvantage of leasing is that leased products depreciate faster than sold products, which reduces the value of off-lease products to durable goods producers. The faster quality depreciation for leased products could be from various sources. First, leased products are used more intensely. For instance, leased commercial aircraft fly 6.5% more hours than owned aircraft (Gavazza, 2011), and leased heavy-duty trucks are driven 9.7% more miles than sold trucks.[3] Second, due to moral hazard, leased products are not well taken care of and are more likely to have accidents (Schneider, 2010).

I calibrate my model's parameter values by matching the model's steady-state predictions to aggregate data from the US heavy-duty truck industry in 2002. In this industry, around 38% of new and used trucks are leased. The key parameters I calibrate are trucking company's preference for leasing and manufacturer's marginal cost of production. The market expansion effect is larger when the preference for leasing is higher. The marginal cost of production implies markup since truck prices are observed. This suggests the extent of the overproduction and price decrease due to the Coase effect, which in turn indicates the magnitude of the time consistency effect. The data moments I use to pin down the parameters in my model are the choice patterns of trucking companies with different characteristics, the aggregate market shares of different trucks, the fraction of new trucks that are leased, and the truck prices.

In the calibration exercise, one challenge is computing the equilibrium of my dynamic model, which has multiple continuous state variables and choice variables. Solving such a model is complicated and requires a lot of computing power. Following Chen, Esteban, and Shum (2013), I apply the collocation method to compute equilibrium.

Using the calibrated parameter values, counterfactual experiments reveal four main findings. First, the overall effects of leasing are huge. Eliminating leasing decreases truck manufacturers' profits by 83.2% and markups by 31.6%.

Second, the benefits from leasing are through the market expansion effect and the time consistency effect. The market control effect is zero. Manufacturers do not scrap any

[1]This effect is pointed out in Waldman (1997) and Hendel and Lizzeri (1999).

[2]This effect is pointed out in Coase (1972) and Bulow (1982).

[3]Calculated from the 1992, 1997, and 2002 Vehicle Inventory and Use Survey by the author.

off-lease trucks in the steady state. The time consistency effect on profit is positive and large. In an environment with full commitment where there is no time consistency effect, eliminating leasing decreases manufacturers' profits by 65.3%, which is smaller than 83.2% in the baseline. Furthermore, the different effects of leasing are interdependent. When there is full commitment, manufacturers scrap over half of the off-lease trucks they own, and the market control effect turns positive.

Third, manufacturers benefit more from leasing when leased trucks depreciate slower. This is because the value of off-lease trucks to manufacturers is higher with a slower depreciation speed. However, the changes in the benefit from leasing are not large. When the extra depreciation for leased trucks increases from zero to around 25%, the relative profit loss from eliminating leasing decreases from 85.0% to 81.2%, and the relative markup loss decreases from 35.9% to 28.9%.

Lastly, manufacturers benefit more from leasing when there is more competition. Since manufacturers compete in a Cournot manner, they produce more than the joint-profit-maximizing industry level. This overproduction leads to profit losses because there are more used trucks in the secondary markets, creating self-competition. Leasing mitigates this effect because leased trucks do not go to the secondary markets. With more competition, the profit loss from overproduction increases and leasing becomes more effective in reducing this loss. When the number of manufacturers increases from 1 to 6, the relative profit loss from eliminating leasing increases from 64.9% to 90.9%. Market structure affects the benefit from leasing on markup in a nonlinear way.

These results have potentially important implications for antitrust policies. It is useful to understand the effects of leasing when studying durable goods industries. Depending on the industry, firms can gain and exercise market power through leasing, in which case ignoring leasing may lead to biased results. That said, this paper does not suggest eliminating leasing as it is not only unrealistic but also undesirable since it decreases consumer surplus. In some cases, policies that limit firms' ability to lease might be useful.

The remainder of the paper is organized as follows. Section 2 discusses the related literature. In section 3, I present my dynamic equilibrium model. Section 4 introduces the US heavy-duty truck industry and discusses the data. Section 5 describes model calibration. I discuss the results of counterfactual experiments in section 6. Section 7 concludes.

2 Related Literature

This paper builds on and adds to four strands of literature. First, a large strand of the literature studies the incentives of producers to lease. Most of them are theoretic works studying specific benefits of leasing or empirical works testing theoretic predictions. Waldman

(1997) and Hendel and Lizzeri (1999) show that leasing may allow producers to gain market power in the markets for used products via the market control effect. Bulow (1982) shows that a durable-goods monopolist may prefer to lease because of the time consistency effect. Other incentives of leasing include that leasing mitigates adverse selection (Hendel and Lizzeri (2002), Johnson and Waldman (2003), Johnson, Schneider, and Waldman (2014), Gilligan (2004)) and that leasing can be used to transfer risk (Wyman (1973), Copeland and Weston (1982)). My paper complements this literature in two ways. First, I allow for multiple interdependent benefits of leasing. Second, I quantify these benefits in an empirical setting. Some theoretic or theory-testing papers study why producers lease in certain cases. For instance, leasing is more likely to occur when leased products depreciate differently from sold products (Desai and Purohit, 1998), when competition decreases (Desai and Purohit, 1999), and when there is a complementary product sold by a competitor (Bhaskaran and Gilbert, 2005). My paper contributes in the way that I allow depreciation and competition to change in counterfactual environments, and quantify the benefits of leasing in these environments.

Second, my paper relates to studies on the corporate decisions to lease. Eisfeldt and Rampini (2009) shows that more financially constrained firms lease more of their capital. Gavazza (2010) shows that users are more likely to lease more-liquid assets. Dasgupta, Siddarth, and Silva-Risso (2007) shows that consumers are more likely to lease cars with higher maintenance costs. This paper relates by allowing consumers to have heterogeneous preferences for leasing.

Third, a series of papers study the impact of leasing on market outcomes. Using data on commercial aircraft, Gavazza (2011) shows that leased assets trade more frequently and produce more output than owned assets. Schneider (2010) finds that leased taxi cabs are more likely to have unpleasant driving outcomes due to moral hazard. Other market outcomes studied include financial performance (Bourjade, Huc, and Muller-Vibes, 2017) and environmental impact (Agrawal, Atasu, and Ülkü, 2021). This paper differs in two ways. First, I focus on two basic yet important market outcomes, profit and markup. Second, I use a structural model, which enables me to study the impact of leasing in counterfactual environments.

Lastly, there is an empirical literature on durable-goods markets using dynamic equilibrium models. Notable examples include Chen, Esteban, and Shum (2013), Esteban and Shum (2007), and Nair (2007). Chen, Esteban, and Shum (2013) is the most related paper in terms of methodology. The authors build and calibrate a model with transaction costs in the secondary market, and quantify the effects of secondary markets on producers' profits. This paper differs from their work by modeling producers as both selling and leasing products. For tractability reasons, I abstract away from transaction cost.

3 Model

I build a dynamic equilibrium model of durable goods oligopoly with leasing, selling, and secondary markets. Since I calibrate the model to the US heavy-duty truck industry and for ease of reference, I describe the durable goods as "trucks", the economic agents which use durable goods as "trucking companies", and the economic agents which produce durable goods as "manufacturers".[4] In the model, trucking companies have heterogeneous valuations for trucks and buy or lease new or used trucks in each period. Manufacturers choose the quantity of new trucks to produce, the fraction of new trucks to sell, and the quantities of off-lease trucks to lease in each period. Prices are determined in a Markov Perfect Equilibrium. Time is discrete. Trucking companies and manufacturers are infinitely lived, forward looking, and time consistent.

Trucks live for 3 periods. Truck ages are indexed by $a = 0, 1, 2$, where $a = 0$ means a new truck. Sold trucks of the same vintage are homogeneous and similarly, leased trucks of the same vintage are homogeneous. I assume there is no adverse selection.[5] Let α_a denote the quality of sold trucks of age a. Leased new trucks have the same quality as sold new trucks but depreciate faster.[6] Let $\lambda_1, \lambda_2 \in [0, 1]$ denote the relative quality differences between leased and sold trucks of age 1 and 2, respectively. The quality of leased age 1 trucks is $\alpha_1(1 - \lambda_1)$ and the quality of leased age 2 trucks is $\alpha_2(1 - \lambda_2)$.

A lease term is one period. I assume that all leased trucks are returned to the manufacturers at the end of the lease term and lessees do not have an option to buy.[7] I further assume that off-lease trucks can only be leased again or get scrapped and do not go to the secondary markets.[8] Trucks randomly die each period due to accidents and breakdowns. Let d_a^S, d_a^L

[4] The model is a general economic model and can be applied to various durable goods industries, not only the heavy-duty truck industry.

[5] I abstract away from adverse selection in order to have a tractable model. As pointed out in the theoretic literature (for example, Hendel and Lizzeri (2002)), leasing can mitigate adverse selection. I expect that manufacturers would benefit more from leasing if there were adverse selection.

[6] Hendel and Lizzeri (2002) shows that for passenger cars, returned off-lease cars are of higher average quality than cars sold in the used market under selling contracts. This is mainly because of adverse selection. I do not find such evidence in the heavy-duty truck industry.

[7] Considering lease contracts with an option to buy will complicate my model and is unnecessary for two reasons. First, in the heavy-duty truck industry, although many lease agreements come with the option to buy at maturity, exercising this option is not common. There is a lot of discussion online on why lease buyout is not a good deal. Second, Hendel and Lizzeri (2002) and Johnson and Waldman (2003) point out that lease contracts with an option to buy are used to reduce the adverse selection problem, and that such contracts are ineffective when the qualities of used goods are observable. Since adverse selection is not the focus of this paper, assuming lessees do not have an option to buy will not affect my results much.

[8] Manufacturers do not have incentives to sell off-lease trucks since that cannibalizes their profits from new trucks. In reality, lease contracts are through local dealers. Leased trucks are returned to dealers but are owned by manufacturers. After trucks are returned, manufacturers lease them again, sell them to the contracted dealers, or put them in auctions for other dealers to buy. I do not study dealership in this paper.

denote the proportion of sold/leased new trucks that survive to age a. The survival rates are exogenous.

3.1 Trucking Companies' Problem

There is a continuum of trucking companies with unit mass on the demand side. There are 6 inside alternatives: buy or lease an age 0 or 1 or 2 truck. The outside option is not using any truck.[9] I denote the inside options by $B0, L0, B1, L1, B2, L2$, where B/L means buy/lease and 0/1/2 means the age of the truck. The outside option is denoted by O. Let J be the set of all alternatives and J_I be the set of all inside options.

A trucking company chooses a sequence of truck choices to maximize its discounted lifetime utility. In each period t, the utility gain of trucking company i from choosing alternative $j \in J$ is

$$v_{ijt} = \theta_i q_j + \xi_{i,a(j)} + \xi_{i,l(j)} + \epsilon_{ijt}$$

for inside options and is $v_{ijt} = \epsilon_{ijt}$ for the outside option. θ_i is i's preference for quality. q_j is the quality of alternative j. $\xi_{i,a(j)}$ is a trucking company-truck age fixed effect which measures i's preference for truck age. $\xi_{i,l(j)}$ is a trucking company-leasing fixed effect which measures i's preference for leasing. The joint cumulative distribution function of $\{\theta_i, \xi_{i,a(j)}, \xi_{i,l(j)}\}_{j \in J_I}$ is F. ϵ_{ijt} is a time-varying utility shock. I assume ϵ_{ijt} is i.i.d. across (i, j, t) and follows an extreme value type I distribution with location parameter 0 and scale parameter σ_ϵ.

Let p_{at}, l_{at} denote the selling price and lease price of an age a truck in period t. The prices are determined in equilibrium, which is described in section 3.3. Trucking companies take current prices as given and form rational expectations of future prices.

Assume that there is no transaction cost and that trucking companies' period utility function is quasi-linear in money. These assumptions imply that the trucking companies' choices in any period does not depend on the past and future, and trucking companies act as if maximizing a single-period utility function in each period.[10] The trucking companies' problem is in essence a static problem.[11] Trucking company i's optimal choice in period t is

[9]In reality, trucking companies can buy or lease multiple trucks, and they may not operate at full capacity. For simplicity, I assume that trucking companies make independent decisions for each truck in their fleets at full capacity. For instance, if a trucking company's fleet capacity is 5 trucks but it only buys 2 new trucks, then I see the company as making 5 independent decisions, of which it chooses to buy a new truck twice and chooses the outside option 3 times.

[10]See Esteban and Shum (2007), Berkovec (1985).

[11]Allowing transaction costs will complicate my model because trucking companies' choices and utilities are state-dependent and my demand model becomes dynamic. Since my supply model is dynamic, having dynamics on both the demand and supply side of the market is not tractable for this project.

determined by comparing the utility function

$$u_{ijt} = v_{ijt} - r_{jt}$$

across all alternatives $j \in J$, where

$$r_{jt} = \begin{cases} p_{0t} - \delta p_{1,t+1}, & \text{if } j = B0 \\ l_{0t}, & \text{if } j = L0 \\ p_{1t} - \delta p_{2,t+1}, & \text{if } j = B1 \\ l_{1t}, & \text{if } j = L1 \\ p_{2t}, & \text{if } j = B2 \\ l_{2t}, & \text{if } j = L2 \\ 0, & \text{if } j = O \end{cases}$$

is the implicit rental price paid for alternative j in t. δ is the time discount factor. For sold trucks, r_{jt} is the difference of the selling price in the current period and the discounted resale price in the next period's secondary market.[12] For leased trucks, r_{jt} equals the lease price.

By the standard logit formula, the probability that trucking company i chooses alternative j in period t is

$$s_{ijt} = \frac{\exp\left((\theta_i q_j + \xi_{i,a(j)} + \xi_{i,l(j)} - r_{jt})/\sigma_\epsilon\right)}{1 + \sum_{k \in J_I} \exp\left((\theta_i q_k + \xi_{i,a(k)} + \xi_{i,l(k)} - r_{kt})/\sigma_\epsilon\right)}.$$

Aggregating up the choices for all trucking companies, the aggregate quantity demanded for alternative j in period t is

$$S_{jt}^{Demand} = \int s_{ijt} \mathrm{d}F, \tag{1}$$

where the integral is with respect to $\{\theta_i, \xi_{i,a(j)}, \xi_{i,l(j)}\}_{j \in J_I}$.

3.2 Manufacturers' Problem

There are M manufacturers producing homogeneous new trucks. All manufacturers have the same constant marginal cost of production c. In each period, manufacturers choose quantities simultaneously to maximize the sum of their current profit and discounted future profit while accounting for the optimality of their future choices.

The state variable, $\boldsymbol{Y}_t$, is a vector of the quantities of used trucks of different ages in the

[12] $j = B2$ is an exception. Since trucks live for 3 periods, sold age 2 trucks do not have any resale value except for a small amount of payment from scrappage, which I set as zero for simplicity.

selling and leasing markets in period t. To be specific, $\boldsymbol{Y}_t$ has 4 elements: the quantity of age 1 trucks in the selling market y^S_{1t}, the quantity of age 2 trucks in the selling market y^S_{2t}, the quantity of age 1 trucks in the leasing market y^L_{1t}, and the quantity of age 2 trucks in the leasing market y^L_{2t}.

The choice variables of manufacturer m in period t are the quantity of new trucks to produce x_{mt}, the fraction of new trucks to sell f_{mt}, the quantity of age 1 off-lease trucks to lease z_{1mt}, and the quantity of age 2 off-lease trucks to lease z_{2mt}. Let $\boldsymbol{X}_{mt} = (x_{mt}, f_{mt}, z_{1mt}, z_{2mt})$ be the vector of manufacturer m's choices, $\boldsymbol{X}_t = (\boldsymbol{X}_{1t}, \ldots, \boldsymbol{X}_{Mt})$ be the vector of all manufacturers' choices, and $\boldsymbol{X}_{-mt}$ be the vector containing all elements of $\boldsymbol{X}_t$ but excluding $\boldsymbol{X}_{mt}$.

Since the quantity of age a ($a = 1, 2$) sold/leased trucks in period $t+1$ is the quantity of age $a-1$ sold/leased trucks in period t that survive to period $t+1$, the law of motion of the state variable $\boldsymbol{Y}_t$ can be written as

$$
\begin{aligned}
y^S_{1,t+1} &= d^S_1 \sum_{m=1}^{M} x_{mt} f_{mt} \\
y^S_{2,t+1} &= \frac{d^S_2}{d^S_1} y^S_{1t} \\
y^L_{1,t+1} &= d^L_1 \sum_{m=1}^{M} x_{mt}(1 - f_{mt}) \\
y^L_{2,t+1} &= \frac{d^L_2}{d^L_1} \sum_{m=1}^{M} z_{1mt},
\end{aligned}
\tag{2}
$$

where d^S_a, d^L_a are the proportions of sold/leased new trucks that survive to age a. I denote the law of motion by $\boldsymbol{L}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$.

Selling prices and lease prices are determined in a Markov Perfect Equilibrium (see section 3.3) and depend on the current state and choice variables. Let $\boldsymbol{P}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$ denote the vector of the inverse demand functions of sold/leased trucks of different ages. In other words, $\boldsymbol{P}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$ is the vector of all selling and lease prices as functions of $\boldsymbol{X}_t, \boldsymbol{Y}_t$.

Let $V_m(\boldsymbol{Y}_t)$ denote manufacturer m's value function. Given the law of motion $\boldsymbol{L}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$, the inverse demand functions $\boldsymbol{P}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$, and the rivals' choices $\boldsymbol{X}_{-mt}$, the profit maximization problem of manufacturer m is described by the following Bellman equation:

$$
\begin{aligned}
V_m(\boldsymbol{Y}_t) = \max_{x_{mt}, f_{mt}, z_{1mt}, z_{2mt}} \; & p_{0t}\left((\boldsymbol{X}_{mt}, \boldsymbol{X}_{-mt}), \boldsymbol{Y}_t)\right) x_{mt} f_{mt} + l_{0t}\left((\boldsymbol{X}_{mt}, \boldsymbol{X}_{-mt}), \boldsymbol{Y}_t)\right) x_{mt}(1 - f_{mt}) \\
& + l_{1t}\left((\boldsymbol{X}_{mt}, \boldsymbol{X}_{-mt}), \boldsymbol{Y}_t)\right) z_{1mt} + l_{2t}\left((\boldsymbol{X}_{mt}, \boldsymbol{X}_{-mt}), \boldsymbol{Y}_t)\right) z_{2mt} \\
& - c x_{mt} + \delta V_m(\boldsymbol{L}\left((\boldsymbol{X}_{mt}, \boldsymbol{X}_{-mt}), \boldsymbol{Y}_t)\right)),
\end{aligned}
\tag{3}
$$

subject to

$$
\begin{aligned}
&0 \le x_{mt} + z_{1mt} + z_{2mt} \le 1 - y_{1t}^S - y_{2t}^S \\
&0 \le f_{mt} \le 1 \\
&0 \le z_{1mt} \le \frac{y_{1t}^L}{M} \\
&0 \le z_{2mt} \le \frac{y_{2t}^L}{M}.
\end{aligned}
$$

The first constraint restricts manufacturer m to sell and lease no more than the available market size.[13] The last two constraints require manufacturer m to lease no more than what they own.[14] Let $\boldsymbol{X}(\boldsymbol{Y}_t)$ denote the vector of all manufacturers' optimal choices as functions of the state variable $\boldsymbol{Y}_t$.

Aggregating up the choices for all manufacturers, the aggregate quantity supplied for alternative $j \in J_I$ in period t is

$$
S_{jt}^{Supply} = \begin{cases} \sum_{m=1}^{M} x_{mt} f_{mt}, & \text{if } j = B0 \\ \sum_{m=1}^{M} x_{mt}(1 - f_{mt}), & \text{if } j = L0 \\ y_{1t}^S, & \text{if } j = B1 \\ \sum_{m=1}^{M} z_{1mt}, & \text{if } j = L1 \\ y_{2t}^S, & \text{if } j = B2 \\ \sum_{m=1}^{M} z_{2mt}, & \text{if } j = L2. \end{cases} \tag{4}
$$

Notice that the $x_{mt}, f_{mt}, z_{1mt}, z_{2mt}$ in equation (4) are the optimal choices of manufacturer m and are functions of the state variable $\boldsymbol{Y}_t$.

3.3 Equilibrium

I focus on a symmetric Markov Perfect Equilibrium, in which the manufacturers' equilibrium decision rules are the same and only depend on the payoff-relevant state variable $\boldsymbol{Y}_t$. The equilibrium is a sequence of trucking companies' choices over time, a sequence of manufacturers' choices over time $\{\boldsymbol{X}_t\}_{t=1}^{\infty}$, a sequence of selling and lease prices over time $\{\boldsymbol{P}_t\}_{t=1}^{\infty}$, and a law of motion $\boldsymbol{Y}_{t+1} = \boldsymbol{L}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$, that satisfy the following requirements:

(i) Optimality: In each period t, trucking companies choose the utility-maximizing alternatives. Manufacturers maximize their profits, i.e., $\boldsymbol{X}_t = \boldsymbol{X}(\boldsymbol{Y}_t)$.

[13] Since the total market size is 1 and there are $y_{1t}^S + y_{2t}^S$ used trucks in the secondary markets, manufacturer m can sell and lease at most $1 - y_{1t}^S - y_{2t}^S$ trucks.

[14] Since the M manufacturers are identical, they own the same amount of off-lease trucks.

(ii) Market clearance: In each period t, demand equals supply for each inside option j, i.e., $S_{jt}^{Demand} = S_{jt}^{Supply}$ for all $j \in J_I$, where S_{jt}^{Demand} is defined in equation (1) and S_{jt}^{Supply} is defined in equation (4). Market clearance determines the current prices $\boldsymbol{P}_t = \boldsymbol{P}(\boldsymbol{X}_t, \boldsymbol{Y}_t)$.

(iii) Consistency of the inverse demand functions: The next period's prices are $\boldsymbol{P}_{t+1} = \boldsymbol{P}(\boldsymbol{X}(\boldsymbol{L}(\boldsymbol{X}_t, \boldsymbol{Y}_t)), \boldsymbol{L}(\boldsymbol{X}_t, \boldsymbol{Y}_t))$. Trucking companies and manufacturers form rational expectations of future prices consistent with the law of motion.

(iv) The law of motion is $\boldsymbol{Y}_{t+1} = \boldsymbol{L}(\boldsymbol{X}(\boldsymbol{Y}_t), \boldsymbol{Y}_t)$, where $\boldsymbol{L}(\cdot, \cdot)$ is defined in equation (2).

In section 5, I compute the steady state of the Markov Perfect Equilibrium and calibrate it to data from the US heavy-duty truck industry.

4 Market Setting and Data

4.1 The US Heavy-Duty Truck Industry

In the US, commercial truck classification is based on vehicles' gross vehicle weight rating (GVWR), which is the maximum weight a vehicle is designed to carry including the weight of the vehicle, accessories, passengers, fuels, and cargo. Trucks with a GVWR of more than 26,001 pounds are heavy-duty trucks. These trucks are used for various purposes including transportation and construction. In this paper, I focus on long-distance freight trucking, which is the major use of heavy-duty trucks. Examples of the trucks under study are straight trucks and tractor-trailers we commonly see on highways.

Buyers/Lessees of heavy-duty trucks are trucking companies engaged in the long-distance transportation of palletized commodities. They typically provide trucking between metropolitan areas and regions that may cross North American country borders and have a driving radius of 200 miles or more. The long-distance freight trucking market is highly fragmented. There were 249 thousand trucking companies in 2002, and more than 90% of them were owner-operators (IBISWorld, 2021b). Trucking companies vary in company size and business volume. There are small companies with fewer than 5 employees and less than \$100 thousand annual revenue as well as larger companies with more than 50 employees and more than \$5 million annual revenue.[15] Lease contracts are commonly used to acquire trucks. In 2002, 37.53% of new trucks were acquired by leasing.

The supply side of the industry is highly concentrated. Freightliner, International, Kenworth, and Peterbilt are four major manufacturers that dominate the production of

[15] According to US Census Bureau (2005), in terms of employment size, 58% of trucking companies have fewer than 5 employees, 34% have 5-50 employees, and 8% have more than 50 employees. In terms of revenue size, 13% of trucking companies have less than \$100 thousand annual revenue, 77% have \$100 thousand to \$5 million revenue, and 10% have more than \$5 million revenue.

heavy-duty trucks.[16] In 2002, the big four manufacturers accounted for 80% of the market in terms of units. Big manufacturers are homogeneous in many aspects. Table 1 shows that the big four manufacturers had similar market shares and leased similar amount of new trucks in 2002. Big manufacturers also have similar cost structures, production technologies, and investment in new engine and safety technologies.

Table 1: The big four manufacturers in 2002

Manufacturer	Market share (%)	Fraction of new trucks leased (%)
Freightliner	36.03	40.58
International	17.43	36.99
Kenworth	13.32	37.22
Peterbilt	12.78	37.89

Notes: All numbers are calculated from the 2002 VIUS. The market share is the percentage of units a manufacturer has in the overall market.

4.2 Data

Three sources of data are used in this paper. The first one is microdata on heavy-duty truck leases and purchases collected in 2002 under a program known as the Vehicle Inventory and Use Survey (VIUS). The 2002 VIUS is a probability sample of all trucks registered (or licensed) in the US as of July 1, 2002. The US Census surveyed about 136 thousand owners of trucks and asked them questions about their trucks, the acquisition and use of their trucks, and about the owners themselves.[17] I observe the model year of the truck, when the truck was acquired, whether the truck was leased or purchased, and the characteristics of the truck operator. I also observe an aggregation weight that enables me to relate the sample to population. By focusing on heavy-duty trucks used for long-distance freight trucking, I get a sample of 3,201 observations representing a population of 1.9 million trucks.

The second piece of data I use is a sample of disposed trucks constructed from three rounds of VIUS, the 2002, 1997, and 1992 VIUS. Each round of VIUS data includes trucks reported to be disposed of in the survey year. For each disposed truck, I observe its model year, disposal time, and how it was disposed.[18] I calculate the average lifetime of sold/leased

[16] These four manufacturers are in fact subsidiaries of manufacturing conglomerates with other brands of trucks and other businesses. Freightliner is owned by Daimler AG. International is a brand of Navistar, whose ultimate parent is Volkswagen. Kenworth and Peterbilt are both subsidiaries of PACCAR Inc but operate as independent and competing manufacturers. Since ownership structure is not the focus of this paper, I treat the four manufacturers as independent companies.

[17] For leased trucks, data was collected from lessees. When a leased truck is registered, the registration certificate will reflect the lessor as the owner, but the lessee's name and address will also be on the registration. In this paper, I use "truck operators" to refer to owners of sold trucks and lessees of leased trucks.

[18] In the data, disposed trucks were sold or given away, traded in, junked/scrapped/otherwise destroyed, returned to leasing company, or repossessed.

trucks by looking at the age of trucks when junked, scrapped, or otherwise destroyed. On average, sold trucks live for 6.6 years and leased trucks live for 6.4 years.

The third data source is a panel of all heavy-duty truck models sold in the US from 2008 to 2011 from annual issues of the Truck Blue Book. For each truck model, I observe the brand name, model name, model year, and its retail price in each quarter from 2008 to 2020. Unfortunately, I only observe the selling prices of trucks. Lease prices are not available. All prices are converted to 2000 constant US dollar using the Consumer Price Index (CPI). Since sold trucks of the same age are homogeneous in my model, I aggregate prices across truck models and get a single aggregate price for each truck age group. Furthermore, since trucks live for 3 periods in my model, I aggregate used trucks younger than 4 years old as age 1 trucks, and used trucks from 5 to 16 years old as age 2 trucks. New trucks are still new trucks. The aggregate selling price is \$63,285.9 for new trucks, \$29,566.1 for age 1 trucks, and \$13,161.5 for age 2 trucks. Details of truck price aggregation are in appendix A.2.

I use two characteristics to measure the heterogeneity of truck operators, or trucking companies. The first one is the average number of pickup/delivery trips per truck each week, and the second one is the fleet size, or the total number of vehicles (including all types of trucks, trailers, and small vehicles) the trucking company has. The average number of trips per week measures the business volume of trucking companies, while the fleet size measures the size of trucking companies.[19]

Table 2 shows summary statistics for trucking companies' characteristics in my sample. The average number of trips per week has a mean of 8.4. Most trucking companies have fewer than 8 trips per week while there are companies with a lot of pickup/delivery trips. Operators of sold trucks and younger trucks tend to have more trips, indicating that trucking companies with a larger business volume might prefer buying and prefer younger trucks. The average fleet size is 57.3 vehicles. There is wide variation in fleet size across trucking companies, ranging from around 10 vehicles to around 100 vehicles. Similar to the average number of trips per week, fleet size might affect trucking companies' preferences for trucks. Operators of sold trucks and younger trucks tend to have a larger fleet size.

5 Calibration

In this section, I describe the parameterization of the model in section 3 and the calibration procedures. I choose some parameters exogenously based on data or recent empirical studies. The other parameters are obtained by finding values that give the best fit between the

[19]The fleet size is potentially endogenous since it is affected by a trucking company's purchase/lease decision. However, due to data limitation, it is the best available variable that I can use to describe the size of trucking companies. As a robustness check, I replace it with the total number of vehicles excluding heavy-duty trucks, and the demand-side calibration results do not change much.

Table 2: Summary statistics for surveyed truck operators

	Mean	Std. Dev.	25%	Median	75%
Average number of trips per week					
All operators	8.4	14	3	4	8
Operators of sold trucks	8.6	14.1	3	4	8
Operators of leased trucks	7.9	13.8	3	4	7
Operators of new trucks	8.9	15.2	3	4	8
Operators of age 1 trucks	7.2	10.4	3	5	7
Operators of age 2 trucks	7.4	12	3	4	7
Fleet size					
All operators	57.3	39	17	66	97
Operators of sold trucks	58.8	37.9	17	66	97
Operators of leased trucks	54.5	40.8	14	66	97
Operators of new trucks	68.9	35.3	47	70	97
Operators of age 1 trucks	38.6	37.8	11	19	67
Operators of age 2 trucks	27.1	29.9	6	14	38
Number of observations			3,201		

model's steady-state predictions and the average aggregate values for the US heavy-duty truck industry in 2002. To reduce the computational burden, I calibrate the demand and supply models separately and in steps.

Table 3 shows the calibrated values of parameters I choose exogenously. The number of homogeneous manufacturers on the supply side is 4, corresponding to the big four truck manufacturers in the US. The time discount factor is set to be 0.98, which is a standard value in the literature. The survival rates for new trucks (d_1^S, d_1^L, d_2^S, and d_2^L) are calibrated to match the average lifetime of sold/leased trucks, which is 6.6 years/6.4 years. For sold trucks, given the death probability of sold trucks in a year η^S, the truck's expected lifetime is

$$\phi(\eta^S) = 0 \cdot \eta^S + 1 \cdot (1-\eta^S)\eta^S + 2 \cdot (1-\eta^S)^2\eta^S + \cdots = \frac{1}{\eta^S} - 1.$$

I therefore solve $\phi(\eta^S) = 6.6$ to obtain $\eta^S = 0.1316$. Since used trucks from 1 to 4 years old are aggregated as age 1 trucks and used trucks from 5 to 16 years old are aggregated as age 2 trucks, the proportion of sold new trucks surviving to age 1 and age 2 are $d_1^S = \frac{1}{4}\sum_{a=1}^{4}(1-\eta^S)^a = 0.7116$ and $d_2^S = \frac{1}{12}\sum_{a=5}^{16}(1-\eta^S)^a = 0.2553$, respectively. The survival rates for leased new trucks are calculated in the same way.

Table 3: Exogenously chosen parameters

Parameter	Calibrated value
Number of manufacturers (M)	4
Time discount factor (δ)	0.98
Proportion of sold new trucks surviving to age 1 (d_1^S)	0.7116
Proportion of leased new trucks surviving to age 1 (d_1^L)	0.7048
Proportion of sold new trucks surviving to age 2 (d_2^S)	0.2553
Proportion of leased new trucks surviving to age 2 (d_2^L)	0.2461

5.1 Parameterization

Trucking company i's preference for truck quality is a linear function of the trucking company's characteristics:

$$\theta_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i},$$

where X_{1i} is the logarithm of i's average number of trips per week and X_{2i} is the logarithm of i's fleet size.

The preference for truck age, $\xi_{i,a(j)}$, is

$$\xi_{i,a(j)} = \begin{cases} 0, & \text{if } a(j) = 0 \\ \gamma_0^a + \gamma_1^a X_{2i}, & \text{if } a(j) = 1 \\ \gamma_0^a + \gamma_2^a X_{2i}, & \text{if } a(j) = 2. \end{cases}$$

$\xi_{i,a(j)}$ is normalized to be zero when trucking company i buys/leases a new truck and is a function of i's fleet size if i buys/leases a used truck. I do not allow $\xi_{i,a(j)}$ to depend on both characteristics of i because otherwise the effects of X_{1i}, X_{2i} on θ_i and $\xi_{i,a(j)}$ are not separately identified. Similarly, I parameterize the preference for leasing, $\xi_{i,l(j)}$, as

$$\xi_{i,l(j)} = \begin{cases} 0, & \text{if } l(j) = 0 \\ \gamma_0^l + \gamma_1^l X_{1i}, & \text{if } l(j) = 1. \end{cases}$$

Trucking company i gets a nonzero utility gain when it leases a truck.

Furthermore, I assume trucking companies' characteristics, (X_{1i}, X_{2i}), jointly follows a lognormal distribution:

$$(X_{1i}, X_{2i}) \sim LogNormal\left(\begin{pmatrix}\mu_1 \\ \mu_2\end{pmatrix}, \begin{pmatrix}\sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2\end{pmatrix}\right).$$

This assumption is needed because of a sampling bias problem in my data. By definition, the surveyed trucking companies have chosen to buy or lease a truck. This means that the outside option, which is not to use any truck, is absent from the survey. In order to include trucking companies choosing the outside option when calculating the aggregate quantities demanded in equation (1), I need to make an assumption on the full distribution of (X_{1i}, X_{2i}).

The parameters I calibrate inside the model can be categorized into four groups. The first group of parameters are related to truck qualities. They are the quality of age 1 sold trucks α_1, the quality of age 2 sold trucks α_2, the extra quality depreciation for age 1 leased trucks λ_1, and the extra quality depreciation for age 2 leased trucks λ_2. Notice that the quality of new trucks, α_0, is not separately identified with the scale of $\beta_0, \beta_1, \beta_2$ and as a result, I normalize it to be 10.

The second group of parameters are related to trucking companies' preferences. They include the parameters in the preference for truck quality $(\beta_0, \beta_1, \beta_2)$, the parameters in the preference for truck age $(\gamma_0^a, \gamma_1^a, \gamma_2^a)$, and the parameters in the preference for leasing (γ_0^l, γ_1^l).

Parameters in the joint distribution of trucking companies' characteristics, $\mu_1, \mu_2, \sigma_1^2, \sigma_2^2$, and σ_{12}, are the third group of parameters.

Two other parameters I calibrate are the scale parameter of ϵ_{ijt}, σ_ϵ, and the marginal cost of production, c.

5.2 Demand-Side Calibration

In the steady state, truck prices are the same in every period. Omitting the t subscript, the utility function of trucking company i choosing alternative j in the steady state is

$$u_{ij} = \theta_i q_j + \xi_{i,a(j)} + \xi_{i,l(j)} - r_j + \epsilon_{ij}.$$

Since utilities are ordinal, dividing all utilities by σ_ϵ does not change trucking companies' choices. With the parameterization of θ_i, $\xi_{i,a(j)}$, $\xi_{i,l(j)}$, the utility function can be rewritten as

$$\tilde{u}_{ij} = \tilde{\beta}_{0j} + \tilde{\beta}_{1j} X_{1i} + \tilde{\beta}_{2j} X_{2i} + \tilde{\epsilon}_{ij}, \tag{5}$$

where $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ are defined in Table 4 and are functions of the parameters to be calibrated. $\tilde{\epsilon}_{ij}$ is i.i.d. across (i, j) and follows a standard extreme value type I distribution. Equation (5) is a standard multinomial logit model where the explanatory variables are X_{1i}, X_{2i}.

As described in section 5.1, the outside option is absent from the survey. As a result, the levels of the $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ coefficients are not identified from the survey data alone. Only the differences in these coefficients across inside alternatives are identified. I rely on aggregate market shares data to identify the levels of these coefficients. The aggregate market share of alternative j is the number of units of j divided by the potential market size. Details on the calculation of aggregate market shares are in Appendix A.1.

Table 4: Expressions of $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$

j	$\tilde{\beta}_{0j}$	$\tilde{\beta}_{1j}$	$\tilde{\beta}_{2j}$
$B0$	$\frac{\beta_0\alpha_0 - p_0 + \delta p_1}{\sigma_\epsilon}$	$\frac{\beta_1\alpha_0}{\sigma_\epsilon}$	$\frac{\beta_2\alpha_0}{\sigma_\epsilon}$
$L0$	$\frac{\beta_0\alpha_0 + \gamma_0^l - l_0}{\sigma_\epsilon}$	$\frac{\beta_1\alpha_0 + \gamma_1^l}{\sigma_\epsilon}$	$\frac{\beta_2\alpha_0}{\sigma_\epsilon}$
$B1$	$\frac{\beta_0\alpha_1 + \gamma_0^a - p_1 + \delta p_2}{\sigma_\epsilon}$	$\frac{\beta_1\alpha_1}{\sigma_\epsilon}$	$\frac{\beta_2\alpha_1 + \gamma_1^a}{\sigma_\epsilon}$
$L1$	$\frac{\beta_0\alpha_1(1-\lambda_1) + \gamma_0^a + \gamma_0^l - l_1}{\sigma_\epsilon}$	$\frac{\beta_1\alpha_1(1-\lambda_1) + \gamma_1^l}{\sigma_\epsilon}$	$\frac{\beta_2\alpha_1(1-\lambda_1) + \gamma_1^a}{\sigma_\epsilon}$
$B2$	$\frac{\beta_0\alpha_2 + \gamma_0^a - p_2}{\sigma_\epsilon}$	$\frac{\beta_1\alpha_2}{\sigma_\epsilon}$	$\frac{\beta_2\alpha_2 + \gamma_2^a}{\sigma_\epsilon}$
$L2$	$\frac{\beta_0\alpha_2(1-\lambda_2) + \gamma_0^a + \gamma_0^l - l_2}{\sigma_\epsilon}$	$\frac{\beta_1\alpha_2(1-\lambda_2) + \gamma_1^l}{\sigma_\epsilon}$	$\frac{\beta_2\alpha_2(1-\lambda_2) + \gamma_2^a}{\sigma_\epsilon}$

I calibrate the demand model in three steps.

(i) Step 1: Using $L2$ as the reference group, estimate the multinomial logit model (5) for $\tilde{\beta}_{0j} - \tilde{\beta}_{0,L2}$, $\tilde{\beta}_{1j} - \tilde{\beta}_{1,L2}$, and $\tilde{\beta}_{2j} - \tilde{\beta}_{2,L2}$ ($j = B0, L0, B1, L1, B2$) by maximum likelihood.

(ii) Step 2: Estimate the coefficients for the reference group, $\tilde{\beta}_{0,L2}, \tilde{\beta}_{1,L2}, \tilde{\beta}_{2,L2}$, together with the parameters in the joint distribution of trucking companies' characteristics, $\mu_1, \mu_2, \sigma_1^2, \sigma_2^2, \sigma_{12}$, by simulated method of moments. I choose two sets of moments to match. First, the aggregate market share of each inside alternative. Second, all first and second moments of X_{1i}, X_{2i} conditional on each inside alternative, i.e., $E(X_{1i}|j)$, $E(X_{2i}|j)$, $E(X_{1i}^2|j)$, $E(X_{2i}^2|j)$, $E(X_{1i}X_{2i}|j)$ for all $j \in J_I$. The second set of moments are simulated. Combining results from step 1 and step 2, I have an estimate for $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ for each inside alternative j. I calculate their standard errors from 20 bootstrap samples.

(iii) Step 3: Calibrate σ_ϵ, all truck qualities parameters ($\alpha_1, \alpha_2, \lambda_1$, and λ_2), and all preference parameters except γ_0^l ($\beta_0, \beta_1, \beta_2, \gamma_0^a, \gamma_1^a, \gamma_2^a$, and γ_1^l) to the estimates of $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ obtained in step 2. I minimize the weighted sum of the squared percentage differences of the coefficients in Table 4 and their estimates, where the weight is the inverse of standard error, meaning that more accurately estimated coefficients get larger weights. I do not use $\tilde{\beta}_{0,L0}, \tilde{\beta}_{0,L1}, \tilde{\beta}_{0,L2}$ in this step because lease prices are not observed in my data. For the same reason, γ_0^l is not identified in the demand model. I obtain the value of γ_0^l in supply-side calibration.

5.3 Supply-Side Calibration

I calibrate γ_0^l and c by matching the supply model's steady-state predictions to data. The manufacturers' dynamic programming problem described in equation (3) has four continuous state variables and four continuous choice variables, imposing a heavy computational burden for the calibration exercise. I overcome this hurdle by making a simplifying assumption that manufacturers lease all off-lease trucks they own and do not scrap. With this assumption, manufacturers only choose the quantity of new trucks to produce and the fraction of new trucks to lease, and the number of continuous choice variables is reduced to two. Assuming manufacturers do not scrap off-lease trucks is not a unrealistic assumption for two reasons. First, sold and leased trucks have similar average lifetime with a small difference of 0.2 years, indicating that leased trucks might not be scrapped more than sold trucks. Second, scrapping off-lease trucks is not standard behavior in the industry. The simplifying assumption is only used in the calibration exercise. In counterfactual exercises in section 6, manufacturers are allowed to scrap off-lease trucks.

The Bellman equation for manufacturer m in the simplified supply model is

$$V_m(\boldsymbol{Y}_t) = \max_{x_{mt}, f_{mt}} \; p_{0t} x_{mt} f_{mt} + l_{0t} x_{mt}(1 - f_{mt}) + l_{1t} \frac{y_{1t}^L}{M} + l_{2t} \frac{y_{2t}^L}{M} - c x_{mt} + \delta V_m(\boldsymbol{Y}_{t+1}),$$

subject to

$$\begin{aligned} &0 \leq x_{mt} \leq 1 - y_{1t}^S - y_{2t}^S - y_{1t}^L - y_{2t}^L \\ &0 \leq f_{mt} \leq 1, \end{aligned}$$

where $\boldsymbol{Y}_{t+1}$ is defined by the law of motion

$$\begin{aligned} y_{1,t+1}^S &= d_1^S \sum_{m=1}^{M} x_{mt} f_{mt} \\ y_{2,t+1}^S &= \frac{d_2^S}{d_1^S} y_{1t}^S \\ y_{1,t+1}^L &= d_1^L \sum_{m=1}^{M} x_{mt}(1 - f_{mt}) \\ y_{2,t+1}^L &= \frac{d_2^L}{d_1^L} y_{1t}^L. \end{aligned} \tag{6}$$

Notice that in manufacturer m's problem, the opponents' choices are fixed. All prices, $p_{0t}, l_{0t}, l_{1t}, l_{2t}$, are determined in equilibrium and are functions of the state and choice variables.

The aggregate quantity supplied for alternative $j \in J_I$ in period t is

$$S_{jt}^{Supply} = \begin{cases} \sum_{m=1}^{M} x_{mt} f_{mt}, & \text{if } j = B0 \\ \sum_{m=1}^{M} x_{mt}(1 - f_{mt}), & \text{if } j = L0 \\ y_{1t}^S, & \text{if } j = B1 \\ y_{1t}^L, & \text{if } j = L1 \\ y_{2t}^S, & \text{if } j = B2 \\ y_{2t}^L, & \text{if } j = L2. \end{cases}$$

I match the model's steady-state predictions of the following three sets of variables to data: (i) the aggregate market shares of each inside alternative; (ii) the selling prices of new trucks, age 1 trucks, and age 2 trucks; and (iii) the fraction of selling.

I calibrate the supply model in four steps.

(i) Step 1: For each guess of γ_0^l and c, use the collocation method to calculate the value function, $V_m(\boldsymbol{Y}_t)$, and the policy functions, $x_m(\boldsymbol{Y}_t), f_m(\boldsymbol{Y}_t)$, of manufacturer m. Since manufacturers are homogeneous, they have the same value function and policy functions.

(ii) Step 2: Calculate the vector of state variables, $\boldsymbol{Y}^{SS}$, in the steady state by solving

$$\boldsymbol{Y}^{SS} = \boldsymbol{L}(\{x_m(\boldsymbol{Y}^{SS}), f_m(\boldsymbol{Y}^{SS})\}_{m=1}^{M}, \boldsymbol{Y}^{SS}),$$

where $\boldsymbol{L}(\cdot)$ is the law of motion defined in equation (6).

(iii) Step 3: Calculate the sum of the squared percentage differences between the model's steady-state predictions of the variables I choose and their values in the data.

(iv) Step 4: Repeat step 1-3 until the sum of the squared percentage differences is minimized.

The details of the collocation method in step 1 are as follows.

(i) Step 1: Take 3 Chebyshev nodes for each state variable $y_{1t}^S, y_{2t}^S, y_{1t}^L, y_{2t}^L$. They form $N = 3^4 = 81$ collocation nodes for $\boldsymbol{Y}_t$. Let $\boldsymbol{T}(y)$ be a column vector of Chebyshev bases of degree 0, 1, and 2. Then $\boldsymbol{g}(\boldsymbol{Y}_t) = \boldsymbol{T}(y_{2t}^L) \otimes \boldsymbol{T}(y_{1t}^L) \otimes \boldsymbol{T}(y_{2t}^S) \otimes \boldsymbol{T}(y_{1t}^S)$, where $\otimes$ denotes Kronecker product, is a column vector of multivariate Chebyshev bases. Write the value function and policy functions as Chebyshev series

$$V_m(\boldsymbol{Y}_t) = \sum_{n=1}^{N} a_n g_n(\boldsymbol{Y}_t), \quad x_m(\boldsymbol{Y}_t) = \sum_{n=1}^{N} b_n g_n(\boldsymbol{Y}_t), \quad f_m(\boldsymbol{Y}_t) = \sum_{n=1}^{N} c_n g_n(\boldsymbol{Y}_t),$$

where $g_n(\boldsymbol{Y}_t)$ is the n-th element of $\boldsymbol{g}(\boldsymbol{Y}_t)$, and a_n, b_n, c_n are coefficients.

(ii) Step 2: Choose starting values for the series of coefficients $\{a_n\}_{n=1}^N$, $\{b_n\}_{n=1}^N$, $\{c_n\}_{n=1}^N$.

(iii) Step 3: For each collocation node $\boldsymbol{Y}^k$ ($k = 1, \ldots, N$) for the state $\boldsymbol{Y}_t$, set the opponents' choices as $x_{-mt} = \sum_{n=1}^N b_n g_n(\boldsymbol{Y}^k)$ and $f_{-mt} = \sum_{n=1}^N c_n g_n(\boldsymbol{Y}^k)$. Then solve the following maximization problem for m's optimal choices, x_m^k, f_m^k, and the maximized profit, V_m^k:

$$\max_{x_{mt}, f_{mt}} \; p_{0t} x_{mt} f_{mt} + l_{0t} x_{mt}(1 - f_{mt}) + l_{1t} \frac{y_1^{L,k}}{M} + l_{2t} \frac{y_2^{L,k}}{M} - c x_{mt} + \delta \sum_{n=1}^N a_n g_n(\boldsymbol{Y}^{k'}),$$

where $\boldsymbol{Y}^{k'}$ is calculated from the law of motion defined in equation (6), holding fixed the opponents' choices x_{-mt}, f_{-mt}. All prices are calculated from equilibrium conditions.

(iv) Step 4: Solve the linear system of equations $V_m^k = \sum_{n=1}^N a_n g_n(\boldsymbol{Y}^k)$ ($k = 1, \ldots, N$) for $\{a_n\}_{n=1}^N$. Solve for $\{b_n\}_{n=1}^N$, $\{c_n\}_{n=1}^N$ in a similar way. These are the updated values of coefficients.

(v) Step 5: Repeat step 3-4 until all a_n, b_n, c_n coefficients converge.

5.4 Identification

The procedures of demand-side calibration indicate that the identification of the parameters I calibrate in section 5.2 is partly from the assumption of a logit model. First, the variations in trucking companies' characteristics and choices identify the differences in the $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ coefficients across inside alternatives. Data on the aggregate market shares identifies the levels of these coefficients. Second, as shown in Table 4, the comparison of $\tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ across j identifies all truck qualities parameters and the ratios of three preference parameters to σ_ϵ ($\gamma_1^l/\sigma_\epsilon$, $\gamma_1^a/\sigma_\epsilon$, and $\gamma_2^a/\sigma_\epsilon$). This comparison is essentially a comparison of the relative importance of characteristics to different alternatives. Third, the comparison of $\tilde{\beta}_{0j}$ across the three selling alternatives identifies σ_ϵ, β_0, and γ_0^a. For σ_ϵ, which measures trucking companies' price sensitivity, its reciprocal can be expressed as

$$\frac{1}{\sigma_\epsilon} = \frac{(\tilde{\beta}_{0,B1} - \tilde{\beta}_{0,B2}) - \left(\frac{\alpha_1}{\alpha_0} - \frac{\alpha_2}{\alpha_0}\right) \tilde{\beta}_{0,B0}}{\left(\frac{\alpha_1}{\alpha_0} - \frac{\alpha_2}{\alpha_0}\right)(p_0 - \delta p_1) - ((p_1 - \delta p_2) - p_2)}.$$

Since $\tilde{\beta}_{0j}$ is related to the aggregate market share of alternative j, the identification of σ_ϵ can be interpreted as being from the variation in aggregate market shares across selling alternatives explained by price differences after controlling for quality differences. Then, since σ_ϵ is identified, $\gamma_1^l, \gamma_1^a, \gamma_2^a$ are identified.

For the joint distribution of trucking companies' characteristics, since it is parameterized as a log-normal distribution, which can be pinned down by first and second moments, identification is from the conditional first and second moments of the characteristics and the knowledge of the aggregate market shares.

The aggregate market share of new trucks, which is new truck production in my model, identifies manufacturers' markups and in turn identifies the marginal cost of production since the new truck price is observed. Data on the fraction of leasing identifies the constant term in the preference for leasing, γ_0^l, since manufacturers lease more when trucking companies have higher preferences for leasing.

5.5 Calibration Results

Table 5 presents the calibrated values of the free parameters, and Table 6 shows the model fit of the supply-side calibration. For conciseness, the model fit of the demand-side calibration is shown in Appendix C. Standard errors are calculated by bootstrapping the entire calibration process (both demand-side and supply-side) 50 times.[20] Throughout, all the monetary numbers are reported in $1,000 in the year 2000.

The quality of age 1 sold trucks is 85.13% of the quality of new trucks and the quality of age 2 sold trucks is 49.08% of the quality of new trucks. Leased trucks depreciate faster than sold trucks. For age 1 trucks, the quality of leased trucks are 12.8% lower than that of sold trucks. For age 2 trucks, the extra quality depreciation for leased trucks is 12.3%.

The marginal cost of production is calibrated at $56.966 thousand dollars. This implies a markup of 6.39%.[21] The implied markup is close to what Wollmann (2018) gets in his study of commercial trucks, which is between 6.1% and 6.6%. It is also close to the 10-year markup estimate in industry reports, which is 7.5% (IBISWorld, 2021a).[22]

The trucking companies' preference for leasing is large. It has an average of $19.164 thousand dollars and a standard deviation of $0.275 thousand dollars. The high preference for leasing could be from various sources. First, leasing is more affordable to financially constrained trucking companies.[23] Leasing removes the huge up-front cost of buying including down payment, sales tax, licensing fees, and others. Furthermore, lease payments are lower than loan payments and a lease is often easier to get than financing for a loan. Since trucking

[20] I bootstrap the survey sample. The data on truck disposal and selling prices is the same throughout.

[21] The definition of markup I use is the difference between the selling price of new trucks and the marginal cost, expressed as a percentage of the selling price of new trucks, i.e., $(p_0 - c)/p_0$.

[22] Comparing the implied markup in my model and the markup reported by the industry has some caveats. As Wollmann (2018) points out, first, manufacturers operate in either other markets or other geographic areas and the reported markup is not specific to the market under study; second, the markup reported in financial statements reflects average cost instead of marginal cost. However, being close to the industry estimate indicates that the implied markup in my model is sensible.

[23] See similar arguments in Gavazza (2010) and Eisfeldt and Rampini (2009).

companies are mostly small-sized owner-operators with potentially limited access to capital markets, it is understandable that they prefer leasing. Second, lease contracts often include service like routine inspections and maintenance, which is not provided when the truck is bought. Such service induces additional cost to manufacturers, which is not considered in this paper, though. As expected, trucking companies' preference for leasing decreases with their business volume as richer companies benefit less from leasing.

Other calibrated parameters have expected sign. For the preference for truck quality, trucking companies with a larger business volume and a larger size prefer high-quality trucks more. For the preference for truck age, trucking companies dislike used trucks and the utility loss from using a used truck increases with the company size. The covariance of the two trucking company characteristics is positive, meaning that companies with a larger size tend to have a larger business volume.

As shown in Table 6, the calibration of my supply model fits data pretty well. The percentage deviation from data for most matched variables is smaller than 3%.

6 Counterfactuals

I do counterfactual experiments to answer three questions. First, how does leasing affect the profitability and market power of durable goods manufacturers? Second, what are the roles that the different effects of leasing (market expansion, market control, and time consistency) may play? Third, how do the effects of leasing depend on underlying market features including quality depreciation and market structure?

For the first question, I eliminate leasing, re-compute equilibrium and steady state, and compare the steady-state outcomes without leasing with the steady-state outcomes with leasing. For the second question, since the various effects of leasing are interrelated and occur in tandem, I assess these effects in turn by making changes to the environment in a way that highlights one effect at a time. To quantify the market control effect, I calculate the effects of leasing in an environment where manufacturers are not allowed to scrap off-lease trucks, and compare with the effects of leasing in the baseline environment. To quantify the time consistency effect, I calculate the effects of leasing in an environment with full commitment where the Coase effect does not exist, and compare with the baseline. To answer the third question, I compare the effects of leasing with different extra quality depreciation for leased trucks and different numbers of manufacturers, while holding all the other parameters fixed at their calibrated values. When comparing steady-state outcomes, I mainly focus on the total profit per manufacture and markup while also looking at other variables to help understand the mechanism.

Table 5: Calibrated parameters

Parameter	Calibrated value
Truck qualities	
Quality of age 1 sold trucks (α_1)	8.513 (1.036)
Quality of age 2 sold trucks (α_2)	4.908 (1.061)
Extra quality depreciation for age 1 leased trucks (λ_1)	0.128 (0.049)
Extra quality depreciation for age 2 leased trucks (λ_2)	0.123 (0.065)
Preference for truck quality	
Constant (β_0)	0.659 (0.792)
log(Average number of trips per week) (β_1)	0.184 (0.099)
log(Fleet size) (β_2)	0.632 (0.159)
Preference for truck age	
Constant (γ_0^a)	-9.339 (1.779)
log(Fleet size)$\times\mathbb{1}\{$Age 1$\}$ (γ_1^a)	-2.156 (1.083)
log(Fleet size)$\times\mathbb{1}\{$Age 2$\}$ (γ_2^a)	-0.823 (0.725)
Preference for leasing	
Constant (γ_0^l)	19.510 (0.820)
log(Average number of trips per week)$\times\mathbb{1}\{$Leased$\}$ (γ_1^l)	-0.713 (0.353)
Joint distribution of trucking companies' characteristics	
Mean of log(Average number of trips per week) (μ_1)	0.485 (0.020)
Mean of log(Fleet size) (μ_2)	1.017 (0.015)
Variance of log(Average number of trips per week) (σ_1^2)	0.149 (0.011)
Variance of log(Fleet size) (σ_2^2)	0.134 (0.006)
Covariance (σ_{12})	0.018 (0.004)
Scale parameter of ϵ_{ijt} (σ_ϵ)	4.607 (1.283)
Marginal cost of production (c), \$1,000	56.966 (1.661)

Notes: Standard errors are calculated from 50 bootstrap samples and are listed in parentheses.

6.1 Assessing the Multiple Effects of Leasing

The first panel of Table 7 presents the baseline counterfactual steady-state outcomes, measuring the overall effects of leasing. Eliminating leasing has huge effects on manufacturers' profits and markups. Without leasing, the profit of each manufacturer decreases by 83.2% and manufacturers' markups decrease by 31.6%.

The market expansion effect plays a big role. When leasing options are added, the quantity of trucks sold and leased increases from 0.0543 to 0.0888, meaning that manufacturers attract many trucking companies to buy or lease from them which would otherwise buy from secondary markets or choose the outside option. The market control effect seems to be very small as manufacturers do not scrap any off-lease trucks. To get a sense of how large the time consistency effect is, notice that when leasing options are added, they normally steal business from the selling option (as reflected in the decrease in the quantity of trucks sold) and decrease the profit from selling. However, the results show that the profit from selling

Table 6: Model fit of the supply-side calibration

Variable	Data value	Model steady-state value
Market share of $B0$ (%)	16.57	16.16
Market share of $L0$ (%)	9.96	9.73
Market share of $B1$ (%)	11.79	11.50
Market share of $L1$ (%)	7.01	6.92
Market share of $B2$ (%)	4.23	4.13
Market share of $L2$ (%)	2.44	2.48
Selling price of new trucks ($1,000)	63.2859	60.8524
Selling price of age 1 trucks ($1,000)	29.5661	27.1758
Selling price of age 2 trucks ($1,000)	13.1615	12.9061
Fraction of selling (%)	62.47	62.43

increases. This indicates that the positive time consistency effect of leasing outweighs the negative effect of business stealing. The higher selling price of new trucks when there is leasing also indicates that leasing mitigates the Coase effect. In terms of consumer surplus, it is higher when there is leasing because (i) trucking companies have more options to choose from, and (ii) there are more trucks available in the market (new truck production increases from 0.0543 to 0.0648).

To better understand the effects of leasing, I assess the market control effect and the time consistency effect in the counterfactuals that follow.

6.1.1 Market Control Effect

I shut down the market control effect channel by not allowing manufacturers to scrap any off-lease trucks. In this counterfactual environment, manufacturers have to lease all off-lease trucks they own and are not able to reduce the cannibalization from used trucks by adjusting their availability. Comparing the effects of leasing in this environment with those in the baseline environment gives the market control effect.

The second panel of Table 7 shows the results. The steady-state outcomes are very close to those in the baseline environment. Considering that no off-lease trucks are scrapped in the baseline, it is believable that the small differences are calculation errors and that the steady-state outcomes in the two environments are identical.[24] There is no market control effect at play.

[24] When computing equilibrium, in order to reduce computational burden, I approximate the inverse demand functions by high-order Chebyshev series and calculate them before using the collocation method. This approximation is necessary because otherwise the computation time is more than ten times longer.

Table 7: Effects of eliminating leasing: assessing the multiple effects of leasing

	With leasing	Without leasing
Panel A. Baseline		
New truck production per mfr	0.0648	0.0543
Fraction of leasing	38.31%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	60.9764	59.6476
Trucks sold per mfr	0.0400	0.0543
Trucks sold and leased per mfr	0.0888	0.0543
Profit from selling per mfr	0.1603	0.1457
Total profit per mfr	0.8665	0.1457 (-83.2%)[b]
Markup	6.58%	4.50% (-31.6%)[b]
Consumer Surplus ($1,000)	4.1310	3.2756
Panel B. Scrappage not allowed		
New truck production per mfr	0.0647	0.0543
Fraction of leasing	37.57%	
Selling price of new trucks ($1,000)	60.8524	59.6476
Trucks sold per mfr	0.0404	0.0543
Trucks sold and leased per mfr	0.0882	0.0543
Profit from selling per mfr	0.1570	0.1457
Total profit per mfr	0.8537	0.1457 (-82.9%)[b]
Markup	6.39%	4.50% (-29.6%)[b]
Consumer Surplus ($1,000)	4.1245	3.2756
Panel C. Full commitment		
New truck production per mfr	0.0657	0.0542
Fraction of leasing	33.33%	
Scrappage of age 1 trucks[a]	0.0090, 57.65%	
Scrappage of age 2 trucks[a]	0.0016, 66.80%	
Selling price of new trucks ($1,000)	61.1486	59.7276
Trucks sold per mfr	0.0438	0.0542
Trucks sold and leased per mfr	0.0731	0.0542
Profit from selling per mfr	0.1832	0.1496
Total profit per mfr	0.4317	0.1496 (-65.3%)[b]
Markup	6.84%	4.62% (-32.5%)[b]
Consumer Surplus ($1,000)	3.6724	3.2635

Notes: All quantities are measured against the potential market size, which is normalized to 1.
[a]First number: quantity of scrapped trucks; second number: percentage of scrapped off-lease trucks.
[b]Number in parentheses: percentage change from eliminating leasing.

6.1.2 Time Consistency Effect

I shut down the time consistency effect channel by computing equilibrium in an environment with full commitment where the Coase effect does not exist. In this counterfactual environment, each manufacturer m chooses once and for all a sequence of selling and leasing decisions, $\{\boldsymbol{X}_{mt}\}_{t=1}^{\infty}$, that maximizes its discounted profits given rivals' choices $\{\boldsymbol{X}_{-mt}\}_{t=1}^{\infty}$ and the state variables in the initial period $\boldsymbol{Y}_{t=1}$. After the decisions are made, manufacturers must commit to their choices and not change when future periods come. I compute the steady-state outcomes with and without leasing. Comparing the effects of leasing in this environment with those in the baseline environment gives the time consistency effect.

For conciseness, the details of the algorithm to compute equilibrium with full commitment are shown in Appendix B.

The third panel of Table 7 shows the results. When there is full commitment, eliminating leasing decreases manufacturers' profits by 65.3% and markups by 32.5%. The decrease in profit is smaller than that in the baseline environment (83.2%), indicating that there is a relatively large time consistency effect. This effect is not significant on markups, though. Another way to see the time consistency effect is by comparing the fraction of leasing in the two environments. With full commitment, manufacturers lease less (33.33% versus 38.31% in the baseline) because there is no Coase effect and manufacturers do not need to use more leasing to mitigate that. Interestingly, when there is full commitment, manufacturers scrap over half of the off-lease trucks they own, meaning that the market control effect is positive in this case. The scrappage of off-lease trucks increases the selling price of new trucks and the profit from selling. The presence of market control effect when there is full commitment reinforces the intuition that the different effects of leasing are interrelated.

6.2 Assessing Quality Depreciation

The magnitude of the gains from leasing depends on how fast leased trucks depreciate relative to sold trucks. Manufacturers have less incentive to lease when leased trucks depreciate faster because the faster quality depreciation reduces the value of off-lease trucks to them. To assess how the effects of leasing depend on the extra quality depreciation of leased trucks, I change the values of the quality depreciation factors λ_1 and λ_2 and compare the steady-state outcomes across different counterfactual environments.

Table 8 presents the results. In the first panel, I let off-lease trucks have the same quality as pre-owned trucks by setting $\lambda_1 = \lambda_2 = 0$. The fraction of leasing increases but only by a small amount (from 38.31% in the baseline to 41.04%). Selling is still attractive to manufacturers since the selling price of new trucks is high. These results indicate that there can be other downsides of leasing that manufacturers trade off against the benefits. These

Table 8: Effects of eliminating leasing: assessing quality depreciation

	With leasing	Without leasing
Panel A. $\lambda_1 = 0, \lambda_2 = 0$		
New truck production per mfr	0.0652	0.0543
Fraction of leasing	41.04%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	61.2701	59.6476
Trucks sold per mfr	0.0384	0.0543
Trucks sold and leased per mfr	0.0910	0.0543
Profit from selling per mfr	0.1654	0.1457
Total profit per mfr	0.9734	0.1457 (-85.0%)[b]
Markup	7.02%	4.50% (-35.9%)[b]
Consumer Surplus ($1,000)	4.1920	3.2756
Panel B. $\lambda_1 = 0.064, \lambda_2 = 0.062$		
New truck production per mfr	0.0650	0.0543
Fraction of leasing	39.74%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	61.1504	59.6476
Trucks sold per mfr	0.0391	0.0543
Trucks sold and leased per mfr	0.0899	0.0543
Profit from selling per mfr	0.1638	0.1457
Total profit per mfr	0.9205	0.1457 (-84.2%)[b]
Markup	6.84%	4.50% (-34.2%)[b]
Consumer Surplus ($1,000)	4.1582	3.2756
Panel C. $\lambda_1 = 0.256, \lambda_2 = 0.246$		
New truck production per mfr	0.0643	0.0543
Fraction of leasing	35.96%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	60.8156	59.6476
Trucks sold per mfr	0.0412	0.0543
Trucks sold and leased per mfr	0.0867	0.0543
Profit from selling per mfr	0.1586	0.1457
Total profit per mfr	0.7765	0.1457 (-81.2%)[b]
Markup	6.33%	4.50% (-28.9%)[b]
Consumer Surplus ($1,000)	4.0674	3.2756

Notes: (i) All quantities are measured against the potential market size, which is normalized to 1.
(ii) In benchmark, the extra quality depreciation for leased trucks are $\lambda_1 = 0.128, \lambda_2 = 0.123$.
[a] First number: quantity of scrapped trucks; second number: percentage of scrapped off-lease trucks.
[b] Number in parentheses: percentage change from eliminating leasing.

effects are beyond the scope of this paper. In the second panel, the extra quality depreciation of leased trucks is half of the benchmark values while in the third panel, depreciation is doubled. As shown in Figure 1, the profit loss and markup drop from eliminating leasing decreases with quality depreciation but this decrease is not large. From zero extra depreciation to an extra depreciation of around 25%, eliminating leasing decreases manufacturers' profits by 81.2%-85.0% and markups by 28.9%-35.9%. In all scenarios, manufacturers do not scrap off-lease trucks.

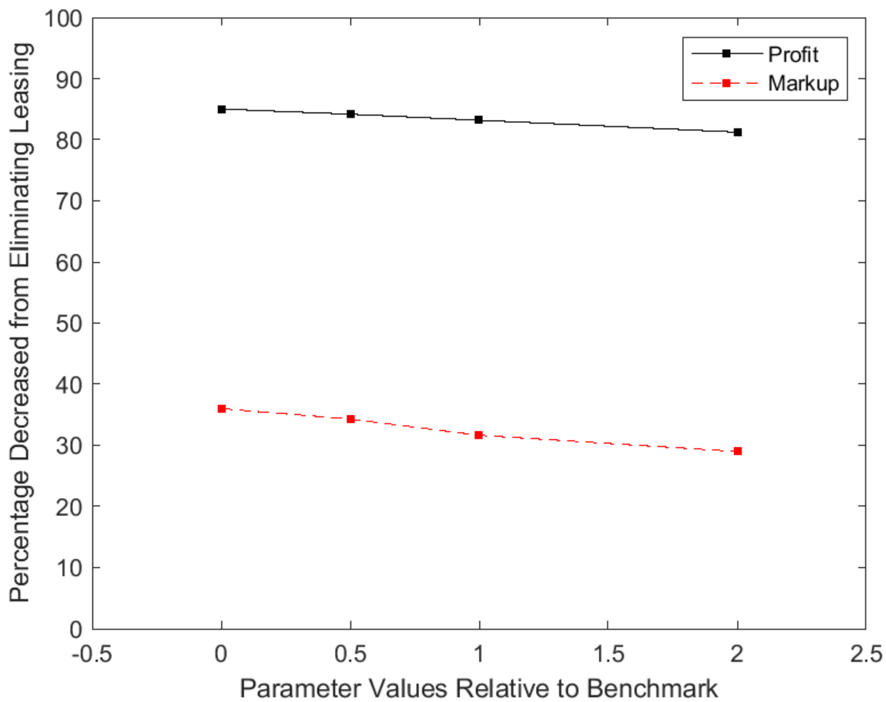

Figure 1: Effects of eliminating leasing on profit and markup with different quality depreciation

To summarize, the effects of leasing is larger when off-lease trucks depreciate slower, but quality depreciation does not have large effects on market outcomes.

6.3 Assessing Market Structure

I next consider how market structure, which is the number of manufacturers on the supply side of the industry, affects the gain from leasing. Leasing should have stronger effects on profits and markups in more competitive markets. Since manufacturers compete in a Cournot manner, they tend to overproduce relative to the optimal industry level because they do not internalize the negative effects of their own output on their opponents' profits. This overproduction leads to profit losses because there are more used trucks in the secondary markets and these used trucks cannibalize manufacturers' profits from selling new trucks.

Table 9: Effects of eliminating leasing: assessing market structure

	With leasing	Without leasing
Panel A. $M = 1$ (Monopoly)		
New truck production per mfr	0.2483	0.1356
Fraction of leasing	86.99%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	83.7165	71.6398
Trucks sold per mfr	0.0323	0.1356
Trucks sold and leased per mfr	0.4583	0.1356
Profit from selling per mfr	0.8638	1.9891
Total profit per mfr	5.6694	1.9891 (-64.9%)[b]
Markup	31.95%	20.48% (-35.9%)[b]
Consumer Surplus ($1,000)	3.8491	1.8125
Panel B. $M = 2$		
New truck production per mfr	0.1253	0.0939
Fraction of leasing	59.85%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	68.0122	63.6630
Trucks sold per mfr	0.0503	0.0939
Trucks sold and leased per mfr	0.1979	0.0939
Profit from selling per mfr	0.5558	0.6291
Total profit per mfr	2.4482	0.6291 (-74.3%)[b]
Markup	16.24%	10.52%(-35.2%)[b]
Consumer Surplus ($1,000)	3.9172	2.7091
Panel C. $M = 6$		
New truck production per mfr	0.0439	0.0382
Fraction of leasing	31.13%	
Scrappage of age 1 trucks[a]	0, 0%	
Scrappage of age 2 trucks[a]	0, 0%	
Selling price of new trucks ($1,000)	58.8723	58.0751
Trucks sold per mfr	0.0303	0.0382
Trucks sold and leased per mfr	0.0572	0.0382
Profit from selling per mfr	0.0577	0.0424
Total profit per mfr	0.4669	0.0424 (-90.9%)[b]
Markup	3.24%	1.91% (-41.0%)[b]
Consumer Surplus ($1,000)	4.2417	3.5198

Notes: (i) All quantities are measured against the potential market size, which is normalized to 1.
(ii) In benchmark, the number of manufacturers is $M = 4$.
[a]First number: quantity of scrapped trucks; second number: percentage of scrapped off-lease trucks.
[b]Number in parentheses: percentage change from eliminating leasing.

Leasing mitigates this effect because leased trucks do not go to the secondary markets. As the number of manufacturers increases, the profit loss from overproduction increases and leasing becomes more effective in reducing this loss.

This intuition is overall supported by counterfactual results reported in Table 9. In monopoly, leasing is used a lot (the fraction of leasing is 86.99%) but eliminating leasing only decreases profit by 64.9%, which is smaller than 83.2% in the baseline environment. This is because monopolist does not suffer from the overproduction problem in Cournot competition. Although leasing is still beneficial, the benefit from mitigating Cournot overproduction is absent. As the number of manufacturers increases, leasing is used less because competition limits manufacturers' abilities to control markets through leasing. However, the benefit from leasing, comparing with scenarios without leasing, increases. In a relatively competitive market with 6 manufacturers, manufacturers almost earn zero profits when there is no leasing. When leasing options are added, manufacturers earn much more profits. Eliminating leasing decreases profits by over 90% in this case.

How market structure affects the impact of leasing on markups is more complicated. As shown in Figure 2, the percentage decrease in markups from eliminating leasing has a nonlinear relationship with the number of manufacturers. As the market becomes more competitive, the effects of leasing on markups decrease first and then increase, indicating that there might be multiple effects at play. Furthermore, the effects on markups do not change with market structure as much as the effects on profits do.

Another interesting result is that manufacturers do not scrap off-lease trucks even in monopoly. This is potentially because of the trucking companies' high preferences for leasing. When trucking companies have a high willingness to pay for leasing, the gain from market controlling by scrapping off-lease trucks might be smaller than the foregone profit from leasing. As a result, manufacturers may not be willing to scrap in such situations.

7 Conclusion

In this paper, I examine how leasing affects the profitability and market power of durable goods oligopolists. I also assess how the effects of leasing depend on underlying market features including quality depreciation and market structure. I develop a dynamic equilibrium model of durable goods oligopoly with leasing, selling, and secondary markets. My model allows for various interrelated effects of leasing in the literature and can be used to quantify them in empirical settings. I calibrate my model to aggregate data from the US heavy-duty truck industry and obtain a good fit.

I find that eliminating leasing decreases manufacturers' profits by 83.2% and markups by 31.6%. These large effects are mainly from two sources. First, manufacturers earn

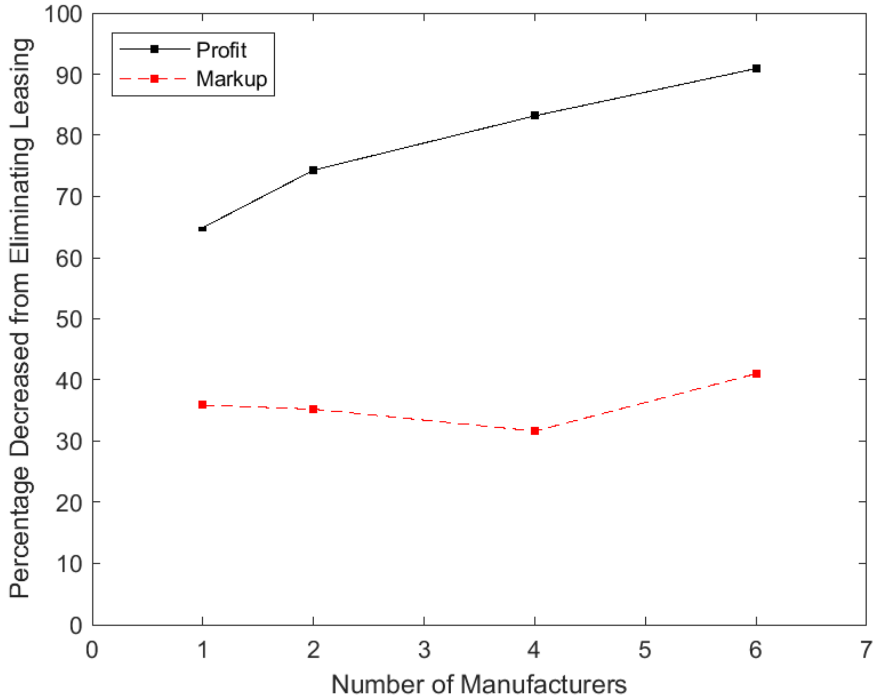

Figure 2: Effects of eliminating leasing on profit and markup with different market structures

profits by offering leases to trucking companies with high preferences for leasing. Second, leasing mitigates the Coase effect suffered by manufacturers without the ability to commit. Manufacturers benefit more from leasing when leased trucks depreciate slower and when there is more competition.

These results have potentially important implications for antitrust policies. Leasing affects firms' profitability and market power in multiple ways. The magnitude of these effects and the overall effect depends on underlying features of industries. Quantifying the effects of leasing is ultimately an empirical question. In some durable goods industries, firms may earn a lot and gain much market power through leasing, in which case ignoring leasing may lead to biased results. Furthermore, leasing might be important to consider when evaluating policies that affect market features as firms may respond by adjusting choices of leasing.

There are shortcomings in this paper that remain to be addressed. First, I have to make several simplifying assumptions to make my model tractable and to facilitate its computation. One of them is the assumption of no transaction cost. In reality, transaction cost is an important trading friction that affects consumers' choices in durable goods industries and has long been a focus of economic research. Another assumption I make is there is no adverse selection, which in reality exists in secondary markets and affects firms' production decisions and profits. One direction for future research is evaluating the impact of leasing with transaction cost and adverse selection. Second, I do not have rich characteristics of trucking companies in my survey data and I do not observe lease prices. As a result, I have to rely on parametric assumptions to identify primitives and generate the unobserved lease prices in model. With richer data, I can build my model in a more flexible way and get more accurate results.

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Appendices

A Data Appendix

A.1 Calculation of Aggregate Market Shares

In section 5.2, I rely on aggregate market shares data to identify the levels of $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$. The aggregate market share of alternative j is the number of units of j divided by the potential market size. I calculate the potential market size as the product of the number of trucking company establishments in 2002, which is 257,348 (IBISWorld, 2021a), and the average number of tractors each establishment has, which is 33.5.[25] The number of new trucks in 2002 is 2,287,046, which is calculated using the sample weight variable in the survey data. Thus, the combined aggregate market share of sold and leased new trucks is

$$s_{B0} + s_{L0} = 2,287,046/(257,348 * 33.5) = 0.2653.$$

In order for the market shares to be consistent with the survival rates of new trucks $(d_1^S, d_2^S, d_1^L, d_2^L)$ and to avoid potential sampling bias, I construct the aggregate market shares using the combined share of new trucks calculated above, the fraction of selling f, and the survival rates of new trucks. Details of the calculation are shown in Table A.1.

Table A.1: Calculation of aggregate market shares

Aggregate market share	Calculation	Value
s_{B0}	$(s_{B0} + s_{L0}) * f$	0.1657
s_{L0}	$(s_{B0} + s_{L0}) * (1 - f)$	0.0996
s_{B1}	$s_{B0} * d_1^S$	0.1179
s_{L1}	$s_{L0} * d_1^L$	0.0701
s_{B2}	$s_{B0} * d_2^S$	0.0423
s_{L2}	$s_{L0} * d_2^L$	0.0244

A.2 Calculation of Aggregate Truck Prices

In my survey data, trucks can live up to 16 years while there are only 3 aggregate truck ages in my model. As described in section 4.2, I aggregate used trucks younger than 4 years old as age 1 trucks, and used trucks from 5 to 16 years old as age 2 trucks. New trucks are still new trucks. The goal of this section is to derive an aggregate price for each aggregate age group.

[25] Calculated from the 2002 Vehicle Inventory and Use Survey by the author. The average number of tractors is used as a proxy for the average number of heavy-duty trucks.

To achieve this, I first aggregate truck prices across truck models within each non-aggregate age group, then I aggregate prices across truck ages.

In the price data I observe the quarterly retail price of each heavy-duty truck model sold in the US from 2008 to 2011. The quarterly price data extends all the way to 2020. With a little abuse of notation, let p^N_{abdq} denote the price of a non-aggregate age a truck with brand b and model d sold in calendar quarter (Q1, Q2, Q3, or Q4) q. I run the following hedonic regression:[26]

$$\log(p^N_{abdq}) = \theta \cdot a + \xi_{bd} + \xi_q + \epsilon_{abdq},$$

where θ is the coefficient for age a, ξ_{bd} is the truck brand-truck model fixed effect, ξ_q is the calendar quarter fixed effect, and ϵ_{abdq} is a standard price shock. For each non-aggregate age group a, the aggregate truck price, P^N_a, is calculated as

$$P^N_a = \exp(\hat{\theta} \cdot a + \bar{\xi}_{bd} + \bar{\xi}_q),$$

where $\hat{\theta}$ is the estimate for θ, $\bar{\xi}_{bd}$ is the average of the truck brand-truck model fixed effect across all truck models, and $\bar{\xi}_q$ is the average of the calendar quarter fixed effect across all truck models. Intuitively speaking, P^N_a is the price of an age a truck with an average truck brand-truck model and sold in an average calendar year. In Table A.2, the second column shows the values of P^N_a and the third column shows the rental prices $P^N_a - \delta P^N_{a+1}$, which is difference of selling price and time-discounted resale price in steady state, of trucks of different ages. Overall, the rental price decreases with truck age, which is consistent with the intuition that younger trucks are more expensive.

Next I aggregate prices across truck ages. The goal is to find three aggregate prices, P^A_0, P^A_1, P^A_2, for the three aggregate truck ages 0, 1, 2, that satisfy $P^A_0 - \delta P^A_1 > P^A_1 - \delta P^A_2 > P^A_2$, meaning that the rental price of trucks decreases with the aggregate truck age.[27] Since age 0 is not aggregated, I let $P^A_0 = P^N_0$. For aggregate age 2 trucks, I set P^A_2 to be the weighted average of P^N_a for $a = 5, \ldots, 16$, where the weight is the number of truck models for each a. I use three steps to calculate the aggregate price of aggregate age 1 trucks. First, I calculate the annual rental price for using a truck from non-aggregate age a_1 to a_2 as

$$r^N_{a_1,a_2} = \frac{1}{a_2 - a_1}\left(P^N_{a_1} - \delta^{a_2 - a_1} P^N_{a_2}\right).$$

Second, I calculate the aggregate annual rental price for using a truck from aggregate age 0 to 1, $r^A_{0,1}$, as the weighted average of $r^N_{a_1,a_2}$ for $a_1 = 0$ and $a_2 = 1, \ldots, 4$, where the weight is

[26] I let the log of price be a linear function of age in the regression, instead of using an age fixed effect. This is because in the price data trucks live up to 12 years while they live up to 16 years in the survey data. I need to predict the prices of trucks older than 12 years old.

[27] Consistent with the model in section 3, the rental price of aggregate age 2 trucks is just P^A_2.

Table A.2: Aggregate truck price for each non-aggregate age

Truck age (a)	Truck price (P_a^N), \$1,000	Rental price ($P_a^N - \delta P_{a+1}^N$), \$1,000
0	63.2859	10.8253
1	53.5312	6.5524
2	47.9375	6.2126
3	42.5765	5.7859
4	37.5414	5.3509
5	32.8474	4.6754
6	28.7469	3.3304
7	25.9352	3.5846
8	22.8067	3.4059
9	19.7968	2.9891
10	17.1507	2.2968
11	15.1570	2.8226
12	12.5862	1.2459
13	11.6023	1.6171
14	10.1890	1.4201
15	8.9478	1.2471
16	7.8578	N/A

Notes: All prices are converted to 2000 constant US dollar.

the number of truck models for each a_1-a_2 pair. Similarly, the aggregate annual rental price for using a truck from aggregate age 1 to 2, $r^A_{1,2}$, is calculated as the weighted average of $r^N_{a_1,a_2}$ for $a_1 = 1, \ldots, 4$ and $a_2 = 5, \ldots, 16$. Lastly, P_1^A is calculated from solving

$$\frac{P_0^A - \delta P_1^A}{P_1^A - \delta P_2^A} = \frac{r^A_{0,1}}{r^A_{1,2}}.$$

The equation means that the ratio of the rental prices of aggregate age 0 and 1 trucks should be equal to the ratio of the annual rental prices of these trucks.

Table A.3 shows the aggregate truck price and the aggregate rental price for each aggregate truck age. These are the aggregate prices I use in the calibration exercises in section 5.

Table A.3: Aggregate truck price for each aggregate age

Truck age (a)	Truck price (P_a^A), \$1,000	Rental price ($P_a^A - \delta P_{a+1}^A$), \$1,000
0	63.2859	34.3111
1	29.5661	16.6678
2	13.1615	13.1615

Notes: All prices are converted to 2000 constant US dollar.

B Computing Equilibrium with Full Commitment

As described in section 6.1.2, in the counterfactual environment with full commitment, each manufacturer m chooses once and for all a sequence of selling and leasing decisions, $\{\boldsymbol{X}_{mt}\}_{t=1}^{\infty}$, that maximizes its discounted profits given rivals' choices $\{\boldsymbol{X}_{-mt}\}_{t=1}^{\infty}$ and the state variables in the initial period $\boldsymbol{Y}_{t=1}$. After the decisions are made, manufacturers must commit to their choices and not change when future periods come. I compute the steady-state outcomes with and without leasing.

For tractability, I follow Chen, Esteban, and Shum (2013) and look for a solution in which each manufacturer commits to a constant sequence of selling and leasing decisions and the industry state variables remain constant.[28] Since manufacturers are homogeneous, I solve for a symmetric equilibrium. Let $\boldsymbol{X}^*$ denote the constant sequence of decisions manufacturers commit to, and $\boldsymbol{Y}^*$ denote the constant industry state variables. Equilibrium requires the following conditions:

(i) When each manufacturer commits to $\boldsymbol{X}^*$ in every period, the industry state is $\boldsymbol{Y}^*$.

(ii) When the industry state in the initial period is $\boldsymbol{Y}^*$, and when all rivals in the initial period and in all future periods, and manufacturer m in all future periods, commit to $\boldsymbol{X}^*$, choosing $\boldsymbol{X}^*$ is manufacturer m's optimal choice in the initial period.

(iii) Trucking companies form rational expectations of future prices consistent with the sequences of manufacturers' choices.

Let $V_{m,t=2}(\boldsymbol{Y})$ denote manufacturer m's net present value at $t = 2$ (i.e., the sum of profits at $t = 2, 3, \ldots$ discounted to $t = 2$), as a function of the state $\boldsymbol{Y}$. I use an iterative algorithm to solve for $\boldsymbol{X}^*$ and $\boldsymbol{Y}^*$.

The details of computing equilibrium when there is leasing are as follows. The algorithm for computing equilibrium without leasing is similar.

(i) Step 1: As described in section 5.3, take $N = 81$ collocation nodes for the state $\boldsymbol{Y}$. Write $V_{m,t=2}(\boldsymbol{Y})$ as a Chebyshev series: $V_{m,t=2}(\boldsymbol{Y}) = \sum_{n=1}^{N} a_n g_n(\boldsymbol{Y})$, where $\{g_n(\boldsymbol{Y})\}_{n=1}^{N}$ is a series of multivariate Chebyshev bases and $\{a_n\}_{n=1}^{N}$ is a series of coefficients.

(ii) Step 2: Choose starting values for the coefficients $\{a_n\}_{n=1}^{N}$ and manufacturers' choices $\boldsymbol{X}^* = (x^*, f^*, z_1^*, z_2^*)$.

[28] As Chen, Esteban, and Shum (2013) points out, by using this approach, I solve directly for a constant solution for the full commitment problem, instead of looking for the steady state of the optimal sequence of choices.

(iii) Step 3: For each collocation node $\boldsymbol{Y}^k$ ($k = 1, \ldots, N$) for the state $\boldsymbol{Y}$, set the choices of manufacturer m and all opponents as $\boldsymbol{X}^*$. Then calculate $V_{m,t=2}(\boldsymbol{Y}^k) := V^k_{m,t=2}$ as

$$V^k_{m,t=2} = p_{0,t=2}x^*f^* + l_{0,t=2}x^*(1 - f^*) + l_{1,t=2}z_1^* + l_{2,t=2}z_2^* - cx^* + \delta \sum_{n=1}^{N} a_n g_n(\boldsymbol{Y}^{k'}),$$

where $\boldsymbol{Y}^{k'}$ is calculated from the law of motion defined in equation (2), holding all manufacturers' choices fixed at $\boldsymbol{X}^*$. All prices are calculated from equilibrium conditions.

(iv) Step 4: Solve the linear system of equations $V^k_{m,t=2} = \sum_{n=1}^{N} a_n g_n(\boldsymbol{Y}^k)$ ($k = 1, \ldots, N$) for $\{a_n\}_{n=1}^{N}$. These are the updated values of coefficients.

(v) Step 5: Solve for the constant industry state $\boldsymbol{Y}^*$ assuming every manufacturer commits to $\boldsymbol{X}^*$ in every period. This is done by solving the equation

$$\boldsymbol{Y}^* = \boldsymbol{L}(\{\boldsymbol{X}^*\}_{m=1}^{M}, \boldsymbol{Y}^*),$$

where $\boldsymbol{L}(\cdot)$ is the law of motion defined in equation (2).

(vi) Step 6: Assuming that the state at $t = 1$ is $\boldsymbol{Y}^*$, and that from manufacturer m's perspective, all opponents at $t = 1, 2, \ldots$ and m itself at $t = 2, 3, \ldots$ commit to $\boldsymbol{X}^*$, solve the following maximization problem for m's optimal choices at $t = 1$, $\boldsymbol{X}^*_{m,t=1}$:

$$\max_{\boldsymbol{X}_{m,t=1}} \; p_{0,t=1}x_{m,t=1}f_{m,t=1} + l_{0,t=1}x_{m,t=1}(1 - f_{m,t=1}) + l_{1,t=1}z_{1m,t=1} + l_{2,t=1}z_{2m,t=1} - cx_{m,t=1} + \delta \sum_{n=1}^{N} a_n g_n(\boldsymbol{Y}'),$$

where $\boldsymbol{Y}'$ is calculated from the law of motion defined in equation (2), holding the opponents' choices fixed at $\boldsymbol{X}^*$. All prices are calculated from equilibrium conditions. Update $\boldsymbol{X}^*$ by m's optimal choices at $t = 1$, $\boldsymbol{X}^*_{m,t=1}$.

(vii) Step 7: Repeat step 3-6 until $\{a_n\}_{n=1}^{N}$ and $\boldsymbol{X}^*$ converge.

Given $\boldsymbol{X}^*$ and $\boldsymbol{Y}^*$, I can calculate the steady-state outcomes.

C Model Fit of the Demand-Side Calibration

Table C.1 shows the model fit of step 2 of the demand-side calibration, in which I estimate the coefficients for the reference group, $\tilde{\beta}_{0,L2}, \tilde{\beta}_{1,L2}, \tilde{\beta}_{2,L2}$, together with the parameters in the joint distribution of trucking companies' characteristics, $\mu_1, \mu_2, \sigma_1^2, \sigma_2^2, \sigma_{12}$, by simulated method of moments.

Table C.2 shows the model fit of step 3 of the demand-side calibration, in which I calibrate σ_ϵ, all truck qualities parameters ($\alpha_1, \alpha_2, \lambda_1$, and λ_2), and all preference parameters except γ_0^l ($\beta_0, \beta_1, \beta_2, \gamma_0^a, \gamma_1^a, \gamma_2^a$, and γ_1^l) to the estimates of $\tilde{\beta}_{0j}, \tilde{\beta}_{1j}, \tilde{\beta}_{2j}$ obtained in step 2.

The model fit is good in both steps.

Table C.1: Model fit of step 2 of the demand-side calibration

Variable	Data value	Model-predicted value
Market share of $B0$ (%)	16.57	20.33
Market share of $L0$ (%)	9.96	10.28
Market share of $B1$ (%)	11.79	7.30
Market share of $L1$ (%)	7.01	4.21
Market share of $B2$ (%)	4.23	4.02
Market share of $L2$ (%)	2.44	2.86
$E(X_{1i}\|j = B0)$	1.8758	1.8886
$E(X_{2i}\|j = B0)$	4.0130	3.8819
$E(X_{1i}^2\|j = B0)$	4.1031	4.1590
$E(X_{2i}^2\|j = B0)$	16.8491	16.6967
$E(X_{1i}X_{2i}\|j = B0)$	7.5113	7.3762
$E(X_{1i}\|j = L0)$	1.8512	1.8597
$E(X_{2i}\|j = L0)$	3.8510	3.5866
$E(X_{1i}^2\|j = L0)$	3.9730	4.0292
$E(X_{2i}^2\|j = L0)$	16.0048	14.1854
$E(X_{1i}X_{2i}\|j = L0)$	7.1661	6.7088
$E(X_{1i}\|j = B1)$	1.8403	1.8389
$E(X_{2i}\|j = B1)$	3.1558	3.0053
$E(X_{1i}^2\|j = B1)$	3.8420	3.9445
$E(X_{2i}^2\|j = B1)$	11.2443	9.8974
$E(X_{1i}X_{2i}\|j = B1)$	5.9468	5.5579
$E(X_{1i}\|j = L1)$	1.7716	1.7601
$E(X_{2i}\|j = L1)$	2.8310	2.8392
$E(X_{1i}^2\|j = L1)$	3.5365	3.5913
$E(X_{2i}^2\|j = L1)$	9.8290	8.8292
$E(X_{1i}X_{2i}\|j = L1)$	4.9176	5.0265
$E(X_{1i}\|j = B2)$	1.8169	1.8089
$E(X_{2i}\|j = B2)$	2.7203	2.7930
$E(X_{1i}^2\|j = B2)$	3.9026	3.8123
$E(X_{2i}^2\|j = B2)$	8.5283	8.5363
$E(X_{1i}X_{2i}\|j = B2)$	5.0301	5.0843
$E(X_{1i}\|j = L2)$	1.7118	1.6943
$E(X_{2i}\|j = L2)$	2.6440	2.7560
$E(X_{1i}^2\|j = L2)$	3.3611	3.3109
$E(X_{2i}^2\|j = L2)$	8.5856	8.3196
$E(X_{1i}X_{2i}\|j = L2)$	4.4381	4.6985

Notes: X_{1i} is log(Average number of trips per week) for i, X_{2i} is log(Fleet size) for i.

Table C.2: Model fit of step 3 of the demand-side calibration

Coefficient	Estimated value from step 2	Model-predicted value
Intercepts ($\tilde{\beta}_{0j}$)		
$j = B0$	-6.0455	-6.0178
$j = B1$	-4.4555	-4.4278
$j = B2$	-4.2101	-4.1824
Coefficients for X_{1i} ($\tilde{\beta}_{1j}$)		
$j = B0$	0.3684	0.3997
$j = L0$	0.3318	0.2450
$j = B1$	0.3294	0.3403
$j = L1$	0.1933	0.1421
$j = B2$	0.2847	0.1962
$j = L2$	0.0589	0.0173
Coefficients for X_{2i} ($\tilde{\beta}_{2j}$)		
$j = B0$	1.4606	1.3717
$j = L0$	1.2610	1.3717
$j = B1$	0.7126	0.6998
$j = L1$	0.5151	0.5506
$j = B2$	0.4497	0.4947
$j = L2$	0.4027	0.4120