Fuel Efficiency Policies in the Chinese Automobile Market:
Evidence from A Random Coefficients Mixed Oligopolistic Differentiated Products Model[1]

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Abstract

We analyze the effects of China's fuel efficiency policies on the Chinese automobile market. China's fuel efficiency policies include: (1) a fuel economy standard that applies to individual vehicle models; and (2) a Corporate Average Fuel Consumption (CAFC) standard that applies to an automobile firm's sales-weighted average fuel consumption. We use a structural econometric model of a mixed oligopolistic differentiated products market that we have developed of the Chinese automobile market, and that we have estimated using a comprehensive data set on the sales, prices, and characteristics of the majority of vehicle makes and models in China, including alternative vehicles, to simulate the effects of counterfactual fuel efficiency policies on alternative vehicle market share and welfare. We find that, consistent with the previous literature on the U.S. CAFE standard, China's CAFC standard, which does not require that each vehicle model achieve a minimum fuel efficiency target, but instead allows firms to average across all the vehicle models that they produce, is inefficient and counteracts China's fuel economy standard. In contrast, the alternative vehicle market share, consumer surplus, private firm profits, and state-owned firm utility would all increase if China removed its CAFC standard and made its fuel economy standard more stringent instead.

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1. Introduction

China is experiencing rapid economic growth and, along with it, rapid growth in vehicle ownership (Darido, Torres, and Mehndiratta, 2014; Liu and Lin Lawell, 2020). In 2009, China's automobile market became the largest in the world, surpassing the U.S. automobile market both in sales and production (Chen, Lin Lawell and Wang, 2020). This rapid increase in vehicle ownership and vehicle usage is associated with issues such as congestion, local air pollution, and global climate change (Lin and Zeng, 2014).

China's automobile policies include two fuel efficiency policies: (1) a fuel economy standard that applies to individual vehicle models; and (2) a Corporate Average Fuel Consumption (CAFC) standard that applies to an automobile firm's sales-weighted average fuel consumption. There were no fiscal penalties on noncompliant carmakers under the standards during the observed time period in this paper and the implementation and enforcement aspects of the standard were only released in 2014 (He and Yang, 2014).

China introduced its fuel economy standard (GB 19578-2004) in September 2004. The fuel economy standard was a fuel consumption of 6.9 L per 100 km (or approximately 34.09 miles per gallon) by 2015. The fuel economy standard applies to passenger cars, SUVs, and light commercial vehicles (LCVs). These vehicles are collectively defined as M1-type vehicles by the European Union, and are defined in the Chinese standard as vehicles with a maximum design speed of at least 50 km/hour and a maximum weight of 3500 kg.

China's Corporate Average Fuel Consumption (CAFC) standard (GB 27999-2011) went into effect in 2012. The CAFC standard is a target level for a firm's sales-weighted average fuel consumption, where the target is a sales-weighted average of individual fuel consumption targets for each vehicle model. In calculating the sales-weighted averages for the CAFC standard, the government uses higher weights for alternative fuel vehicles to encourage their production. Until 2015, a multiplier of 5, 5, 5, and 3 times the quantity sales was used for pure-electric, fuel-cell electric, plug-in hybrid, and energy saving vehicles, respectively. The weights are to gradually decrease thereafter (Chen, Lin Lawell and Wang, 2020).[2]

China's Corporate Average Fuel Consumption (CAFC) standard is similar to the U.S. Corporate Average Fuel Economy (CAFE) standard in that both stipulate that automakers meet a

[2] 2015 annual report of Chinese passenger vehicle fuel consumption 2015 by Innovation Center for Energy and Transportation

minimum sales-weighted average for their vehicle fleets. A firm complies by selling more high-efficiency vehicles (and fewer low-efficiency ones) as a fraction of their total sales (Jacobsen, 2013). The previous literature has identified several drawbacks of fuel economy standards that require automakers to meet a minimum sales-weighted average for their vehicle fleets (Goldberg, 1998; Bento et al., 2009; Knittel, 2011; Klier and Linn, 2012; Jacobsen, 2013; Bento, Gillingham and Roth, 2017; Leard, Linn and McConnell, 2017; Ito and Sallee, 2018; Durrmeyer and Samano, 2018).

In this paper, we analyze the effects of China's fuel efficiency policies on the Chinese automobile market. To do so, we use a structural econometric model of a mixed oligopolistic differentiated products market we have developed and estimated in Chen and Lin Lawell (2021b) that allows different consumers to vary in how much they like different car characteristics on the demand side, and that allows state-owned automobile companies to have different objectives from private automobile companies on the supply side. Our model is estimated using a comprehensive data set on the sales, prices, and characteristics of the majority of vehicle makes and models in China, including alternative vehicles. Alternative vehicles are vehicles that are powered by alternative fuel sources other than gasoline or diesel; and include hybrid cars powered on both gasoline and electricity, purely electric cars, plug-in hybrid cars, and extended range electric vehicles. Our model incorporates two notable features of the Chinese automobile market: some automobile companies in China are state-owned, and some automobile companies in China form international joint ventures (Chen, Lin Lawell and Wang, 2020).

We use our model from Chen and Lin Lawell (2021b) to simulate the effects of counterfactual government fuel efficiency policy. Our results show that, consistent with the previous literature on the U.S. CAFE standard, China's CAFC standard, which does not require that each vehicle model achieve a minimum fuel efficiency target, but instead allows firms to average across all the vehicle models that they produce, is inefficient and counteracts China's fuel economy standard. In contrast, the alternative vehicle market share, consumer surplus, private firm profits, and state-owned firm utility would all increase if China removed its CAFC standard and made its fuel economy standard more stringent instead.

The balance of our paper proceeds as follows. We review the literature in Section 2. Section 3 summarizes our structural econometric model from Chen and Lin Lawell (2021b). We describe the data from Chen and Lin Lawell (2021b) in Section 4. Our counterfactual simulations and their results are described in Section 5. Section 6 discusses our results and concludes.

2. Literature Review

2.1. Vehicle markets and policy

The first strand of literature upon which we build is that on vehicle markets and policy, particularly for alternative vehicles. There is a burgeoning literature on vehicle demand (see e.g., Adjemian, Lin and Williams, 2010; Sallee, West and Fan, 2016; Anderson and Sallee, 2016; Archsmith et al. 2017; Filippini and Wekhof, 2017), including the demand for alternative vehicles (Hidrue et al., 2011; Heutel and Muehlegger, 2015; Holland, Mansur, Muller, and Yates, 2016; Sheldon, DeShazo and Carson; 2016; Li, Lang, Xing, and Zhou, 2017; Zhou and Li, 2018) and the effects of government policy on vehicle demand, particularly for alternative vehicles (Gallagher and Muehlegger, 2011; Beresteanu and Li, 2011; Sallee, 2011; Li, Linn and Spiller, 2013; Hoekstra, Puller and West, 2017; Sheldon and DeShazo, 2017; DeShazo, Sheldon and Carson, 2017; Muehlegger and Rapson, 2019). Axsen, Bailey and Castro (2015) find that car buyers exhibit high degrees of heterogeneity in both preferences and motivations.

The literature on vehicle markets and policy also includes studies of vehicle supply, and the effects of policies on vehicle supply and manufacturer incentives, including for alternative vehicles (Ullman, 2016; Miravete, Moral and Thurk, 2018; Shao, Yang and Zhang, 2019); as well as the literature on government policies related to vehicles (Chen, Esteban and Shum, 2010; Jacobsen and van Benthem, 2015; Sallee and Slemrod, 2012; Bento, Gillingham and Roth, 2017; Kellogg, 2018; Huse and Koptyug, 2019; Levinson, 2019).

We build in particular on the literature on fuel economy standards, much of which has focused primarily on the Corporate Average Fuel Economy (CAFE) standard in the United States (Greene, 1991; Goldberg, 1998; Kleit, 2004; Austin and Dinan, 2005; Anderson and Sallee, 2011; Whitefoot and Skerlos, 2012; Bento et al., 2018). There is widespread agreement that a carbon tax would be more efficient than fuel economy standards at reducing transportation-related carbon dioxide emissions (Davis and Knittel, 2019). Similarly, gasoline taxes may be better than fuel economy standards for addressing gasoline externalities (Jacobsen, 2013) and for addressing a greater number of automobile-related externalities (Parry, Walls and Harrington, 2007; Lin and Prince, 2009).

China's Corporate Average Fuel Consumption (CAFC) standard is similar to the U.S. Corporate Average Fuel Economy (CAFE) standard in that both stipulate that automakers meet a minimum sales-weighted average for their vehicle fleets. A firm complies by selling more high-efficiency vehicles (and fewer low-efficiency ones) as a fraction of their total sales (Jacobsen, 2013). Fuel economy standards that require automakers to meet a minimum sales-weighted average for their vehicle fleets impose a constraint on automakers which creates an implicit subsidy for fuel-efficient vehicles and an implicit tax for fuel-inefficient vehicles (Davis and Knittel, 2019; Bento et al., 2020).

The previous literature has identified several drawbacks to fuel economy standards that require automakers to meet a minimum sales-weighted average for their vehicle fleets. First, instead of complying, some automobile companies may violate the standard and pay the penalties associated with the violation (Goldberg, 1998; Jacobsen, 2013; Durrmeyer and Samano, 2018). Second, automobile companies have an incentive to lower the price of cars with high fuel efficiency and to increase the price of those with low fuel efficiency in order to comply with the regulation or reduce the penalties, and these price distortions may lead to larger negative welfare effects than those from other policies such as feebates (Durrmeyer and Samano, 2018). Third, automobile companies may comply by reducing vehicle weight to improve fuel economy without using new technology (Klier and Linn, 2012; Knittel, 2011), which may or may not increase fatalities depending on the resulting effect on the vehicle weight distribution (Bento, Gillingham and Roth, 2017). Fourth, if the fuel economy standards that require automakers to meet a minimum sales-weighted average for their vehicle fleets vary depending on other attributes of the vehicles that a firm produces, such as vehicle size or vehicle weight, then the regulation may lead to distortions in these other attributes (Leard, Linn and McConnell, 2017; Ito and Sallee, 2018).

A fifth drawback is that when combined with other policies, fuel economy standards that require automakers to meet a minimum sales-weighted average for their vehicle fleets impose additional constraints on firms that may counteract the other policies. Bento et al. (2009) find that an increase in gasoline taxes yields a significantly larger short- and long-run improvement in fuel economy in the absence of a CAFE standard compared with the case of a pre-existing binding CAFE standard. When firms are not constrained by the CAFE standard, producers have greater incentives to change the composition of their car or truck fleets to meet the increased consumer demands for fuel economy that stem from higher fuel costs resulting from an increase in the gasoline tax. In contrast, when firms are constrained by the CAFE standard, the increase in the gasoline tax leads to smaller changes in the composition and average fuel economy of their fleets of cars and trucks (Bento et al., 2009).

2.2. Vehicle markets and policy in China

The second strand of literature we build upon is that on vehicle markets and policy in China. A more detailed review of this literature is provided in Chen, Lin Lawell and Wang (2020).

In terms of vehicle-related policies, Xiao and Ju (2014) explore the effects of consumption-tax and fuel-tax adjustments in the Chinese automobile industry. Nienhueser and Qiu (2016) analyze the impacts of providing renewable energy for electric vehicle charging. Xiao, Zhou and Hu (2017) present a welfare analysis of the vehicle quota system of Shanghai, China. Li (2018) empirically quantifies the welfare consequences of two mechanisms for distributing limited vehicle licenses as a measure to combat worsening traffic congestion and air pollution. Woo et al. (2008) and Cao et al. (2020) study license plate auctions in Hong Kong. Yang et al. (2020) analyze the effect of Beijing's vehicle ownership restrictions on travel behavior. Bai et al. (2020) analyze the impact of the requirement for foreign automakers to set up joint ventures with domestic automakers in return for market access on facilitating knowledge spillover and quality upgrading. Chen, Hu and Knittel (2021) find that China's subsidy program for fuel efficient vehicles boosted sales for subsidized vehicle models, but also created a substitution effect within highly fuel efficient vehicles that greatly reduces the cost-effectiveness of the program. Hu, Yin and Zhao (2021) analyze the battery electric vehicle (BEV) subsidy program in China by estimating a structural model of dynamic demand and Bertrand Nash supply using quarterly sales data at the model-city level from 2016-2019. Using data from the US and China, DeCicco (2013) finds that beyond fundamental R&D, policies to commercialize alternative vehicles are not necessarily required for climate protection.

On the supply side, Hu, Xiao and Zhou (2014) use data on Chinese passenger vehicles to test whether price collusion exists within corporate groups or across groups, and find no evidence for within or cross-group price collusion. Li, Xiao and Liu (2015) estimate a market equilibrium model of the Chinese automobile market with differentiated multiproduct oligopoly, and find evidence for cost reductions through learning by doing and other channels.

In terms of factors affecting vehicle demand in China, Lin and Zeng (2013) estimate the price and income elasticities of demand for gasoline and the vehicle miles traveled (VMT) elasticity in China. In their analysis of brand name types and consumer demand, Wu et al. (2019) find that Chinese consumers prefer vehicle models with semantic brand names rather than alphanumeric, phonetic, or phonosemantic brand names. Sun et al. (forthcoming) analyze the effects of a nationwide consumer boycott of Japanese brands in China in 2012 on sales of automobile brands from different countries-of-origin. Barwick, Cao and Li (forthcoming) document the presence of local protectionism in China's automobile market and show that local protectionism leads to significant consumer welfare loss arising from choice distortions.

3. Structural Model of Chinese Automobile Market

We use the random coefficients mixed oligopolistic differentiated products model of the Chinese automobile market that we have developed and estimated in Chen and Lin Lawell (2021b). This model allows different consumers to vary in how much they like different car characteristics on the demand side, and that allows state-owned automobile companies to have different objectives from private automobile companies on the supply side.

On the demand side, our model in Chen and Lin Lawell (2021b) uses a random coefficients model of vehicle demand (Berry, Levinsohn and Pakes, 1995). A random coefficients model addresses the independence of irrelevant alternatives problem in traditional logit models (McFadden, 1973; McFadden, 1974) by allowing for interactions between unobserved consumer characteristics and observed product characteristics, thus allowing different consumers to vary in how much they like different car characteristics, and thereby generating reasonable substitution patterns.

In a random coefficients demand model, owing to the interactions between consumer preferences and product characteristics, consumers who have a preference for size will tend to attach a high utility to all large cars, and this will induce a larger, more realistic cross-price elasticity between large cars. Thus, unlike traditional logit models that do not allow for interactions between unobserved consumer characteristics[3] and observed product characteristics, our random coefficients model of vehicle demand generates reasonable substitution patterns.

According to the results in Chen and Lin Lawell (2021b), the standard deviations of the marginal utility of our chosen vehicle characteristics are statistically significant in all of the models specified, suggesting that it is important to allow for consumers to vary in how much they like different car characteristics.

On the supply side, our model in Chen and Lin Lawell (2021b) innovates upon the literature by allowing state-owned automobile companies to have different objectives from private automobile companies. We assume a Bertrand (Nash-in-prices) mixed oligopolistic equilibrium among multiproduct firms.

We assume that each private firm maximizes the joint profits over all vehicle models that the firm produces. Unlike private firms, state-owned firms may have objectives other than profit maximization alone. We allow for the possibility that state-owned firms may care about objectives other than profit, and allow the data to tell us whether and how much state-owned firms care about these other objectives. In particular, we specify the utility function of state-owned firms as a weighted sum of several possible objectives, the weights for which we estimate econometrically. These objectives include profits, consumer surplus, and alternative vehicle production.

We include consumer surplus among the possible objectives of state-owned firms following the previous literature that has modeled the objectives of state-owned enterprises as a weighted sum of profits and consumer surplus (e.g., Peltzman, 1971; Timmins, 2002; Hochman and Zilberman, 2015; Kheiravar, Lin Lawell and Jaffe, 2021; Sears, Lin Lawell and Walter, 2021). Since each state-owned firm is at least partially controlled by the government, since the government may potentially consider the utilities of all consumers, we allow for the possibility that state-owned firms care about the utilities of all the consumers in the market in that year.[4] By

[3] Examples of unobservable consumer characteristics that may affect consumer preferences for car characteristics include age, education, gender, family size, occupation, commute distance, risk aversion, preferences for environmental conservation, whether a consumer likes fast cars, whether a consumer likes safe cars, whether a consumer likes large cars, whether a consumer lives in a rural or urban area, whether a consumer drives to remote outdoor areas (where a rugged truck/SUV might be preferred), local protectionism, local car dealers, local promotions, what types of cars their neighbors purchase, whether the vehicle is intended for private household use or instead for public or business use, and anything else that may affect how much different consumers like different car characteristics.

[4] It is possible that the Chinese central government may care about the utilities of all its consumers. Thus, it is possible that state-owned firms that are at least partially owned by the central government may care about the utilities of all its consumers. In addition, the central government controls the appointment, evaluation, promotion, and demotion of

choosing the prices of the vehicle models it produces, each state-owned firm not only directly affects the prices of their own vehicle models, but, since each firm is best responding to every other firm in the Bertrand (Nash-in-prices) mixed oligopolistic equilibrium, each state-owned firm also indirectly affects the prices of the vehicle models produced by other state-owned and private firms. We therefore allow for the possibility that state-owned firms may care about consumer surplus; whether they actually do is an empirical question that our econometric estimation enables us to examine.

We define alternative vehicles as vehicles that are powered by alternative fuel sources other than gasoline or diesel. These alternative vehicles include hybrid cars powered on both gasoline and electricity, purely electric cars, plug-in hybrid cars, and extended range electric vehicles. We include alternative vehicle production among the possible objectives of state-owned firms since alternative vehicle production appears to be an objective the Chinese government cares about and has prioritized for some time. For example, in 2009 the central government issued documents calling for an ambitious production target of 500,000 electric vehicles by 2011 (Howell, Lee and Heal, 2015). China's twelfth Five-Year Plan (2011-2015) – its core economic and social development roadmap – identified the alternative fuel vehicle industry as one of seven strategic emerging industries to which the country would devote enhanced policy and financial support (Marquis, Zhang and Zhou, 2013). In addition, as China more recently revealed when it announced its "Made in China 2025" strategic plan in 2015, alternative vehicles are among the 10 areas where the country plans to take the lead worldwide (Tse and Wu, 2018). Alternative vehicles are only produced by state-owned firms during the time period of our analysis.

Our parameter estimates in Chen and Lin Lawell (2021b) show that state-owned car companies may have different objectives from private car companies. Results show, however, that the majority of the weight (92%) is on profit, with some weight on consumer surplus (6%) and a little weight on alternative vehicle production (2%). Thus, although state-owned car companies

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subnational officials in China, and the career paths of these officials are determined by the performance of their jurisdictions (Xu, 2011). The central government directly controls the key positions at the province level and grants the provincial government the power to appoint key officials at the prefecture level (Suárez Serrato, Wang and Zhang, 2019). Thus, state-owned firms that are at least partially owned by local governments in China are at least partially controlled by the Chinese central government as well. Thus, state-owned firms, whether partially owned by the central or local governments, are all at least partially controlled by partially the central government, and therefore may care about the utilities of all consumers.

care about other objectives such as consumer surplus and alternative vehicle production, their primary objective is to make profits.

To examine whether joint ventures between Chinese automobile companies and different international car companies have different marginal costs, our model in Chen and Lin Lawell (2021b) includes dummies for joint ventures with each international car company in the specification of marginal costs. To examine whether Chinese automobile companies that form joint ventures with international car companies have better technology, our specification for marginal cost includes interactions between the international joint venture dummy with some of the technology-related car characteristics. The technology-related car characteristics we use are: whether the car is an alternative vehicle, fuel efficiency, and horsepower. Furthermore, to examine whether Chinese automobile companies that form joint ventures with international car companies from a particular country have better technology, our specification for marginal cost also includes interactions between an international joint venture country dummy and technology-related vehicle characteristics.

The parameter estimates in Chen and Lin Lawell (2021b) show that Chinese car companies that form international joint ventures with car companies in the U.S. and Japan have lower marginal costs of technology-related vehicle characteristics. Moreover, when comparing international joint ventures with car companies in the U.S. and Japan, the marginal costs of fuel efficiency and of alternative vehicles tend to be lower in joint ventures with Japanese firms, while the marginal costs of horsepower tend to be lower in joint ventures with U.S. firms.

China's automobile policies include (1) a fuel economy standard that applies to individual vehicle models; and (2) a Corporate Average Fuel Consumption (CAFC) standard that applies to an automobile firm's sales-weighted average fuel consumption (Chen, Lin Lawell and Wang, 2020). There were no fiscal penalties on noncompliant carmakers under the standards during the observed time period in this paper, and the implementation and enforcement aspects of the standard were not released until 2014, after the observed time period in this paper (He and Yang, 2014). Since the standards were not binding and noncompliance occurs frequently in the observed data, we do not impose these policies as constraints on firms, but instead measure any costs firms may have incurred from violating the respective standards. Although firms did not incur any direct explicit financial penalties from violating the standards (He and Yang, 2014), it is possible that firms that did not comply with the standards may have faced other perceived, indirect, and/or implicit costs; such costs may include, for example, administrative costs or possible indirect costs from government disapproval. It is also possible that firms that over-complied with the standards (by having a better fuel economy than was required) may have received some benefits -- whether perceived, indirect, implicit, or otherwise -- from doing so; such benefits may include, for example, the possibility of subsidies, preferential taxes, discount loans, or other benefits from the government (Yu et al., 2019). Thus, to measure the effects of China's fuel economy standard and Corporate Average Fuel Consumption (CAFC) standard, our model in Chen and Lin Lawell (2021b) includes three fuel efficiency policy interaction terms in the marginal cost.

The first fuel efficiency policy interaction term is the fuel economy standard minus fuel efficiency, which measures if a firm incurs costs if it produces a car with worse fuel economy than the fuel economy standard. A positive coefficient on the fuel economy standard minus fuel efficiency would mean that a firm incurs costs if it produces a car with worse fuel economy than the fuel economy standard, and also that a firm benefits if it produces a car with better fuel economy than the fuel economy standard.

The second fuel efficiency policy interaction term is a dummy variable for the CAFC policy being in effect. Since the CAFC went into effect in 2012 (Chen, Lin Lawell and Wang, 2020), this CAFC policy dummy is equal to 1 for the years 2012 onwards, and is 0 before 2012. Although the CAFC was not binding during the 2010-2013 period of our data set (Chen, Lin Lawell and Wang, 2020), by including this term we allow for the possibility that the presence of the CAFC may affect marginal costs. The CAFC policy dummy measures if firms face higher marginal costs when the CAFC policy is in effect. A positive coefficient on the CAFC policy dummy would mean that firms face higher marginal costs when the CAFC policy is in effect, possibly in part from the compliance costs of having to average the fuel efficiency over all their cars to meet the CAFC standard.

The third fuel efficiency policy interaction term is the CAFC policy dummy interacted with the difference between the CAFC target and fuel efficiency, and measures if a firm incurs costs from producing a car with worse fuel economy than the CAFC target when the CAFC is in place. Even though the CAFC was not binding during the period of our data set, by including this term we allow for the possibility that the presence of the CAFC may adversely affect a firm if it produces a car with worse fuel economy than the CAFC target. For example, if a firm produces a car with worse fuel economy than the CAFC target, then it becomes harder for the firm to meet the CAFC, and this term may capture, for example, the resulting increase in possibility that the firm may incur some fine, penalty, or cost if it does not meet the CAFC. A positive coefficient on the CAFC policy dummy interacted with the difference between the CAFC target and fuel efficiency would mean that a firm incurs costs from producing a car with worse fuel economy than the CAFC target when the CAFC is in place, perhaps because by doing so it then becomes harder for the firm to meet the CAFC.

According to the results in Chen and Lin Lawell (2021b), the coefficient on the fuel economy standard minus fuel efficiency is positive and significant, which means that a firm incurs costs if it produces a car with worse fuel economy than the fuel economy standard, and also that a firm benefits if it produces a car with better fuel economy than the fuel economy standard. The coefficient on the dummy variable for the Corporate Average Fuel Consumption (CAFC) policy being in effect is positive and significant, which means that firms face higher marginal costs when the CAFC policy is in effect, possibly in part from the compliance costs of having to average the fuel efficiency over all their cars to meet the CAFC standard. The coefficient on the CAFC policy dummy interacted with the difference between the CAFC target and fuel efficiency is significant and positive, which means that a firm incurs costs from producing a car with worse fuel economy than the CAFC target when the CAFC is in place, perhaps because by doing so it then becomes harder for the firm to meet the CAFC.

For more details on our random coefficients mixed oligopolistic differentiated products model of the Chinese automobile market that we have developed and estimated in Chen and Lin Lawell (2021b), including details about the demand model, supply model, instruments, estimation, identification, parameter estimates, model validation, and welfare results, see Chen and Lin Lawell (2021b).

4. Data

Our model in Chen and Lin Lawell (2021b) is estimated using a comprehensive annual data set on the sales, prices, and characteristics of the majority of vehicle makes and models marketed in the Chinese automobile industry over the years 2010 to 2013. Our data set consists of 2,215 vehicle models over the years 2010 to 2013.

We delineate vehicle models as follows. First, we treat each year as a separate market, each with a different set of vehicle models to choose from, and therefore treat vehicle models from different years as different vehicle models that may differ in their price and characteristics. Second, since some models have different engine displacements, we further delineate vehicles by "model displacement", which we define as a combination of a model with a specific engine displacement. For example, the Toyota Camry model comes in engine displacements of 1.6L and 1.8L, which we categorize as two different model displacements. For each model, we have collected information on price and quantity sales for each engine displacement of that model. Third, for each model displacement, we have also collected information on vehicle characteristics for each style within that model. We treat each style of a model-displacement-year as a single vehicle model observation as long as it differs from other styles within that model in any of the vehicle characteristics we examine.

The quantity sales data for each model displacement is collected from the China Auto Market Almanac. We have collected two sets of price data, both in units of 10,000 RMB. We obtained data on prices for each model displacement from the *China Automotive Industry Yearbook*. Since there are different styles for each model displacement, we also obtained data on prices for each style of each model displacement from *www.autohome.com.cn*, which is one of the largest vehicle websites in China.[5] We confirm that prices from the two data sets are comparable. The price data we collect is the nominal manufacturer's suggested retail price (MSRP); transactions prices are unfortunately not available. We obtain information about vehicle characteristics from *www.autohome.com.cn.*

Unlike in the U.S. and France,[6] China's automobile market has infrequent promotions from manufacturers or dealers, and retail prices are often very close to or the same as MSRPs (Li, Xiao and Liu, 2015; Barwick, Cao and Li, forthcoming). Promotions are mostly concentrated among low-end vehicle models (Hu, Xiao and Zhou, 2014; Li, Xiao and Liu, 2015). For high-end

[5] Other famous and widely used car websites include: *http://auto.sohu.com*, *http://auto.163.com*, *http://auto.sina.com.cn*, *http://auto.qq.com*

[6] In the context of U.S. auto market, Busse, Silva-Risso and Zettelmeyer (2006) suggest that the actual transaction price could be quite different from MSRP due to dealer and consumer promotions; Hellerstein and Villas-Boas (2010) show that the median transaction prices could be several thousand dollars less than the MSRP and exhibit more monthly variation than the MSRP; and Langer and Miller (2012) document that automakers use cash incentives to offset changes in fuel expenses due to gasoline price fluctuations and suggest that consumer demand for fuel economy could be underestimated if manufacturer discounting is ignored. In the case of the French automobile market, D'Haultfoeuille, Durrmeyer and Février (2019) find that discounting arising from price discrimination is significant.

models, transaction prices could be even higher than MSRPs (Li, Xiao and Liu, 2015). Consumers of high-end models are usually less sensitive to the price. In addition, luxury good purchases that are socially observable could be driven by concerns of status seeking and conspicuous consumption that are well documented among Chinese consumers (Brown, Bulte and Zhang, 2011). Given the unavailability of transaction price data, and given that any potential bias on the estimates of price elasticities in China may not be as severe as suggested by those studies on auto markets in the U.S. and France, we follow the automobile demand literature, including the literature on the Chinese automobile market (Deng and Ma, 2010; Hu, Xiao and Zhou, 2014; Li, Xiao and Liu, 2015; Barwick, Cao and Li, forthcoming), and use MSRPs in our analysis.

We delineate firms as follows. If the name of the car manufacturers are different in *www.autohome.com.cn*, we treat the manufacturers as different Chinese automobile companies. Since each international joint venture is at least partially controlled by the international car company involved in the joint venture (Hu, Xiao and Zhou, 2014), if a Chinese automobile company forms joint ventures with different international car companies, each international joint venture that the Chinese automobile company forms with a different international car company is considered a different firm. There are 56 firms in our sample, of which 43 involved a joint venture with an international car company for at least one year over the 2010-2013 period of our data set.

One notable feature of the Chinese automobile industry is that some of the Chinese automobile companies are state-owned. We obtain information about the ownership of the car companies from *baike.baidu.com* and from China Industry Business Performance Data. Since the majority of car companies in China are operated under shareholding system, there are few car companies that are 100% state-owned. Nevertheless, governments do hold a majority of the stocks of some of the companies. Throughout the paper, a stated-owned firm is defined as a car manufacturer for which a majority of the stock of its parent company (i.e., more than 50%) is held by either the central or local Chinese government. Of the 56 firms in our sample, 44 of them are state-owned.

There are 6 vehicle models (i.e., 6 model-displacement-style-year observations) in our data set that are powered by alternative fuel sources other than gasoline or diesel. These alternative vehicles include hybrid cars powered on both gasoline and electricity, purely electric cars, plug-in hybrid cars, and extended range electric vehicles. The number of alternative vehicles sold by a firm in a year for firm-years with alternative vehicle sales ranged from 350 to 7,302 alternative vehicles.

Table 1 presents summary statistics for price, quantity, and the vehicle characteristics we have chosen to focus on in our structural econometric model: fuel efficiency, length, weight, passenger capacity (in terms of the number of seats), and horsepower. Unlike in the U.S., where the measurement of fuel efficiency is mileage per gallon, China uses a fuel consumption measurement of liters per 100 kilometers (the smaller the value is, the better in terms of energy efficiency). Our fuel efficiency variable is therefore the reciprocal of the fuel consumption measurement, and is in units of 100 kilometers per liter of gasoline.

We use annual data on the adult population (ages 15-64) from World Development Indicators to proxy for the automobile market size. The total quantity sales for year over 2010-2013 was approximately 28.8 million vehicles per year; the total market size over 2010-2013 was approximately 990.8 million people (of age 15-64). We use data on annual urban income across all provinces from the China Statistical Year Book.

For further information about the vehicle characteristics in our data set, including descriptive statistics and graphs showing distributions of and trends in vehicles characteristics in the Chinese automobile market, see Chen, Lin Lawell and Wang (2020).

5. Counterfactual Simulations

One advantage of estimating a structural econometric model is that we can use the estimated parameters to simulate demand, supply, and welfare under counterfactual scenarios. We use the parameters estimated from our structural model in Chen and Lin Lawell (2021b) to run counterfactual simulations to analyze the effects on demand, cost, and welfare of different counterfactual government policies.

For each counterfactual scenario, we calculate statistics for market shares, costs, and welfare in 2013. The market share statistics we calculate include the total market share for all alternative vehicles. The cost statistics we calculate include the mean marginal costs for alternative vehicles, and the mean marginal costs for all cars. The welfare statistics we calculate include: consumer surplus; total firm profits for private firms; average firm profits for private firms; total firm utility for state-owned firms, average firm utility for state-owned firms. The simulated statistics are calculated by solving for a fixed point, since market shares are a function of price and prices are a function of market shares. We bootstrap the standard errors.

We assume that the parameters we estimate do not change under the different counterfactual scenarios. Since our utility parameters measure the marginal utility of different vehicle characteristics, including price, it seems reasonable to assume that the marginal utility of vehicle characteristics would not change under a counterfactual government policy, at least in the short run. Similarly, since the cost parameters already include parameters on interactions between government policy and vehicle characteristics, it seems reasonable to assume that parameters in marginal costs would not change under a counterfactual government policy, at least in the short run. For the parameters in the objective function of state-owned firms, we assume the weights on the different terms in a state-owned firm's objective function and the parameters in alternative vehicle production objective would not change under a counterfactual government policy, at least in the short run. If anything, the decision to change government policy might be induced by parameters in consumer utility, firm costs, and/or the objectives of state-owned firms, rather than the other way around.

We simulate the effects of various counterfactual government policies on equilibrium demand, cost, and welfare. For each counterfactual government policy we simulate, we calculate statistics for market shares, costs, and welfare in 2013, and then conduct a two-sample t-test to compare each statistic from the new car scenario with the respective statistics from the base-case simulation of the status quo. The results are presented in Table 2, which reports, for each respective statistic (column), the difference between the statistic under the counterfactual simulation (row) and the statistic under the status quo base-case simulation.

A first set of counterfactual policies we simulate regards the fuel economy standard. If we remove the fuel economy standard, the mean marginal costs for all cars increase; there is no significant change in either the mean marginal costs for alternative vehicles or in the alternative vehicle market share; and consumer surplus, average private firm profit, and average state-owned firm utility all increase. Thus, removing the fuel economy standard will benefit both consumers and firms, and does not affect alternative vehicle market share.

We also simulate a set of scenarios that increase target under the fuel economy standard by 5% to 35%, and find that, of these scenarios, mean marginal costs for all cars increase the most when we increase the target by 20%; the alternative vehicle market share increases the most when we increase the target by 15%; consumer surplus increases the most when we increase the target by 25% (although consumer surplus increases even more when we remove the fuel economy standard), average private firm profit increases the most when we increase the target by 35%, and average state-owned firm utility increases the most when we increase the target by 20%. Increasing the target under the fuel economy standard by 15% or 20% yields the best outcome, and will increase the alternative vehicle market share as well as benefit both consumers and firms.[7]

A second set of counterfactual policies we simulate regards the Corporate Average Fuel Consumption (CAFC) standard. If we remove the CAFC standard, mean marginal costs for alternative vehicles and mean marginal costs for all cars will increase. Nevertheless, removing the CAFC standard leads to a significant increase in alternative vehicle market share, consumer surplus, average private firm profit, and average state-owned firm utility. Thus, removing the CAFC standard will increase the alternative vehicle market share, as well as benefit consumers and firms.

We also simulate increasing the target under the CAFC standard by 5% to 25%, and find that the alternative vehicle market share, consumer surplus, average private firm profit, and average state-owned firm utility are all higher when we remove the CAFC standard than when we increase its target.

We also simulate a counterfactual policy in which we remove both the fuel economy standard and the CAFC standard. We find that removing all fuel economy standards leads to a significant increase in the mean marginal costs for all cars, but also a significant increase in alternative vehicle market share, consumer surplus, average private firm profit, and average state-owned firm utility.

Since we find that removing the CAFC standard will increase the alternative vehicle market share, as well as benefit consumers and firms, we also simulate a set of counterfactual policies in which we both (i) remove the CAFC standard, and also (ii) vary the fuel economy standard from no fuel economy standard, to the status quo fuel economy standard, to an increase in the target under the fuel economy standard of 5% to 35%. All these combinations lead to a significant increase in alternative vehicle market share, consumer surplus, average private firm profit, and

[7] The relationships between policy stringency and outcomes may be non-monotomic because we are simulating equilibrium outcomes when supply and demand re-equilibrate under the counterfactual policy.

average state-owned firm utility. Of these combinations, combining no CAFC standard with an increase in the target under the fuel economy standard by 25% leads to the largest increase in alternative vehicle market share. Removing both the CAFC standard and the fuel economy standard leads to the largest increase in consumer surplus. Combining no CAFC standard with the status quo fuel economy standard leads to the largest increase in average private firm profit and average state-owned firm utility. Of these combinations, the best combination is combining no CAFC standard with an increase in the target under the fuel economy standard of 25%, which leads to the largest increase in alternative vehicle market share, and large increases in consumer surplus, average private firm profit, and average state-owned firm utility.

6. Discussion and Conclusion

In this paper, we analyze the effects of China's fuel efficiency policies on the Chinese automobile market. To do so, we use a structural econometric model of a mixed oligopolistic differentiated products market we have developed and estimated in Chen and Lin Lawell (2021b) that allows different consumers to vary in how much they like different car characteristics on the demand side, and that allows state-owned automobile companies to have different objectives from private automobile companies on the supply side. Our model is estimated using a comprehensive data set on the sales, prices, and characteristics of the majority of vehicle makes and models in China, including electric vehicles, hybrid vehicles, and alternative-fueled vehicles. Our model incorporates two notable features of the Chinese automobile market: some automobile companies in China are state-owned, and some automobile companies in China form international joint ventures.

We use our model from Chen and Lin Lawell (2021b) to simulate the effects of counterfactual government fuel efficiency policy. Our counterfactual policy simulations yield several main results. First, it is possible for an increase in the target under the fuel economy standard to lead to increases in alternative vehicle market share, consumer surplus, average private firm profit, and average state-owned firm utility. All else equal, a more stringent fuel economy standard favors vehicles whose fuel efficiency exceed their respective target, lowering their relative prices, which has the possibility of increasing alternative vehicle market share; increasing consumer surplus, particularly for consumers of fuel efficient and/or alternative vehicles, and those who can now switch to fuel efficient and/or alternative vehicles as a result of their lower relative price; increasing average private firm profit; and/or increasing average state-owned firm utility.

Second, the CAFC standard is inefficient: the alternative vehicle market share, consumer surplus, average private firm profit, and average state-owned firm utility would all be higher if the CAFC standard were removed altogether compared to either the status quo, or counterfactual scenarios in which we make the CAFC more stringent. The inefficiency of the CAFC standard arises in part because the CAFC standard does not require that each vehicle model achieve a minimum fuel efficiency target, but instead allows firms to average across all the vehicle models that they produce; in part owing to the compliance cost and computational cost burden to firms of having to average across all the vehicle models they produce; and also in part because there is already a fuel economy standard in place. Our result that China's CAFC standard is inefficient and imposes additional constraints on firms that may counteract the fuel economy standard is consistent with Bento et al. (2009), who find that a pre-existing binding CAFE standard counteracts the effects of another policy, an increase in gasoline taxes.

Third, the policy that yields the best outcome of all the counterfactual policy scenarios we considered is one that combines a removal of the CAFC standard with an increase in the target under the fuel economy standard of 25%, which leads to large increases in alternative vehicle market share, consumer surplus, average private firm profit, and average state-owned firm utility. Thus, since the CAFC standard is inefficient, it is best to remove it and make the fuel economy standard more stringent instead. Since the fuel economy standard applies to all cars while the CAFC standard does not require that each vehicle model achieve a minimum fuel efficiency target, but instead allows firms to average across all the vehicle models that they produce, removing the CAFC standard and making the fuel economy standard more stringent will best ensure that all cars meet a stringent minimum fuel efficiency target.

Our research points to several potential avenues for future research. A first potential avenue for future research is to model a firm's choice of vehicle characteristics for each vehicle they produce. In this paper, we have endogenized each firm's choice of vehicle price, but have taken the vehicle characteristics as given. It is possible that the choice of vehicle characteristics may depend on government policy and also on whether the firm has formed an international joint venture. In future work we hope to endogenize the choice of vehicle characteristics as well.

A second related avenue for future research is endogenize the choice of cars, including alternative vehicles, for the Chinese market. In ongoing, complementary work, for example, Chen and Lin Lawell (2021a) analyze the effects of introducing a new alternative vehicle on alternative vehicle market share and welfare.

A third potential avenue for future research is to model the dynamic decision-making of the firms, including their dynamic decisions to introduce new cars and form international joint ventures. In this paper, following the previous literature, we have modeled the decisions of both private and state-owned firms as a static game. In future work we hope to model the firms' decisions as a dynamic game.

A fourth potential avenue for future research is to also incorporate the dynamics of the used car market, building on the models of Busse, Knittel and Zettelmeyer (2013); and the dynamic decision-making of consumers, including the decision to scrap older vehicles and the joint decisions of vehicle ownership and vehicle usage (vehicle miles driven), building on the models of Gillingham et al. (2016) and Li, Liu and Wei (2021). When considering the dynamic impacts in the used car market, Jacobsen (2013) finds that the overall welfare costs of the U.S. Corporate Average Fuel Economy (CAFE) standards are regressive. Bento et al. (2020) find that including multi-market interactions involving the used car market and scrappage are important for providing accurate predictions of the costs and benefits of fuel economy standards.

Fifth, while our structural econometric model of a mixed oligopolistic differentiated products market allows different consumers to vary in how much they like different car characteristics on the demand side, it is estimated using product-level and aggregate market-level data, since our comprehensive data set on the sales, prices, and characteristics of the majority of vehicle makes and models in China, including alternative vehicles, is at the aggregate market level. Berry, Levinsohn and Pakes (2004) show how rich sources of consumer-level information on vehicle choice can help to identify demand parameters in a widely-used class of differentiated products demand models. Disaggregate models of vehicle choice using consumer-level data for the U.S. automobile market have enabled previous researchers to incorporate and analyze additional realistic features such as brand loyalty (Train and Winston, 2007) and the intergenerational transmission of brand preferences (Anderson et al., 2015). In future work we hope to find and obtain consumer-level vehicle choice data for the Chinese automobile market that would enable us to further refine our model of vehicle demand to incorporate and analyze additional realistic features of vehicle choice. Having more disaggregated data would also enable us to better incorporate features such as local protectionism (Barwick, Cao and Li, forthcoming) and to analyze the effects of any local government policies.

A sixth potential avenue for future research is to analyze demand-side policies as well as supply-side policies for alternative vehicles. The government policies we analyze in this paper, including fuel economy policies, are primarily supply-side policies. Chen, Hu and Knittel (2021) and Qian (2018) analyze China's subsidies for fuel efficient and electric vehicles. As our national data precludes us from analyzing local subsidies (Qian, 2018), and as the effective date and the duration of the national subsidy for particular fuel efficient vehicle models are not clear to firms or consumers (Chen, Hu and Knittel, 2021), we do not incorporate subsidies in our model. In future work we hope to analyze and compare demand-side policies and supply-side policies and their interactions with each other.

Our research has important implications for industry, government, society, academia, and NGOs. Our model of the demand and cost in the Chinese automobile market has implications for industry, particularly car manufacturers interested in better targeting cars, including alternative vehicles, for the Chinese market. Our estimates of the factors that affect demand and supply in the Chinese automobile market have important implications for policy-makers interested in developing incentive policies to increase market penetration of alternative vehicles with potential environmental and climate benefits.

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Table 1. Summary statistics, 2010-2013

Variable	# Obs	Mean	Std. Dev.	Min	Max
Price (1,000 Yuan)	2,215	158.40	119.87	28.8	899.6
Quantity	2,215	51,986.65	53,832.95	1	263,408
Alternative vehicle (dummy)	2,215	0.003	0.052	0	1
Fuel efficiency (100 km/L)	2,215	0.134	0.021	0.078	0.233
Length (mm)	2,215	4,500.09	319.83	3,400	5,175
Weight (kg)	2,215	1,373.05	235.89	815	2,310
Capacity (number of seats)	2,215	5.093	0.432	4	7
Horsepower (PS)	2,215	137.33	41.22	46	310

Table 2. Counterfactual policy simulations

	Difference from status quo base case in:					
	Mean marginal costs for alternative vehicles (1000 Yuan)	Mean marginal costs for all cars (1000 Yuan)	Alternative vehicle market share	Consumer surplus (1000 Yuan)	Average private firm profit (billion Yuan)	Average state-owned firm utility (billion Yuan)
Fuel economy standard:						
No fuel economy standard	0.00	18.46***	0.000000	202.80***	7.45*	6.24**
Increase target by 5%	-14.50	-10.28	-0.000059**	81.00*	-10.13**	-2.56
Increase target by 10%	16.10	23.05***	0.000065***	163.70***	10.05**	7.30**
Increase target by 15%	26.80	30.18***	0.000108***	173.80***	13.75***	9.44***
Increase target by 20%	17.50	34.31***	0.000070***	177.30***	9.24**	10.85***
Increase target by 25%	11.30	8.47	0.000045*	193.80***	-2.79	3.14
Increase target by 30%	1.20	18.52***	0.000005	184.70***	7.96**	6.17**
Increase target by 35%	17.80	33.56***	0.000071***	-29.80	17.73***	9.80***
Corporate Average Fuel Consumption (CAFC) standard:						
No CAFC standard	58.90*	89.22***	0.000238***	323.40***	49.42***	25.86***
Increase target by 5%	25.10	27.10***	0.000101***	220.10***	13.01***	8.27***
Increase target by 10%	13.10	20.22	0.000053*	187.60***	9.71**	6.70**
Increase target by 15%	-3.10	0.73	-0.000013	145.10***	-8.58**	1.10
Increase target by 20%	15.70	31.83***	0.000063***	158.00***	7.98**	10.14***
Increase target by 25%	9.10	5.56	0.000036	169.50***	-4.29	-4.29
No CAFC standard, combined with:						
No fuel economy standard	40.70	57.02***	0.000165***	514.10***	26.51***	17.50***
Status quo fuel economy standard	58.90*	89.22***	0.000238***	323.40***	49.42***	25.86***
Increase fuel economy target by 5%	58.50*	88.64***	0.000236***	318.80**	49.12***	25.70***
Increase fuel economy target by 10%	43.80	59.24***	0.000177***	513.50***	28.17***	18.04***
Increase fuel economy target by 15%	19.20	34.94***	0.000078***	408.70***	15.69***	10.59***
Increase fuel economy target by 20%	43.00	58.16***	0.000174***	503.60***	27.62***	17.73***
Increase fuel economy target by 25%	62.80*	83.82***	0.000254***	442.80***	42.48***	24.72***
Increase fuel economy target by 30%	18.20	33.41***	0.000074***	394.50***	14.91***	10.15***
Increase fuel economy target by 35%	52.30	70.57***	0.000211***	488.40***	37.32***	21.12***

Notes: Table reports, for each respective statistic (column), the difference between the statistic under the counterfactual simulation (row) and the statistic under the status quo base-case simulation. Significance stars following the difference from base case indicates the significance of a two-sample t-test of the difference between the statistic in the counterfactual simulation and that in the base-case simulation. Significance codes: * p<0.05; ** p<0.01; ***p<0.001