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论文题目：Carbon Tax or Carbon Emission Quota on Carbon Market: A Theory on Traditional Internal Combustion Engine Vehicle Regulation

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论文题目 Carbon Tax or Carbon Emission Quota on Carbon Market: A Theory on Traditional Internal Combustion Engine Vehicle Regulation

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摘要 In this paper, we propose a tractable model to analyze how consumer's choice of traditional internal combustion engine vehicles leads to over pollution, and what could policymaker do to reduce pollution and improve total welfare. In the most ideal case, the benevolent planner distributes equal wealth among the same group of consumers, which we call the first-best policy. However, this is not feasible, so we come up with two applicable second-best policies: carbon tax on income and introduction of carbon emission quota on carbon market. Theoretical analysis shows that carbon tax can reduce pollution, given that the medium-income electric vehicle consumers are rising. The optimal carbon tax policy, therefore, should trade-off pollution effect and income effect. Regarding the conditions of market clear and consumers' indifference both make pollution quota the only policy choice, carbon emission quota policy is quite implementable. Furthermore, we proved the optimal pollution quota in the carbon emission quota policy is lower than that in the competitive case and under that in the first-best case. We also numerically compared the four equilibrium outcomes to reach a holistic vision.

关键词: carbon tax; carbon market; pollution quota; electric vehicle; regulation

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1 Introduction

The Paris Agreement was sanctioned by parties of the United Nations Framework Convention on Climate Change (UNFCCC) on the 21st session of the Conference of the Parties (COP 21) and went into effect in November last year. It is a milestone that sets a target for reducing greenhouse gas emissions (GHG) and combating the climate change.

Attending the Paris Agreement, Europe should double its efforts on abating global warming, while other major emitters, including China, have even heavier duties in fair-share carbon dioxide removal (2-3 times to minor emitters) due to multiplying impacts of massive emissions. Indeed, this further proves that causing climate change and more, carbon emission is a global challenge yet to counter. As the world's second-largest economy and the largest developing country, China has shouldered additional responsibilities for the international community by performing Paris Agreement. In September 2020, President Xi Jinping made the official announcement at the 75th session of the United Nations General Assembly (UNGA) that China will strive to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060.

China is the world's biggest source of CO_2 (BP, 2019; UNFCCC, 2019), seriously polluting the emission at growing tendency. China ranks 15th with the CO_2 emissions per unit of GDP and ranks 42th with per capita CO_2 emissions in 2019 (Crippa et al., 2020). Meanwhile, China's fossil energy and GHG from the industrial process are 11.2 billion tons and 13.6 billion tons of CO_2 equivalent, respectively (Olivier and Peters, 2020). On top of the current situation, China's CO_2 emissions from fossil energy and cement have shown average annual growth of 1.4%, respectively, between 2010 and 2018 (Friedlingstein et al., 2020).

With the proposal of the "Double carbon" goal, China plans to enter the inflection point in the environmental Kuznets Curve. However, the pressure is still largely under China's actual conditions on the ecological environment before and after the peak platform period in China (Wang, 2020). To accomplish "Double carbon" and realize its goal of balancing economic growth and environmental benefits, the Chinese government has made policies in key domains such as power, industry, transportation, and negative emissions technology, to accelerate industrial transformation promotion, technological innovation, and energy structure adjustment (WRI China, 2020).

Facing the challenges, China has set implementation goals for emission peaks and carbon neutrality to reduce carbon emissions. Strategies in China's 14th five-year plan, for example, aims to transform the growing pattern from high carbon fast increase into green and sustainable development, on top of China' concepts of external and internal bi-cycles. The delicate balance between economy and environment for the transformation requires especially innovations, a crucial factor is to integrate the commercial market and the carbon reduction cause, in order to achieve a sustainable future.

As one of the major countries for online retail and express delivery, the transportation of these products alone has caused the CO_2 equivalent emission to surge from 0.3 to 13.7 Mt. during 2007 and 2018 and may reach its fivefold by 2035. However, mitigations of GHG can reach 102-134 $MtCO_2e$, with proper policies on carbon pricing, etc. (Kang et al., 2021)

Chinese government keeps focusing on climate change. It will greatly alleviate life and health problems caused by vehicle-exhausted emissions and coordinately improve urban ecological and health benefits for the residents of cities, especially megacities, with the promotion of EVs (Liang et al., 2019). With further developments of China's economy and the population policy reform, the residents' demand for travel tools will continue to increase in the next stage. Under the "Double carbon" plan, EVs will become the best choice for consumers, due to the increasingly tight energy and environmental constraints on vehicles (Du, Lin, and Guan, 2019). Since China has promulgated the "notice on carrying out the pilot work of demonstration and promotion of energy-saving and new-energy vehicles" in 2009, EVs have been recognized as an important low-carbon travel mode and have been promoted vigorously by governors. In general, the development of EV subsidy policy can be divided into three stages: pilot stage (2009-2010), rapid development stage (2010-2013), and decline stage (2014-present). At the initial stage of the development of EVs, the government tried to help deal with the problem of high costs about technology, production, and use through subsidies, and created "comparative advantages" for EVs. In the long run, however, subsidy policy "subsidy dependence" in automobile enterprises, which has seriously impeded the efficiency of subsidies. Therefore, the threshold of government subsidies has gradually increased, and the number of subsidies shows a downward trend in recent years.

But problems remain. Separated to the market system, EVs are not cheap enough to survive without government subsidies. Even more, Safarzyńska, Jeroen, and van den Bergh

(2018) indicate electricity generated by renewable energy may triple in price, wiping out subsidy incentives' effects.

A good way to turn this situation around is the carbon trading system. Carbon trading is established for the commercial trading of carbon emission quotas. According to Tan and Lin (2020), charging facilities and subsidies are more suitable as jumper, which can be removed once the EV development has started. An optimal fossil fuel vehicles reduction rate chosen by the government can replace the subsidy in supporting the EV development, especially with a dynamic industrial subsidy policy.

To be precise, carbon tax and personal carbon trading have shown more important influence for carbon emission reduction than tax exemption and restrictions on purchase, driving, and charging (Li et al., 2019a). Nevertheless, we have put inadequate attention on structuring and refining the carbon tax in China. This article attempts to examine the relationship between government burden, customer utility, and carbon emission optimization, and establish the model for the best carbon emission quota. With this quota, traditional vehicles, which are expected to emit more carbon dioxide than the quota suggests, would buy an extra quota from the EVs. This expectation not only benefits the government budget through replaced subsidies but also empowers EVs to become a component in the market independently.

To employ the model, EV products are to be less vulnerable as a vibrant part of the lively market system. By achieving this, carbon dioxide from transportation will be largely reduced. This will improve the environment and social welfare and reduce inequality. For example, by 2030, electrifying 27% of private vehicles, etc. can reduce annual premature deaths by about 17,456 by decreasing air pollution and promoting health (Liang et al., 2019). New energy also alleviates the environmental justice issues in lower-income countries. Unequal exposure to air pollution due to poverty, race, age, or gender will be eased out by higher air quality.

The paper is organized as follows: In Section 2, we summarize the study on the environmental benefits and the subsidy policy of EVs. Section 3 presents our analytical framework, theoretical model, and analytical solution. We derive the first-best policy under centralized decision and the second-best policy under competitive equilibrium. Section 4 introduces carbon tax policy and carbon emission quota to investigate whether these two kinds of common and feasible government intervention would help improve social welfare, and which kind of intervention would perform better under certain circumstances. Section 5 compares carbon tax policy and carbon emission quota policy together with the first-best case in a numerical way. Section 6 concludes our findings and elaborates several policy implications.

2 Literature review

Climate change and sustainable development are becoming the most urgent topics in this century. For both targets, controlling carbon emissions is essential (Salvia et al., 2021). The Paris Agreement isn't being effectively implemented and more solutions to reduce carbon dioxide emission are needed. As a major carbon emitter, China is also committed to turning to the stage of high-quality development. It aims at controlling carbon emissions, increasing carbon sinks, and balancing the total amount of carbon participating in the rapid carbon cycle. To this end, in general, China is expected to slow down the rate of increase in carbon emissions gradually during rapid economic development, achieve carbon peaks in 2030, and then begin to reduce carbon emissions. The current studies in carbon capture, utilization, and storage (CCUS) technology show that some promising solutions with closely related analyses on financial mechanisms, and technical methods for CCUS are lacking. There is a long way to go to achieve carbon neutrality (Jiang and Ashworth, 2021).

Emissions from traditional internal combustion engine vehicles (ICEVs) have always been one of the main sources of road traffic emissions in various countries, while EV is a good alternative. Now, the US has a 19Gt CO_2 mitigation gap from the goal of temperature rising within 2 °C during 2015-2050, equaling 350 million more running EVs. Under this condition, it will be wiser to promote EV usage while restricting the average fuel consumption of traditional vehicles (Milovanoff, Posen, and Maclean, 2020). In China, car ownership and the popularity of new energy automobiles are both soaring. The latter contributes to a reduction in GHG and an increase in energy efficiency. Electronic cars will be beneficial for environmental and energy security issues (Du, Lin, and Guan, 2019). The NOx emission has seen a decline due to the EVs adaptation in China, especially in the southern part, where better marketing potential exists and clear energy utilization (Li et al., 2019b). Encouraging people to switch from traditional ICEVs to EVs can help reduce GHG and improve energy efficiency, which is conducive to environmental and energy security issues. Internationally, China occupies half of the EV market and has great potential to create a better climate and healthy environment. As a responsible power, we need to promote the free flow of production factors and the optimal allocation of resources actively, and achieve green development through technological reforms, even though we are undergoing significant changes unseen in a century.

Some critical studies have confirmed that the pollutant concentration will be significantly reduced only when about 50% of the car's energy is substituted. Although some people doubt the impact of EVs accordingly, the low percentage change also contributes to the improvement of living indicators such as air quality. Although some people doubt the effects of EVs, a 2020 case study of Beijing indicates that investments in EVs significantly increased the reduction of CO_2 and NOx, respectively, where CO_2 and NOx are both air pollution stimulators (Chen et al., 2018b).

The carbon tax and personal carbon trading have shown more important influence than tax exemption and purchase, driving, charging restrictions on carbon emission reduction (Li et al., 2019a). First, the principle of carbon tax is more administrative. This kind of "one size fits all" policy is mainly suitable for homogeneous enterprises. The production efficiency of each enterprise is similar, so similar tax policies can be applied fluently. At present, Chen et al. (2018a) shows that if there is no subsidy for EVs, high-type EVs will be substituted by ICEV, depending on the relative consumer density. A 10% addition of tax incentive will galvanize EVs' sale share to increase for about 3%. But tax incentives can be too expensive for CO_2 emission reduction (Yan, 2018). For companies with higher production efficiency than the average in a certain industry, carbon tax may inhibit the growth of their economic value.

The personal carbon trading is a market policy, which is more beneficial to highly heterogeneous companies. High-efficiency enterprises can obtain more production benefits in a certain level of inputs, so they can purchase carbon emission rights in the market. That is, obtain carbon emission quotas. The above explains the redistribution of carbon emissions. Carbon emission rights transactions are based on the economic value produced by different companies, which is more market-oriented and flexible. In fact, complex situations are often dealt with by carbon trading (Certified Emission Reduction). Comparing the two emission reduction methods, mandatory carbon trading accounted for 99.07% of market transactions, while European Union Emission Trading Scheme (EUETS) accounted for 83.73%. carbon tax is not only more popular in the market: using the relevant policies of carbon credits, EVs can also gain more advantages and become an organic part of the market economy in carbon tax, no longer relying on subsidies. Therefore, this paper will focus on the mandatory carbon trading market for EVs.

However, China's vehicle emission management is not yet complete. There are still common problems in the technology, cost, infrastructure, and externalities of EVs, such as EVs' performance, shortage of charging infrastructure, and consumers' lack of awareness of EV technology. In terms of infrastructure, studies have shown that household charging, highway fast charging once four days, and supplementary vehicles will support about 40% of EVs. After the marketization of EVs, issues such as product performance and consumer perception will be resolved by market mechanism itself. A case study in Beijing proves that incentive policy measures are one of the main factors that affect EV development (Huang and Ge, 2019). This is coordinate to the previous and should be considered by governors.

Another field related to this research is the environmental effect analysis of EVs. As EVs enter the lives of residents widely, professors have doubted their environmental benefits gradually. Previous studies believe that EVs can improve urban air quality by reducing traffic exhaust emissions. For instance, Ferrero, Alessandrini, and Balanzino (2016) used the air quality monitoring data of Milan's suburban highways in Italy within one month in winter to quantitatively answer how EV occupancy affects the air quality improvement performance. The research uses a Lagrangian single-particle model to characterize the meteorological changes, chemical reactions of pollutants and traffic flow near the highway and simulates the emission situation under different EV occupancy rates. Only reaching about 50% replacement will the pollutant concentration significantly reduce. But lower percentage also helps with the air quality improvement (Ferrero, Alessandrini and Balanzino, 2016).

Based on the life-cycle assessment, in fact, EVs realize the regional transfer of pollution emissions-from the fuel emissions of Traditional ICEVs to the power generation emissions of power plants, which is upstream in the industry chain (Ji et al., 2015; Li et al., 2019b; Shen et al., 2019). Therefore, the emission reduction effect of EVs depends on the energy structure of the power plant to a certain extent. Based on the assessment of well-to-wheel pollutant emissions, Li et al. (2019b) found that due to the different power generation and transmission structures in China's provinces, the emission reduction effects show obvious regional differences. Specifically, the potential for emission reduction is even greater in regions that use clean energy, such as hydropower, to generate electricity. When the material used in the power plant is still fossil fuel, replacing Traditional ICEVs with EVs may not make any difference (Wu et al., 2019a; Wu et al., 2019b). The environment will be greatly damaged, aggravating the imbalance of regional development. Ji et al. (2015) reviewed 34 Chinese cities that use EVs and their power sources from the perspective of fair development. Based on the results of the PM2.5 intake fraction assessment model, they pointed out that rural areas on average, it bears 77% of the transferable pollution emissions.

In the future, the large-scale application of clean energy in China's power grids will help achieve regional environmental equity. According to estimates by Shen et al. (2019), by 2030, the share of clean energy power generation in China's northern and northeastern power grids will increase by 2 to 4 times, and the proportion of low-carbon power generation in the southern and eastern power grids will reach 55%; With the improvement of EV technology, the emission reduction benefits of battery electric vehicles (BEVs) supported by China's power grid in 2030 can even reach 50%.

In the context that fossil fuel power generation still occupies an important share of the electricity market, how to minimize the social costs of all aspects of the EV industry is the focus of further study. Fang et al. (2018) considered the externalities of the EV power supply process and determined the optimal charging time based on the combinations of carbon prices and electricity prices within a day in the Sacramento area of the United States in 2013. This study found that in periods or regions where carbon prices are high (above 90$/ton), EV owners choose to charge at work during the day instead of charging at home during the night, which lowers social costs, and better balances the personal interests of EV owners with general environmental benefit. Chen et al. (2018b) simulated the charging behavior of vehicles and found that light-duty EVs which choose the "slow charging" mode are proved to be more effective in reducing carbon emissions during the charging process.

The research in this article is also a good supplement to the field of promotion of EVs. In the process of low-carbon economic transition, factors influencing the popularization of EVs have always been the focus of scholars. From the personal perspective, consumers' cognition and perception influence their car purchase behavior. Short-term thinking consumers are accustomed to separate the cost of purchasing a car from that of maintaining a car. Under the incentives of the government's subsidy policy, it is easier for them to choose EVs than rational consumers, inevitably ignoring the increase in charging costs brought about by the price increase of new energy electricity in the future (Safarzyńska, Jeroen and van den Bergh, 2018). For some groups, especially the low-income and the elderly, the benefits brought by government subsidies to EVs are more significant, so they are willing to adopt EVs in response to the policy; On the contrary, as the social environment has little impact on the high-income population, so the policy is not effective for them (Yang et al., 2019). Huang and Ge (2019) proved based on the Beijing EV market survey that the deeper consumers' understanding of EVs and government-related incentive policies, the stronger their willingness to adopt EVs; however, young people and high-income people tend to hold a positive attitude towards the government's economic incentives, this is not consistent with the findings of Yang et al. (2019).

The market environment also has an important impact on the sales structure of automobiles. Due to different power systems, the substitution relationship between EVs and Traditional ICEVs changes with fluctuations in international oil prices and local electricity prices (Zhu et al., 2019; Du et al., 2019). Favorable market policies have also guided consumers' choices. Empirical research in Europe and the United States confirm that excise tax concessions and subsidies can significantly expand the market share of EVs (Yan, 2018; Zambrano-Gutierrez et al., 2018). In addition, the construction of charging infrastructure can not only create a better operating environment for EV drivers, but also help enhance the implementation effect of government incentive policies (Zambrano-Gutierrez et al., 2018).

The role of financial support in fostering emerging industries is affirmed. In the initial stage of industry development, due to large R&D investment and insufficient production scale, EV production costs are high, and profitability is weak. Financial subsidies can stimulate enterprises to enter the EV market, fund their R&D activities, and promote technology to establish corporate competitiveness (Wang, Pan and Zheng, 2017). Then, improve the acceptability of purchase prices, stimulate consumers' demand (Ma, Xu and Fan, 2019), increase corporate capital accumulation, and help the EV industry to develop sustainability in the process of "learn by doing" (Zhu et al., 2019). Government purchases directly increase the penetration rate of EVs and form a good demonstration effect in society (Du et al., 2019).

The performance and price of EVs have always been pivotal considerations for consumers in purchasing decisions (Ma, Xu and Fan, 2019). However, the EVs currently running on the market do not have obvious advantages compared with Traditional ICEVs in terms of battery storage and service life, travel range, driving speed, safety and purchase cost (Tarei, Chand and Gupta, 2021). Therefore, the supply-side upgrade based on technological improvement and mass production is the key to improving consumer attitudes.

When EVs have insufficient mileage, the lack of charging infrastructure will further aggravate the anxiety of their drivers. Having high energy demand, it is not only necessary to set up charging facilities at home, workplace and highways completely, but also more flexible auxiliary vehicles of charging should be applied to make up for the shortcomings of EV battery performance (Wei et al., 2021).

In order to stimulate the potential of the EV market, the government has adopted high subsidies in the past ten years, which causes its own financial burden to be heavy, even exceeding the budget (Dong, 2017). From the perspective of long-term development of the industry, due to information asymmetry, the government's R&D investment for enterprises has a "crowding effect". Under the protection of subsidy policies, the industry has a weak sense of innovation and serious homogenization competition (Zhou et al., 2015). Subsidies from local governments have also led to local protectionist forces, distorting the role of the market to a certain extent, and rent-seeking behaviors often occur. In addition, although the purchase of public vehicles reduces the travel costs of public officials and increases the income of them invisibly, it shields the bad habits of consumption regardless of price and mileage (Dimitropoulos et al., 2016), which contributes adverse effects to social development.

However, even if the government intends to reduce the negative effects of the policy by canceling subsidies, the inertia of the system will create a sense of "imbalance" in the previously subsidized companies, thus uniting similar companies to form resistance to policy changes, increasing the government's transaction costs, and reducing reduce the flexibility of fiscal tools (Zhou and Pan, 2019). Moreover, the cost of EVs will not be immediately reduced due to the reduction of subsidies. Once the government cuts back subsidies, consumers with high loss aversion (such as low- and middle-income people) will choose not to enter the EV market and instead support Traditional ICEVs market (Chen et al., 2018a). The statistical analysis of Ma, Xu and Fan (2019) also confirmed that the trim of the list of government-subsidized EV types can immediately cause the market share of EVs to shrink.

In order to gradually release the burden of financial subsidies and enhance the independent development capacity of the EV industry, under the guidance of the Ministry of Finance of the People's Republic of China (MOF), subsidies for all types of EVs are in a state of decline until they are completely canceled. At the same time, finding the effective alternative policies and alleviating the market turmoil caused by the withdrawal of direct subsidies has become the academic pursuit of many professors. There exist abundant examples of the significant claims on topic. Zhu et al. (2019) analyzed the game between the government, charging infrastructure builders, and EV consumers, and proposed that the government can gradually replace direct subsidies by increasing funding for charging infrastructure construction; it can also use the method of cooperating with private capital to construct charging facilities (Ma, Xu and Fan, 2019), which can save government expenditures while realizing a grow in social welfare. Zhou and Pan (2019) believe that compared with direct government subsidies, tax reductions for the EV industry are more in line with the law of the market, besides, it can stimulate the industry's endogenous motivation and avoid its dependence on policy protection. Ma, Xu, and Fan (2019) believe that substituting subsidies with convenient policies such as no threshold for EV purchase or no limitation of travel will cater to the needs of vehicle consumers better, especially in first and second-tier cities. Song et al. (2020) proposed that an optimal reduction rate is capable of replacing the subsidy in supporting the EV development, especially with a dynamic industrial subsidy policy. An integrated mechanism is important in this case. More stringent emission standards and updated fuel standards will be effective (Zhu, Wang, and Zhang, 2019).

3 Model setting

We assume there is a continuum consumer of measure 1, each consumer is endowed with income m follows a specific distribution, $m \sim F(m)$. The consumer makes choice between EV and traditional ICEV, which costs p_1 and p_2 respectively. Then consumers will use all the residual income for consumption. Due to environmentally friendly policy, we assume EV is cheaper than traditional ICEV, while traditional ICEV is better for consumer in terms of utility, but less environmentally friendly and will cause e unit of pollution. Consumer's utility depends on consumption c, capturing total consumption after purchasing vehicles, and utility of driving vehicle u, and the environment measured by total pollution E. We assume a Cobb-Douglas utility function as follows:

$$\begin{aligned} &U(c,u,E) = A(E)c^{\sigma}u^{1-\sigma} \\ &s.t. \qquad c = m - p \end{aligned} \tag{1}$$

where $E = \int_{\{m|\text{choose gasoline vehicle}\}} dF(m)$ denotes the sum of pollution, $A(E)$ is a decreasing function of total pollution E. To exclude corner solution, we assume $p_1 < p_2 < \underline{m},\ u_1 < u_2, 0 < \sigma < 1$

Under competitive market, there are infinitely many consumers who make choice, each consumer will take total E pollution as given. Then we could derive that there exists a threshold income level m^*:

$$m^* = \frac{\left(\frac{u_2}{u_1}\right)^{\frac{1-\sigma}{\sigma}} p_2 - p_1}{\left(\frac{u_2}{u_1}\right)^{\frac{1-\sigma}{\sigma}} - 1} \tag{2}$$

Satisfying $U(m^* - p_1, u_1, E) = U(m^* - p_2, u_2, E)$. Consumers whose income higher than m^* will choose traditional ICEV because of diminishing marginal utility gain in consumption. Therefore, there are in total $1 - F(m^*)$ consumers with traditional ICEV, causing total amount of $e\left[1 - F(m^*)\right]$ pollution. The social welfare function under competitive market could then be written as, where the last equation follows from the threshold condition $U(m^* - p_1, u_1, E) = U(m^* - p_2, u_2, E)$:

$$W^0 = A\left(e\left[1-F\left(m^*\right)\right]\right)\left[\int_{\underline{m}}^{m^*}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right)+\int_{m^*}^{\overline{m}}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right)\right] \tag{3}$$

In the following two sections, we will discuss first-best policy under centralized decision firstly, where income could be transferred arbitrarily between consumers given total wealth unchanged, and decisions are made so as to maximize social welfare. Then we come to more realistic situations and discuss second-best policy under competitive equilibrium, where consumers make their own decision to maximize utility, and government intervene market through carbon tax policy or carbon emission quota on carbon market.

3.1 First-best policy under centralized decision

Firstly, we assume there exists a benevolent social planner capable of imposing an arbitrary income distribution and assigning certain number of consumers to buy EVs. Then the unconstrained social planner's problem could be written as:

$$\begin{aligned} &\max_{G(),m^{fb}} A\left(e\left[1-G\left(m^{fb}\right)\right]\right)\left[\int_{p_1}^{m^{fb}}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dG\left(m\right)+\int_{m^{fb}}^{+\infty}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dG\left(m\right)\right] \\ &s.t. \quad \int_{p_1}^{+\infty} m dG\left(m\right)=\int_{\underline{m}}^{\overline{m}} m dF\left(m\right) \end{aligned} \tag{4}$$

With an arbitrary capacity of distributing wealth according to $G(m)$, it is feasible to broaden the range of income from p_1 to $+\infty$, and the social planner's only constraint here is that total wealth should be constant. Then the social planner chooses a threshold m^{fb} such that consumers whose income below m^{fb} buy EVs, and those with higher income buy traditional ICEVs. Because of diminishing marginal utility gain in consumption, the contrary case that more wealthy people hold EVs and less wealthy hold traditional ICEVs is obviously not optimal. To prove it, we assume $m_1 > m_2$, suppose that consumer 1 choose EV and consumer 2 chooses traditional ICEV, then social planner could improve social welfare by switching the vehicle between the two guys, while keeping total pollution unchanged. Due to super modularity of $U(c,u,E)$ in c and u, social welfare is improved since $u_1^{1-\sigma}\left[\left(m_1-p_1\right)^{\sigma}-\left(m_2-p_2\right)^{\sigma}\right]>u_2^{1-\sigma}\left[\left(m_2-p_1\right)^{\sigma}-\left(m_1-p_2\right)^{\sigma}\right]$, which is equivalent to $U\left(m_1-p_1,u_1,E\right)+U\left(m_2-p_2,u_2,E\right)>U\left(m_2-p_1,u_1,E\right)+U\left(m_1-p_2,u_2,E\right)$. Therefore, the benevolent social planner will always assign traditional ICEVs to more wealthy consumers and

EVs to fewer wealthy ones. The following proposition shows that the first-best policy is featured with equal wealth among a certain kind of consumers.

Proposition 1 (Equality) *The optimal wealth distribution* $G(m)$ *is that two groups of consumers are equally wealthy with the same kind of vehicle. That is,* $G(m^{fb})$ *consumers with income* m^l *buying EVs and* $1-G(m^{fb})$ *consumers with income* m^b *buying traditional ICEVs, satisfying* $m^l \le m^{fb} \le m^h$*, and the constraint* $m^l G(m^{fb}) + m^h\left[1-G(m^{fb})\right] = \int_{\underline{m}}^{\overline{m}} m dF(m)$

Proof: The key target here is to prove $G(m)$ is actually two probability mass at m^l and m^h given certain amount of total pollution $e\left[1-G(m^{fb})\right]$. We prove this by contradiction. Assume that there exist two consumers in the same group with unequal income m_1, m_2. Then sum up the wealth and split it equally will always improve social welfare by Jensen's Inequality and the concavity of utility function: $2A(E)\left(\frac{m_1+m_2}{2}-p\right)^{\sigma} u^{1-\sigma} > A(E)(m_1-p)^{\sigma} u^{1-\sigma} + A(E)(m_2-p)^{\sigma} u^{1-\sigma}$. Iterating the process above within the group will always improve welfare and finally leads to equal wealth. ■

Then the social planner's problem is simplified as choosing a certain amount of total pollution so as to maximize total welfare, with two groups of equally wealthy consumers, and the total wealth constant. From Proposition 1 we know that $G(m)$ is actually two probability mass at m^l and m^h, therefore the exact value of m^{fb} does not matter since as long as $m^l \le m^{fb} \le m^h$, $G(m^l) = G(m^{fb})$. The specified result depends on the parameters, especially the function form of $A(\cdot)$, which determines how much pollution is optimal and the corresponding proportion of consumers holding traditional ICEVs $1-G(m^{fb})$.

If the amount of total pollution is given exogenous, for example countries which joined Paris Agreement under the UNFCCC are regulated to reduce the impacts of climate change and are promoted to set specific emissions targets. The following Corollary states the optimal wealth distribution given certain amount of total pollution.

Corollary 1 (Optimal Policy Given Total Pollution) If a certain amount of total pollution E^{fb} is given exogenous, then first-best policy indicates $1-\frac{E^{fb}}{e}$ consumers with income m^l buying EVs and $\frac{E^{fb}}{e}$ consumers with income m^h buying traditional ICEVs, satisfying $m^l = \frac{(p_1 u_2 - p_2 u_1)\frac{E^{fb}}{e} + u_1 \int_{\underline{m}}^{\bar{m}} m dF(m)}{u_2 \frac{E^{fb}}{e} + u_1\left(1-\frac{E^{fb}}{e}\right)}$ and $m^h = \frac{\int_{\underline{m}}^{\bar{m}} m dF(m) - \left(1-\frac{E^{fb}}{e}\right)m^l}{\frac{E^{fb}}{e}}$.

Proof: From Proposition 1, given a certain amount of total pollution E^{fb}, the social planner's problem could be written as:

$$\max_{m^l, m^h} \left(1-\frac{E^{fb}}{e}\right)\left(m^l - p_1\right)^{\sigma} u_1^{1-\sigma} + \frac{E^{fb}}{e}\left(m^h - p_2\right)^{\sigma} u_2^{1-\sigma}$$

$$s.t. \qquad \left(1-\frac{E^{fb}}{e}\right)m^l + \frac{E^{fb}}{e} m^h = \int_{\underline{m}}^{\bar{m}} m dF(m)$$

We integrate $G\left(m^{fb}\right) = 1-\frac{E^{fb}}{e}$ into the social planner's problem and simplify the optimization problem into an easily solved one. The restriction is that total wealth is constant, and equally assigned to $\left(1-\frac{E^{fb}}{e}\right)$ consumers with m^l and $\frac{E^{fb}}{e}$ consumers with m^h. The social planner now maximize:

$$\max_{m^l} \left(1-\frac{E^{fb}}{e}\right)\left(m^l - p_1\right)^{\sigma} u_1^{1-\sigma} + \frac{E^{fb}}{e}\left[\frac{\int_{\underline{m}}^{\bar{m}} m dF(m) - \left(1-\frac{E^{fb}}{e}\right)m^l}{\frac{E^{fb}}{e}} - p_2\right]^{\sigma} u_2^{1-\sigma}$$

Taking F.O.C and we could arrive the result after some calculation. ■

Without loss of generality, the possibility that everyone is endowed with same income and buys electric or traditional ICEVs also exists. The case that everyone buying EVs is optimal if the environmental problem is so severe and the country is easily suffered from more pollution and is restricted in greenhouse gas emission ($E^{fb}/e \to 0$ and $-A(0)'$ large, marginal increase in greenhouse gas emission will be harmful), or if total wealth is shorted (marginal utility gain in consumption large). The case that everyone buying traditional ICEV is opposite: if the country is given a large quota in greenhouse gas emission ($E^{fb}/e \to 1$ and $-A(0)'$ small, even large increase in greenhouse gas emission will not be so destructive), or total wealth is abundant (marginal utility gain in consumption could be ignored). The proof is the same as Proposition 1, iterating the process of making wealth equal among all the consumers and deviation to the other kind of vehicles can be proved inefficient.

3.2 Second-best policy under competitive equilibrium

Since it is generally not feasible to impose an arbitrary income distribution in reality, we are going to analyze a social planner's constrained optimization problem, or second-best policy. We assume social planner could force an income threshold level m^{sp}, such that consumers with income higher than m^{sp} buy traditional ICEV. Therefore, there are in total $1-F\left(m^{sp}\right)$ consumers with traditional ICEV, causing total amount of $e\left[1-F\left(m^{sp}\right)\right]$ pollution. Social welfare is maximized such that:

$$W^{sp}=\max_{m^{sp}} A\left(e\left[1-F\left(m^{sp}\right)\right]\right)\left[\int_{\underline{m}}^{m^{sp}}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right)+\int_{m^{sp}}^{\bar{m}}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right)\right] \tag{5}$$

Proposition 2 (Over Pollution) *Because of the ignored negative externality of pollution, there exists over pollution under competitive market* $m^{sp}>m^{*}$, *which means government prefers more consumers buying EVs compared with competitive market equilibrium*

Proof: Calculate how marginal changes in m^{*} could affect social welfare competitive market equilibrium:

$$\begin{aligned}
\frac{\partial W^{0}}{\partial m^{*}}&=\frac{\partial A\left(e\left[1-F\left(m^{*}\right)\right]\right)}{\partial m^{*}}\left[\int_{\underline{m}}^{m^{*}}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right)+\int_{m^{*}}^{\bar{m}}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right)\right]\\
&+A\left(e\left[1-F\left(m^{*}\right)\right]\right)\frac{\partial\left[\int_{\underline{m}}^{m^{*}}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right)+\int_{m^{*}}^{\bar{m}}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right)\right]}{\partial m^{*}}\\
&=-A'\left(e\left[1-F\left(m^{*}\right)\right]\right)ef\left(m^{*}\right)\left[\int_{\underline{m}}^{m^{*}}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right)+\int_{m^{*}}^{\bar{m}}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right)\right]\\
&>0
\end{aligned}$$

where the last equation follows from the threshold condition and application of Newton-Leibniz formula, and the last inequality is due to our assumption that $A\left(E\right)$ is a decreasing function of total pollution E. ■

In intuition, the result from competitive market is featured with a higher proportion of consumers buying traditional ICEV than the social optimal case, thus cause over-pollution, which means marginal decrease in the number of consumers buying traditional ICEV will lead to higher social welfare at market equilibrium. In the next section, we would introduce carbon tax policy and carbon emission quota to investigate whether these two kinds of common and feasible government intervention would help improve social welfare, and which kind of intervention would perform better under some certain circumstances.

4 Carbon tax policy and carbon emission quota policy

4.1 Carbon tax policy

We introduce fiscal-neutral carbon tax policy, with income carbon tax rate t on all the consumers. For the ease of computation, we assume that income m follows a uniform distribution $m \sim F(m) = U[\underline{m}, \overline{m}]$. All the collected tax will be immediately transferred to all the consumers equally, therefore consumer with income m becomes $m' = m - t[m - E(m)]$, where $E(m) = \int_{\underline{m}}^{\overline{m}} m dF(m)$ is the total wealth and $tE(m)$ is the transfer payment.

We could prove that carbon tax policy will induce a new uniform income distribution $m' \sim G(m') = U[\underline{m'}, \overline{m'}]$; where $\underline{m'} = \underline{m} + \frac{t}{2}(\overline{m} - \underline{m})$ and $\overline{m'} = \overline{m} - \frac{t}{2}(\overline{m} - \underline{m})$.

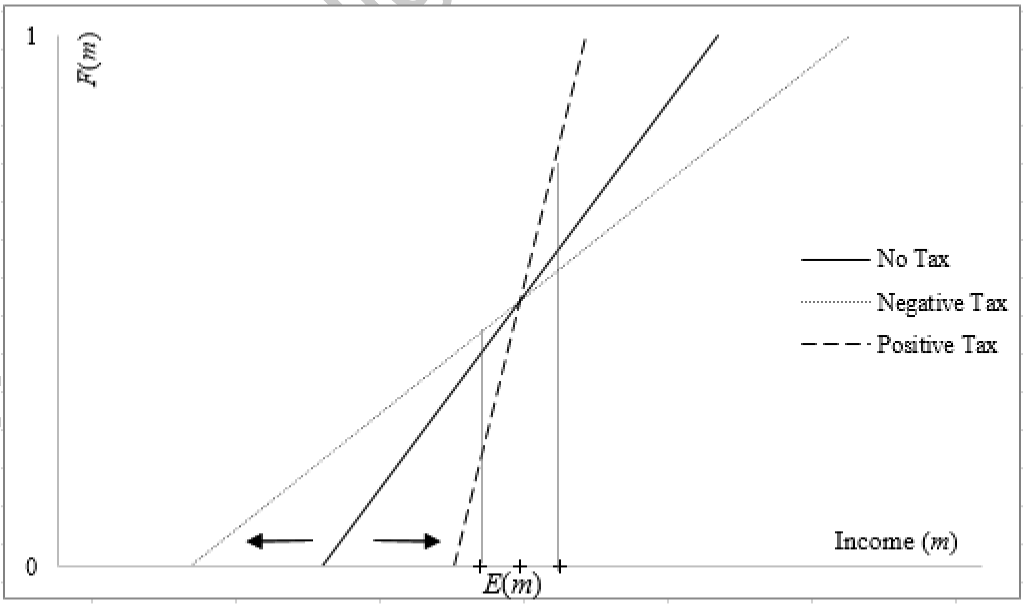

Figure 1: Illustration of tax effect

Figure 1 illustrates the effect of carbon tax policy on income distribution: a positive carbon tax policy ($t > 0$) reduces the income gap between rich and poor, leading to a more concentrated wealth distribution, while a negative carbon tax policy ($t<0$) broadens the gap and makes the wealth distribution more dispersed.

The intuition is straight forward: given positive tax rate ($t>0$) on income, more wealthy consumers are taxed more, but the transferred payment is equal for everyone. When faced with carbon tax policy, consumer's threshold income m^* satisfying $U\left(m^*-p_1,u_1,E\right)=U\left(m^*-p_2,u_2,E\right)$ will not be changed, but the total pollution will be different due to different wealth distribution, as Figure 1 illustrated.

For instance, if $m^*>E\left(m\right)=\frac{\overline{m}+\underline{m}}{2}$ and $t>0$, then $A\left(1-e\left[1-G\left(m^*\right)\right]\right)<A\left(1-e\left[1-F\left(m^*\right)\right]\right)$, which means positive carbon tax policy will reduce total pollution, and induce better environment, but not necessarily better social welfare (discussed later). Since carbon tax policy's effect on social welfare can be decomposed into two parts, one is through environment channel $A\left(E\right)$, another is through individual consumer's income, thus its utility from consumption and choice of vehicles:

$$\frac{\partial W}{\partial t}=\underbrace{\frac{\partial A\left(e\left[1-G\left(m^*\right)\right]\right)}{\partial t}\left[\int_{\underline{m}'}^{m^*}\left(m-p_1\right)^{\sigma}u_1^{1-\sigma}dG\left(m\right)+\int_{m^*}^{\overline{m}'}\left(m-p_2\right)^{\sigma}u_2^{1-\sigma}dG\left(m\right)\right]}_{\text{Pollution Effect}}$$
$$+\underbrace{A\left(e\left[1-G\left(m^*\right)\right]\right)\frac{\partial\left[\int_{\underline{m}'}^{m^*}\left(m-p_1\right)^{\sigma}u_1^{1-\sigma}dG\left(m\right)+\int_{m^*}^{\overline{m}'}\left(m-p_2\right)^{\sigma}u_2^{1-\sigma}dG\left(m\right)\right]}{\partial t}}_{\text{Income Effect}} \quad (6)$$

The following Lemma shows how different carbon tax policy affects total pollution, which we call pollution effect.

Lemma 1 (Pollution Effect): *Depending on whether carbon tax policy is positive or negative and threshold income* m^**, there are four cases:*

	Positive Carbon Tax ($t>0$)	Negative Carbon Tax ($t<0$)
More EV $\left(m^*>\frac{\overline{m}+\underline{m}}{2}\right)$	Total Pollution ↓	Total Pollution ↑
More traditional ICEV $\left(m^*<\frac{\overline{m}+\underline{m}}{2}\right)$	Total Pollution ↑	Total Pollution ↓

Table 1: Carbon tax policy and total pollution

The above Lemma formally summarizes the intuition from Figure 1. When the consumer with average wealth is buying EVs $\left(m^* > \frac{\overline{m}+\underline{m}}{2}\right)$, imposing normal positive tax will reduces the gap between rich and poor, which leads to consumers below average income richer and those above average income poorer. Then those who originally buy traditional ICEVs will deviate because of declined income, while those who gain from carbon tax policy will still buy EVs. The reason is that tax-neutral consumer with average income still chooses EVs, and consumer with income below average could not exceed average even after gain from tax, thus still choosing EVs. In the opposite case $\left(m^* < \frac{\overline{m}+\underline{m}}{2}\right)$, carbon tax policy will make consumer with income below average wealthier, and since the threshold m^* is less than average, some consumers whose wealth exceed m∗ will now turn to choose traditional ICEVs. Though it is mathematically feasible to impose negative tax ($t<0$) and induce less total pollution. In reality, it is quite rare to transfer from "poor" to "rich", since *ad valerem* tax is generally positive.

Then we analyze carbon tax policy's income effect, which influences total social welfare through income distribution net of pollution effect. From before we know after tax t, income distribution will be changed into $G(m') = U\left[\underline{m'}, \overline{m'}\right] = U\left[\underline{m} + \frac{t}{2}\left(\overline{m}-\underline{m}\right), \overline{m} - \frac{t}{2}\left(\overline{m}-\underline{m}\right)\right]$, then we could write social welfare net of pollution effect as:

$$\int_{\underline{m}+\frac{t}{2}\left(\overline{m}-\underline{m}\right)}^{m^*} \left(m-p_1\right)^\sigma u_1^{1-\sigma} dG(m) + \int_{m^*}^{\overline{m}-\frac{t}{2}\left(\overline{m}-\underline{m}\right)} \left(m-p_2\right)^\sigma u_2^{1-\sigma} dG(m) \tag{7}$$

where $G(m)$ is a function of tax rate t, which makes derivative relatively tedious to calculate.

$$\begin{aligned}
&\frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}\left(\overline{m}-\underline{m}\right)}^{m^*} \left(m-p_1\right)^\sigma u_1^{1-\sigma} dG(m) + \int_{m^*}^{\overline{m}-\frac{t}{2}\left(\overline{m}-\underline{m}\right)} \left(m-p_2\right)^\sigma u_2^{1-\sigma} dG(m)\right] \\
&= \frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}\left(\overline{m}-\underline{m}\right)}^{m^*} \frac{\left(m-p_1\right)^\sigma u_1^{1-\sigma}}{(1-t)\left(\overline{m}-\underline{m}\right)} dm + \int_{m^*}^{\overline{m}-\frac{t}{2}\left(\overline{m}-\underline{m}\right)} \frac{\left(m-p_2\right)^\sigma u_2^{1-\sigma}}{(1-t)\left(\overline{m}-\underline{m}\right)} dm\right] \\
&= \frac{-\left[\left(\underline{m}+\frac{t}{2}\left(\overline{m}-\underline{m}\right)-p_1\right)^\sigma u_1^{1-\sigma} + \left(\overline{m}-\frac{t}{2}\left(\overline{m}-\underline{m}\right)-p_2\right)^\sigma u_2^{1-\sigma}\right]}{2(1-t)} \\
&+ \frac{\left(\overline{m}-\frac{t}{2}\left(\overline{m}-\underline{m}\right)-p_2\right)^{\sigma+1} u_2^{1-\sigma} - \left(\underline{m}+\frac{t}{2}\left(\overline{m}-\underline{m}\right)-p_1\right)^{\sigma+1} u_1^{1-\sigma} + \left(p_2-p_1\right)\left(m^*-p_2\right)^\sigma u_2^{1-\sigma}}{(1-\sigma)(1-t)^2\left(\overline{m}-\underline{m}\right)}
\end{aligned}$$

(Evaluated $t=0$)

$$\frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}(\overline{m}-\underline{m})}^{m^*}(m-p_1)^{\sigma}u_1^{1-\sigma}dG(m)+\int_{m^*}^{\overline{m}-\frac{t}{2}(\overline{m}-\underline{m})}(m-p_2)^{\sigma}u_2^{1-\sigma}dG(m)\right]$$

$$=\frac{-\left[(\underline{m}-p_1)^{\sigma}u_1^{1-\sigma}+(\overline{m}-p_2)^{\sigma}u_2^{1-\sigma}\right]}{2}$$

$$+\frac{(\overline{m}-p_2)^{\sigma+1}u_2^{1-\sigma}-(\underline{m}-p_1)^{\sigma+1}u_1^{1-\sigma}+(p_2-p_1)(m^*-p_2)^{\sigma}u_2^{1-\sigma}}{(1-\sigma)(\overline{m}-\underline{m})}$$

The equation above denotes the marginal effect of carbon tax policy on social welfare net of pollution effect, evaluated at the original status ($t=0$). Combined with Lemma 1 we could easily write the sufficient condition for carbon tax policy that could marginally improve social welfare.

Proposition 3 (Sufficient Condition for Carbon Tax Policy) *If carbon tax policy induces both positive (negative) pollution effect and positive (negative) income effect, then the carbon tax policy improves (declines) social welfare. There are two sufficient cases as follows:*

1) If $\frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}(\overline{m}-\underline{m})}^{m^*}(m-p_1)^{\sigma}u_1^{1-\sigma}dG(m)+\int_{m^*}^{\overline{m}-\frac{t}{2}(\overline{m}-\underline{m})}(m-p_2)^{\sigma}u_2^{1-\sigma}dG(m)\right]>0$ *and* $m^*>\frac{\overline{m}+\underline{m}}{2}$*, then positive carbon tax policy will improve social welfare while negative carbon tax policy will decline social welfare.*

2) If $\frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}(\overline{m}-\underline{m})}^{m^*}(m-p_1)^{\sigma}u_1^{1-\sigma}dG(m)+\int_{m^*}^{\overline{m}-\frac{t}{2}(\overline{m}-\underline{m})}(m-p_2)^{\sigma}u_2^{1-\sigma}dG(m)\right]<0$ *and* $m^*<\frac{\overline{m}+\underline{m}}{2}$*, then positive carbon tax policy will decline social welfare while negative carbon tax policy will improve social welfare.*

Proof: Decompose the effect of tax into two parts, pollution effect and income effect. $m^*>\frac{\overline{m}+\underline{m}}{2}$ indicates $t>0$ will reduce pollution, which is positive pollution effect. $\frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}(\overline{m}-\underline{m})}^{m^*}(m-p_1)^{\sigma}u_1^{1-\sigma}dG(m)+\int_{m^*}^{\overline{m}-\frac{t}{2}(\overline{m}-\underline{m})}(m-p_2)^{\sigma}u_2^{1-\sigma}dG(m)\right]>0$ indicates $t>0$ will improve welfare through income effect. Sum up the above two positive effect will lead to improved social welfare obviously. The other parts are the same.■

To pin down the income effect, further calculation indicates that:

$$\frac{\partial}{\partial t}\left[\int_{\underline{m}+\frac{t}{2}(\overline{m}-\underline{m})}^{m^*}(m-p_1)^{\sigma}u_1^{1-\sigma}dG(m)+\int_{m^*}^{\overline{m}-\frac{t}{2}(\overline{m}-\underline{m})}(m-p_2)^{\sigma}u_2^{1-\sigma}dG(m)\right]>0$$

$$\Leftrightarrow 2(p_2-p_1)(m^*-p_2)u_2^{1-\sigma}+\left[2(\overline{m}-p_2)-(1+\sigma)(\overline{m}-\underline{m})\right](\overline{m}-p_2)u_2^{1-\sigma}$$
$$-\left[2(\underline{m}-p_1)+(1+\sigma)(\overline{m}-\underline{m})\right](\underline{m}-p_1)u_1^{1-\sigma}>0$$

$$\Leftrightarrow\left[2(\overline{m}-p_2)-(1+\sigma)(\overline{m}-\underline{m})\right]\overline{U}>\left[2(\underline{m}-p_2)+(1+\sigma)(\overline{m}-\underline{m})\right]\underline{U}$$

where the last $\Leftarrow$ comes from $(m^*-p_2)u_2^{1-\sigma}>(\underline{m}-p_1)u_1^{1-\sigma}$, and $\overline{U}$, $\underline{U}$ denote the individual utility of the most wealthy consumer and most poor consumer respectively. We argue that in most cases $\left[2(\overline{m}-p_2)-(1+\sigma)(\overline{m}-\underline{m})\right]\overline{U}>\left[2(\underline{m}-p_2)+(1+\sigma)(\overline{m}-\underline{m})\right]\underline{U}$ holds because of the relatively large gap between rich and poor. In this way, we come to a brief conclusion that income effect is positive in most cases, and so long as $m^*>\frac{\overline{m}-\underline{m}}{2}$, which means more consumers are willing to buy traditional ICEVs, positive carbon tax policy will lead to better social welfare.

4.2 Carbon emission quota on carbon market

In this section we analyze whether carbon emission quota could perform better than carbon tax policy. From the previous above analysis, carbon tax policy is limited under some circumstances. For example, if pollution effect indicates that most people prefer traditional ICEVs, then normal carbon tax policy will cause more pollution. Besides, fiscal-neutral carbon tax policy largely changes the distribution of wealth, which may not be considered appropriate because income effect may distort consumers' behavior in other market beyond vehicles.

If the government now introduce carbon emission quota in which each consumer is endowed with equal amount of carbon license, so traditional ICEV drivers need pay extra money f to buy license from EV drivers. In equilibrium, all the carbon license will be held by traditional ICEV drivers, and market clear condition indicates $f\left(1-F\left(m^c\right)\right)=rF\left(m^c\right)$, where r is EV driver's revenue from selling license, and m^c is the threshold income under carbon emission quota satisfying $U\left(m^c+r-p_1,u_1,E^c\right)=U\left(m^c-f-p_2,u_2,E^c\right)$. Here the government controls total pollution by issuing certain number of licenses, which indirectly forces the level of total pollution E^c. Given the pollution quota, the indifference condition and market clear condition above solves r , f and m^c . Therefore, we could formally describe the social planner's problem with carbon emission quota as follows:

$$
\begin{aligned}
&\max_{E^c} A\left(E^c\right)\left[\int_{\underline{m}}^{m^c}\left(m+r-p_1\right)^\sigma u_1^{1-\sigma} dF(m)+\int_{m^c}^{\bar{m}}\left(m-f-p_2\right)^\sigma u_2^{1-\sigma} dF(m)\right] \\
&s.t. \quad E^c=e\left(1-F\left(m^c\right)\right) \qquad (8\text{-}1) \\
&\qquad U\left(m^c+r-p_1, u_1, E^c\right)=U\left(m^c-f-p_2, u_2, E^c\right) \qquad (8\text{-}2) \\
&\qquad f\left(1-F\left(m^c\right)\right)=rF\left(m^c\right) \qquad (8\text{-}3)
\end{aligned}
\tag{8}
$$

Proposition 4 (Optimal Pollution under Carbon Emission Permits) *Under carbon emission quota, social planner's optimal pollution* E^c *is solved from above, and the threshold income mc satisfies* $m^c > m^*$ *and* $m^c \neq m^{sp}$.

Proof: Assume that mc solves social planner's problem with carbon emission quota, then

$$
m^c=\arg\max_{m^c} A\left(e\left(1-F\left(m^c\right)\right)\right)\left[\begin{array}{l}\int_{\underline{m}}^{m^c}\left(m+r-p_1\right)^\sigma u_1^{1-\sigma} dF(m) \\ \quad +\int_{m^c}^{\bar{m}}\left(m-\frac{F\left(m^c\right)}{1-F\left(m^c\right)} r-p_2\right)^\sigma u_2^{1-\sigma} dF(m)\end{array}\right]
$$

$$
\left(\frac{u_2}{u_1}\right)^{1-\sigma}=\left(\frac{m^c+r-p_1}{m^c-\frac{F\left(m^c\right)}{1-F\left(m^c\right)} r-p_2}\right)^\sigma=\left(\frac{m^*-p_1}{m^*-p_2}\right)^\sigma
$$

The first line is derived from social planner's problem with carbon emission quota, replacing E^c and f using (8-1) and (8-3), while the second line shows that r is a function of m^c , solved from (8-2). Another useful observation here is the second equation in the second line, which is derived from competitive market equilibrium. Define social welfare as a function of threshold m^c :

$$
W\left(m^c\right)=A\left(e\left(1-F\left(m^c\right)\right)\right)\left[\begin{array}{l}\int_{\underline{m}}^{m^c}\left(m+r\left(m^c\right)-p_1\right)^\sigma u_1^{1-\sigma} dF(m) \\ \quad +\int_{m^c}^{\bar{m}}\left(m-\frac{F\left(m^c\right)}{1-F\left(m^c\right)} r\left(m^c\right)-p_2\right)^\sigma u_2^{1-\sigma} dF(m)\end{array}\right] \tag{9}
$$

where $r\left(m^c\right)$ is solved by the indifference condition (8-2), as a function of m^c .

To prove $m^c > m^*$, we consider a carbon emission permit with total pollution quota of m^*. Then we could derive from (8-2) and (8-3) to get $r\left(m^c\right) = f\left(m^c\right) = 0$. Now evaluating social planner's problem at $m^c = m^*$ indicates $\left.\frac{\partial W\left(m^c\right)}{\partial m^c}\right|_{m^c = m^*} = \frac{\partial W^0}{\partial m^*} > 0$ from proposition 2. Then social planner will choose optimal pollution level E^c lower than the competitive case $e\left(1 - F\left(m^*\right)\right)$, which means higher m^c.

To prove $m^c \neq m^{sp}$, we consider a carbon emission permit with total pollution quota of m^{sp}. From (8-2) and (8-3) we get $r\left(m^{sp}\right) \neq 0$. Now evaluating social planner's problem at $m^c = m^{sp}$:

$$
\begin{aligned}
&\left.\frac{\partial W\left(m^c\right)}{\partial m^c}\right|_{m^c = m^{sp}} \\
&= \frac{\partial}{\partial m^{sp}} A\left(e\left(1 - F\left(m^{sp}\right)\right)\right) \left[\begin{array}{l} \int_{\underline{m}}^{m^{sp}} \left(m + r\left(m^{sp}\right) - p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right) \\ + \int_{m^{sp}}^{\bar{m}} \left(m - \frac{F\left(m^{sp}\right)}{1 - F\left(m^{sp}\right)} r\left(m^{sp}\right) - p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right) \end{array} \right] \\
&\neq \frac{\partial}{\partial m^{sp}} A\left(e\left(1 - F\left(m^{sp}\right)\right)\right) \left[\begin{array}{l} \int_{\underline{m}}^{m^{sp}} \left(m - p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right) \\ \qquad + \int_{m^{sp}}^{\bar{m}} \left(m - p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right) \end{array} \right] \\
&= 0
\end{aligned}
$$

The first equation above just replace r with indifference condition, while the second inequation uses $r\left(m^{sp}\right) \neq 0$, and the fact that m^{sp} is optimal under $r = f = 0$. $\left.\frac{\partial W\left(m^c\right)}{\partial m^c}\right|_{m^c = m^{sp}} \neq 0$ therefore, indicates optimal level of pollution E^c is different from the section before, and $m^c \neq m^{sp}$. ■

To sum up, carbon emission permit allows the government to easily implement a certain level of total pollution E^c through quota, and it is indeed better to reduce pollution compared with competitive market. It could be easily noticed that under carbon tax policy, the threshold income level is also m^*. While carbon tax policy may reduce pollution by distorting income distribution, carbon emission quota can certainly reduce pollution since $m^c > m^*$. The advantage of carbon emission quota is that government could reduce total pollution by issuing a certain amount of carbon license $E^c = e\left(1-F\left(m^c\right)\right)$, and the desired level of pollution could be feasibly implemented without distorting income distribution. Yet the price of vehicles may be distorted, and the optimal threshold will be different from m^{sp}, which is the case that government forces an amount of total pollution.

5 Numerical simulations

In this section we will compare carbon tax policy and carbon emission quota policy together with first-best case in a numerical way. From before we know the corresponding optimal carbon tax and carbon emission quota policy could hardly be solved analytically, with the function form of income distribution $F\left(m\right)$ and pollution function $A\left(E\right)$ unknown.

Therefore we assume that income m follows a uniform distribution $m \sim F\left(m\right) = U\left[\underline{m}, \overline{m}\right]$, and the utility loss regard to pollution is $A\left(E\right) = a + bE$, where the negative b could be considered as the marginal disruptive effect of total pollution. In the latter part, we will consider competitive market equilibrium, first-best policy, carbon tax policy and carbon emission quota policy.

We will numerically solve the equilibrium and optimal policy, which is the carbon tax rate and carbon emission quota respectively. Then we will compare these results and simulate under some other parameter space. In the benchmark case the parameter space is as follows: $\underline{m} = 10, \overline{m} = 15, p_1 = 3, p_2 = 8, u_1 = 6$, $u_2 = 10, \sigma = 0.5, A\left(E\right) = 1 - 0.1E$, and we normalize the per unit pollution from a traditional ICEV $e = 1$.

We could easily arrive the competitive market equilibrium with $m^* = \dfrac{\left(u_2/u_1\right)^{\frac{1-\sigma}{\sigma}} p_2 - p_1}{\left(u_2/u_1\right)^{\frac{1-\sigma}{\sigma}} - 1} = 15.5, E = \dfrac{\overline{m} - m^*}{\overline{m} - \underline{m}} e = 0.45$ and the welfare

$$W^0 = A\left(e\left[1-F\left(m^*\right)\right]\right)\left[\int_{\underline{m}}^{m^*}\left(m-p_1\right)^{\sigma} u_1^{1-\sigma} dF\left(m\right) + \int_{m^*}^{\overline{m}}\left(m-p_2\right)^{\sigma} u_2^{1-\sigma} dF\left(m\right)\right] = 8.24.$$

In the latter sections, we will firstly keep the benchmark parameter unchanged in order to compare different cases. Since we have written the simulation program in *MATLAB* as algebraic forms, it is convenient for us to change the parameters and simulate again, from which we would figure out the optimal policy choice under other conditions.

5.1 Numerical simulation with first-best policy

In this section we assume that there exists a benevolent social planner who could impose an arbitrary income distribution so as to maximize total welfare. From the theoretical analysis above, we know that first-best policy is featured with same level of wealth among consumers who make the same choice.

Firstly, we impose a restriction on total pollution E^{fb}. With the help of **Corollary 1**, given a certain amount of total pollution E^{fb}, the first-best policy indicates $1-\frac{E^{fb}}{e}$ consumers with income m^l buying electric vehicles and $\frac{E^{fb}}{e}$ consumers with income m^h buying traditional ICEVs, satisfying $m^l = \frac{\left(p_1 u_2 - p_2 u_1\right)^{\frac{E^{fb}}{e}} + u_1 \int_{\underline{m}}^{\overline{m}} mdF\left(m\right)}{u_2 \frac{E^{fb}}{e} + u_1\left(1-\frac{E^{fb}}{e}\right)}$ and $m^h = \frac{\int_{\underline{m}}^{\overline{m}} mdF\left(m\right) - \left(1-\frac{E^{fb}}{e}\right)m^l}{\frac{E^{fb}}{e}}$.

Therefore, we consider different levels of pollution and simulate the first-best policy in Table 2.

Total Pollution E	$0.1e$	$0.2e$	$0.3e$	$0.4e$	$0.5e$	$0.6e$	$0.7e$	$0.8e$	$0.9e$	e
Welfare W	8.49	8.48	8.43	8.37	8.28	8.17	8.04	7.89	7.72	7.53

Table 2: First-best policy under given pollution

Social planner could improve social welfare obviously by averaging the wealth among the same group of consumers. We could find that even under the same level of total pollution as competitive equilibrium ($E = 0.45e$), the first-best policy leads to a locally optimal social welfare of $W = 8.33$, which is larger than that of competitive case $W^0 = 8.24$. The welfare gain is purely from a better wealth distribution, which roots from the goodness of equality given the Cobb-Douglas utility function form.

Since policy maker could impose any level of total pollution under unconstrained case, the optimization could be considered as searching all the pollution level from 0 to e, simulate the corresponding wealth distribution as well as the total welfare, and lastly pick the highest welfare, which is illustrated in Figure 2 below. We optimize exactly as above in *MATLAB*, and the optimal pollution is $E^{fb} = 0.08e$, with total welfare $W^{fb} = 8.49$. Under this specific parameter setting, first-best policy would constrain a much lower pollution level compared with competitive market, thus far less consumers buying traditional ICEVs, which stems from the ignored negative external pollution effect. Besides, although the marginal effect of pollution here is not significant ($b = -0.1$), the first-best policy would impose a low level of total pollution compared with competitive case.

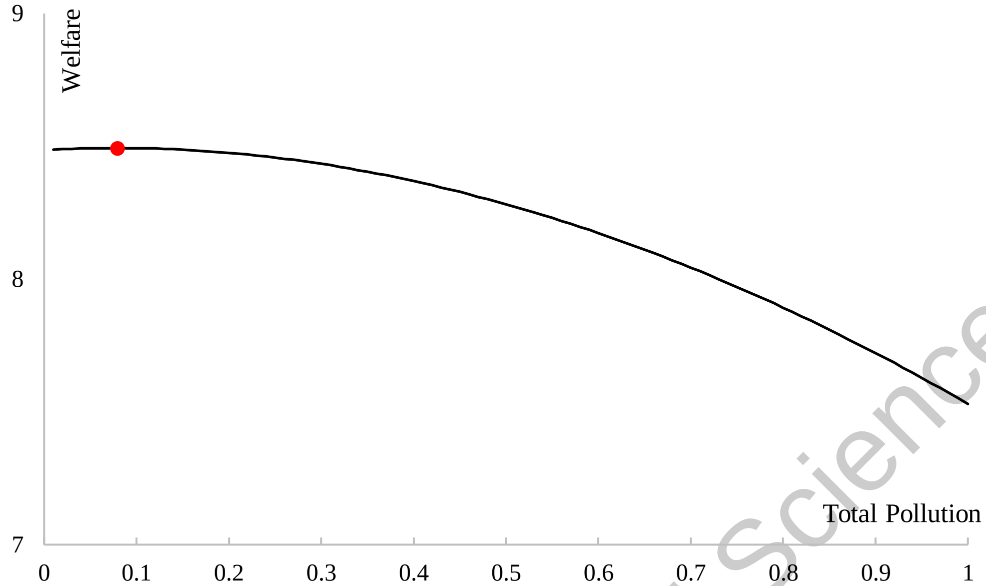

Figure 2: Pollution and welfare under first-best policy

5.2 Numerical simulation with carbon tax policy

If it is not feasible to impose an arbitrary income distribution for the social planner, we could only try second-best policy such as carbon tax or carbon emission quota, which was discussed before in a theoretical way. In this section, we would like to numerically analyze how different carbon tax rate could change income distribution, thus leading to different level of total pollution and social welfare.

Given the carbon tax rate t, a new uniform income distribution $m' \sim G(m') = U\left[\underline{m}', \overline{m}'\right]$ will be introduced, where $\underline{m}' = \underline{m} + \frac{t}{2}\left(\overline{m} - \underline{m}\right)$ and $\overline{m}' = \overline{m} - \frac{t}{2}\left(\overline{m} - \underline{m}\right)$. Then the equilibrium will be similar to the competitive case, with only a distorted income distribution. In the theoretical analysis, we know that under our parameter space which satisfying $m^* > \frac{\overline{m} + \underline{m}}{2}$ a positive carbon tax rate will improve social welfare through pollution channel. When carbon tax policy is introduced, there are more consumers whose income is above the threshold income level m^*, which leads to less pollution. However, from **Proposition 3** there is another income channel which would have influence on social welfare, and the exact direction of income effect is hard to decide given its complicated form.

In this way, we solve for the optimal carbon tax rate similarly as the above section, searching all the grids of carbon tax rate from $t_{\min}$ to $t_{\max}$, decomposing its two channels numerically, and finding the exact rate that leads to highest social welfare. To avoid make the analysis meaningful, we restrict $t_{\max} = 0.89$ to satisfy $\overline{m}' = \overline{m} - \frac{t}{2}\left(\overline{m} - \underline{m}\right) > m^*$, otherwise the carbon tax rate is so high that nobody would buy a traditional ICEV, which contradicts to reality obviously. Figure 3 below shows how different carbon tax rate would change the social welfare compared with competitive equilibrium. The black curve is the total welfare under different carbon tax rate, drawn on the left axis, while the red and blue curve are pollution effect and income effect, drawn on the right axis.

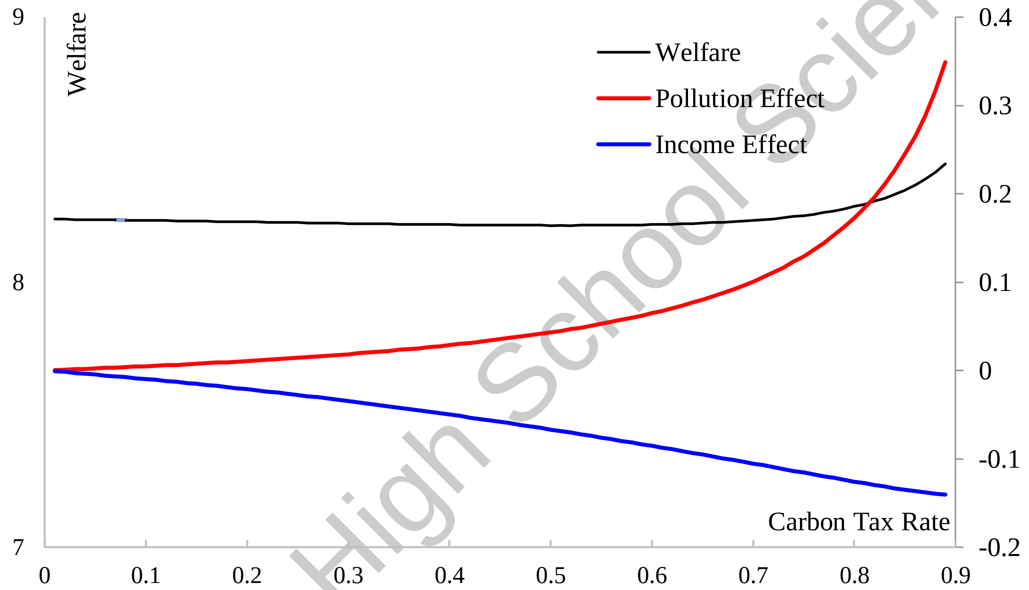

Figure 3: Social welfare and two effects under carbon tax policy

Through the optimization, we come to the optimal carbon tax rate $t^{fb} = t_{\max} = 0.89$, with total pollution $E^t = 0.05$ and social welfare $W^t = 8.45$, which further can be decomposed as +0.349 for *pollution effect* and −0.141 for *income effect*.

Here the positive carbon tax rate largely reduce pollution and improves social welfare, and this effect which we call *pollution effect* far outweighs the welfare loss due to distortion in income distribution, which we call *income effect*. We can also try that under other parameter settings, it is possible for carbon tax rate to be lower or even negative to induce second-best.

5.3 Numerical simulation with carbon emission quota policy

Another second-best policy which is quite feasible and common for social planner to improve social welfare is to introduce carbon emission quota. From the theoretical analysis before, optimal carbon emission quota policy would be equivalent to finding the optimal pollution quota E^c. After the quota is decided, traditional ICEV drivers need pay extra money f to buy license from EV drivers. In the equilibrium, market clear condition indicates $f\left(1-F\left(m^c\right)\right)=rF\left(m^c\right)$, together with the threshold income under carbon emission quota satisfying $U\left(m^c+r-p_1,u_1,E^c\right)=U\left(m^c-f-p_2,u_2,E^c\right)$. Therefore r, f and m^c could be solved from above as a function of pollution quota E^c.

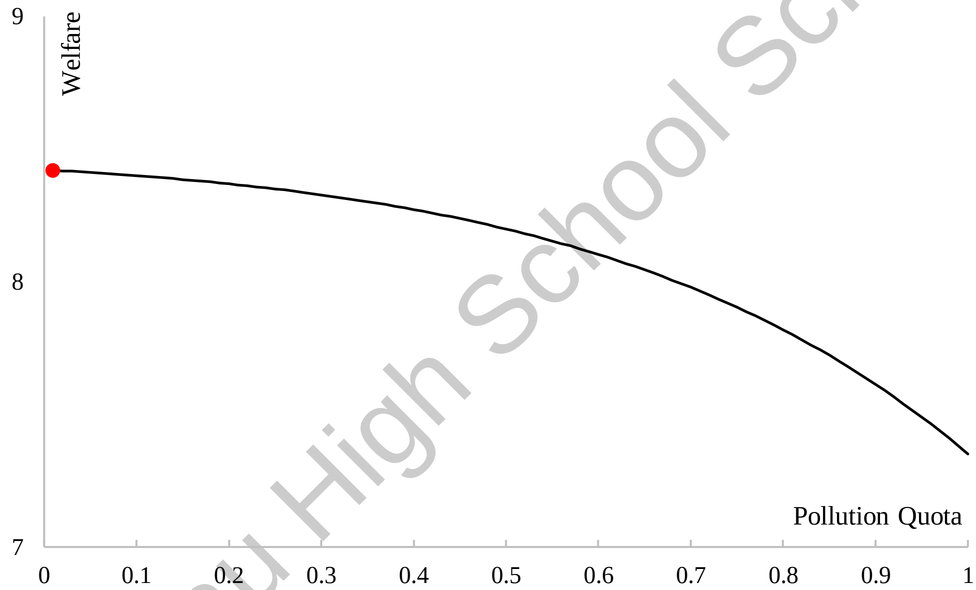

Figure 4: Social welfare and total pollution quota

In this numerical analysis section, we try different levels of quota through $0.01e$ to e, and solve the equilibrium in order to find the one with the highest social welfare $W\left(m^c\right)=A\left(E^c\right)\left[\int_{\underline{m}}^{m^c}\left(m+r-p_1\right)^{\sigma}u_1^{1-\sigma}dF\left(m\right)+\int_{m^c}^{\overline{m}}\left(m-f-p_2\right)^{\sigma}u_2^{1-\sigma}dF\left(m\right)\right]$.

The outcome for carbon emission quota is illustrated below in Figure 4, and we find that optimal level of total pollution quota $E^c=0.01$, corresponding to social welfare $W\left(m^c\right)=8.42$. The simulation coincides with **Proposition 4** such that $m^c=19.9>m^*=15.5$, and $m^c\neq m^{sp}$.

5.4 Comparison with different policies

The above three sections simulate the first and second-best policies for us to compare. Figure 5 below draws the social welfare and corresponding total pollution under the four equilibrium outcomes.

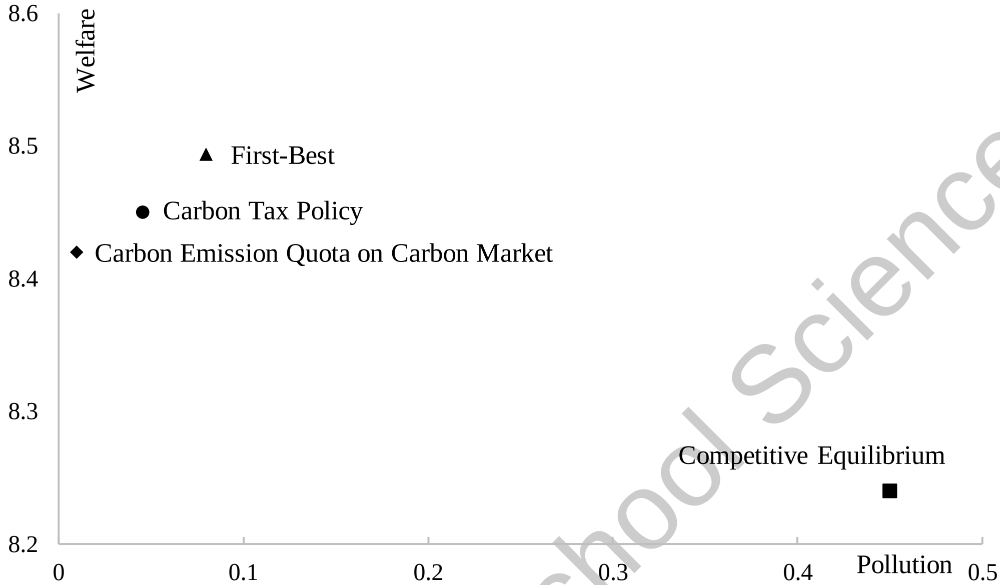

Figure 5: Social welfare and pollution under four equilibriums

We observe that in this parameter setting: 1) Competitive market equilibrium leads to highest level of total pollution and thus lowest level of social welfare; 2) First-best policy lowers the total pollution to a medium level compared with second-best policy, and leads to highest social welfare. Besides even under other pollution level, the wealth equality policy will leads to best outcome; 3) both the two second-best policies, carbon emission quota and carbon tax policy, leads to a quite low level of total pollution. And in this case, carbon emission quota would induce the lowest level of pollution, but not a higher welfare compared with carbon tax policy. In reality, the most significant advantage of carbon emission quota is that government could easily implement a certain level of total pollution by quota, but carbon tax rate on income could distort income distribution, of which the other harmful effects are not considered in our stylized model here.

For extension into other parameter spaces, we could try other parameter settings and compare the three cases. The results from theoretical analysis will always be held: first-best policy leads to highest social welfare with medium level of pollution, and competitive equilibrium is with over pollution. And it remains uncertain whether carbon tax or carbon emission quota better than other second-best policy, but both could improve social welfare compared with competitive equilibrium.

6 Conclusions

This paper considers the consumers' choice between EVs with zero carbon emissions and traditional ICEVs with carbon emissions. Due to the negative externality of CO_2 emission of traditional ICEVs, there is an excessive pollution problem in the equilibrium of perfect competitive market. We build up a theoretical model and analyze that the optimal distribution policy is that the wealth is equally distributed among the consumers of EVs and traditional ICEVs, and the total amount of pollution will be less than that of perfect competition.

Furthermore, we discuss the feasible suboptimal policy in competitive market and derive several results. Firstly, under the condition that most people select traditional ICEV, the carbon tax policy can reduce the poverty gap, lower the total pollutant emissions and improve the welfare. Meanwhile, the income effect of tax will also affect the welfare. Under relatively loose assumptions, the net effect of carbon tax can improve the welfare. Secondly, the introduction of carbon emission quota is equivalent to punishing traditional ICEVs and subsidizing EVs. At this time, the government can control the expected total pollutant emissions. The optimal total pollution quota is less than that in the competitive market, but it is still different from the social optimization, since the subsidies and punishment are equivalently changing the income in an indirect way. In addition, our research shows that as long as the government chooses the total pollutant emissions in the carbon emission quota, the subsidies and penalties will be automatically cleared through the carbon emission quota without the government calculating or giving.

In the future study, we will extend the theoretical model based on the two optimal decision equations obtained in this paper, and discuss the optimal carbon tax rate in different situations and the optimal carbon emission quota in carbon market, and then compare the welfare of carbon tax policy and carbon emission quota policy.

Subsidy policy has also played an important role in the development of the EV industry. However, relevant policies still need to be optimized and improved. We suggest that it is effective to gradually reduce or cancel the direct cash subsidy, adopt more policy tools like tax deduction and reduction, low interest loan support, etc., and reduce the vehicle use cost and improve the level of supporting facilities, and takes the experience of developed countries into consideration.

China is transitioning to a high-quality development and is committed to transition from high carbon growth to green development. The core of green development is the new development concept, and the key to the new development concept is circulation. In the face of profound changes unseen in a century, we must to actively promote the flow of production factors, optimize the allocation of resources, and achieve green transformation and development by scientific and technological system reform. EVs carry the concept of green development, but the development still rely on government subsidies. Based on the implementation of relevant policies of carbon emission quota, EVs can obtain more development opportunities and become an organic part of the market economy in carbon trading. The carbon trading among the EVs will also take more and more weights of the scientific and technological reform of green development.

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1. 论文的选题来源、研究背景；

作者是以能源与环境经济学为专业方向的青年研究者。受UN 环境署、UN 可持续发展委员会和 COP 等会议与模拟 UN 会议影响，在日常研究中，作者长期关注可持续发展与气候变化等重大环境议题。在高中生选拔性国际研学计划中，作者对人类因素造成气候变化异常等现象及其对生态系统平衡、人类生活、能源消耗领域的影响有了更为深入的理解；在后续的学习中，进一步学习到环境治理与经济发展间的内在联系，以及碳减排的相关市场机制设计，并在康奈尔大学的绿色城市课程中，进一步学习到如何应用数学建模方法研究经济金融问题，明晰市场机制减少碳排放的作用机理。

经济的可持续发展必须建立在绿色、节能、低碳的发展理念上。自“十二五”发展规划以来，我国愈发重视全球环境治理与全球气候变化问题，提出绿色发展、低碳发展等重要战略，并积极应对。2020 年 9 月，习近平总书记在七十五届联合国大会上提出了我国新的碳达峰目标和碳中和愿景。基于国家“碳达峰、碳中和”战略实现的研究背景，作者开始思考碳排放权交易、碳税、绿色电力证书、碳汇交易等政策对于减排效果的影响。

二十国集团（G20）财金渠道下增长框架工作组将无形资产融资列为 2021 年重要议题，而政府补贴是主要体现。汽车碳排放约占我国交通领域碳排放的75%，约占全社会碳排放的7.5%，由于电动汽车在使用阶段比传统内燃机汽车具有显著削减石油消耗、降低温室气体和污染物排放的作用，因此，电动汽车发展战略的实施与推进成为应对能源危机和环境问题的重要举措之一，但是通过补贴手段无法支撑电动汽车的长期可持续发展。基于此，作者思考是否可以通过碳排放权交易、碳税等市场机制推动电动汽车补贴改革，实现短期经济复苏与绿色低碳转型长期需求间的平衡。

本文的研究既是作者学术活动重心，也是基于应对气候变化问题、应对能源行业转型的思考凝练。前期研究鼓励作者不自限在实践应用层上，也致力于基础理论的研究。

2. 每一个队员在论文撰写中承担的工作以及贡献；

作者在论文撰写中阅读和学习相关文献，基于消费者对传统内燃机汽车与电动汽车的选择问题，通过经济金融建模，理论分析了碳税和碳排放权额度等政策的作用机制，以及对于污染排放的影响。作为论文唯一作者，独立完成论文所有内容，并积极在与指导老师沟通中协调深化研究。

3. 指导老师与学生的关系，在论文写作过程中所起的作用，及指导是否有偿；

在前期的研究计划阶段，作者在阅读相关文献时，受到中国科学院数学与系统科学研究院吴添老师已发表的研究内容的启发，因此写信与吴老师联系，分享并探讨学术观点和问题。本文的雏形受到老师指点，在作者希望针对该题目深入研究并参加丘成桐中学科学奖时，吴老师接受邀请，并成为指导老师。

论文写作中，吴老师推荐和提供了学术论文参考，指导细化数学金融建模。

吴老师是无偿指导。他的关心、耐心和细心深深影响作者；因为他的知识和思维指导，才令本篇论文成为可能。

4. 他人协助完成的研究成果。

作者作为碳政策研究相关机构的青年实习生，曾获得不同论文平台的专业文献数据访问渠道，运用在本论文中。

如有必要， 请附上团队成员和指导老师的简历。

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