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Low Speed Vehicles in China: Analysis of Current Market Status, Travel Intensity, Cost and Environmental Impacts

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Low Speed Vehicles in China: Analysis of Current Market Status, Travel Intensity, Cost and Environmental Impacts

By

JINPENG GAO
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

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Approved:

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Daniel Sperling

Gil Tal

Committee in Charge

2022

ABSTRACT

The dissertation focuses on understanding the low-speed vehicle (LSV) markets and their impacts on China's future energy use and emissions. I focused on four main areas: 1) current markets status of LSVs, including sales and population, vehicle characteristics, main OEMs, and related policies; 2) vehicle travel intensity of different LSVs and conducting data analytics on real-world LSEV GPS data to understand their different travel patterns; 3) total cost ownership analysis to compare the cost benefits of different vehicle types, conducting sensitivity analysis to understand the variability of levelized costs; 4) energy and emission analysis in different provinces of China to explore the geospatial and technological variations.

In chapter 2, I examined key market information, including key sales statistics and stocks, manufacturers and models, technology development, and government's major policies for LSVs including low-speed electric vehicles (LSEVs), rural vehicles (RVs) and gasoline/electrified two-wheelers (G2Ws, E2Ws). I found that despite LSVs facing obstacles such as fierce competitions from car industries and stringent government policies, the LSV industries are developing rapidly and account for a stable market share of new vehicle sales.

In chapter 3, I collected by-second GPS data of LSEVs and conducted data analysis to understand the heterogeneity of travel behaviors such as VKT distributions and travel frequencies. I visualized and calculated daily vehicle travel distributions, number of daily trips, travel behaviors differences between weekdays and weekends, and travel behaviors before and during the COVID-19 pandemic. It is found that LSEVs can provide comparable mobility level with E2Ws, RVs and G2Ws. It is also found that the stay-at-home orders and stricter regulations on LSEVs have discouraged LSEV users from operating their vehicles during the COVID-19 pandemic.

In chapter 4, I developed a comprehensive total cost of ownership model for different low-speed vehicles and their replacement options by considering the impact of factors such as monetary factors and consumer behaviors. Sensitivity analysis such as Monte Carlo simulation were applied to find the stochastic dominance between different vehicles in terms of total costs and levelized costs. It is found that EVs have lower cost of ownership compared with their gasoline or diesel counterparts and the biggest cost component for gasoline/diesel vehicles is the fuel cost while the biggest cost component for EVs is the purchase cost. For 2/3W comparison, the levelized cost is about 0.5 RMB/km for gasoline 3W motorcycles and 3W rural vehicles, while it is about 0.37 RMB/km for gasoline 2Ws and the about 0.2 RMB/km for electrified 2Ws and 3Ws. For 4W comparison, the levelized cost for compact gasoline car and BEVs with 500km range are both around 2 RMB/km, and about 1.5 RMB/km for the BEVs with 300km range and compact PHEVs, while LSEVs have the lowest levelized cost about 0.75 RMB/km. It is also found that LSVs such as LSEVs have very similar cost compared with their counterparts such as Micro EVs due to the higher lead-acid battery cost for LSEVs, implying that replacing lead-acid batteries with lithium-ion batteries will not increase the cost of ownership.

In chapter 5, I conducted a well-to-wheel energy and emission analysis of various vehicle types and utilized data on vehicle energy efficiency coupled with a high-resolution grid emission rate data. By considering the technological and geospatial heterogeneity, the energy use and carbon emissions were compared for different provinces, and it is found that the greener grid will enhance the GHG reduction benefits with electrification, for example provinces such as Qinghai, Sichuan with a lower coal-based electricity generation percentage have a larger potential of GHG reduction.

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CHAPTER 1 INTRODUCTION

1.1 Background

China has a large population of low-speed vehicles, including low-speed electric vehicles (LSEVs), rural vehicles (including three-wheelers and four-wheelers), and motorcycles (gasoline and electrified ones). LSEVs are smaller, simpler, slower, and cheaper vehicles, and virtually unknown outside of China. Internationally, there are similar products in other countries, such as neighborhood electric vehicles in the US, Kei cars in Japan and quadricycles in EU.

LSEVs in China have been popular in certain provinces and cities, even though they are largely ineligible for government subsidies that are designed for regular plug-in electric vehicles (PEVs). LSEVs are also subject to restrictions and potential bans. Although LSEVs have been outside the control of government regulations and incentive policies, by relying on local technology and resources, they have rapidly grown and have provided practical, low-cost mobility to low-income populations. Like LSEVs, rural vehicles and motorcycles are widely used in small cities, towns and rural areas in China and are potentially subject to restrictions in the future.

The adoption of LSEVs is significant because, along with their economic, air quality, and energy benefits compared with gasoline vehicles, low-speed vehicles are also driving the development of regular PEV markets (Bo Chen & Midler, 2016a; Ling, Cherry, & Yang, 2019; Wang & Kimble, 2011). Rural vehicles and motorcycles serve low-income residents as essential transportation tools but are subject to potentially large usage of fossil fuels and corresponding emissions of greenhouse gases (GHGs). Despite their popularity, low-speed vehicles are also associated with several issues including traffic regulation, safety, and battery pollution, and thus subject to public debates on whether to ban or regulate them (Fang & Zhu, 2015; F. Zhao, Zhao, & Liu, 2017).

Due to obstacles such as data unavailability, limited research interests, there exist some big gaps in the studies of low-speed vehicles in China:

1) The legal status of low-speed vehicles is not clear yet due to the lack of national and industrial standards, although there are several drafts released for comments.
2) There is a lack of data and literature about the market status of current low-speed vehicles.
3) The vehicle travel intensity for LSEVs is not clear due to the lack of data and associated research.
4) The energy, emission, and cost benefits about these different low-speed vehicles have not been systematically studied.

To better understand the low-speed vehicle markets and their impacts on China's future energy use and emissions, I focus on four main areas:

1) Current market status of low-speed vehicles, including sales and population, vehicle characteristics, main OEMs, and related policies.
2) Vehicle travel intensity for different low-speed vehicles and conducting data analytics on real-world LSEV GPS data to understand their different travel patterns.
3) Total cost ownership analysis to compare the cost benefits of different vehicle types, conducting sensitivity analysis to understand the variability of levelized costs.
4) Energy and emission analysis for different vehicle types in different provinces of China to explore the geospatial and technological variations.

1.2 China’s changing transportation landscape: 1996 vs. 2006 vs 2016

In 1996, 70% of China’s 1.2 billion people lived in the rural countryside but the country experienced rapid urbanization during this period. Bicycles, public transit, and motorcycle use experienced tremendous growth. However, the automobile industry was still in an infant stage, producing slightly less than a half million passenger cars pers year. For every 1,000 people: 360 owned bicycles, 17 owned motorcycles, and only 3 owned a personal car (J X Weinert, 2007). By 2006, the proportion of people living in the countryside fell to 57% and for every 1,000 people, 350 owned bicycles, 90 owned motorcycles, and 10 owned a personal car (J X Weinert, 2007). The electric two-wheeler (E2W) emerged as a mode of transportation that was virtually non-existent and with an ownership rate of 30 out of 1,000. Another unique mode was Chinese Rural Vehicles (CRVs), which enjoyed a steady increase since 1996 and was owned by about 17 people per 1,000 one decade later.

By 2016, the proportion of people living in the countryside fell to 41%. For every 1,000 people, 270 owned bicycles, 65 owned motorcycles, 158 owned personal cars, 145 owned E2Ws, about 6.5 owned CRVs. From 2006 to 2016, the ownership of bicycles, motorcycles and CRVs declined while the ownership of personal cars and E2Ws increased along with the increased urbanization in China. People living in the countryside or earning a lower income replaced their previous inferior mode with personal cars or electric bikes.

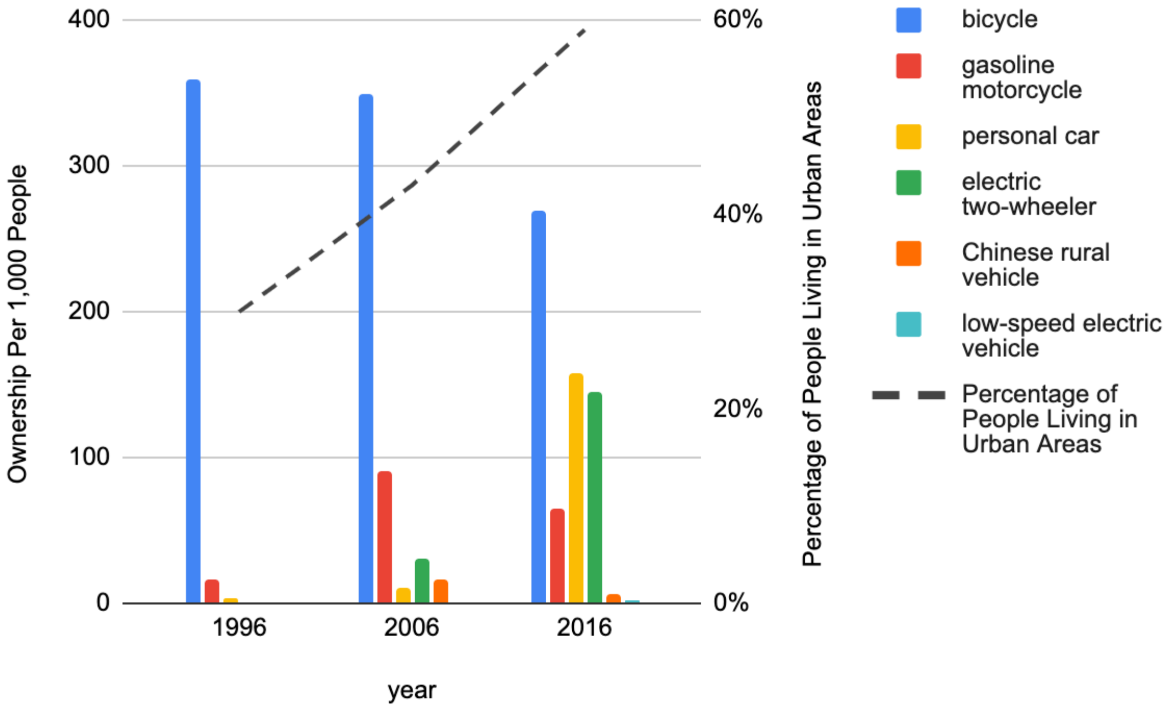

***Figure 1 The ownership of different transportation choices changed rapidly from 1996 to 2016 in China with urbanization**.*

The people living in urban areas has risen from 30% to 59% in 20 years and over this time period, transportation mobility solutions became increasing motorized and began to electrify. [1]

Figure 2 shows the growth in motorized vehicle annual sales over the past decade. By 2016, annual sales of passenger vehicles exceeded those of motorcycles and reached close to those of E2Ws. Annual sales of CRVs remained stable while the electrified low-speed rural vehicles (LSEVs) enjoyed a fast growth in sales. The sales of E2Ws and gasoline motorcycles continued to decline from 2012 through 2017. With the slower growth of E2W and motorcycles, consumers are expected to switch their transportation tools from these inferior low-speed 2-wheelers to superior cars. However, for residents in rural areas or lower-tier cities, owning a car would be very costly and other less expensive replacing options such as LSEVs start to

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[1] 1996 and 2006 data from (J X Weinert, 2007) For 2016 data, E2W data from http://www.hk-eve.com/html/hnnews/hnhyxw/2017022362.html; LSEV data from (Research and Markets, 2021). Gasoline motorcycle, CRV and Passenger cars data from (China Automobile Dealers Association, 2020)

popularize in these markets. It is essential to understand the current status of these low-speed vehicle markets, the cost to own these vehicles compared with other alternatives and their energy use and emission advantages/disadvantages.

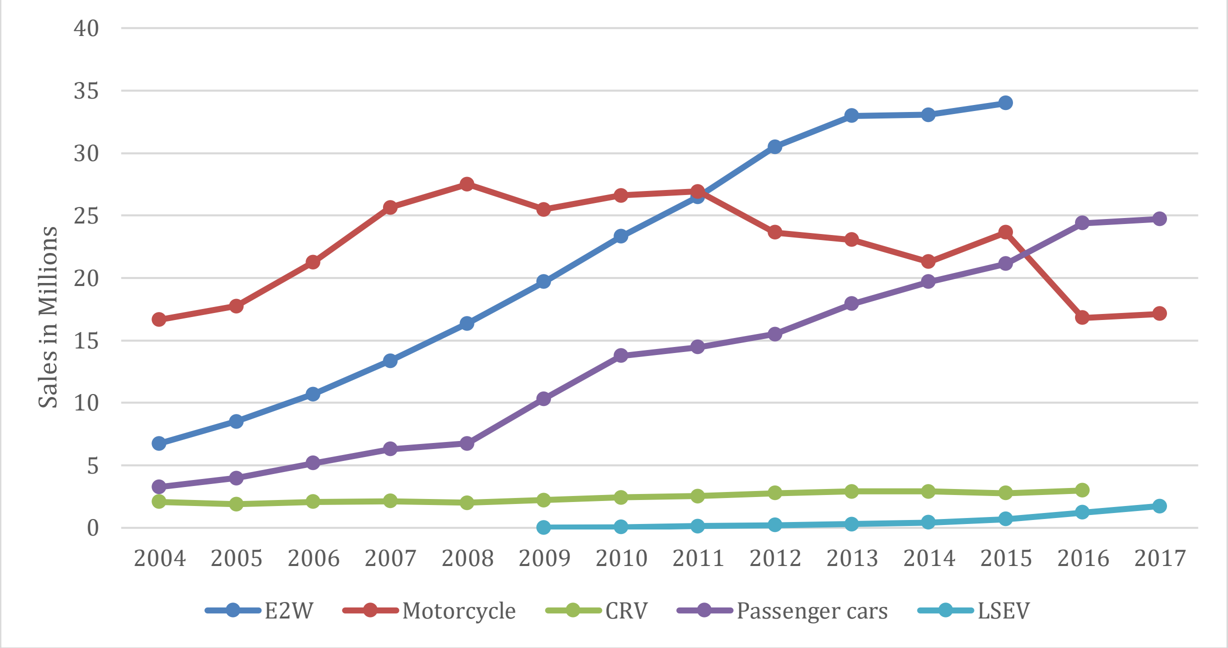

***Figure 2 Sales comparison from 2004 through 2017 for five types of vehicles in China*.**

Sales of CRV, LSEV, E2W and passenger cars continuously increase while motorcycles peaked around 2008 and kept a relatively constant sale afterwards. Data source: E2W data is from (Jonathan X. Weinert, Ma, Yang, & Cherry, 2007) and https://pdf.dfcfw.com/pdf/H3_AP202106021495539270_1.pdf?1622654019000.pdf; LSEV data from (Research and Markets, 2021). Gasoline motorcycle, CRV and Passenger cars data from (China Automobile Dealers Association, 2020)

1.3 LSVs around the world

There is a lack of national regulations even though some drafts for comments have been released and under discussion. According to the draft for comments *Battery electric passenger cars — Specifications GB/T 28382* released in 2021 by The Ministry of Industry and Information Technology (MIIT, 2021), low-speed electric vehicles are defined by a set of specific characteristics across many vehicle attributes, most notably having a curb weight of less than 750kg, maximum speeds between 40 and 70 km/h, a range of more than 100 km, and a battery energy density of more than 70 Wh/kg, etc. However, this draft for comments is still under debates and the final standards for LSEVs are lacking.

Outside of China, there are many similar products which have similar low-speed characteristics, such as Kei cars in Japan, neighborhood electric vehicles (NEVs) in the US and L-category vehicles in Europe.

Japanese Kei Car

The kei car or light automobile, known outside of Japan as a city car, ultra-mini, or microcar, is the Japanese vehicle category for the smallest highway-legal cars with restricted dimensions and engine capacity. There are also microvans and kei trucks within the Japanese kei car classification. However, I will focus on passenger kei vehicles in Japan in this section.

The kei-car category was created by the Japanese government in 1949 and regulations have been revised several times since. These regulations specify a maximum vehicle size, engine capacity, and power output, so that owners may enjoy both tax and insurance benefits. According to the latest regulation[2], the max length, width and height are 3.4m, 1.48m and 2.0m, respectively, and the max displacement and max power of the engine are 660 cc and 47 kW.

US Neighborhood Electric Vehicle

Low-speed vehicle (LSV) is a federal approved street-legal vehicle classification which came into existence in 1998 under Federal Motor Vehicle Safety Standard 500 (FMVSS 500). LSVs are defined as a four-wheeled motor vehicle that is usually built to have a minimum speed of 20 mph and a top speed of 25 mph, and have a maximum loaded weight of 3,000 lbs (1,400 kg) (National Highway Traffic Safety Administration, 1998). LSVs are subject to all provisions applicable to a motor vehicle and must meet federal safety standards. The operator of a LSV may

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[2] https://www.airia.or.jp/info/system/02.html

not operate the vehicle on any roadway with a posted speed limit greater than 35 mph except to cross a roadway at an intersection. Therefore, LSVs are mostly used in colleges and industrial campuses, National and State parks, correctional facilities, etc.

LSVs can be powered either by electric or gasoline, and the electric version is also called neighborhood electric vehicles (NEVs). In California, NEVs are classified by the California Air Resources Board (CARB) as zero-emission vehicles (ZEV) and are eligible for a purchase rebate of up to $750 with a minimum battery capacity of 5 kWh[3].

EU Quadricycles

The quadricycle is a European Union vehicle category for four-wheeled microcars, which allows these vehicles to be designed to less stringent requirements when compared to regular cars. Quadricycles are defined by limitations in terms of weight, engine power, dimension and speed. There are two types of quadricycles including light quadricycles (L6e) and heavy quadricycles (L7e). According to the EU regulation published in 2013 (The European Parliament and the Council of the European Union, 2013), light quadricycles are four-wheel vehicles with a maximum speed no more than 45 km/h and the mass weight under 425kg without batteries, equipped with a maximum of two seating positions. Based on different usage, the rated power varies from 4 to 6 kW. Heavy quadricycles are four-wheel vehicles with a maximum speed no more than 90 km/h (some sub-categories such as heavy on-road quadricycles do not have maximum speed limit) and the mass weight under 450kg without batteries, equipped with a maximum of 2-4 seats based on different usages. The rated power should not exceed 15 kW.

The following table summarizes and compares the low-speed vehicles in different countries or regions. Except for Japan where most low-speed vehicles are gasoline powered,

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[3] https://afdc.energy.gov/laws/all?state=CA#Laws%20and%20Regulations

low-speed vehicles in other countries or regions including the US, EU and China are mostly powered by electric. There is a similar requirement for vehicle dimensions that vehicles shouldn’t exceed 4m×2m×2.5m while there is no requirement in the US. The curb weight requirements are lower than the average weight of a midsize car, whose curb weight is around 1500kg[4]. The maximum speeds are normally not allowed to exceed 70 km/h except for L7e, in which some sub-category does not have any maximum speed limitation. Lastly, all vehicles are required to have four wheels while the number of seats varies in different countries/regions.

Table 1 Comparison of Vehicle Specifications in Low-speed Vehicles Regulations.

Adapted from (JAMA, 2019; MIIT, 2021; National Highway Traffic Safety Administration, 1998; The European Parliament and the Council of the European Union, 2013)

Country	Classification	Power Source	Dimension (L*W*H, m)	Curb Weight (kg)	Maximum Speed (km/h)	Rated Power (kW)	Number of Seats	Number of Wheels
Japan	Kei car	Mostly gasoline	≤ 3.4, ≤ 1.48, ≤ 2	×	×	47	4	4
United States	Neighborhood electric vehicle	Electric	×	1,361	32-40	×	×	4
EU	L6e	Electric	≤ 3-4 ≤ 1.5-2 ≤ 2.5	425 (without batteries)	45	4-6	≤ 2	4
	L7e	Electric	≤ 3.7-4 ≤ 1.5-2 ≤ 2.5	450 (without batteries)	90 to no restriction	15	≤ 2-4	4
China*	Low speed electric vehicle	Electric	≤ 3.5 ≤ 1.5 ≤ 1.7	750	40-70	×	≤4	4

China*: Currently there is no official national standards for low-speed electric vehicles. The Ministry of Industry and Information Technology released the drafts for comments in July of 2021, explicitly included the four-wheel low-speed electric vehicles (LSEVs) into the pure battery electric vehicle category, and renamed LSEVs as ‘micro low-speed electric passenger cars’ (MIIT, 2021).

1.4 Research questions

For a long period of time, low-speed vehicles lacked interest from the research community and from industry due to the simplicity of its technology, low-profit, and its potential consumers

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[4] https://cars.lovetoknow.com/List_of_Car_Weights

being low-income populations. However, the long-ignored vehicles served a large percentage of population and their impact on energy use and GHG emissions is estimated to be significant due to their large stock and high density of vehicle usage.

Specially, researchers hypothesized that LSEVs and electrified two-wheelers have great potential in energy use and GHG emission reduction and their users are potential candidates for more advanced PEVs (Fang & Zhu, 2015; Ling et al., 2019; Wang & Kimble, 2012). Therefore, understanding these users' purchase and driving behaviors will provide more implication of policy leverage to encourage the purchase of PEVs.

The goal is to understand the historical backgrounds, status, and future trends of low-speed vehicles in China (including LSEVs, Chinese rural vehicles (CRVs), gasoline and electrified two-wheelers). I attempt to analyze low-speed vehicle markets and their corresponding use characteristics, cost, energy and emission benefits by answering following questions:

1) What is the historical background and current status of low-speed vehicles (including sales and stocks, OEMs, vehicle characteristics, policies)?
2) What are the use characteristics, travel behaviors of low-speed vehicles?
3) What are the cost benefits of low-speed vehicles compared to other replacement options?
4) What are the energy and environmental impacts of low-speed vehicles considering China's different electricity generation profiles in each province?

In Chapter 2, I examine key market information, including key sales statistics and stocks, manufacturers and models, technology development, and government's major policies for low-speed vehicles including LSEVs, rural vehicles and gasoline/electrified 2-wheelers. In a nutshell, low-speed vehicle industries are developing rapidly and account for a stable market share of new vehicle sales, despite being faced with fierce competition and strict governmental regulations.

In Chapter 3, literature reviews of the vehicle travel intensity for different types of vehicles are conducted in order to understand the heterogeneity of travel behaviors for different vehicles. For LSEVs, I collaborate with an LSEV maker to collect by-second GPS data of 539 LSEVs for a week from web APIs, conduct data analysis and calculations for daily vehicle travel distributions, number of daily trips, travel behavior differences between weekdays and weekends.

In Chapter 4, a TCO model for different low-speed vehicles and their replacement options is developed by considering the impact of factors such as monetary factors and consumer behaviors, which enabled us to quantify the cost differences between various vehicle types in China. Sensitivity analyses such as Monte Carlo simulations were also applied to find the stochastic dominance between different modes in terms of total costs and levelized costs.

Lastly in chapter 5, I conduct an energy and emission analyses of various vehicle technologies for different provinces in China and tried to observe any geospatial and temporal differences. I utilize data on vehicle energy efficiency coupled with a high-resolution grid emission rate data. By considering the technological and geospatial heterogeneity, the energy use and carbon emissions were compared for different vehicle types and provinces.

CHAPTER 2 MARKET OVERVIEW

The available literature contains limited information about China’s low-speed vehicles (LSVs). For E2Ws, Weinert and Cherry have done extensive research of cost benefit analysis, life cycle analysis, travel pattern analysis, driving factors and resisting forces analysis in China in their Ph.D. dissertations (Weinert 2007; Cherry 2007). For CRVs, Sperling et al. investigated the Chinese rural vehicles (CRVs) by conducting comprehensive interviews with over 100 Chinese farmers and CRV users, and two largest CRV manufactures, and analyzed the vehicle technology, government policy, environmental impacts, market demand and industry dynamics, and found that increasing government regulation (mostly for emissions and safety) had profound effects on the industry (Sperling, Lin, & Hamilton, 2004). Ling et al. conducted structured interviews to provide initial insight of motives for mini-EV (low-speed electric vehicles) choice and purchase, travel behavior and safety (Ling et al., 2019). There are other studies (Chen and Midler 2016b; Chen and Midler 2016a; Chen 2018; Kimble and Wang 2013; Wang and Kimble 2011; Wang and Kimble 2012) related to LSEVs which are focused on one area such as cost, energy/emission.

However, there are no comprehensive studies about the LSV markets in China, which prevents other researchers from understanding and evaluating the energy/emission impacts of the market segment. Therefore, this chapter will give an overview of the low-speed vehicle markets in China by discussing the key sales and stock statistics, OEMs and models, technologies, product characteristics, and government major policies.

2.1 Definitions and classifications

The broad category of Low-Speed Vehicles (LSVs) mainly includes electric bicycles, electric scooters motorcycles, tricycles, diesel rural vehicles and low-speed EVs. The most common characteristics of these vehicles are that they normally have a maximum speed no more than 70km/h and most of the vehicles are affordable transportation solutions for rural and suburban transportation in China. As is shown in Figure 3, low-speed mobility solutions can be divided into three groups based on number of wheels:

Two-wheelers (2Ws)

- Electric 2Ws mainly includes electric bicycles, electric mopeds, electric motorcycles. The definitions and specifications can be found in the following table. In China, electric motorcycles are not popular partially due to the motorcycle ban in major cities (Guo et al. 2020). Thus, in this study, I will only consider electric bicycles and electric scooters as they are more popular in China.
- Gasoline 2Ws mainly includes gasoline scooters and motorcycles. In China, gasoline scooters refer to the gasoline two-wheelers that have the maximum speed lower than 50km/h and the engine size lower than 50cc, while gasoline motorcycles refer to the gasoline two-wheelers that have the maximum speed larger than 50km/h and the engine size larger than 50cc (Standardization Administration of China, 2017).

Table 2 Definitions of electric bicycles, scooters and motorcycles.

Adapted from (MIIT, 2018).

Specification	Non-motorized	Motorized	
	Electric bicycle	Electric scooter	Electric motorcycle
Maximum speed (km/h)	≤25	>25, ≤50	>50
Curb weight (including battery) (kg)	≤55	>55 (non-mandatory)	>55 (non-mandatory)
Motor power (kW)	≤0.4	>0.4, ≤4 (non-mandatory)	>4 (non-mandatory)
Battery voltage (V)	≤48	No requirement	No requirement
Have pedals	Yes	No	No

Three-wheelers (3Ws)

- Electric 3Ws: Electric tricycles are mostly used in logistics industries such as parcel delivery and food-delivery due to the low running cost and loose regulations on electric tricycles (Zhang, Chen, Li, & Zhong, 2019). According to GB/T 10757, there are four specific features: 1) the maximum speed is 15km/h; 2) the maximum load is 180kg; 3) the carriage box is enclosed with uniform identification; 4) the design is specially made for delivery of fast freight.
- Gasoline 3Ws: As a counterpart to Electric 3Ws, it is no longer popular in major cities due to the motorcycle bans[5]. However, gasoline 3Ws are still accounting for substantial market shares in rural areas.
- Diesel 3Ws: 3-wheeled CRVs that mainly exist in rural areas of China. The main purpose of this kind of vehicle is for farm product transportation and cargo transportation (Teter, 2011).

Four-wheelers (4Ws)

- Electric 4Ws: The low-speed electric vehicles, emerged in the last five years, and became popular in both rural and urban areas of China. Most of them are equipped with lead-acid

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[5] Chinese wikipedia and website that contains the information of motorcycle bans in about 190 Chinese cities.

batteries to lower the manufacturing cost while there are more and more models equipped with lithium-ion batteries (Research and Markets, 2021).

- Diesel 4Ws: 4W CRVs are the most common diesel vehicles in China that belong to low-speed vehicle category. These vehicles normally have a higher price and maximum speed than the Diesel 3W CRVs and mostly used for farm product transportation and cargo transportation in rural areas (Sperling et al., 2004).

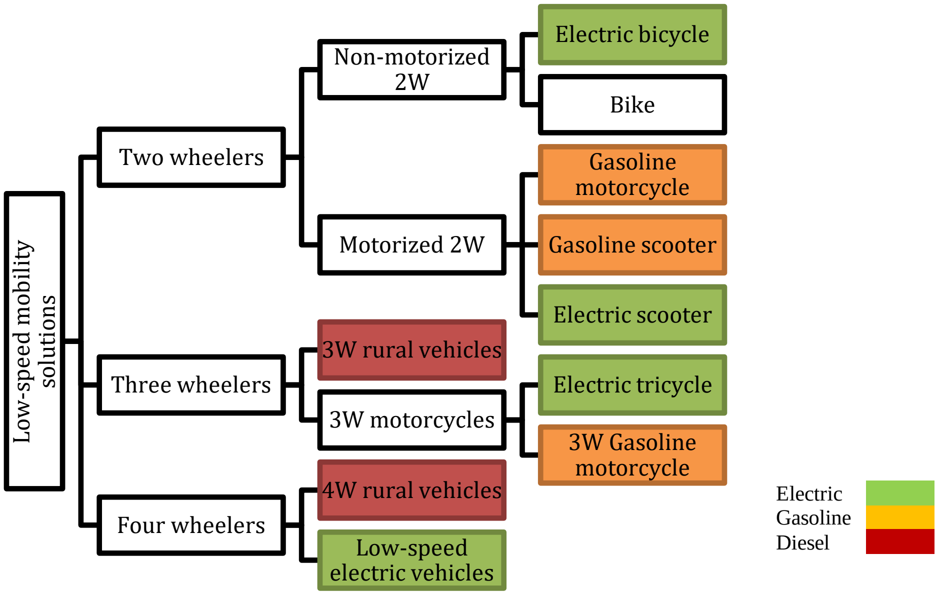

Figure 3 Classifications of low-speed mobility solutions.

Based on number of wheelers, there are three main categories, two-wheelers, three-wheelers and four-wheelers.

2.2 Low-speed vehicle markets

In this subsection, each category of low-speed mobility solutions in details of the sales, stocks, OEMs, technologies and related national and local policies is discussed.

2.2.1 Electric two-wheelers

According to the 2019 Blue Book for New National Standard EVs[6], E2Ws production has been increasing and staying stable in recent years. In 2018, the total production number of E2Ws reached about 33 million. Due to the rapid urbanization and increased disposable income, the inelastic demands for E2Ws continue to increase despite some modes such as LSEVs and cheap gasoline cars competing for some market share. The population of E2Ws reached 250 million and the population of electric tricycles (E3Ws) reached 50 million in 2017, with an accumulated production value of over hundred billion RMB[7].

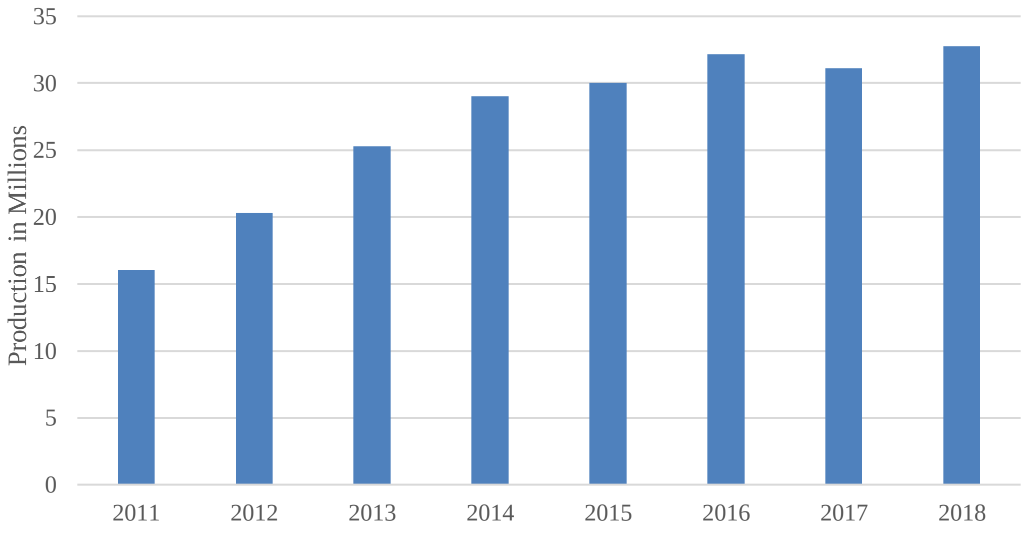

Figure 4 The production of E2Ws from 2011 to 2018.

The production of electric two-wheelers has been increasing since 2011 and doubled its production from 15 million in 2011 to over 30 million in 2018. By end of 2018, the population of E2Ws has reached 0.25 billion. However, due to stricter regulations for E2Ws released in 2018 and market saturation, the E2W production is stable around 32 million. Source of the production and population numbers of E2Ws: https://mp.weixin.qq.com/lps.

As is shown in the below table, the two main types of E2Ws are electric bicycles (with pedals) and electric scooters (without pedals). Electric bicycles are equipped with pedals and thus can be both human-powered and pedal-assist e-bikes, while electric scooters without pedals can only be

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[6] https://www.zhizhi88.com/articles/727.html
[7] http://www.chinanews.com/cj/2017/04-17/8201800.shtml

powered with electric. The main differences include that the electric scooters have a higher power and top speed compared to electric bicycles, resulting in a higher fuel consumption rate and a higher price while their electric ranges are comparable. The pictures in the table show their typical outlooks.

Besides the two mentioned electric 2Ws, there is another type of electric scooters which is called electric kick scooters or standing electric scooter. The electric kick scooters have grown in popularity with the introduction of scooter-sharing system that use apps allowing users to rent the scooters by the minute[8]. As the name indicates, the electric kick scooters are not equipped with pedals and seats so that users need to stand when operating the scooters. Compared with the other two electric 2Ws, electric kick scooters are more lightweight while the performance is similar. The picture in the table below shows the typical outlook of an electric kick scooter.

Table 3 Comparison of different types of electric two-wheelers

Type	**Power (kW)**	**Top speed (km/h)**	**Fuel Use (kWh per 100 km)**	**Range (km)**	**Picture**
Electric bicycle	0.25-0.35	20-30	1.2-1.5	30-40	
Electric scooter	0.3-0.5	30-40	1.5-2.0	30-40	
Electric kick scooter	0.25-0.67	20-30	1.0-1.9	20-45	

E2Ws have become a very popular transportation mode for Chinse consumers because they provide convenient, yet relatively inexpensive form of private mobility and therefore, partially

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[8] https://en.wikipedia.org/wiki/Motorized_scooter#Mechanics

substitute for public transit or regular bicycling. Specifically, electric kick scooters have been popular in China and the production number reached 3.64 million units in 2020, accounting for over 85% of global production[9]. However, since there are no well-established regulations for electric kick scooters, most of the produced electric kick scooters are exported to EU and north America.

Figure 5 shows that the E2W sales numbers and market shares by brand in 2018. Yadea and Aima are the top two E2W makers and account for 37% of total sales. Yadea reached 5 million sales and Aima reached 4.5 million sales in 2018.

Figure 5 E2W sales by e-bike producers in 2018.

The unit of vertical axis is 10,000 vehicles. The horizontal axis illustrates the different brand names. Starting from left to right, the E2W brand names are: Yadea, Aima, Tailg, Xiaodao, Luyuan, Sunra, Jinjian, Lvjia, Lima, Lvju, Birdie, Zuboo, Honda-Sundiro, Opai, Byvin, Supaq, Slane, Bodo, Dayang-chok, Niu. The figure is from zol.com.cn and the data source is stated to be collected from public information.

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[9] www.shorturl.at/bR289

Due to the lack of data in electric tricycles and electric kick scooters, I will exclude both from the analysis conducted in this chapter. However, I will still include E3Ws in the total cost of ownership analysis in the Chapter 4.

2.2.2 Gasoline motorcycles

Sales of motorcycles (including both domestic markets and overseas markets) increased rapidly from 1985 to 2010 according to Figure 6 and Figure 7. After 2010, the sales number started to decrease, and the motorcycle markets reached the sale peak around 2010. In 2009, the global financial crisis broke out and China's number of motorcycle exports declined significantly, with the sales of motorcycles falling by 7.5% compared to the previous year. To encourage the development of motorcycle markets, China government released a campaign called *'the motorcycle to the countryside'*[10] in 2009 to expand markets in rural markets, which made China motorcycle markets steadily growing in both sales and productions. In 2010 and 2011, the motorcycle markets rebounded, and the production reached 26.69 million and 27 million, respectively. The *'motorcycle to the countryside'* campaign ended in 2012 and overdrew future demand in rural markets, leading to Chinese motorcycle markets experiencing their largest crisis ever. Furthermore, motorcycle markets experienced fierce competitions from both car industries and E2W industries and decreased over 10% annually in production. By 2017, total production of motorcycles reduced over 10 million compared with the peak year in 2008.

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[10] http://www.gov.cn/gzdt/2009-03/16/content_1260172.htm

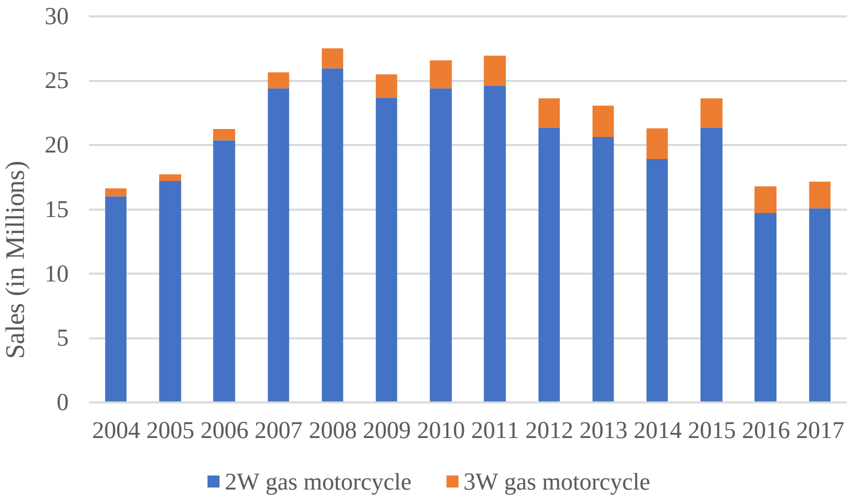

***Figure 6 Two-wheel and three-wheel gasoline motorcycle sales from 2004 to 2017**.*

Sales of 3W gasoline motorcycles have been increasing from 2004 to around 2010. However, compared to 2W gasoline motorcycles (G2Ws), 3W still accounts for a small market share. In 2017, the sales of G2Ws were only about 15 million compared to the peak sales in 2008, which was about 26 million. Source: (China Automobile Dealers Association, 2020)

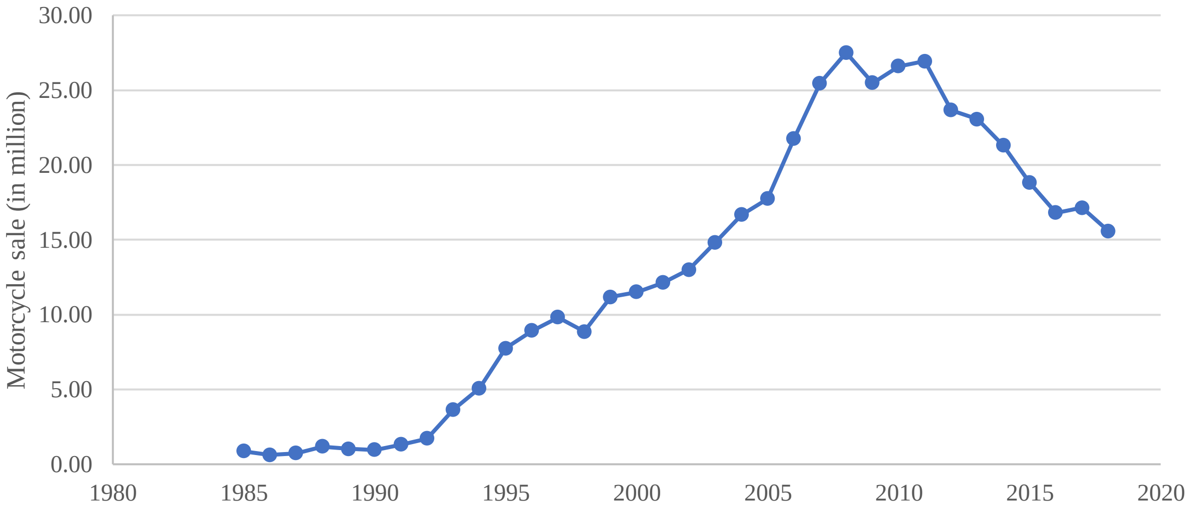

***Figure 7 Motorcycle sales from 1985 to 2017**.*

Sales peaked around 2010 and saturated due to a campaign known as 'motorcycle to the countryside'. After 2010, sales started to decrease continuously due to the fierce competitions with both E2W and car industries. In 2018, the sale has reduced over 12 million to 15 million compared with the peak sale in 2008. There are several reasons for the big drop of motorcycle sales such as fierce competitions from both car and E2W industries, and stricter regulations and city bans on motorcycles. Source: (China Automobile Dealers Association, 2020) and CARTAC G2W internal reports

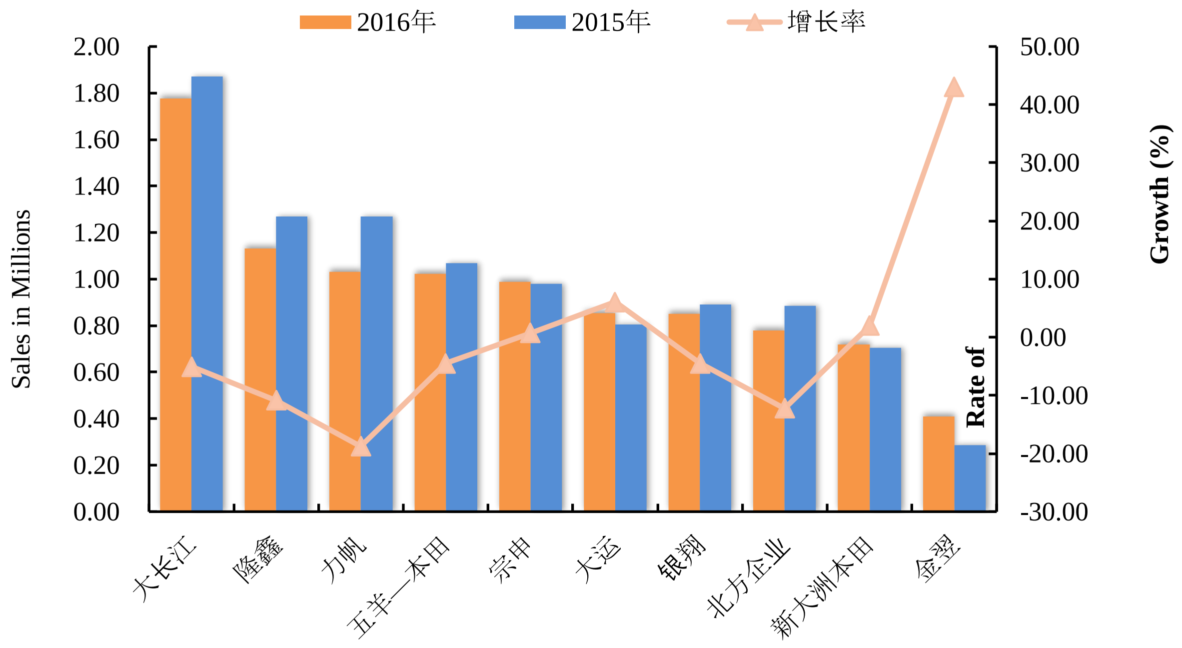

Figure 8 The top 10 gasoline motorcycle makers in 2015 and 2016.

Starting from left to right, the labels of x-axis are: Dachangjiang, Loncin, Lifan, Wuyang-Honda, Zongshen, Dayun, Yinxiang, Luoyang Northern, Xindazhou-Honda, Jinyi. Compared with 2015, except for Dayun, Xindazhou-Honda and Jinyi, sales of all other companies declined with different extents. All top ten makers take about 56.88% of total motorcycle market sales in 2016[11].

The following table gives an overall comparison of two-wheelers, including bicycles, E2Ws and G2Ws in terms of power, top speed, fuel consumption and range. Gasoline engines generally provide 10 times power compared with electric motors and the top speeds are also doubled for G2Ws compared with E2Ws. In terms of fuel economy, E2Ws normally consumes 1.5 kWh per 100km, which is equivalent to 0.16 Liter gasoline. Therefore, the fuel consumption rate for G2Ws is about 12~19 times of the fuel consumption rate for E2Ws. G2Ws can provide 120-200 km ranges which is about 4-5 times of the range that E2Ws can provide.

Table 4 Attributes comparison of two-wheelers in terms of power, top speed, fuel consumption and range.

Classification	**Types**	**Power (engine size, kW)**	**Top speed (km/h)**	**Fuel consumption (L/100 km or kWh/100km)**	**Range(km)**

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[11] The data is from the CARTAC G2W internal confidential report.

Bicycle	Human-powered	None	10-15	None	None
E2W	Electric bicycle	0.25-0.35	20-30	1.2-1.5	30-40
	Electric scooter	0.3-0.5	30-40	1.5	30-40
G2W	Gasoline scooter	3-5 (equivalent to 50-125 cc)	50-80	2-3	120-200
	Gasoline motorcycle	4-6 (100-125cc)	60-80	2-3	120-200

2.2.3 Chinese rural vehicles

Chinese Rural Vehicles (CRVs) provide a cheap means of freight and agricultural transport and play a pivotal role in the economic development of China's rural regions. Figure 9 illustrates the sales number of Chinese Rural Vehicles (CRVs) from 2004 to 2016, including both 4-wheel CRVs and 3-W CRVs. From 2004 to 2013, the sales of CRVs steadily increased. After that, CRV sales kept stable and in 2016, the sales reached 3 million. Sales of 4W CRVs were very stable and around 500 thousand units per year, while the sales of 3W CRVs generally kept increasing from 2005 to 2016. The sales number before 2004 is not available publicly now but several papers discussed the sales pattern before 2004. The market for CRVs reached its glory day in 1999 when the sales of CRVs reached 3.2 million (Sperling et al., 2004; Teter, 2011). This peak came shortly after the central government passed the first technical and safety standards for CRVs in 2004.

On May 1st, 2004, the *National People's Congress* passed *the Road Traffic Safety Law* (GB 7258-2004). This shifted the management, regulation, and enforcement of CRV-related rules from the *Agricultural Machinery Departments* to the *Departments of Public Safety* at all levels of government. One month later, the *National Development of Reform Commission* released the *Policy for the Development of the Automobile Industry*, which initiative formally reclassified CRVs as a class of automotive vehicles and integrated the entire CRV industry into the rest of the automobile industry. This new legislation resulted in a sharp increase in fees and taxes (Teter, 2011).

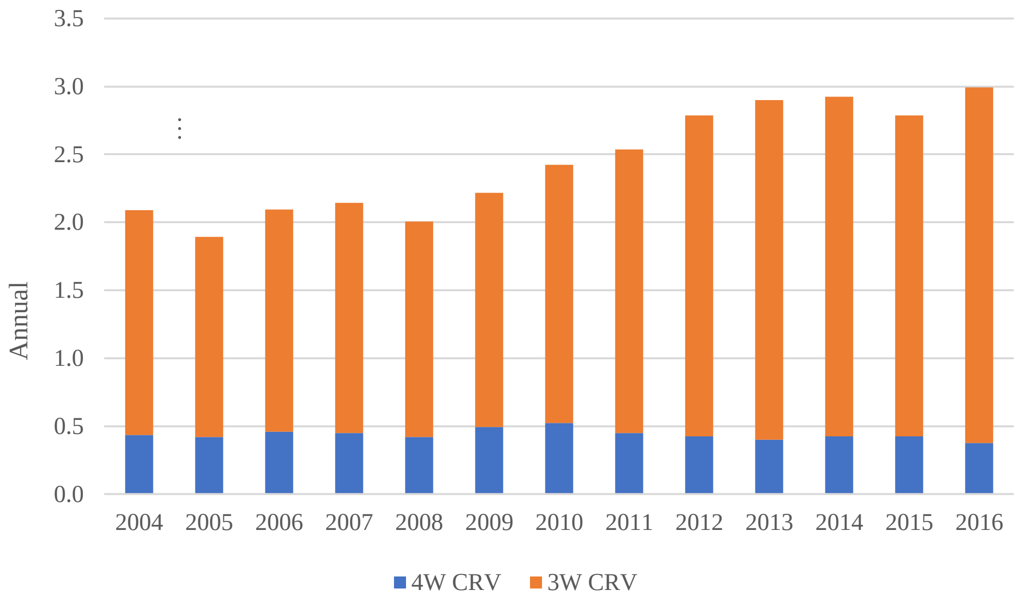

Figure 9 Sales of Chinese Rural Vehicles from 2004 to 2016*.*

Data sources include China Automotive Industry Yearbook 2004-2016; 2020 China's Auto Market Almanac

The following table includes the comparison of 3W CRVs and 4W CRVs (both low-end and upscale ones) in terms of vehicle dimensions, engine types, cylinders, fuel consumption rate, curb weight and payload, speed, and price. I compared 3RVs and 4RVs in terms of vehicle dimensions, engine types, cylinders, engine power, fuel consumption rate, curb weight, payload, performance, and price. 3RVs, which is more popular than 4RVs, is smaller in vehicle size/weight/max speed and engine size, resulting in lower fuel consumption rate and lower MSRP. Back to 2002, about 80% of the 22 million CRVs are powered by single-cylinder diesel engines originally designed for stationary agricultural machinery (Sperling et al., 2004). Similar data is not available for current CRV markets but as far as the author's knowledge, most 3W RVs and low-end 4W RVs are still equipped with single-cylinder engines, which are very inefficient and less expensive, and produce large amounts of pollutants and GHG emissions compared with four-cylinder diesel engines.

Table 5 Chinese Rural Vehicle Attribute Comparison.

Source: summarized from various online websites such as vehicle retail categories on taobao.com and jd.com.

Classification	3W RV	4W RV	
Types	-	Low-end	Upscale
Vehicle dimensions (m)	3.55 x 1.22 x 1.38	4.1 x 1.5 x 1.7	5.39 x 1.76 x 2.27
Engine	Single cylinder, diesel, 4 gears	Single cylinder, diesel, 1360 cc	485 four-cylinder, diesel, 2156 cc
Rated fuel consumption (l/100km)	6	8.42	9.5
Engine power (kW)	NA	22-30	30
Curb weight (kg)	NA	1,800	2,050
Rated payload (kg)	1,000	1,500	3,000
Max speed (km/h)	NA	60	80
Price (RMB)	10,000	26,000	60,000 – 85,000

The development of CRV industries seems to be leading to electrification of rural transport, but without the support of national policymakers. Around 2005, simple 3-wheel electric motor-carts began appearing in the Chinese rural areas. At the same time, electric 2-wheelers were expanding primarily in eastern cities but to a lesser extent in rural areas. These 3-wheel electric motor-carts played a similar role as the 3-wheel CRVs such as transporting produce to households and local markets. According to Teter’s master thesis in 2011, while they do not match 3-wheel CRVs in terms of horsepower, durability, maneuverability, and ease of repair, 3-wheel electric motor-carts do provide short-distance passenger and cargo transport and can be used for farm field operations (Teter, 2011). Many CRV owners consider them a viable and affordable replacement for aging low-horsepower 3-wheel CRVs. As shown in Figure 10, the electric motor-carts’ outlook is very similar to diesel 3-wheel CRVs but with different power source.

***Figure 10 Electric vehicles transformation from motor-carts to Shanzhai (knockoff) electric vehicles**.*

The electric motor-carts are developed from 3-wheel CRVs to serve as a replacement option. Later, some CRV makers began producing inexpensive, light, low-speed electric vehicles. These vehicles were called 'Shanzhai' (roughly translated as 'knockoff') vehicles (pictured on the far right). All these early-stage 'EVs' are equipped with lead-acid batteries mainly due to its low price, but also causing potential lead pollution because of improper disposal of lead-acid batteries.

2.2.4 Low-speed electric vehicles

At the same time, several CRV makers began producing inexpensive, light, low-speed electric vehicles, capable of reaching up to 50-70 km/h and around 100 km range on a single charge. The These vehicles were called 'Shanzai' (roughly translated as 'knockoff') vehicles (see Figure 10), which is a copy or imitation of some popular cars. By late 2007, Shifeng, Wuzheng, and Benma from Shandong province (the three leading manufacturers of three-wheel RVs) began marketing simple, inexpensive low-speed plug-in electric vehicles with lead-acid batteries. Sales were encouraged by prefecture-level policies exempting low-speed electric vehicles from road tolls and other yearly automotive fees and, in some cases, access to non-freeway roads without a driver's license[12].

The LSEV industry is China's bottom-up and market driven BEV industry, formed in lower tier cities. The LSEV industry started in Shandong in 2007 and began to spread to neighborhood provinces (Hebei, Henan, Jiangsu) in the following years. Figure 11 shows the diffusion of LSEV markets in China. This market was created by efforts of companies from

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[12] Prefecture-level policy summary (in Chinese) can be found in https://www.diandong.com/zixun/45533.html

different industries, including companies producing CRVs, E2Ws, gasoline motorcycles, golf carts or special purpose vehicles (sightseeing vehicles, neighborhood electric vehicles, police cruisers), and a few from traditional car industries (Wang & Kimble, 2012).

Figure 11 The diffusion of LSEV markets in China.

The initial market of LSEVs started within the Shandong province around 2007. LSEV markets then spread to neighborhood provinces such as Hebei, Henan and Jiangsu.

LSEV markets have grown rapidly even without the government's support. The vehicles have provided a low-cost mobility solution for certain groups of people in urban and rural areas. Despite the low battery range and speed, it has penetrated the market due to its mobility, affordability, space-saving size, and low operation and maintenance cost. Moreover, it attracts more elders, and residents from low-tier cities and rural areas, which accounts for a large share of population in China. According to some interviews with LSEV users, LSEVs mostly substitute for electric bikes and motorcycles.

However, the rapid growth of LSEVs has led to issues related to traffic regulations, safety, and battery pollution. There is still a big gap in studies of LSEVs in China: the identity of LSEVs is still unclear due to the lack of national and industrial standards: public policies concerning LSEVs, and regulations are lagging far behind the rapid increasing LSEV market and central/local governments have heated debates on whether to ban or regulate LSEVs.

Even without any subsidies, the LSEV market has grown faster than the traditional PEV market. As is shown in Figure 12, the sales of LSEVs in 2017 was about 1.7 million, more than double the sales of PEVs in 2017, which was around 0.777 million.

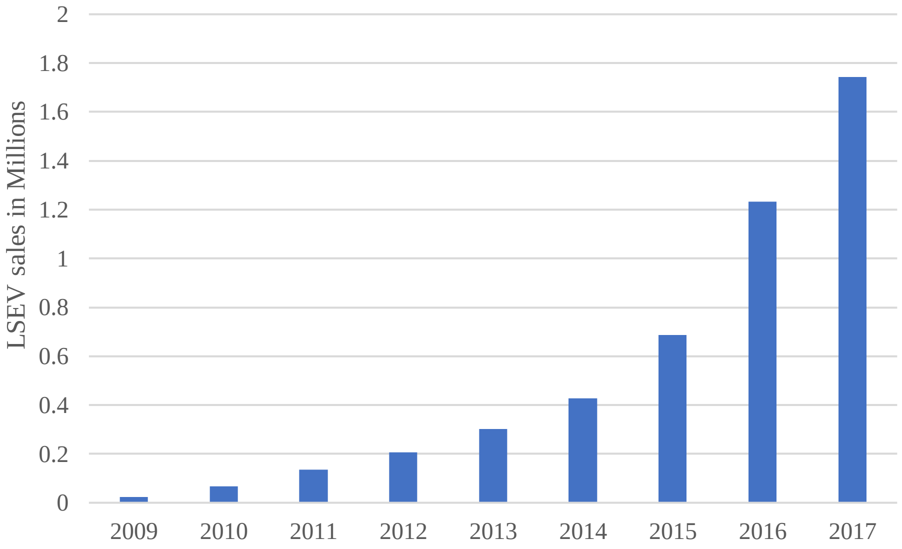

Figure 12 LSEV sales from 2009 to 2017.

Despite negligible volumes in 2009, consistent exponential growth through 2017 has led to nearly 2 million sales of LSEVs in less than a decade.

Shandong province is the largest LSEV market both in production and sales since 2008. Sales of LSEVs in Shandong province accounted for about half of the total sales in China in 2017, which was around 0.76 million units. From 2015 to 2018, the production number in each month increases except in 2018, when the Chinese government started to curb the rampant production of LSEVs by closing unlicensed manufacturers and halting construction of new factory plants. Provincial government must shut down unlicensed local LSEV makers and stop them from producing at plants of licensed automakers. Additionally, provincial governments must stop approving new plants and halt expansion of existing factories for LSEVs in areas under their jurisdiction and set a timeframe to phase out the use of LSEVs by residents through scrappage and government-sponsored buyback programs.

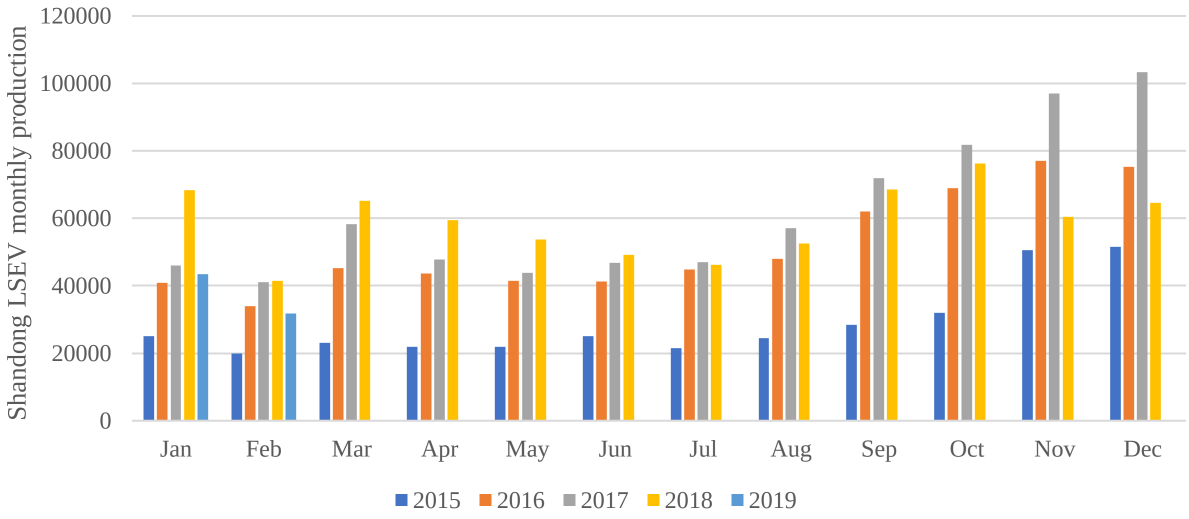

***Figure 13 Monthly production of LSEVs in Shandong Province from 2015 to Feb of 2019*.**

The production in Shandong provinces has a seasonality pattern during each year, where the production number spikes in the last few months of the year. The drop of production numbers in January and February of 2019 also indicates the large influence of the guidelines.

The following table compares the top-selling 4W LSEVs in China from January to October of 2017 in terms of prices, OEMs, dimensions, curb weight, max speed, electric range and sales number. The prices range from 19,800 to 43,800 RMB (equivalently to $2,877~$6,365 as in Aug 2020), while the average price is around 30k RMB, which is lower than the average MSRP (about 40k RMB) of low-cost internal combustion engine vehicles (ICEVs). The curb weight is below 900kg, which is much lighter than normal gasoline cars, whose weight is over 1,200 kg.

The maximum speed for LSEVs is between 35~55 km/h and the electric range is around 80~130km, which are also lower than the speed and range of PEVs.

Table 6 Top 10 best-sellers of four-wheel LSEVs in China from January to October of 2017.

Source: https://www.d1ev.com/news/shuju/58984 Note: Since the data comes from self-reporting of the LSEV makers, companies such as Shifeng didn't release their sales data to the local government. Therefore, Shifeng may have some best sellers not included in the data source. Also, low-end 3W LSEV makers does not provide reliable data for the sales of 3W LSEVs, and thus no 3W LSEVs are included in the below table.

Rank	**Model**	**OEM**	**Dimension(mm)**	**Curb weight(kg)**	**Maximum speed(km/h)**	**Electric range(km)**	**Price (Base model)**	**Sales (2017, Jan-Oct)**
1	S50	Levdeo	3426*1570*1570	756	45	100-120	39800	23402
2	Q series	Yogomo	3110*1410*1510	650	40	110	30800	22393
3	E330	Yogomo	3450*1500*1500	736	45	110-120	30800	21234
4	D70	Jinpeng	3500*1540*1520	860	47	110	33800	17128
5	V5	Lichi	3388*1542*1558	No info	55	100-130	43800	15230
6	V2	Lewei	2670*1300*1480	550	35	80	19800	12050
7	X5	Jinpeng	2722*1555*1653	680	40	100-110	20800	8235
8	YD360	Yuedi	3611*1655*1512	887	35	95	29800	7800
9	Jirui 280	Lichi	2800*1400*1520	No info	35	80	19800	7303
10	C01	Lichi	3239*1585*1541	No info	50	100-120	39800	5200

For most LSEV models, consumers can choose to upgrade their vehicles from pure electric to range-extended electric vehicles, where LSEV makers add a range extender such as a gasoline engine to LSEVs to extend their ranges. For example, YD360 has a version with both motor and a 200cc gasoline engine, where the price increases by 1,000 RMB and the range increases from 95 km to 500 km. Since air conditioners and adds-up are also optional for low-end LSEVs, consumers can purchase to add air conditioner (2,000 RMB), power steering (1,000 RMB) and alloy wheels (500 RMB). According to an interview conducted by d1ev.com[13], most LSEV purchasers are very sensitive to price, and they would rather stand high temperature in summer and coldness in winter than to spend extra money to add air conditioners to their vehicles.

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[13] https://www.sohu.com/a/207665873_114771

Three categories can be classified according to LSEVs' retail prices and product characteristics. Figure 14 shows the pictures of different LSEV models with different prices, including the knockoff "Smart Fortwo" LSEV, the golf-cart looking LSEV and the three-wheeled low-end LSEV. In

Table **7**, official micro BEVs and three types of LSEVs are compared in terms of the price, top speed, battery type, range and battery capacity, motor power and charging methods.

Compared with LSEVs, micro BEVs are more expensive before and even after government incentives. The top speed of BEVs is over 100 km/h while LSEVs can't exceed 80 km/h. Lithium-ion batteries are predominant in micro BEVs while LSEVs are mostly equipped with lead-acid batteries and a few high-end LSEVs are also equipped with lithium-ion batteries. Since lithium-ion batteries have higher energy density, micro BEVs normally have longer ranges, larger battery capacities and can therefore be equipped with electric motors with higher power. The most widely used charging method for these small electric cars is 220V home charging and it is very common to see informal "fly-line" charging with extension cords passed through windows and doors to vehicles parked at the curb (Hove & Sandalow, 2019). The comparison of the three types of LSEVs with micro BEVs can be found in

Table **7**.

Figure 14 Three types of LSEVs (Low-end, medium and high-end LSEVs).

This picture is taken by autohome.com.cn in 2015 at a low-tier city in Shandong, China. The detailed characteristic of these three types of LSEVs are described in

Table ***7****. Picture credit to https://www.autohome.com.cn/news/201502/862611.html*

Table 7 Comparison of official micro BEVs with three types of LSEVs in terms of price, top speed, battery, motor and charging methods.

Category	Price (k RMB)	Top speed (km/h)	Battery type	Battery range (km)	Battery capacity (kWh)	Motor power (kW)	Charging
Micro BEV	100~170 before incentive, 50~70 after incentive	Over 100	Lithium ion	Over 150	15	Over 30	220 V but faster charging capable
High-end LSEV	Over 40	60~80	Mostly lead-acid, a few lithium ion	100	Around 10	Over 10	220 V
Medium-end LSEV	20~40	40~60	Mostly lead-acid, a few lithium ion	80~100	6 or 7.2	4~10	220 V
Low-end LSEV	Under 20	Below 40	Lead-acid	Below 80	4.8 or 6	Around 4	220 V

To better understand how LSEVs fit into current EV market in China, Table 8 is used to compare the differences between PHEVs, BEVs and LSEVs in terms of performance, sales, price, usage, etc. PHEVs are classified into premium and mainstream and BEVs are classified into premium, mainstream and low-end. LSEVs, which are also called unofficial micro BEVs, are targeted as low-end products. Examples of models for different categories are given in the table. For PHEVs, dedicated chargers or 220V cord can be used depending on charging mode availability. For BEVs, only dedicated chargers are used except for low-end BEVs, while low-end BEVs can also use 220V charging cord. For LSEVs, only slow charging mode is used with 220V charging cord. PHEVs and LSEVs are mainly used by private owners while BEVs can be used for carsharing, fleet, taxi and rental purposes. Most of PHEVs and BEVs have high safety standards and high quality, while low-end BEVs and LSEVs have lower quality compared with other categories. Most vehicle categories are targeted at tier 1-2 cities except for low-end BEVs and LSEVs, whose targeted cities are lower tier cities and rural areas.

The biggest difference between LSEVs and other types is the lower top speed of LSEVs. Most BEV vehicle categories can receive huge amounts of incentives and PHEVs can also receive incentives based on their electric range and batteries. However, premium PHEVs can’t receive incentives due to the smaller electric range below the required range, and LSEVs can’t receive incentives since lead-acid batteries are used. For the sales in 2017 and 2018, LSEVs outsells all other vehicle categories. LSEVs are the hidden EVs in China and serves the large population with lower income, living in lower tier cities and rural areas.

Table 8 Detailed comparison between PHEV, BEV and LSEV in terms of models, charging mode, usage, safety and quality, market, speed, price and incentives, battery, sales.

Cited and adapted from (B Chen, 2018)

Vehicle group	Examples of models	Main charging mode	Clients & usages	Safety & quality	Market	Max speed (km/h)	Price before incentive (k RMB)	Price after incentive (k RMB)	Battery	Total sales 2018 Jan-Oct	Total sales 2017
Premium PHEV	BMW X5 PHEV, Audi A6 e-tron	Gasoline, dedicated charger	Private	High	Tier 1-2 cities	230	>360	-	Lithium 9-15 kWh	16,000	Very few
Mainstream PHEV	BYD Qin, Roewe eRX5	Gasoline, 220V or dedicated charger	Private	High	Tier 1-2 cities	140	>190	>160	Lithium 10-15 kWh	170,000	107,00
Premium BEV	Tesla Model S, Model X, BMW i3, Nio ES8	Dedicated charger	Private, carsharing	High	Tier 1-2 cities	225	>420	>320[14]	Lithium 30-100 kWh	8,000	15,000
Mainstream BEV	BYD e6, BYD Tang, BYD e5	Dedicated charger	Fleet, Taxi, Rental, Private	High	Tier 1-2 cities	140	200-350	100-250	Lithium 20-60 kWh	150,000	130,000
Low-end BEV (Official Micro BEV)	BAIC EC Series, Chery eQ EV, JAC iEV6E, Zoyte e200	220V, fast charging capable	Private, carsharing	Medium to Low	Low tier cities, cities with purchase restriction	100	100-170	50-90	Lithium or Lead Acid 10-30 kWh	300,000	310,000
LSEV (Unofficial Micro BEV)	Levdeo S50, Yogomo Q, Yogomo E330, Lichi V5	220V only	Private	Low to Very Low	Low tier cities, rural area, cities with purchase restriction	80	30-50	-	Lead Acid <10 kWh Very few Lithium	1,160,000	1,500,000

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[14] Imported Premium BEVs are currently not eligible for purchase subsidies and faced with custom duties

2.3 Related policies

China central and local governments have released many policies and regulations to support or imped the development of LSVs. In order to better understand the market dynamics, it is very essential to discuss the related policies that regulate the LSV markets and qualitatively evaluate the impact. Therefore, an overview of recent LSV policies from local and central governments is summarized as below in Table 9. The detailed discussions can be found in following sub-sections.

Table 9 Overview of recent E2W, G2W, CRV and LSEV policies.

Category	City	Date	Name of Regulations	Main Contents
E2W	National	1999	National Standard for E2Ws (GB17761-1999)	Set to establish performance limits for E2Ws with respect to speed, weight, power.
CRV	National	2004	The Automobile Industry Development Policy and Road Traffic Safety Law (GB1589-2004)	The policies integrated CRVs into the conventional auto industry. This means a sharp increase in fees, taxes, and stricter standard requirement.
E2W	Local	1996-2008	Local policy difference: City-level E2W ban and promote, and finally reversed ban	Shanghai promoted E2Ws from 1996 to combat poor air quality and high motorized vehicle use. For example, Beijing originally banned E2W from on-road due to safety and negative effects on traffic, but gradually reverse E2W ban.
G2W	City-level	2004-present	Motorcycle Ban in over 200 cities	Big cities such as Beijing, Shanghai, Guangzhou, Shenzhen (北上广深), motorcycles are banned from use in city area by limiting license plates (Shanghai) or directly banning from driving on-road.
CRV	National	2007	Emission Standards (GB19756-2005)	Require CRV makers to register all models they produce. For the first time, 2007 emission standards mandate binding limits on HC, CO, NOx, and PM emissions of new CRVs.
LSEV	National	July, 2015	Provisions on the Administration of Newly Established Pure Electric Passenger Vehicle Enterprises	Set the standards for LSEV companies to upgrade to NEV companies
LSEV	National	Oct, 2016	“Upgrade a batch, regulate a batch and eliminate a batch” Announcements	Upgrading qualified low-speed electric vehicle manufacturers to battery electric passenger vehicle companies, standardizing technical standards, market entry, regulatory system and administration for low-speed electric vehicles, eliminating unqualified companies and their products.
LSEV	Shandong	March, 2017	Shandong’s Thirteen’s Five-year Plan for Emerging Industries’ Development and Planning	License plates and insurances of LSEVs should be regulated. LSEVs should be a safer, more convenient, lower-cost and more appropriate technology.
E2W	National	May, 2018	New National Standard for E2Ws (GB17761-2018)	Clearly classified electric bicycle, electric scooter and electric motorcycle by speed, weight, pedal requirements.

G2W	National	Jul, 2018	Motorcycle National Emission Standard (China Stage IV) (GB14622-2016)	New motorcycle models must be equipped with EFI system to reduce emission and pollution and increase fuel efficiency.
LSEV	National	Nov, 2018	Announcements on Further Regulating Low-speed EV industry and Curbing New Capacity	Provincial governments are required to carry out a thorough investigation of enterprises engaged in the manufacturing of low-speed EVs in their regions and shut down unlicensed local low-speed EV makers. New capacity related to production of such vehicles will not be approved. Applications for market entry of new models will not be approved under the new regulations.

2.3.1 E2W policies

In 1999, the earliest national standards for E2Ws (GB17761-1999) were released to set the performance limits for E2Ws with respect to speed, weight and power. At the same time, several local E2W related policies were released from 1996 to 2008. Some cities banned E2W usage due to the concerns regarding traffic safety while other cities promoted the development of E2Ws. Shanghai promoted E2Ws from 1996 to combat poor air quality and high motorized vehicle use, while Beijing originally banned from on-road use due to safety and negative effects on traffic, but gradually reverse E2W ban. In May of 2018, the new national standards for E2Ws (GB17761-2018) were released and clearly classified two-wheelers into electric bicycles, electric scooters and electric motorcycles by speed, curb weight, battery/motor and pedal requirement.

2.3.2 G2W policies

From 2004, over 200 cities have announced motorcycle bans. Big cities such as Beijing, Shanghai, Guangzhou, Shenzhen have effectively limited motorcycles from use within their respective cities by limiting license plates (Shanghai) or directly banning from driving on-road. In July of 2018, motorcycle national emission standards (China stage IV) (GB14622-2016) were released to require that new motorcycle models must be equipped with the electronic fuel injection (EFI) system to reduce emission and pollution and increase fuel efficiency (Ministry of Ecology and Environment, 2018).

2.3.3 CRV policies

In 2004, the Automobile Industry Development Policy and Road Traffic Safety Law (GB1589-2004) was released (National Automotive Standardization Technical Committee, 2004). The policies integrated CRVs into the conventional auto industry, leading to a sharp increase in fees, taxes, and stricter standard requirement for CRVs. In 2007, new emission standards for CRVs were released, requiring these vehicles to follow binding limits on HC, CO, NO_x, and PM emissions and manufacturers to register all models they produced (Ministry of Ecology and Environment of the People's Republic of China, 2006).

2.3.4 LSEV policies

The central government encouraged the provincial industrial associations to enact their own local LSEV policies first as early as in 2011 (Ou et al., 2017) without giving any guidelines or instructions. From 2011, Shandong, Fujian, Jiangsu, Zhejiang provinces and Luoyang, Zhumadian, Xingtai, Loudi, Foshan, Xiangyang, Gaoyang, Bijie, Hechi cities released local temporary policies regulating LSEVs. These policies primarily include conditions of manufacturing, product standards, allowable travel areas, registration and license requirement, vehicle insurances and accident liability (F. Zhao et al., 2017). The provincial government has created "temporary" local policies and regulations to promote the development, which include tax rebates, funding of LSEV R&D, permission to drive LSEVs on roads, and toll waivers for LSEV owners (Wang & Kimble, 2012).

On July 10th of 2015, the *Provisions on the Administration of Newly Established Pure Electric Passenger Vehicle Enterprises* proposed by State Development & Reform Commission (SDRC) and Ministry of Industry & Information Technology (MIIT) came into effective. LSEV industries which satisfy the requirements of pure electric passenger vehicle enterprises can be upgraded to new energy vehicle (NEV) enterprises and manufacture NEVs. NEV companies, such as Zhidou, Yogomo, Benma, and Green Wheel, used to be LSEV companies.

In 2016, the Chinese central government announced the first official guideline for LSEV industries, which is to "upgrade a batch, regulate a batch and eliminate a batch"[15]. Upgrading a batch means upgrading qualified low-speed electric vehicle manufacturers to battery electric passenger vehicle companies; Regulating a batch means standardizing technical standards, market entry and administration for low-speed electric vehicles; Eliminating a batch means eliminating unqualified companies and their products. However, the guidelines only worked as directional suggestions but not legislations.

In November of 2018, the Chinese government moved to curb the rampant production of LSEVs by closing unlicensed manufacturers and halting construction of new plants. Provincial governments must shut down unlicensed local LSEV makers and stop them from producing at plants of licensed automakers. Additionally, provincial governments must stop approving new plants and halt expansion of existing factories for LSEVs in areas under their jurisdiction and set a timeline to phase out the use of LSEVs by residents through scrappage and government-sponsored buyback programs.

LSVs, including electrified/gasoline 2Ws, rural vehicles and LSEVs, experienced extraordinary growth in the last two decades to the present due to factors such as technical, policy, economic factors. Current market status such as sales and populations, vehicle characteristics and policies are discussed in this chapter. There are a variety of policy impacts for different types of LSVs.

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[15] https://news.cnstock.com/industry,rdjj-201610-3923537.htm

E2Ws are being both promoted and banned in different cities across China. While some support E2W since they are a cleaner and more affordable transportation tool compared with gasoline motorcycles and cars, and provide better accessibility compared with bicycles. Others argue that E2Ws create chaos on the road when mixing with cars and bicycles. National E2W standards that classify electric bicycles and scooters more explicitly provide guidelines for manufacturers to produce E2Ws that are safer both to E2W riders and other vehicle users on the road.

The sharp rise in motorcycle ownership and usage in China has created challenges such as high frequency of motorcycle-related accidents and fatalities; increasing motorcycle-related pollution and congestion; and motorcycle snatch theft and robbery (Guo et al., 2020). In order to address these challenges, policymakers in China have introduced "motorcycle restriction policies", including stopping new motorcycle license issuance, banning motorcycles from main streets, banning motorcycles from the central business district (CBD), banning non-local licensed motorcycles, etc. (Guo et al., 2020) By 2019, more than 190 cities in China have implemented at least one type of motorcycle restriction policy[16]. In response, sales and production of gasoline motorcycles dropped significantly in recent years. Motorcycles are yet still popular in rural and suburban areas due to less strict regulations and better accessibility.

The CRV industry experienced rapid growth around 2000 but started to slow down after the new policy was released in 2004 to integrate CRVs into the auto industry, which means a sharp increase in both fees and taxes, and harsher standards. Since the main users are rural residents who use CRVs for farm production and cargo transportation, their replacement options are very limited due to the specialization of their use. The current CRV policy also requires

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[16] http://www.chmotor.cn/sidelight_detail.php?id=46119 (in Chinese)

lower emission and pollution rates for their diesel engines. Therefore, gasoline trucks or LSEVs with better cargo capacity and higher torques could be good alternatives.

Local governments have provided multiple policies to promote the development of LSEVs. The reasons for the huge supports from local governments include GDP growth, job opportunities and technological transformation. However, since there are no requirements or standards for LSEV manufacturing and drivers' licenses, many accidents and causalities happened involving LSEVs[17]. The central government thinks more differently from the perspectives of regulators and gives guidelines to curb the rampant production of LSEVs and regulate LSEV industries by drafting the national standards for LSEVs, yet the policymaking has been undergoing for over four years and still no national standards have been released.

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[17] https://www.sohu.com/a/277069566_99957909 (in Chinese)

CHAPTER 3 VEHICLE TRAVEL INTENSITY ANALYSIS

Vehicle travel intensity (kilometers traveled per vehicle per year or VKT) is very important because it directly impacts the vehicle cost ownership, vehicle fuel use, and emissions. An understanding of VKT in China across various vehicle modes could substantially improve the estimation accuracy of fuel use and carbon emissions, and thus guide appropriate energy and emission policies. However, the level of understanding of China’s VKT is poor mainly due to the lack of data. Unlike many developed countries that release their vehicle-use data on a routine basis, China does not officially publish VKT data (Huo, Zhang, He, Yao, & Wang, 2012). To better understand the VKT status, studies of vehicle travel intensities for normal-speed vehicle types such as light-duty vehicles (LDVs), buses, trucks have been conducted in different cities in China.

In this chapter, I made a comprehensive comparison of VKTs for different vehicle types from existing studies. For LSVs such as E2Ws, G2Ws and RVs, I summarized the VKT findings from different literatures and made reasonable assumptions. For LSEVs, I analyzed collected GPS data and calculated VKT numbers. Following table summarized the VKT findings and the related data sources.

Table 10 Comparison of AVKTs for different vehicle types.

Based on multiple sources and our analysis, the annual VKT are compared below. The lower bound and high bound of AVKT are obtained for sensitivity analysis in the next chapter.

Modes	Mean AVKT	Lower bound	Higher bound	Source
Bike	2500	2000	3000	Author’s estimation
E2W	3500	3000	4000	(C. R. Cherry, Weinert, & Xinmiao, 2009; C Cherry, 2007; Ling et al., 2019)
Electric scooter	4000	3500	4500	(C. R. Cherry et al., 2009; C Cherry,

				2007; Ling et al., 2019)
Gasoline scooter	7000	4000	10000	(Huo et al., 2012)
Gasoline motorcycle	7000	4000	10000	(Huo et al., 2012)
E3W	5000	4500	5500	Author’s estimation from E2W
G3W	8000	5000	11000	Author’s estimation from G2W
3RV	17750	12100	23400	(Huo et al., 2012)
Low-end 4RV	22400	15400	29400	(Huo et al., 2012)
High-end 4RV	22400	15400	29400	(Huo et al., 2012)
LSEV	8750	3500	14000	Author’s data exploration
Micro BEV	8750	3500	14000	Assume Micro BEV drivers share similar driving profile with LSEVs’
Compact BEV	12500	10000	15000	(Hou, Wang, & Ouyang, 2013)
Micro gasoline car	12500	10000	15000	(Hou et al., 2013)
Compact gasoline car	12500	10000	15000	(Hou et al., 2013)

3.1 Overview of existing studies

Huo et al. (2012) collected VKT survey data in China from sources such as governments and survey agencies and conducted additional surveys during 2004 and 2010 in different cities such as Beijing, Chengdu, Foshan, Yichang, Tianjin, etc., and for different vehicle types including light-duty passenger vehicles (such as private light-duty vehicles and taxis), buses, trucks (Huo et al., 2012). Hou et al. (2013) carried out a comprehensive survey in Beijing in 2009 and collected over 500 questionnaires, and they found out that the average DVKT of the private passenger vehicle in Beijing was 46.35 km, and 68.2% of the travels were within 50 km while only 9.1% were longer than 100 km (Hou et al., 2013). However, there is a still big gap for understanding the vehicle travel intensity for low-speed vehicles (LSVs) in China due to limited data and research interests. In order to comprehensively evaluate the vehicle fuel use and emission in China, it is very essential to study the vehicle travel intensity for LSVs.

Since Motorcycles (MCs) are not suitable for long-distance travel, their VKT is usually low (Huo et al., 2012). Internationally, the VKT for MCs varies from 1700 km in France; to 3000-4000 km in the United States, Mexico, and Germany; to 6700 km in the United States during the 1990s; The VKTs for 2018 and 2019 in the United States are 3729 km and 3685 km, respectively (U.S. Federal Highway Administration, 2019). In China, survey studies have also shown a large variation in VKT for Chinese MCs, ranging from 4000 to 10,000 km (Huo et al., 2012). MCs use-intensity has shown to be stable in the US and from the author's perspective, MCs' use-intensity in China will also be stable and ranging from 4000 to 10,000 km per year for different cities and different ages of MCs.

For rural vehicles (RVs), they have low engine power and speed, yet their VKT levels could be high because they can be used intensively for moving goods such as farm products. Since RVs do not usually have mileage meters installed, it is very difficult to collect VKT data on RVs in China. Surveys conducted in 2011 (Huo et al., 2012) show that 3RVs travel 21,000 km/year and 4RVs travel 28,000 km/year, which are close to the findings of the National Pollutants Survey (25,000 km for 3RVs and 28,000 km for 4RVs). However, the VKT for RVs is still not well studied and these data, although limited, can provide some helpful information about the characteristics of VKT and help understand the energy use and emissions caused by RVs.

Compared with MCs and RVs, e-bikes draw more attention from academia both domestically and internationally. Earlier surveys conducted in Kunming and Shanghai show that the average VKT for e-bikes is 2454 km per year (Cherry 2007). Another survey conducted in Shijiazhuang shows that e-bike riders averagely ride 5.8 km/trip and make 2-4 trips per day (Weinert 2007). If we assume that they travel 260 days in a year, the VKT will be 3016-6032 km per year. The lower bound of the VKT range in Shijiazhuang is close to the average VKT obtained from Kunming and Shanghai, while the upper bound is much higher, which might be due to the different travel behaviors in different cities.

Research on Chinese LSEVs is limited, and there are no quantitative studies that have been conducted on LSEVs vehicle use intensity. Wang and Kimble (2012) discussed the emerging market for LSEVs in China and examines the various constraints and challenges it faces. They also conducted qualitative analysis with three scenarios that the central government limits, supports or wait for the market to evolve itself to understand the future development of the LSEV market in China. However, there is no travel behavior, cost or energy/emission analysis conducted. Fang & Zhu (2015) from CARTAC (China Automotive Technology and Research Center) discussed the challenges and proposed policy suggestions regarding the rapidly emerging LSEV products.

However, no studies on travel behaviors are conducted. Chen (2018) conducted 5 field research between April 2013 and January 2016 to understand the electric vehicle strategies for foreign OEMs in China. They interviewed 17 EV dealerships, including both LSEV and official micro-BEV dealerships, about the dealership general information, customer profile, usage, product, services and legal issues in Weifang, Shandong province, and found that LSEV users are mostly men over 45 years old and the main purposes are to send kids to school, shopping, leisure and drunk driving since they don’t need driver licenses and comply with traffic regulations when on road. Another finding is that 90% of owners already have a gasoline car in their family and LSEVs work as their 2nd family car. For vehicle travel intensity, LSEV users travel about 30 km/day while official micro-BEV users travel about 60 km/day. Ling et al. (2019) have relied on structured interviews to explore initial light on motives for LSEVs’ choice and purchase, model choice, travel behavior, and safety. In-depth interviews with 34 LSEV owners in Kunming, China reveal an owner profile that is predominately retired male with high household income, less than half of users with a driver license, and their purchase motives are mostly driven by their age or physical limitations, the convenience and low cost of the vehicle and charging, and the vehicles' low speed. Their limited interviews show that the average VKT per year is about 6000 km. Assuming the drivers travel for 260 days per year, the DVKT is about 23 km/day. However, due to the small sample size and limited scope of the interviews, the vehicle travel intensity has not been comprehensively studied for different cities and different regions (both urban, suburban and rural areas).

3.2 LSEV data

3.2.1 Data acquisition and source

LSEVs are quite popular in China yet lacking in research, especially on LSEV drivers' travel behaviors. In order to better understand the travel behaviors of LSEVs, I collaborated with a Chinese local LSEV manufacturer called LEVDEO and obtained historical GPS data of 539 LSEVs all over China. Shandong LEVDEO Automobile Co., Ltd. is in Weifang, Shandong Province and was founded in 2008 to be a low-speed electric vehicle company. It has over 6 low-speed electric vehicle models including S50, D80 and so on by 2018. In 2018, LEVDEO acquired Shaanxi Qinxing Automobile Co. Ltd., obtained the qualification of new energy commercial vehicles and special vehicles, and created western China production base–LEVDEO-Qinxing. In 2019, LEVDEO acquired YEMA Auto to produce low-end gasoline cars, targeting the young generations in third and fourth tier cities.

The GPS data is collected from vehicle onboard devices and records vehicle daily travel data at the second-by-second time resolution and includes datetime, vehicle travel speed, travel distance, longitude and latitude, vehicle status, vehicle identification number. I have collected data of 539 LSEVs for consecutive seven days both in 2019 and 2020 in order to see any time disparity between weekdays and weekend, pre-COVID and COVID periods. It is found that there are 361 vehicles operating for the week I collected data from, and about 34% of the LSEVs are idling or not operating in 2019, while there are only 7% of the LSEVs still operating in 2020.

Due to the limitation of the small sample size given the huge variation in vehicle types, demographics and geography, the results might be biased. According to Chapter 2, there are mainly three types of LSEVs, which include low-end, medium-end and high-end, while Levdeo only produces medium and high-end products whose price ranges from 30k to 70k RMB. Most of the Levdeo LSEV users are in Shandong and its neighborhood provinces, while there are vehicles located as north as in Heilongjiang and as south as in Yunnan. Therefore, there will be bias due to the model variation and geography.

Data summary:

Our collected dataset includes about 7.4M data records with 13 features in 2019 before COVID-19 and 0.75M data records in 2020 during COVID-19. A comprehensive explanation of the 13 features and summary statistics of the data are shown as below.

Explanation of features:

- c: the angle that the vehicle is pointing to
- datetime: the date and time when that row of data is recorded
- distance (m): the travel distance from previous row to current row
- i: file name of icon (this is irrelevant to our study)

- id: the unique id of each data row
- lat: the current latitude of the vehicle at the timestamp (datetime)
- lng: the current longitude of the vehicle at the timestamp (datetime)
- olat: the original latitude at last timestamp (datetime)
- olng: the original longitude at last timestamp (datetime)
- s (km/h): the real-time travel speed
- stop: indicator variable, 0 means the vehicle is moving and 1 means the vehicle is sitting idle.
- sn: the vehicle identification number

Table 11 Summary of 2019 and 2020 datasets.

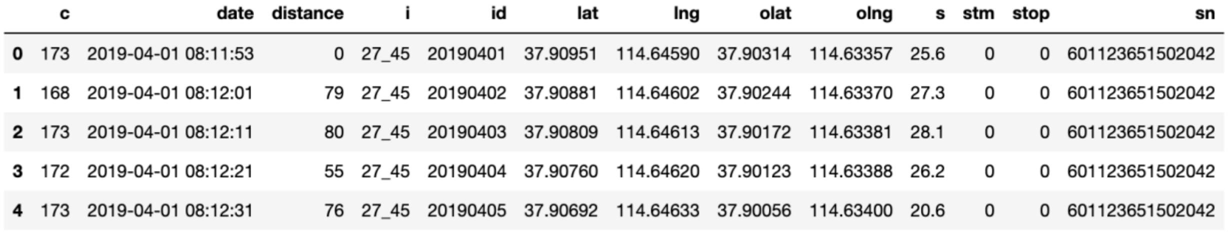
Date	**Cars in operation**	**Number of Observations**	**Average speed (km/h)**	**Location bounding with lower left and upper right GPS coordinates**
4/1/19-4/7/19	69%	7.44M	25.53	[25.34N, 100.42E] in Yunnan -> [46.83N, 130.35E] in Heilongjiang
4/1/20-4/7/20	7%	755k	24.76	[26.76N, 104.29E] in Guizhou -> [40.88N, 122.74E] in Liaoning

From the above table, it is observed that for the same 539 LSEVs, over 60% of vehicles stop operating from pre-COVID to COVID periods. There are two potential reasons: 1) Residents are required to stay at home and minimize unessential trips by the Chinese central and local governments due to the widespread of COVID-19 2) unlawful LSEVs are restricted to be used especially in urban areas. The average travel speed is about 25 km/h, which is similar to the speed obtained from surveys and interviews. This LSEV product from Shandong is sold to the most northern province Heilongjiang and very southern province Yunnan, which implied the quick diffusion of LSEV markets.

3.2.2 Feature engineering

To better understand the travel behaviors, feature engineering techniques are applied to the datasets to create new features, remove wrong data or outliers. Newly created features and following data processing steps are explained below. The below table shows some examples of the raw data and cleaned data. After cleaning and feature engineering, we add features such as day of week, hour of day, minute of hour, etc.

Table 12 Raw data and clean data examples



	c	date	distance	i	id	lat	lng	olat	olng	s	stm	stop	sn
0	173	2019-04-01 08:11:53	0	27_45	20190401	37.90951	114.64590	37.90314	114.63357	25.6	0	0	601123651502042
1	168	2019-04-01 08:12:01	79	27_45	20190402	37.90881	114.64602	37.90244	114.63370	27.3	0	0	601123651502042
2	173	2019-04-01 08:12:11	80	27_45	20190403	37.90809	114.64613	37.90172	114.63381	28.1	0	0	601123651502042
3	172	2019-04-01 08:12:21	55	27_45	20190404	37.90760	114.64620	37.90123	114.63388	26.2	0	0	601123651502042
4	173	2019-04-01 08:12:31	76	27_45	20190405	37.90692	114.64633	37.90056	114.63400	20.6	0	0	601123651502042

c	date	distance	i	id	lat	lng	olat	olng	s	stm	stop	sn	dayofweek	day	hour	minute	second
173	2019-04-01 08:11:53	0	27_45	20190401	37.90951	114.64590	37.90314	114.63357	25.6	0	0	601123651502042	Mon	1	8	11	53
251	2019-04-01 08:13:51	1	27_270	20190413	37.90509	114.64460	37.89870	114.63229	2.6	0	0	601123651502042	Mon	1	8	13	51
169	2019-04-01 08:14:11	23	27_45	20190415	37.90481	114.64459	37.89843	114.63228	11.4	0	0	601123651502042	Mon	1	8	14	11
63	2019-04-01 08:15:31	21	27_45	20190423	37.90508	114.65043	37.89877	114.63808	2.7	0	0	601123651502042	Mon	1	8	15	31
354	2019-04-01 08:18:21	4	27_0	20190439	37.91419	114.64914	37.90787	114.63679	13.1	0	0	601123651502042	Mon	1	8	18	21

Our dataset mainly contains temporal variables, geospatial variables and variables that describe the vehicle status such as travel speed/distance, vehicle state, etc. Temporal variables include the day of week, weekday or weekend, and the time at hourly, minute and second resolution that the data was recorded. Geospatial variables include the latitude and longitude of the vehicle's real-time positions. Additional variables include vehicle speed, vehicle distance traveled between two timestamps and vehicle state which can be either moving or idling.

Due to common GPS errors such as internet disconnection and signal interference, there are some data errors such as very high speed or distance that will need to be pre-processed before diving deep into the data. Based on different filters below, the data is cleaned and processed.

- **Speed:** Even though I don't know exactly the vehicle model for specific vehicle, I do know all these vehicles are low-speed electric vehicles with maximum speed around 120 km/h. In this case, all data records that have a speed over 120 km/h can be regarded as outliers, which might be caused by device failures or systematic errors.
- **Distance:** Since the distance recorded for each row is the distance from last timestamp to current timestamp (which is in seconds), the distance between these two timestamps shouldn't exceed 35 m (120/3.6=35m)
- **Vehicle State:** A binary variable called "stop" indicate the vehicle state that whether the vehicle is moving or not. Therefore, distance and speed should be zero when the vehicle is not moving.

The GPS location data is visualized and from the below heatmap, it is observed that while most of the LSEVs are in Shandong, Hebei, Henan provinces, there are also vehicles located as north as in Heilongjiang and as south as in Yunnan. Since Levdeo, the LSEV maker, is in Shandong, the main markets of Levdeo are also in Shandong province and its neighboring provinces. Most of the LSEVs are in either rural areas or low-tier cities according to previous surveys and studies (Bo Chen & Midler, 2016a; Wang & Kimble, 2012). It should also be noted that our data can only represent the geolocation distribution of LSEVs manufactured by Levdeo but cannot represent the distribution of whole population of LSEVs, thus creating selection bias due to limited data sources.

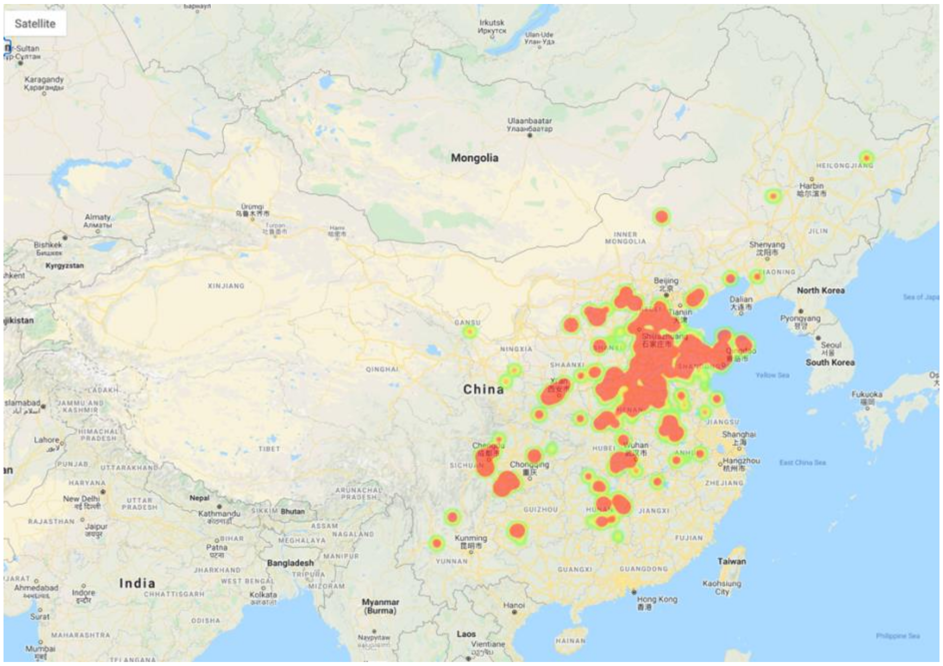


Figure 15 Geolocation heatmap of LSEVs for Levdeo

3.3 Analysis of LSEV behaviors

Daily vehicle kilometer traveled (DVKTs) are compared for weekdays and weekends in 2019 to understand the different travel patterns. Summary statistics such as mean, median and skewness are in the caption description. There are several findings: Most LSEV users travel around 20 km/day on both weekdays and weekends, which is very close to the DVKT values obtained from previous interviews listed below. According to Chen's dealership surveys, the DVKT for LSEVs is about 30 km/day (B Chen, 2018). From Ling's interviews, the AVKT is around 6000 (Ling et al., 2019), which can be translated to about 23 km/day if we assume LSEV drivers travel 260 days per year. It is also found that LSEVs travel longer distances on weekends than on weekdays. The longest daily distance traveled is over 150km on weekends compared with 80km on weekdays.

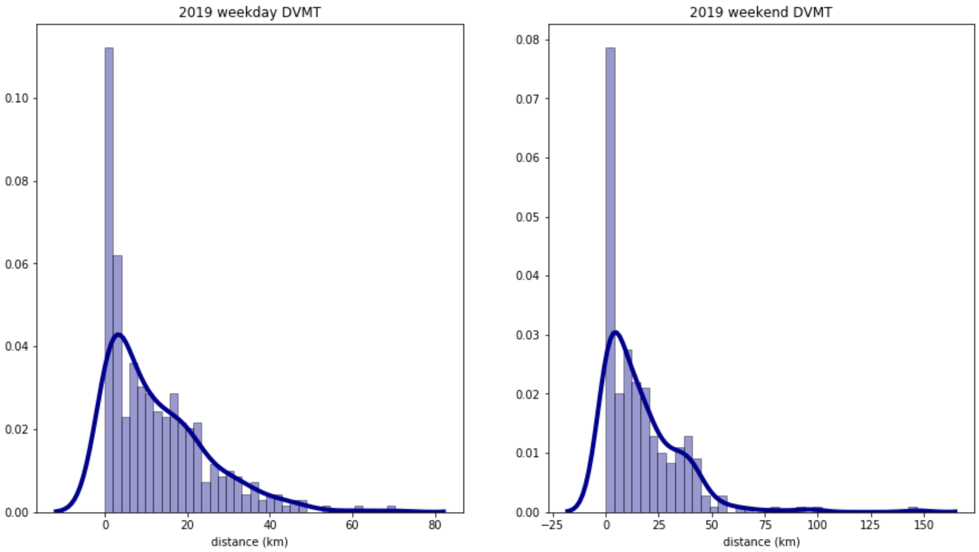


Figure 16 Histogram and density plot of average DVMT for weekdays and weekends in 2019.

Left plot: Weekday DVMT distribution (mean = 12.53 km, median = 9.35 km, standard deviation = 12.1 km, skewness = 1.32 (indicate the distribution is left skewed), # of observations = 356). Right plot: Weekend DVMT distribution (mean = 16.79 km, median = 11.76 km, standard deviation = 18.47 km, skewness = 2.41 (indicate the distribution is also left skewed), # of observations = 268). The total population of the sample is 539 and the time duration is from 4/1/2019 to 4/7/2019. The longest daily travel distance among these vehicles in weekdays is about 80 km and in weekends is about 150 km, while most of the vehicles travel under 20 km daily. LSEVs travel longer trips on weekends than on weekdays.

I perform a Kolmogorov-Smirnov test to determine whether the distributions for weekdays and weekends are statistically different. Kolmogorov-Smirnov test (KS test) is a nonparametric test of the equality of continuous, one-dimensional probability distributions that can be used to compare two samples by quantifying the statistic of a distance between the two empirical distribution function of samples (Massey, 1951). The KS test result shows the statistic is 0.118 and p-value is 0.025, which means we are over 95% confident that these two distributions are significantly different and LSEV drivers have driven differently on weekdays compared to weekends, which is consistent with previous studies that point out that commuting is one of the main travel purposes(Chen and Midler 2016; Fang and Zhu 2015).

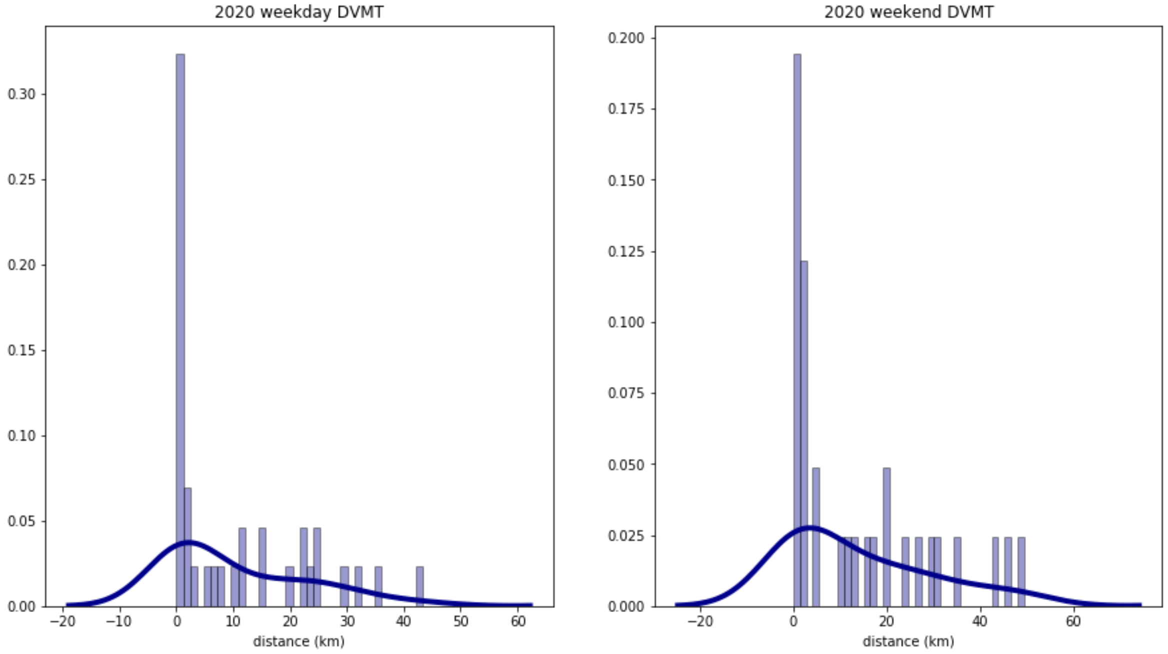


Figure 17 Histogram and density plot of average DVMT for weekdays and weekends in 2020.

Left plot: Weekday DVMT distribution (mean = 10.42 km, median = 4.04 km, standard deviation = 12.21 km, skewness = 1.05 (indicate the distribution is left skewed), # of observations = 36). Right plot: Weekend DVMT distribution (mean = 13.85 km, median = 7.26 km, standard deviation = 15.4 km, skewness = 0.99 (indicate the distribution is left skewed), # of observations = 30). The total population of the sample is 539, and the time duration is from 4/1/2020 to 4/7/2020. The longest daily travel distance among these vehicles in both weekdays and weekends is around 40 km, while most of the vehicles travel under 20 km daily.

I collected the GPS data for the same time period in 2020 for these 539 LSEVs to compare the travel behavior changes. The first finding is that there are only 36 LSEVs still operating in 2020. Two possible reasons for the significant decline of LSEV usage are the COVID-19 and stricter regulations on LSEV operations. Due to the stay-at-home order to prevent the widespread of COVID-19 in China, people were advised to reduce their unnecessary travel. Another reason is that the central and local governments also implemented stricter regulations to curb the production, sale and use of illegal LSEVs due to considerations of safety issues and regulatory challenges such as lead-acid battery recycling, ambiguity of vehicle defections, etc. (F. Zhao et al., 2017).

Figure 18 is the speed distribution of a random selected workday for a randomly selected vehicle to understand the travel frequency of LSEV users. The y-axis is the vehicle speed in km/h which can indicate the vehicle operating status and further to conclude the number of trips in a day. There are several key takeaways from the plot. Firstly, there are totally three trips happened during a normal workday, which is very similar to E2W users travel frequency 2-4 trips. Secondly, the first trip happened around 8am, the second trip happened around 5pm and the last trip around 9pm. It is very likely that the first and second trips are commute trips due to the trip occurring time. The two trips last no more than one hour and have a maximum speed under 25 km/h. The third trip is very short and could possibly be GPS noises or a moving the car for charging: the LSEV user might start the car and move the car to the charging outlet for overnight recharging, which can explain the relative short duration and fixed time of vehicle movement at night. Lastly, due to the lower travel speed and the volatility of the speed, we can confidently guess these trips happens on local streets instead of freeways.

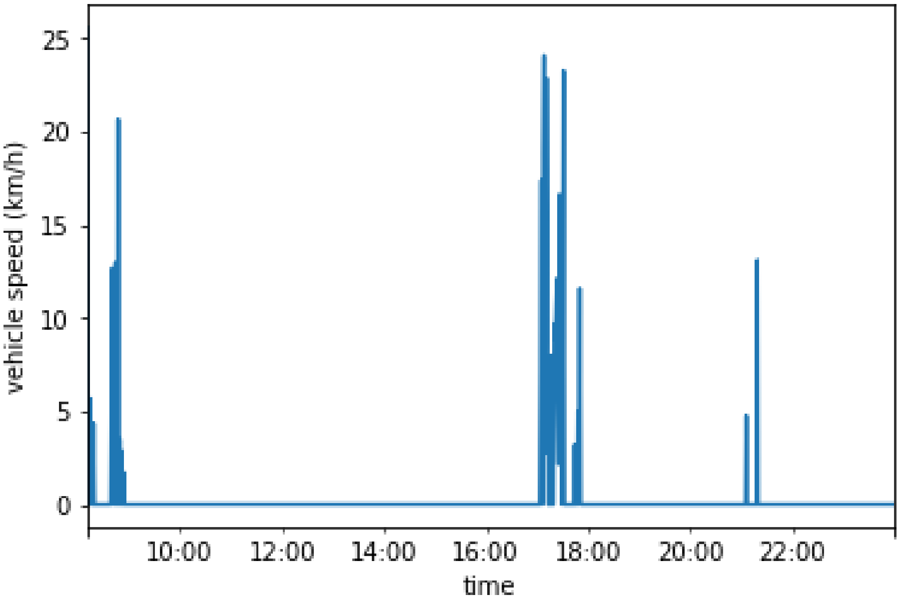


Figure 18 The speed distribution over time for a randomly selected vehicle on 4/1/2019.

This is an example of a typical workday for an LSEV, and we can observe there are three instances of trips happening during a day. From the travel time we can guess that the first trip and second trip could be commute trips, which happened around 8am and 5pm. The third trip was around 9pm and this trip was shorter than other two trips during the day. All three trips have a maximum speed lower than 25 km/h and the trip length is short as well. Due to the lower travel speed and the volatility of the speed, we can confidently guess these trips happens on local streets instead of on freeways.

In order to better evaluate the travel frequency, one week data is visualized below both in Figure 19 and Figure 20. The key takeaways are summarized and discussed here. There are three trips on Monday, zero trip on Tuesday, three trips on Wednesday, four trips on Thursday, two trips on Friday, one trip on Saturday and three trips on Sunday. Averagely, 2.4 trips happened during weekdays while 2 trips happened during weekends. And the average daily number of trips is 2.3 for a selected week. All the trips have a maximum speed lower than 25 km/h and confirms that this vehicle travels on local roads. Commute trips are more common during weekdays than weekends and the LSEV user is likely to have a stable job. Weekend trips are more random during the day which could be family travel, leisure or shopping trips. There are 4 short trips at around 9pm on Monday, Wednesday, Thursday and Sunday, respectively. The LSEV user might start the car and move the car to the charging outlet for overnight recharging, which can explain the relative short duration and fixed time of vehicle movement at night. With this assumption, the average number of recharging per day is about 0.57 (4/7).

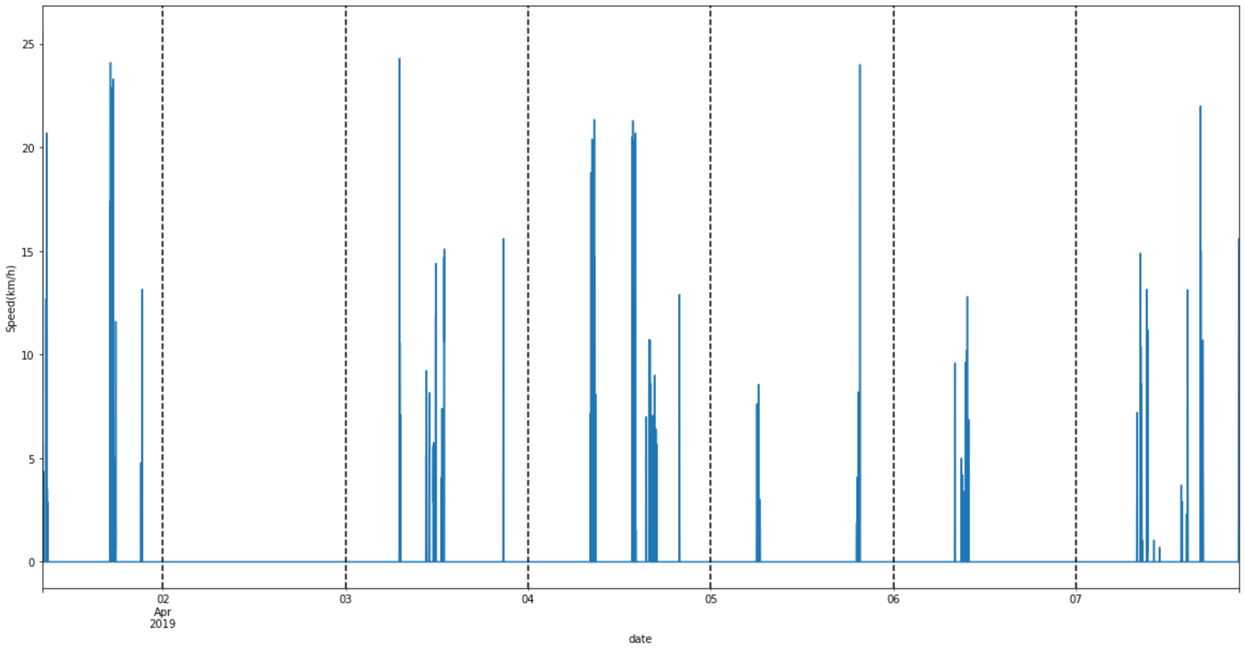


Figure 19 Speed of a vehicle over a week (Monday ~ Sunday).

From the plot, we can observe that, there are three trips on Monday, zero trip on Tuesday, three trips on Wednesday, four trips on Thursday, two trips on Friday, one trip on Saturday, three trips on Sunday. The average number of trips is about 2.3 per day. And all the trips have a lower speed than 25 km/h and relatively shorter duration.

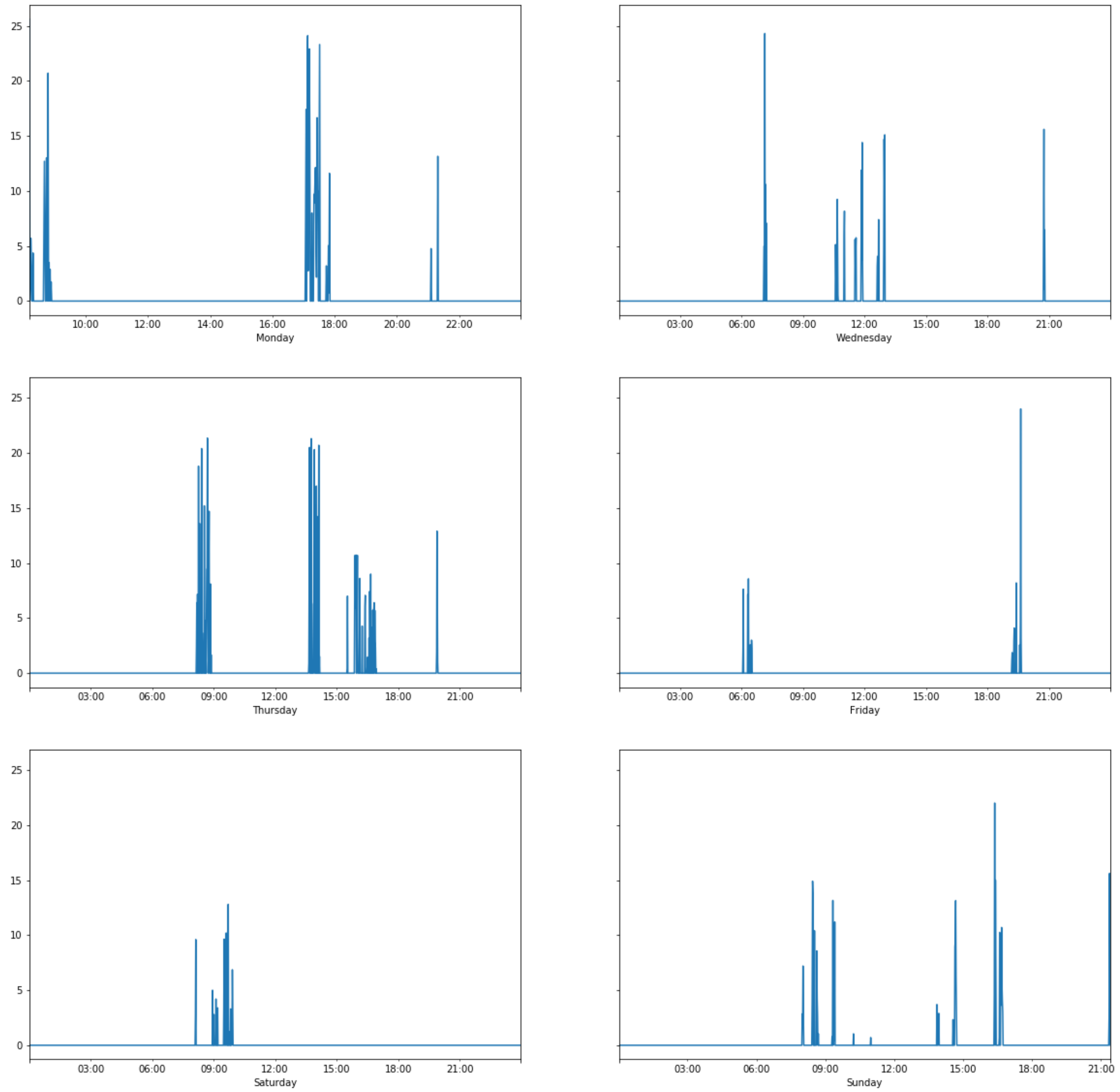


Figure 20 Speed over time for a week (except Tuesday).

The LSEV user normally have two trips in the morning and in the evening. The morning trips either happen around 9am or before 7am, and the evening trips happen around 5pm or 9pm. It is noticed that around 9pm there will be a short trip, which is likely to be a charging move: the LSEV user might start the car and move the car to the charging cable for overnight recharging, which can explain the relative short duration and fixed time of vehicle movement at night.

The average daily travel speed for both weekdays and weekends are calculated and illustrated in the plot below. It is observed that most of the vehicles have a daily average travel speed from 10 km/h to 30 km/h, while the highest daily average speed is about 50 km/h, which indicates the travel is probably on local, rural routes instead of highways. The speed distribution is bimodal and is slightly left-skewed, which means there are more vehicles that travels with a lower daily average speed. The travel speed of weekdays is also relatively higher than of weekends, and the types of trips might also be different for weekdays and weekends. For example, there are more commute trips during weekdays and more leisure trips during weekends.

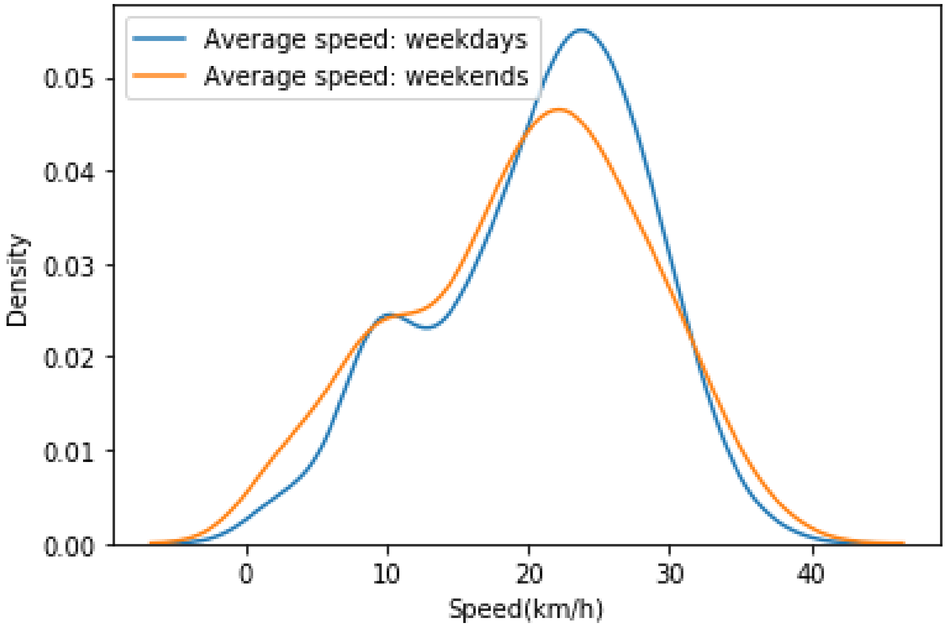


Figure 21 Average daily vehicle speed distributions for weekdays and weekends.

Most of the daily average travel speed are between 10 and 30 km/h, while the highest daily average speed is about 50 km/h. The speed distributions are bi-modal, and the distributions are also different between weekdays and weekends possibly due to different trip purposes.

3.4 Discussion and conclusion

This chapter provides the first quantitative analysis into LSEVs' daily travel behaviors. It is found that the a sample of 539 LSEVs over a week at 2019, the daily VMT for LSEVs is around 12.5km on weekdays compared to 16.8km on weekends, and most of the vehicles travel under 20 km daily. The average number of trips is around 2.3 trips per day and the maximum speed is under 25 km/h, which confirms that LSEVs travel on local roads. In the comparison between pre-COVID and COVID periods, it is found that there were only 36 LSEVs out of 539 LSEVs still operating during COVID periods in 2020, and the average daily travel distance also dropped by 3km, which likely indicates a strong impact of COVID-19 on people's travel demands.

To better understand the VKT status of LSEVs, I also compared the VKT of LSEVs with the light-duty vehicles (LDVs). Huo et al. (2012) conducted VKT surveys for private LDVs in several Chinese cities during 2004 and 2010 and estimated the annual VKT for private LDVs is about 17,500 km and the mean DVKT is about 48 km (Huo et al., 2012). Surveys conducted in Beijing in 2009 for 480 drivers found that the average DVKT for private passenger vehicles was 45.35 km with the standard deviation of 38.66 km, while the DVKT of the sample ranges from 3 km to 300 km. The distribution for the DVKT was also right skewed with 25% of drivers' DVKT less than 20 km and 50% of drivers' DVKT less than 30 km (Hou et al., 2013). For the DVKT of LSEVs in our samples, the average DVKT was 12.39 km with the standard deviation of 12.35 km, which is about 27% of the average DVKT of private passenger vehicles in Beijing in 2009. Although LSEVs can't provide comparable mobility level of private passenger cars, they could still provide similar levels of mobility compared with e-bikes, CRVs or motorcycles. For example, Kunming's e-bike owners travel about 12 km/day during weekdays (Ling et al., 2019), which is comparable to 12.53 km/day for LSEVs during weekdays from our GPS data. From Ling's interview (Ling et al., 2019), we also learned that most LSEV users were male, elderly, retired, with high household incomes and about 60% of the respondents did not have a driver license. These users have shifted from electric bike users to LSEV users while maintaining similar travel intensities, meaning their previous travel demands were met with their new mode.

The analysis of LSEVs' travel behaviors is very critical for researchers and policymakers to understand the impacts of the new travel mode. Firstly, the potential energy saving, and emission reduction potential can be more accurately evaluated for LSEVs; secondly, the better understanding of the travel behaviors can help policymakers to better evaluate the roles of LSEVs in the current transportation system; thirdly, the cost of owning LSEVs compared with other modes can be calculated and compared so that users can make more reasonable purchase decisions.

CHAPTER 4 TOTAL COST OF OWNERSHIP ANALYSIS

Over the past decade, the adoption rate of plug-in electric vehicles (PEVs) has significantly increased in China, and PEVs are expected to account for about 5.4%[18] of China's new vehicle sales by 2020. PEVs have the potential to reduce oil dependency, air pollution, and greenhouse gas emissions. Therefore, China has a variety of incentive programs and supporting policies designed to encourage the adoption of PEVs, but policymakers anticipate that these incentives will phase out within the next few years when the cost of owning a PEV will be comparable to that of owning a combustion engine vehicle. Therefore, it is imperative to compare the total cost of ownership (TCO) between PEVs and other alternatives, to inform consumers' purchase decisions and guide policy makers' incentive program decisions.

Aside from PEVs (which are heavily subsidized by Chinese governments), low-speed vehicles (which are unofficially considered micro EVs), have grown rapidly over the last decade without government incentives, as discussed in Chapter 2. In 2020, some micro EVs with lithium-ion batteries (which are slightly more expensive than LSEVs), outsold their competitors such as micro gasoline cars and compact EVs. Wuling Hongguang released a new micro-EV in July of 2020, which is called Wuling Hongguang Mini EV. It is a microcar with a 9.2 kWh lithium-ion battery and a range of 120 km or a 13.8 kWh battery with a range of 170 km, with a starting price of US$4,162. In 2020, the Honguang Mini EV sold 120,000 units after six months on the market, ranking as the second best-selling PEV in the world after the Tesla Model 3.

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[18] http://www.gov.cn/xinwen/2021-01/15/content_5580088.htm

A total cost of ownership analysis (TCO) calculates the total cost of owning a car through its lifetime, including the purchase price, taxes, fees, fuel costs, maintenance costs, battery replacement costs (for electric vehicles), residual values, etc. Total costs can be divided by the total distance traveled during a vehicle's lifetime to facilitate fair comparisons between different types of vehicles, this is a form of a levelized cost. It is usually used to inform consumers of the lowest-cost technology based on the life-cycle cost of a given technology. In addition to differences in policies, consumer characteristics, such as different travel behaviors, and economic activity levels, TCO analysis varies by country.

In a study conducted in Beijing (H. Hao, Wang, Zhou, Wang, & Ouyang, 2015), it was found that the levelized costs of a conventional vehicle (CV) and a battery electric vehicle (BEV) decreased from 1.44 yuan/km for an 8-year vehicle lifetime to 1.01 yuan/km for a 15-year vehicle lifetime, whereas the levelized costs of a CV decreased from 1.40 yuan/km for an 8-year vehicle lifetime to 1.04 yuan/km. BEVs may become more cost competitive with conventional vehicles with the decrease in battery cost even if the subsidies may be phased out in near future. Hao et al. (2021) studied expanded total ownership cost with consumer heterogeneity and range anxiety and found out that 250-350 km range EVs have advantages in cities with plate restriction while ICEVs have advantages in cities without plate restriction. They also found that in cold-weather northern China, 400-450 km range EVs have advantages, and the cost-effective all-electric range for BEVs in 2025 will decrease due to improved battery performance in cold weather and more charging infrastructure (X. Hao, Lin, Wang, Ou, & Ouyang, 2020). Ouyang et al. (2021) analyze the total cost of ownership for CVs, PHEVs, and BEVs over 5- and 10-year periods in China based on a consumer-oriented model and find that small BEVs will achieve parity before 2025, medium-sized and large BEVs will do so around 2030, and small and medium PHEVs will perform better regarding costs than large models. Furthermore, the authors suggest that incentive policies and oil prices are likely to have a significant impact on the time until EVs reach parity (Ouyang, Zhou, & Ou, 2021).

Yet, few studies have been conducted on micro EVs and low-speed vehicles. Making informed purchases requires an understanding of the total cost of ownership of these low-end vehicles and their replacements. Additionally, understanding the additional costs involved in upgrading from inferior replacements, such as E2Ws, motorcycles, and CRVs, to EVs is critical. Our work evaluates the current policies regarding these technologies and provides recommendations for streamlining a transition to EVs.

Therefore, an analysis of the total cost of ownership (TCO) of 17 different mobility solutions, ranging from 2-wheelers to 4-wheelers, is conducted to evaluate the relative costs of different mobility solutions. The first section of this chapter describes the methods and assumptions for the TCO analysis, including the types of vehicles to be compared, vehicle driving profiles, and TCO models. In the second section of this chapter, I examine the cost components, which include both fixed costs and variable costs throughout the vehicle's lifecycle. The third part of the analysis conducts a variety of sensitivity analyses including Monte Carlo simulations. Lastly, I discuss the findings and implications of the study from a cost-benefit perspective.

4.1 Methodology and assumptions

4.1.1 Mobility options

Among the vehicles to be compared are 2-wheelers, 3-wheelers and 4-wheelers with different fuel types such as gasoline, diesel and electric. For some of the vehicle types, I was able to collect model specifications and price information. This helped us identify the distributions of some key variables such as MSRP and fuel economy. The following three tables provide basic information about the 17 mobility solutions.

Table 13 Two-wheelers to be compared in our TCO model.

Type	Bike	E-bike lead-acid	E-bike lithium-ion	E-scooter lead-acid	Gasoline scooter	Gasoline motorcycle
Power source	Na	Electric	Electric	Electric	Gasoline	Gasoline
Top speed (km/h)	8-12	20-30	20-30	30-40	50-80	60-80
Fuel efficiency (kWh/100km or liter/100km)	Na	1-2	1-2	1.5-2	2-4	2.5-6
Vehicle lifetime	3-5	3-6	3-6	5-8	5-8	7-12
Battery type	Na	Lead-acid	lithium-ion	Lead-acid	Na	Na
Battery lifetime	Na	2-3	3-5	2-4	Na	Na

Table 14 Three-wheelers to be compared in our TCO model.

Type	Electric tricycles	Three-wheel gasoline motorcycle	Three-wheel Chinese rural vehicles
Power source	Electric	Gasoline	Diesel
Top speed(km/h)	25-35	60-80	50-60
Fuel economy (kWh/100km or liter/100km)	2-4	4-8	3-7
Vehicle lifetime	5-8	7-12	5-9
Battery type	Lead-acid	Na	Na
Battery lifetime	2-3	Na	Na

Table 15 Four-wheelers to be compared in our TCO model.

Type	Low-end CRV	High-end CRV	LSEV with lead-acid batteries	LSEV with lithium-ion batteries	Micro BEVs	Compact BEVs	Micro gasoline cars	Compact gasoline cars
Power source	Diesel	Diesel	Electric	Electric	Electric	Electric	Gasoline	gasoline
Top speed (km/h)	60	80	35-55	50-70	100	Over 150	Over 150	Over 150
Fuel economy (kWh/100km or liter/100km)	8.5	9.5	6-8	5.5-7.5	10-13.5	12-17	4-8	5-12
Vehicle lifetime	5-9	8-12	5-11	5-11	5-11	6-12	6-12	6-12
Battery type	Na	Na	Lead-acid	Lithium-ion	Lithium-ion	Lithium-ion	Na	Na
Battery lifetime	Na	Na	1-2	3-5	4-6	4-6	Na	Na

4.1.2 Driving profiles

The following is a summary of the vehicle travel intensity for different vehicle types. The TCO analysis will be based on the discussion of the vehicle travel intensity studies from the previous chapter. To account for uncertainty, following assumptions are made to estimate annual VKTs (AVKTs) and their lower/upper bounds in the absence of sources.

- The AVKT for bikes is derived by assuming the daily VKT is 7km and multiplying the VKT with 365 days. The lower and upper bounds for AVKTs are calculated by assuming 500km error bands.
- The AVKT for E3Ws is assumed to be higher than those for electric scooters. 1000km has been added to account for the longer distances for E3Ws.
- The AVKT for G3Ws is assumed to be higher than those for gasoline motorcycles, thus 1000km has been added to the AVKT and lower/upper bounds of gasoline motorcycles to derive those for G3Ws.
- The AVKT for LSEVs is calculated from the previous chapter by analyzing the GPS data.
- The AVKT for Micro BEVs is assumed to be the same with LSEVs for simplicity.

Table 16 Driving profiles for different vehicles to be compared in our TCO model.

Mobility Solution	Mean AVKT	Lower bound	Higher bound	Source
Bike	2500	2000	3000	Author’s estimation
E2W	3500	3000	4000	(C. R. Cherry et al., 2009; C Cherry, 2007; Ling et al., 2019)
E-scooter	4000	3500	4500	(C. R. Cherry et al., 2009; C Cherry, 2007; Ling et al., 2019)
G-scooter	7000	4000	10000	(Huo et al., 2012)
G-motorcycle	7000	4000	10000	(Huo et al., 2012)
E3W	5000	4500	5500	Author’s estimation from E2W
G3W	8000	5000	11000	Author’s estimation from G2W

3RV	17750	12100	23400	(Huo et al., 2012)
Low-end 4RV	22400	15400	29400	(Huo et al., 2012)
High-end 4RV	22400	15400	29400	(Huo et al., 2012)
LSEV	8750	3500	14000	Author's data exploration
Micro BEV	8750	3500	14000	Assume Micro BEV drivers share similar driving profile with LSEVs'
Compact BEV	12500	10000	15000	(Hou et al., 2013)
Micro gasoline car	12500	10000	15000	(Hou et al., 2013)
Compact gasoline car	12500	10000	15000	(Hou et al., 2013)

I have performed a Monte Carlo simulation to determine which of the cost components is the most significant in determining the total cost of ownership in the following TCO model. Since there are few high-resolution data for most of the vehicles to be compared, a triangle distribution is assumed by setting the mean, lower and upper bounds of the AVKTs, as is shown in Table 16.

4.1.3 Methodology

In Figure 22, I divide the total cost of ownership into two main categories, fixed costs and variable costs. The fixed costs are one-time purchases that occur during the purchase of the vehicle, which include the *MSRP* (Manufacturer's Suggested Retail Price), purchase tax, and purchase subsidy. As variable costs occur every year, the discount rate will need to be considered for variable costs that will occur in the future. The average life expectancy of a vehicle is *n* years, measured from its purchase to its end of life, depending on the choice of vehicle. The scrapped vehicles still possess residual value; however, I consider the value of scrapped vehicles to be zero in this analysis.

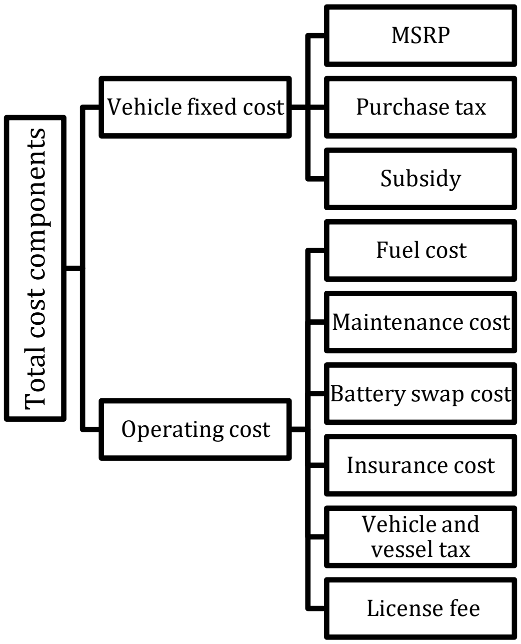

Figure 22 The decomposition of the total costs of ownership, which includes fixed cost and operating costs.

Fuel costs, maintenance costs, insurance costs, vehicle and vessel taxes, license fees, and battery swap costs are the main components of variable costs. Generally, the battery pack needs to be replaced every two to three years, depending on the specific type and usage of the battery. I calculated the average battery cost per year by dividing the total cost of battery swapping with the lifetime of the vehicle to approximate the battery swap cost. To calculate the levelized cost of the vehicle, I divided the TCO_n by the total vehicle kilometers traveled during the vehicle's lifetime.

$$TCO_n = FC + VC = MSRP + PT - SUB + \sum_{i=1}^{n} \frac{(FC_i + MC_i + IC_i + VVT_i + LF_i + BC_i)}{(1 + DR)^{i-1}} \tag{1}$$

$$Cost/km = \frac{TCO_n}{\sum_{i=1}^{n} VKT_i} \tag{2}$$

In the first equation above, the TCO_n is the total cost of ownership for vehicles lasting n years; the *FC* is the fixed cost and the *VC* is the variable cost; the *MSRP* is the Manufacturers

Suggested Retail Price, the *PT* is the purchase tax, which is a certain percentage of the *MSRP* based on the different type of vehicles; the *SUB* is the monetary subsidy that will be deducted from the *MSRP* and some of the plug-in electric vehicles are qualified to receive the subsidy based on the battery capacity and density power, etc.

For the second part of the equation, the FC_i is the fuel cost at the vehicle age *i*; the MC_i is the maintenance cost at the vehicle age i; the IC_i is the insurance cost at the vehicle age i; the VVT_i is the vehicle and vessel tax at the vehicle age *i*; the LF_i is the license fee at the vehicle age *i*, the BC_i is the battery swap cost at the vehicle age *i*; the *DR* is the discount rate, which I used 7.5% as the value in the analysis, with a sensitivity analysis to address the uncertainly, where the upper and lower bound of discount rate is 10% and 5%, respectively; the VKT_i is the vehicle annual travel distance at the vehicle age *i*.

Specifically, for the FC_i, it can be calculated by the following equation, where the *FE* is the vehicle fuel economy (liter/100km or kWh/100km) and the *FP* is the fuel price (RMB/Liter or RMB/kWh).

$$FC_i = FE \times FP \times VKT_i \qquad 3$$

Additionally, alternative transportation costs are typically considered for vehicles such as E2Ws and BEVs due to the gap between the range of an EV and a gasoline car (Ouyang et al., 2021). However, this cost is not considered due to a lack of information about their travel demands and how their demands are met.

4.2 Cost components analysis

4.2.1 Vehicle MSRPs and related tax

A vehicle's purchase price, which includes both the MSRP and certain taxes, varies depending on the vehicle characteristics. In the following figures, I compare the MSRP disparities for different counterparts using publicly available data.

Electric bikes (with either lead-acid or lithium-ion batteries), electric scooters and gasoline scooters have similar MSRPs, however electric scooters have the highest average MSRP, and gasoline scooters have the largest variations. Due to the large inherent difference in gasoline motorcycles, the MSRP distribution for gasoline motorcycles is largely variable and the average MSRP is higher (over 7k RMB) than that for other modes. Generally, the MSRP of gasoline motorcycles increases with engine size; some luxury and larger motorcycles have MSRPs that exceed 10K RMB, while some domestically manufactured motorcycles have MSRPs that are less than 4K RMB. I only use the average MSRP for bikes as a baseline MSRP.

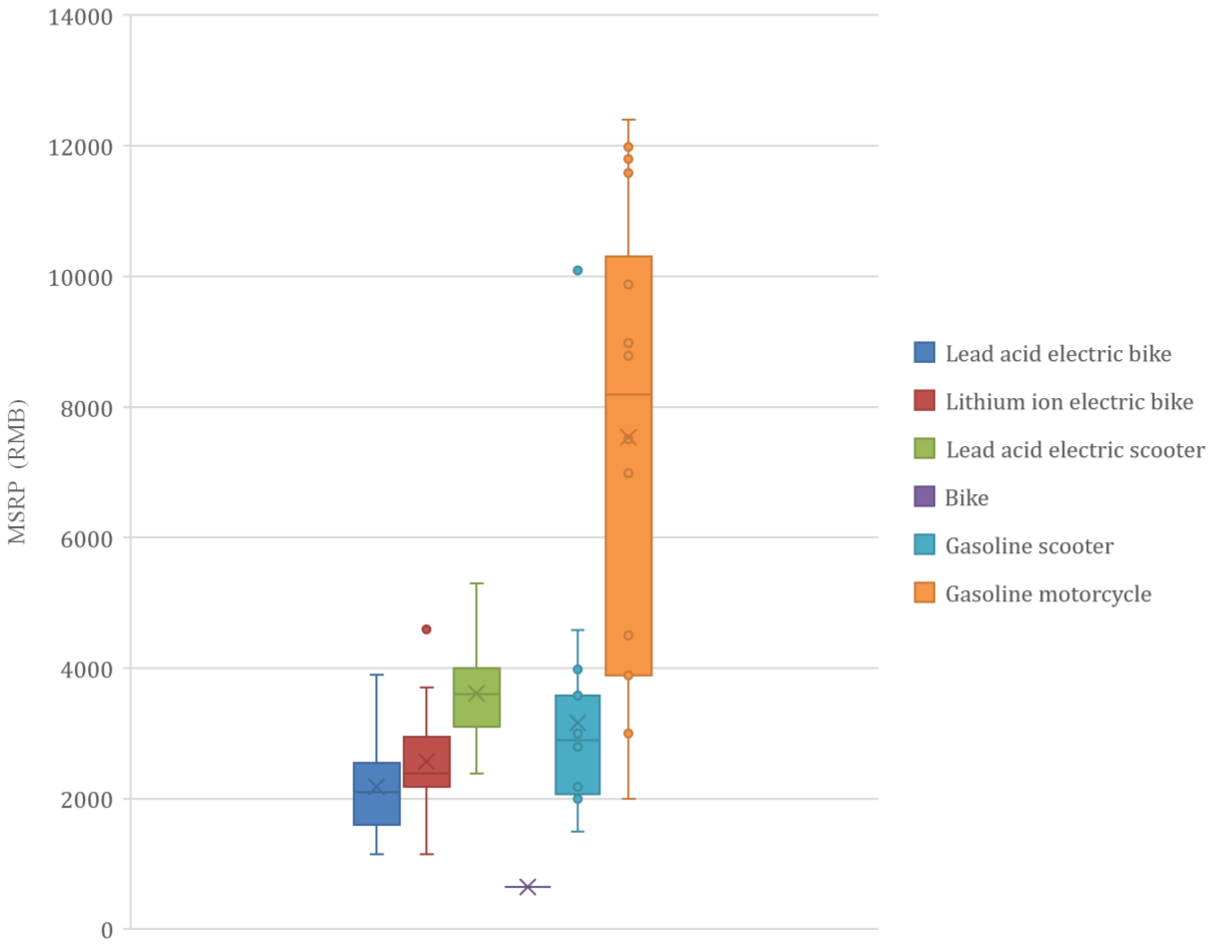

Figure 23 The MSRP distributions for all two-wheelers by models are compared here.

MSRPs of electric bikes/scooters and gasoline scooters are similar mainly due to their similar functionalities and targeted users, and they are mainly used for short-distance commute/leisure activities, etc. However, MSRPs of gasoline motorcycles varies significantly due to the large inherent differences in terms of motorcycle classes, functionality and characteristics, for example, motorcycles can be used both for short and long-distance commute.

It is observed that the average MSRP for three-wheelers is similar between CRVs and G3Ws, however, E3Ws are significantly cheaper. Due to the higher torque and power of diesel engines, CRVs are primarily used for the transport of heavy cargo or farm products. In contrast, E3Ws and G3Ws are typically used for daily deliveries, commercial transportation, etc. Due to a lack of data and inherent differences (discussed in Chapter 2), LSEVs with lead-acid batteries have a much widely spread MSRP of about 30k RMB than three-wheelers, while LSEVs with lithium-ion batteries and 4W-CRVs (low-end) have a much greater average MSRP (over 40k RMB). Due to the much more powerful diesel engines and larger size of high-end 4W-CRVs, the MSRP is typically over 70k RMB. For the purpose of reference, I only plotted average MSRPs of LSEVs with lithium-ion batteries and 4W-CRVs (both low and high end) due to a lack of data.

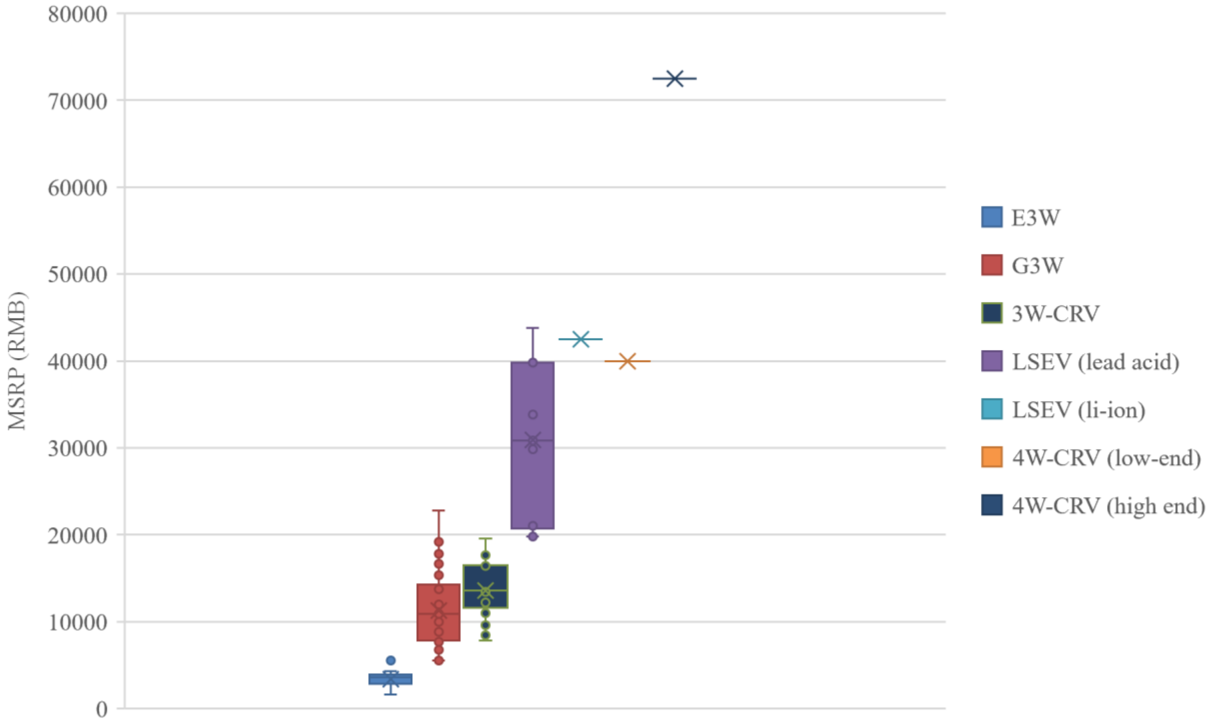

Figure 24 Comparison of the MSRP distributions for three-wheelers and a portion of four-wheelers by models.

Four-wheelers are more expensive than three-wheelers. For vehicles with same number of wheels, gasoline/diesel vehicles are more expensive than electric vehicles.

To illustrate the disparity in prices, I compared the average MSRPs for different vehicles in Figure 25.

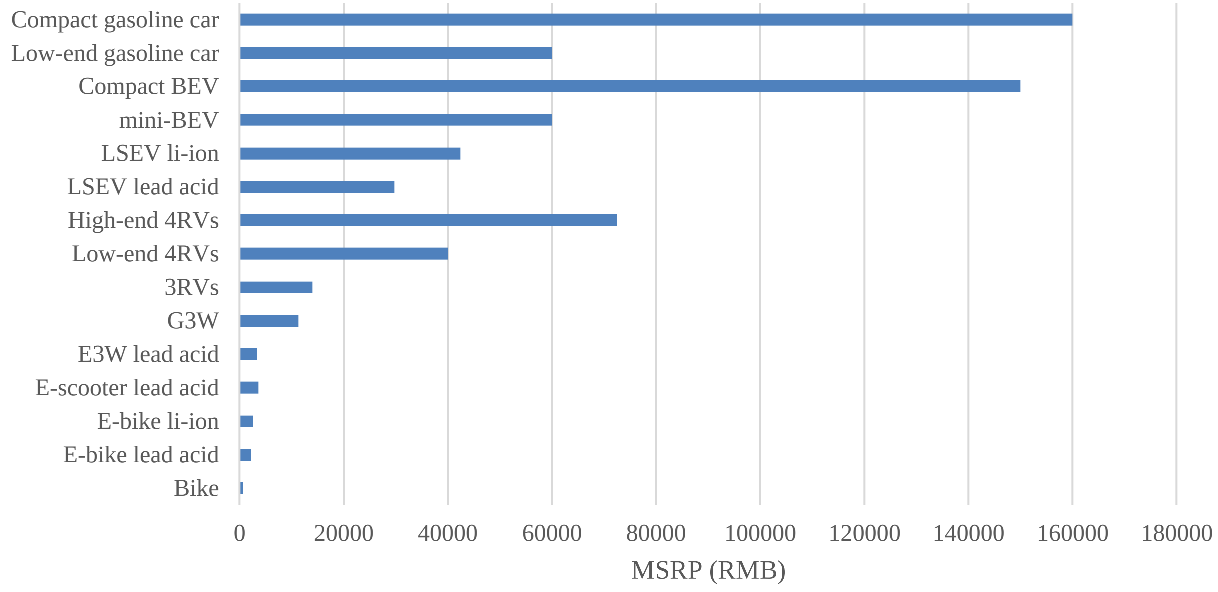

Figure 25 Comparison of the average MSRPs for all the modes in our TCO model.

For compact-sized vehicles, it has been observed that gasoline cars are slightly more expensive than electric cars, while 4RVs are cheaper than the previous two types. Compared to gasoline cars and mini-BEVs, LSEVs are cheaper than both.

Depending on the kind of vehicle, vehicle purchase taxes vary and are levied by a certain percentage of the vehicle purchase price. The value added tax (VAT, which is 13%) is imposed on sellers but is included in the vehicle purchase price, so when determining the vehicle purchase tax, I divide the MSRP by 1.13 and then multiply by 10% to obtain the vehicle purchase tax, which is approximately 8.85%. It should be noted that the vehicle purchase tax rate in China is the same in all provinces, since it is only imposed on the national level, and there are no provincial or local taxes to be paid on vehicle purchases.

A vehicle purchase tax is only imposed on motorized vehicles, whereas some vehicles, such as electric vehicles, are exempt from paying the tax due to the NEV subsidy. Two-wheelers considered in our analysis are exempt from purchase tax except gasoline motorcycles with engines larger than 150cc. The LSEVs are not taxed because they are currently not legal vehicle types and are also considered non-motorized vehicles, even though some LSEVs already fall into the category of motorized vehicles due to their top speeds. Table 17 summarizes the MSRP and purchase tax. The purchase tax for gasoline and diesel motor vehicles is approximately 8.5% of the MSRP, while electric vehicles are exempt from purchasing tax as they receive government subsidies or have an illegal status (LSEVs). The purchase tax does not apply to non-motorized modes such as bicycles, e-bikes and scooters.

Table 17 The average MSRPs and purchase tax for different types of vehicles.

Category	**Average MSRP (RMB)**	**Average purchase tax (RMB)**
Bike	650	0
Electric bicycle (lead-acid)	2183	0
Electric bicycle (lithium-ion)	2566	0
Electric scooter	3612	0
Electric tricycle	3401	0
Gasoline scooter	5000	0
Gasoline motorcycle	7500	664
G3Ws	11287	999
3RVs	14000	1239
Low-end 4RVs	40000	3540
High-end 4RVs	72500	6416
LSEV (lead-acid)	29800	0
LSEV (lithium-ion)	42500	0
Mini-BEV	60000	0
Compact BEV	140000	0
Low-end micro gasoline car	60000	5310
Compact gasoline car	160000	14159

4.2.2 Subsidy policies

The monetary incentives for NEVs in China include three components: direct purchase incentives, purchase tax exemptions, and exemptions from vessel taxes. Following our discussion on the purchase tax in section 4.2.1, I will move on to discussion on the use tax in section 4.2.4. In this section, I will discuss the purchase incentive.

The Chinese central government has provided substantial amounts of financial support to stimulate the purchase of electric vehicles. It is also gradually reducing subsidies at a steady pace and intensity. During 2018, the updated NEV subsidy policies eliminated the subsidy program for passenger PEVs whose electric range is below 150km and whose battery energy density is below 105 Wh/kg. As of 2019, BEVs with a range under 250 kilometers will no longer qualify for purchase subsidies. Subsidies for vehicles with a range over 250 kilometers will be halved as well. In 2020, BEVs with a range greater than 300 kilometers could receive subsidies with a 10% reduction compared to last year. There will be a 20% reduction in 2021 as well. We can see in Figure 26 that the range requirements and subsidy amount for both BEVs and PHEVs from 2013 to 2021 are becoming more stringent, the subsidies are becoming fewer, and small BEVs or mini BEVs (usually with a shorter electric range) will not be eligible for any purchase subsidies.

The BAIC EC180 was the top seller in the 2017 Chinese PEV markets, selling 78,079 units. Beijing residents who purchase EC180 can skip the purchase lottery and obtain the license plate without participating in the purchase lottery. Another reason is the lower price under the previous subsidy policy. In 2017, BAIC EC180 (maximum range over 200 km) received central government and local government subsidies as well as manufacturers' subsidies. Nevertheless, under the new subsidy policies, since the energy density of EC180 batteries is 103.5 Wh/kg, which is below the threshold value of 105 Wh/kg, EC180's energy density coefficient will be zero, and therefore EC180 will not receive subsidies from governments following 2018. In response to new subsidy policies, BAIC decided to withdraw the EC180 from the market.

In the next figure, we can observe that from 2013 to 2021, China's subsidies for BEVs and PHEVs decreased over time. In 2013, BEVs with a range over 80 km and PHEVs may qualify for subsidies. In 2014 and 2015, the subsidy amounts were reduced by 5% and 10%, respectively. The subsidy for BEVs with a range of more than 250 km increased to 55k RMB in 2016, while the subsidy for BEVs with a range of 150-250 km remained the same as in 2015, while the subsidy for low-range BEVs was significantly lowered and the lowest required range rose to 100 kilometers. In 2016, the subsidy for PHEVs decreased to 30k RMB. To reduce the dependence of NEV industries on monetary subsidies, all subsidies were reduced by 20% in 2017. BEV subsidies were redesigned in 2018 in order to encourage long-range BEVs and discourage short-range BEVs. Subsidies for BEVs with a range less than 250 kilometers were no longer available in 2019, while subsidy amounts for qualified models decreased by 50%. By 2020, the lowest BEV range was 300 km, and a 15% price cut was applied to all qualified models. Subsidies were reduced by 20% in 2021 compared to last year. So far, only BEVs with a range of more than 300 km and PHEVs with a NEDC-tested range of 50 km will be eligible for subsidies.

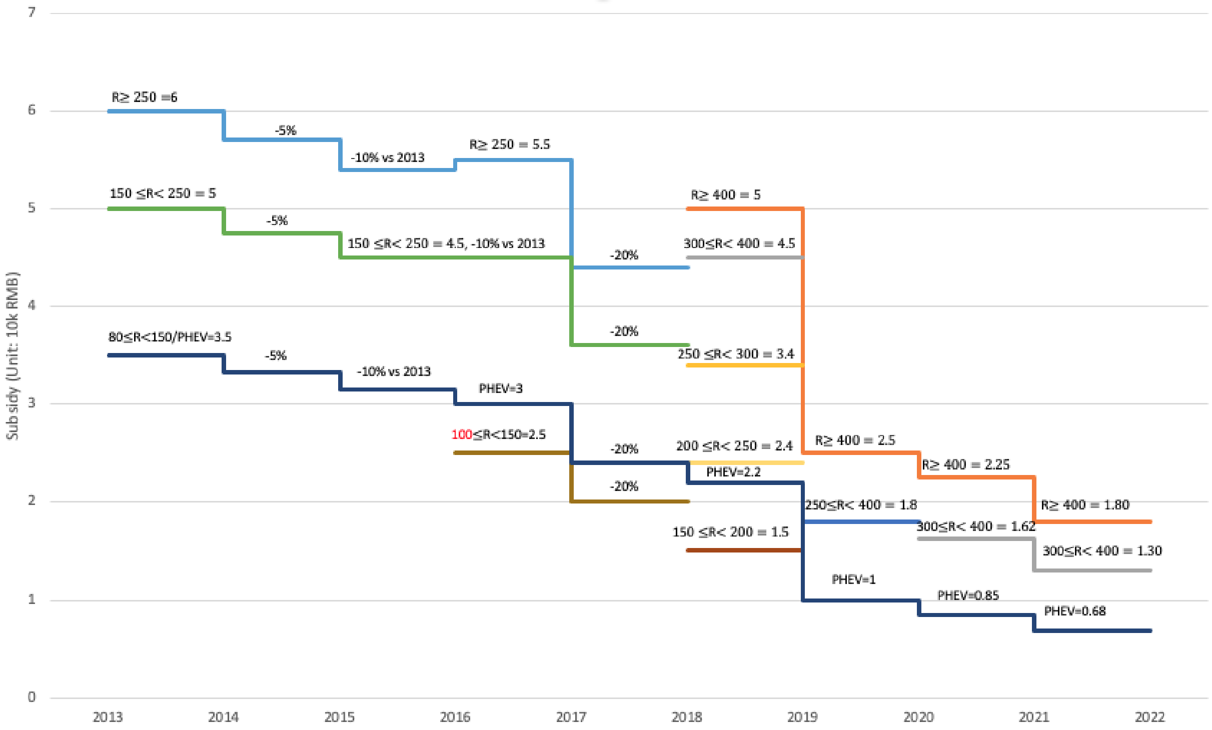

***Figure 26 Range requirements for BEVs and PHEVs' subsidies in China*.**

Along with the requirement for electric range, EVs must also meet certain fuel consumption levels and battery energy density requirements in order to qualify for subsidies. More information on these two other requirements is available here[19].

In our analysis, only compact BEVs with a range of over 300 kilometers are subsidized. To better assess the total cost of ownership for various vehicles, I will include a compact BEV model with a range of over 400 km as well as a compact PHEV model with a range of over 50 km. The Wuling Hongguang MINI EV, which is a micro EV with a range of under 200 km, is not subsidized under current policy. However, as of January 2021, the company had sold over 160,000 units, which will be used to represent the micro EV category in our model. The table below summarizes the subsidies available for different NEV models (equipped with lithium-ion batteries) in our TCO model.

Table 18 Vehicle MSRPs and subsidies for different PEV models in our TCO models.

Based on different electric ranges of BEVs and PHEVs, certain models are selected to evaluate the effectiveness of new subsidy policies in 2021.

Type	Mini BEV	Compact BEV	Compact BEV	Compact PHEV
Vehicle class	A00	A0	A0	A0
Electric range (km)	120 or 170	346	510	120
Representative models	Hongguang MINI EV	Volkswagen Bora EV	Aion S	BYD Qin Plus DM-i
Average MSRP (RMB)	37,600 or 43,600	140,000	180,000	145,800
Subsidy in 2021 (RMB)	0	13,000	18,000	6,800

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[19] https://finance.sina.com.cn/tech/2021-01-05/doc-iiznezxt0674655.shtml

4.2.3 Fuel cost

Distance traveled, fuel economy, and fuel price all contribute to fuel cost. The VKTs were discussed in Chapter 3 and the results will be directly used here.

Online fuel economy data are collected for multiple vehicles within each category. Fuel economy data collected is labeled as value and tested under the new European driving cycle; therefore, adjustments should be made to consider real-world fuel economy. It has been shown in previous studies that the actual fuel consumption rate is about 15% higher than the labeled rate (H. Hao et al., 2015). Therefore, I have made a 15% adjustment for all four-wheelers in comparison with the labeled fuel consumption rate. The improvement in engine and motor technologies is likely to improve the fuel economy of these vehicles in the future. However, I did not model this fuel economy improvement in our TCO model due to a lack of data.

I have compiled the labeled fuel consumption rates from various BEV models. On average, micro BEVs have a fuel economy of 12 kWh/100km, whereas compact BEVs have a fuel economy of 14 kWh/100km.

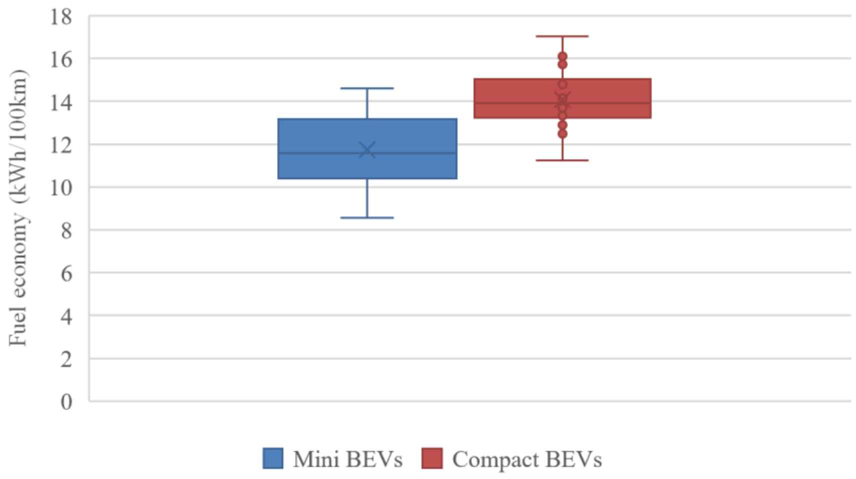

Figure 27 Fuel consumption rate for mini and compact BEVs.

LSEVs typically consume 8 kWh of fuel per 100 kilometers[20], which is much lower than the fuel consumption of a mini-BEV or compact BEV. For a small, cheap gasoline vehicle such as the Cherry QQ, the fuel consumption rate is approximately 6L/100km[21]. Based on the fuel consumption rates of different vehicles, I compared the fuel consumption rates based on different fuel types below.

Table 19 Vehicle labeled fuel consumption rates for all the vehicle models in our TCO model

Vehicle type	Fuel type	Labeled fuel consumption rate
E-bike	Electric, lead-acid battery	1-2 kWh/100km
E-bike	Electric, lithium-ion battery	1-2 kWh/100km
E-scooter	Electric, lead-acid battery	1.5-2 kWh/100km
Electric tricycle	Electric, lead-acid battery	2-4 kWh/100km
Gasoline scooter	Gasoline	2-4 L/100km
Gasoline motorcycle	Gasoline	2-6 L/100km
3W gasoline motorcycle	Gasoline	4-8 L/100km
3W rural vehicle	Diesel	3-7 L/100km
4W low-end rural vehicle	Diesel	6.6-10.5 L/100km
4W high-end rural vehicle	Diesel	6.3-20 L/100km
LSEV	Electric, lead-acid battery	6-10 kWh/100km
LSEV	Electric, lithium-ion battery	6-10 kWh/100km
Mini BEVs	Electric, lithium-ion battery	10-13.5 kWh/100km
Compact BEVs	Electric, lithium-ion battery	12-17 kWh/100km
Compact PHEVs	Electric, lithium-ion battery	3.8 L/100km[22]*
Low-end small gasoline car	Gasoline	4-8 L/100km
Compact gasoline car	Gasoline	5-12 L/100km

* Based on a news report, this number represents the total fuel consumption including both electric and gasoline-powered vehicles. To simplify our analysis, I will not assume the proportion of electric versus gasoline mode and will directly use the data from the source.

In Beijing, the price of 92# gasoline, comparable to 87# gasoline in the United States, was 7.08 RMB/L on July 1st, 2021. As of July 1, 2021, the price of 0# diesel in Beijing was 6.76 RMB/L [23]. In our TCO model, I use 7.08 RMB/L for the gasoline price and 6.76 RMB/L for the diesel price. Depending on the charging mode and city, the electricity price may differ. According to

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[20] http://finance.sina.com.cn/roll/2017-02-10/doc-ifyamvns4700329.shtml

[21] https://k.autohome.com.cn/spec/14915/ge7/?pvareaid=3454625#dataList

[22] https://finance.sina.com.cn/tech/2021-03-09/doc-ikknscsh9623550.shtml

[23] https://oil.usd-cny.com/

the report about China Electricity Price in 36 cities[24], the average price is 52 RMB per 100 kWh. Therefore, throughout our model, I will use a price of 0.52 RMB/kWh.

A further item to note, but not shown in the following charts, is that electricity prices in rural areas were about 50% higher than in urban areas before 1998 (J X Weinert, 2007). Due to significant government investments in electricity infrastructure in rural areas, rural electricity prices have fallen to urban levels. As a result of this price decrease, the rural E2W market has expanded rapidly, enabling rural consumers to accept other electrified transportation tools such as electric motor-carts and LSEVs. Due to the sparse distribution of gas stations in rural areas, it is much more convenient for LSEV users in rural areas to charge at home rather than refuel at gas stations.

4.2.4 Non-fuel O&M cost

The non-fuel O&M cost includes maintenance cost, insurance cost, vehicle and vessel tax and license fee. Normally, insurances consist of compulsory insurance and commercial insurance. In this study, I only consider compulsory insurances due to the large variations for commercial insurances for different vehicles.

Insurance is not usually purchased for bikes or electric bikes since they are regarded as non-motorized vehicles. For other vehicles in our analysis, the costs of compulsory insurance are presented in

Table **20**. Vehicle and vessel use taxes and license fees are imposed on different vehicles quite differently, as is shown in

Table **20**. Bikes, electric bicycles, and electric tricycles, also have no compulsory insurance due to their low speed and non-motorized category though a vehicle/vessel tax or

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[24] https://www.ceicdata.com/en/china/electricity-price-36-city

license fee is often charged. Also, since currently LSEVs are illegal and not specifically categorized into any type of vehicles, they do not incur fees/taxes or compulsory insurance.

***Table 20 Compulsory insurance, vehicle and vessel tax and license fees*.**

The relevant data are collected from various Chinese websites including autohome.com.cn, sohu.com.

Category	Compulsory insurance (RMB/year)	Vehicle and vessel tax (RMB/year)	License fee (RMB/year)
Bike	0	0	0
Electric bicycle	0	0	0
Electric scooter	156	25	95
Electric tricycle	0	0	0
Gasoline scooter	120	120	300
Gasoline motorcycle	120	120	300
G3Ws	120	120	300
3RVs	340	300	200
Low-end 4RVs	340	420	300
High-end 4RVs	950	900	300
LSEV lead-acid	0	0	0
LSEV lithium-ion	0	0	0
Mini BEV	950	300 (not waived due to not meeting subsidy standard)	500
Compact BEV	950	0 (waived due to NEV subsidy policy)	500
Compact PHEV	950	0 (waived due to NEV subsidy policy)	500
Low-end micro gasoline car	950	300	500
Compact gasoline car	950	480	500

Due to the lower running speed and lower curb weight of 2-wheelers, 3-wheelers, and LSEVs, they have normally lower maintenance costs than normal-speed vehicles, such as BEVs and gasoline-powered cars. Due to the insufficient data for the maintenance cost, I used data from previous studies and made some reasonable assumptions based on information about LSEVs, BEVs, and gasoline automobiles.

A small gasoline vehicle has a lower maintenance cost than a Micro BEV but is slightly higher than an LSEV. Kimble and Wang point out in their paper that the simple product architecture of an LSEV reduces maintenance costs and makes it simpler for non-specialists to repair (Kimble & Wang, 2013). One LSEV consumer reported that the cost for maintenance is usually 100-200 RMB (14.53 ~ 29.07 USD) every 5,000 km. As only one consumer responded to the interview[25], this number may be roughly estimated. Sohu.com reported that the maintenance cost for a BAIC EV series electric car is 440 RMB per 20,000 kilometers excluding battery costs[26]. To contrast, the maintenance cost for a BAIC E series gasoline car is 1,474 RMB per 20,000 kilometers. The maintenance cost of a small gasoline vehicle such as the Cherry QQ (1.0L, MT) will be significantly lower, as indicated by the maintenance information provided by a Cherry 4S shop[27], which amounts to about 3,231 RMB per 60,000 km. The battery replacement is not included in the maintenance cost, but rather, it is discussed in detail in 4.2.5. In the following example, I assume that electric bicycles with lithium-ion batteries, electric scooters, and electric tricycles have the same maintenance cost as electric bicycles, and that gasoline scooters and G3Ws have the same maintenance cost as gasoline motorcycles. As there are very few studies and data available about the maintenance of rural vehicles, I assume the maintenance costs to be similar to those of gasoline motorcycles, with slightly higher costs for high-end 4RVs. The maintenance cost for compact PHEVs is estimated to be equal to that for compact BEVs and gasoline cars at 0.05 RMB/km.

Table 21 Summary of maintenance cost per km for vehicle models in our analysis.

Category	**Maintenance cost (RMB/km)**
Bike	0.0075 (Weinert, 2007)
Electric bicycle (lead acid battery)	0.0375 (Weinert, 2007)
Electric bicycle (lithium-ion battery)	0.0375
Electric scooter	0.0375
Electric tricycle	0.0375
Gasoline scooter	0.0765
Gasoline motorcycle	0.0765 (Weinert, 2007)
G3Ws	0.0765
3RVs	0.0765
Low-end 4RVs	0.0765
High-end 4RVs	0.08
LSEV (lead-acid battery)	0.030 (Authors' calculation from above)

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[25] http://finance.sina.com.cn/roll/2017-02-10/doc-ifyamvns4700329.shtml
[26] https://www.sohu.com/a/114634505_464093
[27] https://www.autohome.com.cn/2989/0/43/Section.html

LSEV (lithium-ion battery)	0.030 (Authors' calculation from above)
Mini-BEV	0.022 (Authors' calculation from above)
Compact BEV	0.030 (Authors' calculation from above)
Compact PHEV	0.05
Low-end micro gasoline car	0.054 (Authors' calculation from above)
Compact gasoline car	0.0737 (Authors' calculation from above)

4.2.5 Battery cost and lifetime

This section discusses battery cost and lifespan for lead-acid batteries and lithium-ion batteries on different vehicles. In general, there are three main usages for lead-acid batteries: start-light-ignition (SLI), power storage, and traction. The SLI battery is used primarily for starting automobiles, illumination and starting motorcycles, as well as starting CRVs. Storage batteries provide emergency power when the primary power supply fails and are widely used in telecommunications systems, uninterrupted power supply (UPS) and electrical energy storage systems (Tian, Wu, Gong, & Zuo, 2015). Traction batteries are commonly installed in electric bikes, low-speed electric vehicles, touring cars, and forklifts to provide higher power capacity and output.

Compared to lithium-ion batteries, traction lead-acid batteries are heavy, large, and short-lived. Typically, lead-acid batteries can lasts 3-5 years on average by design; however, because of temperature, overcharging, and over-discharging, the lead-acid batteries normally last for around two years when used on LSEVs. If the lifetime of an LSEV is 8 years, then four sets of lead-acid batteries must be replaced, which will result in a significant increase in the cost of owning an LSEV. In a compact gasoline vehicle, lead-acid batteries are primarily used for SLI, and their lifespan is approximately four years, so two sets of lead-acid SLI batteries are expected to be replaced over an eight-year period (Tian et al., 2015).

Generally, lithium-ion batteries have a much longer life than lead-acid batteries, and BEV manufacturers in China provide warranties for either 8 years/150,000 km or 8 years/120,000 km, and some manufacturers offer lifetime warranties for lithium-ion batteries. For consumers, the battery swap is free during the warranty period. On China's EV markets, I have collected battery capacity data for micro BEVs, compact BEVs, and compact PHEVs. These data can be applied to our battery cost calculation in our TCO models. Figure 28 illustrates the distribution of battery capacity among different PEVs. According to our observation, most mini BEVs are equipped with batteries of 20-30 kWh, while compact BEVs have batteries that are 20 kWh larger than mini BEVs. Compact plug-in hybrid vehicles typically have smaller batteries (about 10 kWh) to provide a shorter electric range.

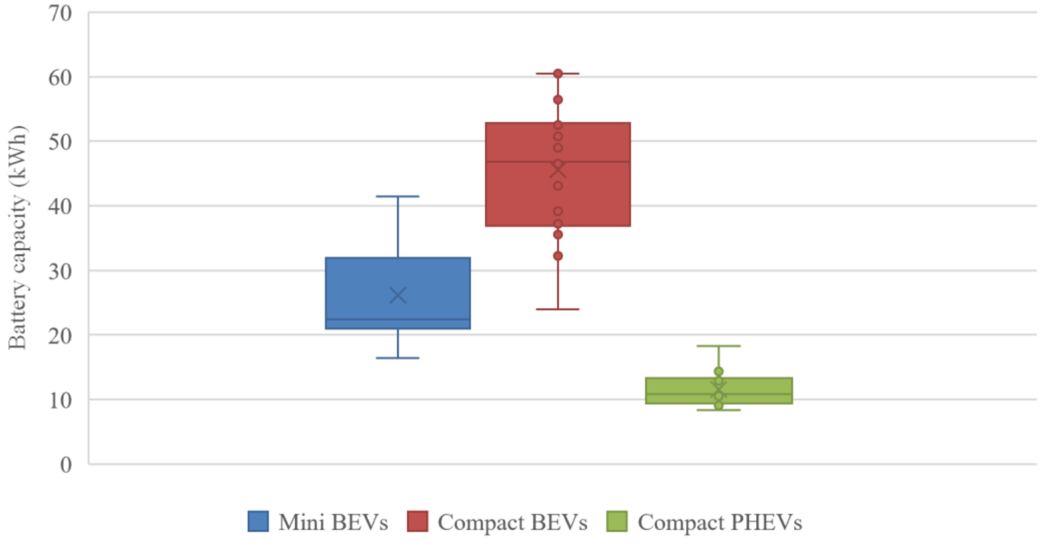

Figure 28 Battery capacity for mainstream mini BEVs, compact BEVs and compact PHEVs in China.

Most of mini BEVs are equipped with batteries around 20 kWh capacity while compact BEVs are equipped with larger batteries around 40~50 kWh capacity. For compact PHEVs, most batteries are about 10 kWh. The data sources include d1ev.com and vehicle manufacturers' official websites.

Studies have been conducted on the cost projections for electric vehicle batteries. Nevertheless, I will not consider battery cost reduction, battery lifetime expansion, and battery energy density improvement in this study, due to a lack of data and our intention for the TCO models to serve as a snapshot of current technologies rather than to forecast future vehicle costs.

According to various studies and reports[28], the cost of lithium-ion batteries is approximately 1000 RMB/kWh (about $150/kWh), with the cost of batteries expected to continue to decrease by about 7-10% per year. Lead-acid batteries are cheaper to purchase, which are about 750 RMB/kWh (about $110/kWh) but have a shorter life span, lower energy density, and require more frequent replacement over the course of a vehicle's lifespan. Our study uses a cost of 800-1200 RMB/kWh for lithium-ion batteries and 600-900 RMB/kWh for lead-acid batteries to include more variability in the analysis.

In lead-acid batteries, the battery life varies depending on the intensity of use. In electric bicycles, scooters and tricycles, the battery can last for two to three years (Tian et al., 2015). In contrast, based on our interviews with LSEV dealers and drivers, it is common practice to replace batteries every two years. In addition, I differentiate battery life for lithium-ion batteries based on the type of vehicle. It is assumed that the li-ion battery life is approximately 5-7 years for electric bicycles, and 4-6 years for electric cars for simplicity purpose.

Table 22 Summary of battery cost, liftetime and capacity for vehicles in the TCO models

Vehicle type	Battery type	Battery cost (RMB/kWh)	Battery lifetime (years)	Battery capacity (kWh) [29]
Electric bicycle	Lead acid	600-900	2-3	0.5-0.7
Electric bicycle	Lithium-ion	800-1200	5-7	0.5-0.7
Electric scooter	Lead acid	600-900	2-3	1-1.5
Electric tricycle	Lead acid	600-900	2-3	1.2-3.2
LSEV	Lead acid	600-900	1.5-2.5	4-10
LSEV	Lithium-ion	800-1200	4-6	7-13
Mini BEV	Lithium-ion	800-1200	4-6	19.5-32.9
Compact BEV	Lithium-ion	800-1200	4-6	36-55.2
Compact PHEV	Lithium-ion	800-1200	4-6	8.32-14.38

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[28] https://www.bloomberg.com/news/articles/2020-12-16/electric-cars-are-about-to-be-as-cheap-as-gas-powered-models

[29] Battery capacity data is collected from various sources such as jd.com, taobao.com, dealer interviews and user interviews.

4.2.6 Vehicle lifetime

Typically, a fixed holding period such as 5 years or 10 years is used for calculating the TCO cost of various mobility solutions. Residual values are ignored in the studies due to a lack of data on the residual values of different types of vehicles. In our case, I have considered the real lifetime of a variety of vehicles by relying on different sources and estimates from authors.

The lifetime of bikes is estimated based on user interviews and online sources. I assume that the battery life of electric bicycles with lithium-ion batteries will be the same as that of electric bicycles with lead-acid batteries. Based on Weinert's dissertation (J X Weinert, 2007), the life expectancy of gasoline scooters is estimated to be 5-8 years. As a result of their similar price and functionality, electric scooters and electric tricycles are assumed to have the same lifetime as gasoline scooters. Gasoline motorcycles and 3W gasoline motorcycles (G3Ws) are predicted to have a longer lifetime than gasoline scooters. According to Sperling et al. (2004), the useful life of a 3W RV and a 1-cylinder 4W CRV (low-end 4RVs) is six years, while the useful life of a multi-cylinder 4W CRV (high-end 4RVs) is nine years.

Table 23 Vehicle lifetime comparison for different types of vehicles.

Category	**Vehicle lifetime (years)**
Bike	3-5 (Authors’ estimation)
Electric bicycle (lead acid battery)	3-6 (J X Weinert, 2007)
Electric bicycle (lithium-ion battery)	3-6 (Authors’ estimation)
Electric scooter	5-8 (Authors’ estimation)
Electric tricycle	5-8 (Authors’ estimation)
Gasoline scooter	5-8 (J X Weinert, 2007)
Gasoline motorcycle	7-10 (Authors’ estimation)
G3Ws	7-10 (Authors’ estimation)
3RVs	4-8 (Sperling et al., 2004)
Low-end 4RVs	4-8 (Sperling et al., 2004)
High-end 4RVs	7-11 (Sperling et al., 2004)
LSEV (lead-acid battery)	5-11 (Interviews and Authors’ estimation)
LSEV (lithium-ion battery)	5-11 (Interviews and Authors’ estimation)
Mini-BEV	5-11 (Assumed to be the same with LSEVs)
Compact BEV	6-12 (Assumed to be the same with compact gasoline cars)
Low-end micro gasoline car	6-12 (Assumed to be the same with compact gasoline cars)
Compact gasoline car	6-12 (Interviews)

4.3 Results

4.3.1 Total cost of ownership analysis

Figure 29 illustrates the total cost of ownership for a variety of two and three wheelers. (1) Due to the high price of fuel, gas and diesel powered two- and three-wheelers are more expensive than electric powered two- and three-wheelers. 2) For electric modes, the largest part of the total cost is the purchase cost, while for gasoline or diesel modes, the largest part is the fuel cost. The variations for gasoline motorcycles, G3Ws, and 3RVs are significant as a result of the substantial variations in vehicle lifetime and vehicle mileage.

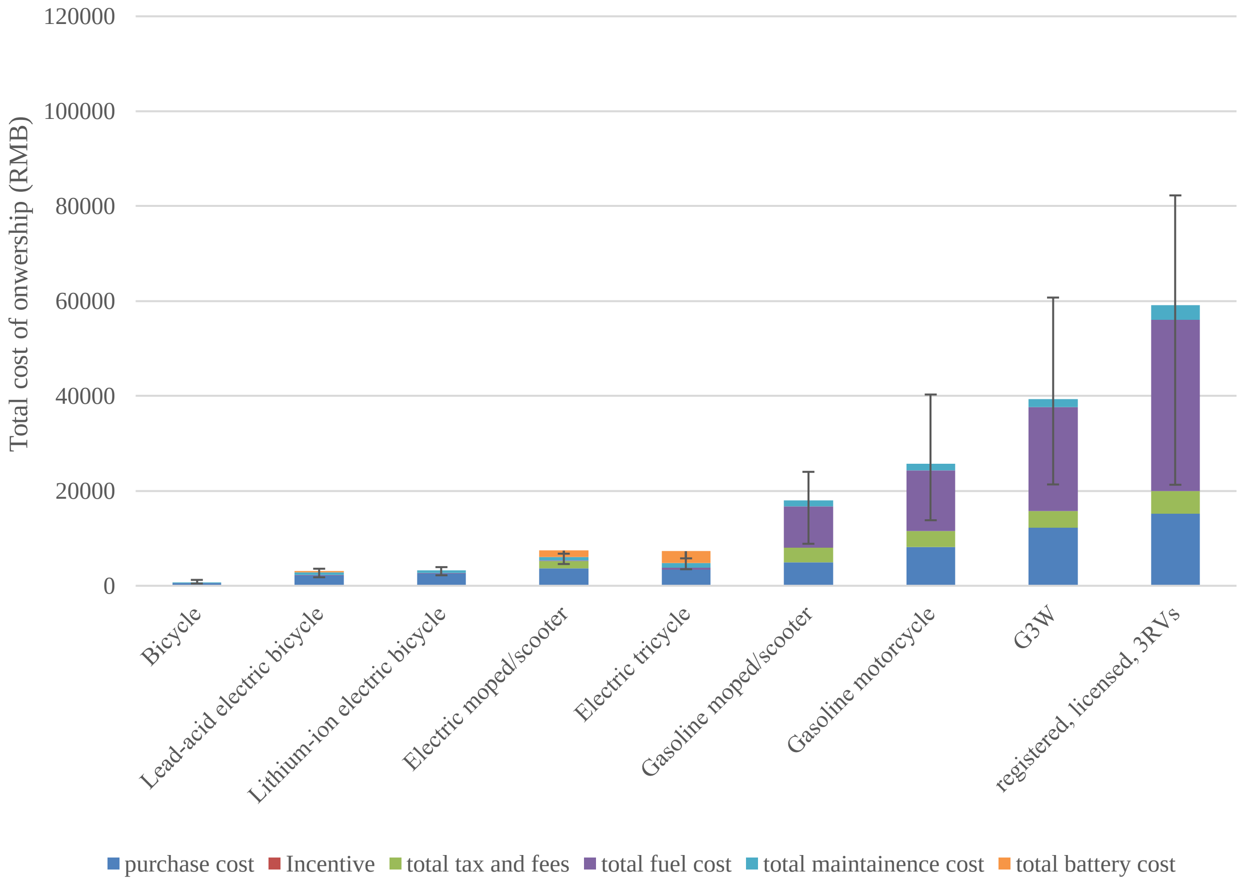

Figure 29 Comparison of total cost ownership for 2Ws and 3Ws with error bars.

To calculate the present TCO, all variable costs, such as annual taxes and fees, fuel costs, maintenance costs, and battery exchange costs, are discounted. In order to obtain the lower and upper bounds of TCOs for different vehicle types, the error bars were obtained using Monte Carlo simulation in R.

In Figure 30, by examining the levelized costs (cost per kilometer) of two and three wheelers, we can see that there is a smaller gap between the electrified and non-electrified modes compared with the total costs of ownership above. I assume that the driving profiles and life expectancies of each vehicle are different. Because non-electric vehicles are driven more frequently and for longer periods of time than electric vehicles, the gap in levelized costs between the two will narrow.

For electricity-powered modes and bicycles, the most significant component is the purchase price, while the cost of the batteries plays a significant role for lead-acid-fueled 2/3 wheelers. The battery of a lithium-ion battery electric bicycle should not need to be replaced during its lifetime based on our assumptions about the battery life and the lifespan of the bicycle. Consequently, the levelized cost of lithium-ion electric bicycles is close to parity with lead-acid electric bicycles. Another significant cost-saving factor for electrified modes, other than battery-powered scooters, is the annual taxes and fees charged by the state. Since non-motorized vehicles such as e-bikes and e-tricycles are exempt from annual registration fees and inspection fees, the additional tax and fees saved in the levelized costs makes owning a non-motorized vehicle a more cost-effective decision.

Fuel is the largest cost component of gasoline/diesel 2/3 wheelers due to their low fuel efficiency and higher fuel prices compared to electric powered vehicles. Purchase cost is the second largest cost component, followed by tax and fees. Non-electric 2/3 wheelers have a levelized cost of approximately 0.4 RMB/km, which is about twice as high as electric 2/3 wheelers around 0.2 RMB/km.

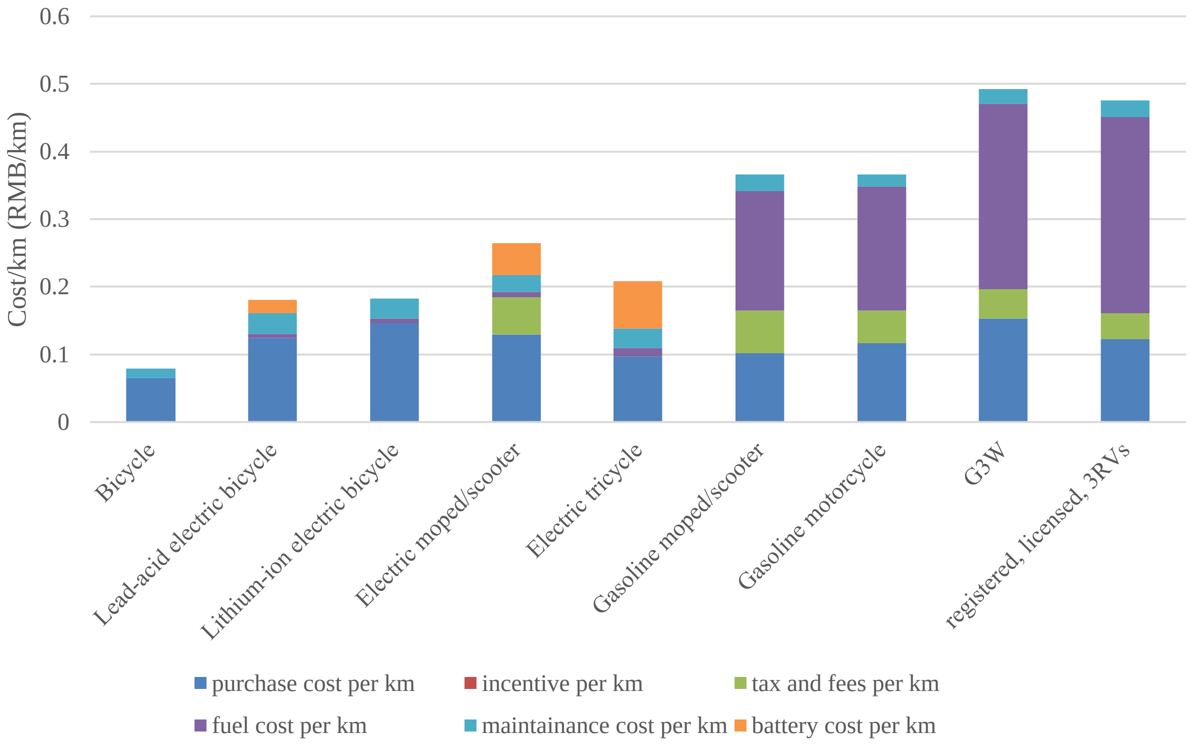

Figure 30 Comparison of cost per km for 2/3 Ws.

Normalized by use of VKTs, we can observe that purchase costs are the largest cost component for electric vehicles (2/3 Ws) and bicycles, followed by battery costs as the second largest component except for bicycles and lithium-ion electric bicycles (there will be no battery swapping during the lifetime of the vehicle). The largest cost component for gasoline 2/3 Ws is the fuel cost, followed by the purchase cost.

There are primarily four types of four-wheel vehicles with different technologies or classes. Rural vehicles, low-speed electric vehicles, battery electric vehicles, and gasoline cars constitute the four types. According to Figure 31, for rural vehicles of low- or high-end types, the most significant component of total cost is the fuel cost, due to the extremely poor fuel economy. The largest component of the cost of LSEVs and BEVs is the purchase price, while the second largest component is the cost of replacing batteries during the vehicle's lifetime. The only vehicle type that is eligible for the purchase subsidy is the compact BEV. For gasoline cars, the largest component of the cost is the purchase price, and the second largest component is the fuel cost. In addition, it is noteworthy that the large variation in total costs for RVs is due to a large variation in vehicle lifetimes and fuel efficiency.

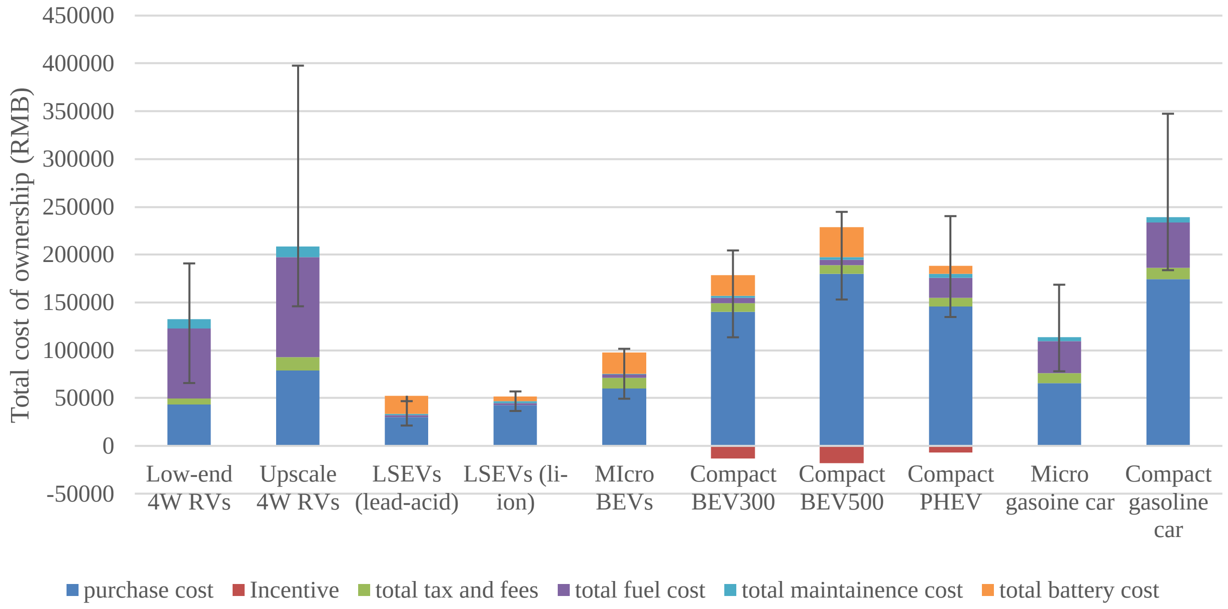

Figure 31 Comparison of total cost ownership for 4Ws with error bars.

To calculate the present TCO, all variable costs, such as annual taxes and fees, fuel costs, maintenance costs, and battery exchange costs, are discounted. In order to obtain the lower and upper bounds of TCOs for different vehicle types, the error bars were obtained using Monte Carlo simulation in R.

In terms of levelized costs (cost per kilometer) of four wheelers, the composition of the levelized costs (cost per kilometer) of BEVs and gasoline cars is quite different, as shown in Figure 32. Due to the high initial purchase costs associated with a compact BEV and gasoline car, the levelized vehicle purchase cost is higher than any other cost. Due to BEVs' efficient powertrain and low electricity costs, the levelized fuel costs for BEVs are quite small. It is the same for LSEVs that the purchase cost dominates the cost component. Due to the short lifespan of lead-acid or lithium-ion batteries, the second largest component of the cost of BEVs and LSEVs is the battery costs. In comparing the LSEVs with lead-acid batteries and lithium-ion batteries, it was found that the LSEVs with lead-acid batteries have higher battery costs than the LSEVs with lithium-ion batteries. This is because lead-acid batteries have a shorter lifespan and over four batteries will need to be swamped during the lifetime of the LSEVs. In rural vehicles, one notable finding is that the fuel cost exceeds the levelized purchase cost primarily due to the lower price of RVs compared with gas cars, and the exceptionally low fuel efficiency of diesel engines used in rural vehicles.

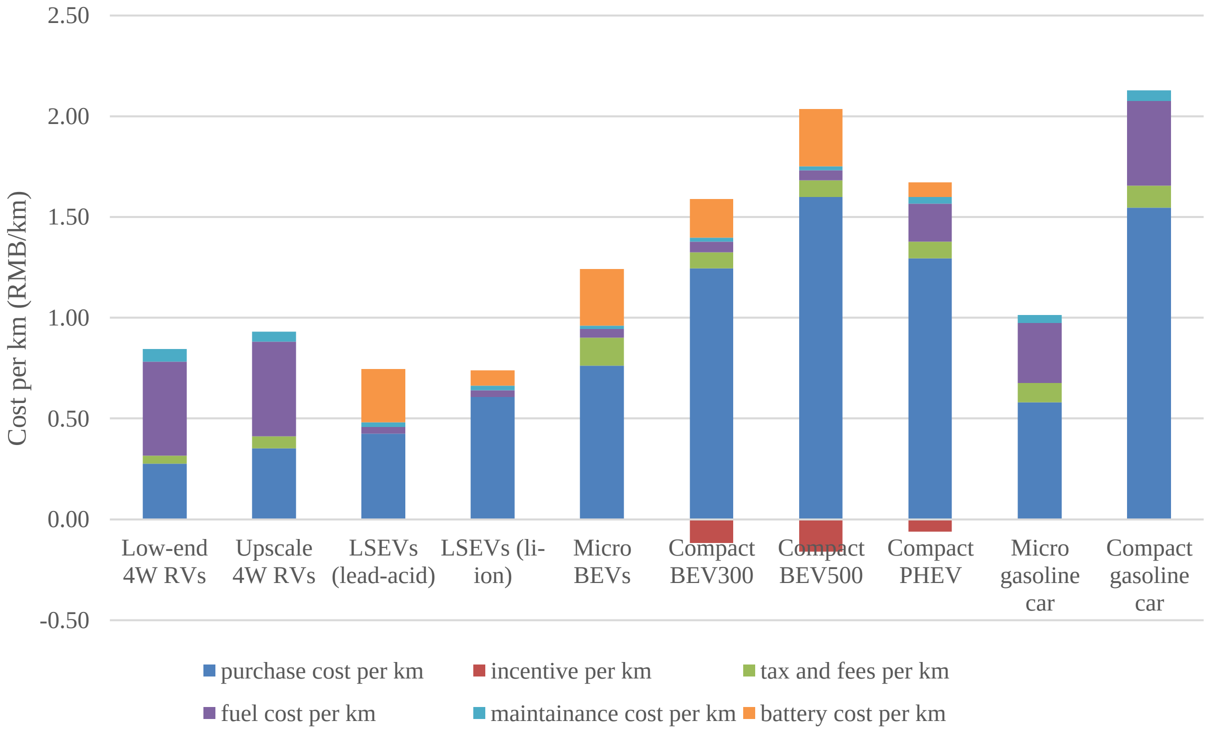

Figure 32 Comparison of cost per km for 4Ws.

Normalizing by VKTs, we observe that the purchase cost is the largest cost component for electric 4Ws, followed by battery cost. The largest cost component for diesel 4Ws (low-end and upscale RVs) is fuel, followed by purchase costs. For gasoline cars, the largest cost component is the purchase price, followed by the cost of fuel.

4.3.2 Sensitivity analysis

In this section, a Monte Carlo stochastic simulation of 100,000 total cost calculations for each type of vehicle is designed and implemented to determine the change in TCOs and cost per km associated with changing transportation modes while capturing uncertainty and heterogeneity. The simulation of the vehicle cost of ownership is based on publicly available data from various journals, papers, and websites, as well as estimates from previous sections in this chapter. Monte Carlo methods are used to understand the variability and stochasticity of costs when owning different types of vehicles. We can also identify the most important variables that can impact the cost of owning a vehicle, and therefore, these important variables could be used as policy levers to promote the purchase of more energy-efficient and greener vehicles.

Using Monte Carlo simulation to estimate the total cost of 2/3 wheelers, the following two figures indicate an obvious stochastic dominance of gasoline and diesel vehicles over electric vehicles. Four fossil-fueled two and three-wheeler vehicles, including G3Ws, low-end 3W RVs, gasoline scooters and gasoline motorcycles, are significantly more expensive to own than electric two and three wheelers and bicycles. Due to the higher uncertainty in some variables such as VKT, vehicle lifetime, etc., the greater range of the total cost curve for these fossil-powered vehicles also indicates the greater uncertainty in total cost.

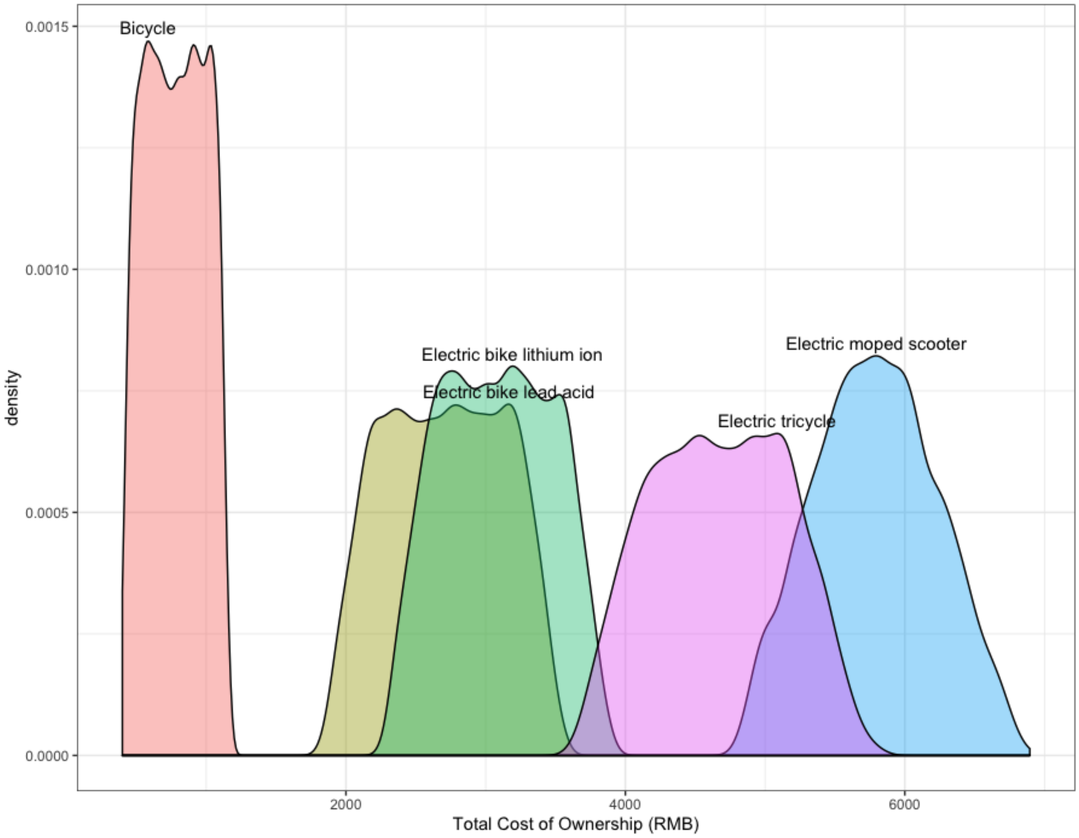

Figure 33 TCO comparison of 2Ws and 3Ws (Electric)

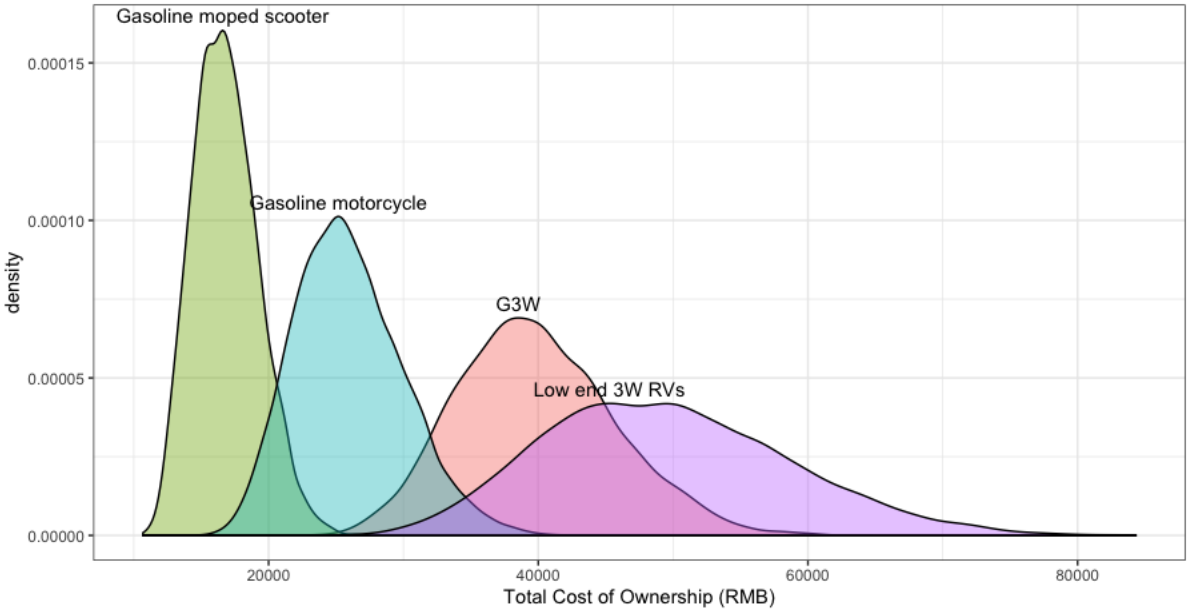

Figure 34 TCO comparison of 2Ws and 3Ws (Gasoline and Diesel).

The gasoline and diesel 2/3Ws dominate the electric 2/3Ws in an obvious stochastic manner. In general, gasoline/diesel vehicles have higher VKTs and therefore higher fuel costs, thus causing their dominance. In addition, the wider ranges of gasoline/diesel 2/3Ws indicate that the variables are more volatile and that the total costs are easily impacted.

Changing from total cost to levelized cost, the stochastic dominance is no longer evident as in TCOs. Figure 35 demonstrates that the G3Ws, G2Ws (gasoline motorcycles and gasoline scooters) and low-end 3W RVs still have a stochastic dominance over other modes, but the difference is smaller. Considering that the levelized cost is commonly used to compare the cost of traveling for different modes of transportation, the overlap indicates that there is no clear advantage to some modes over others in terms of cost. Moreover, based on the plot, we can also conclude that the cost per kilometer for electric 2/3Ws is under 0.3 RMB/km, while the cost per kilometer for gasoline/diesel 2/3Ws is approximately 0.4-0.7 RMB/km. G3Ws have the highest levelized cost and gasoline scooters have the lowest levelized cost among the four gasoline/diesel vehicles, while gasoline motorcycles and low-end 3W RVs have a distribution of levelized costs that is very similar. Overall, owning an electric mode of 2/3 wheelers is less expensive than owning a gasoline/diesel mode of 2/3 wheelers in terms of total cost of ownership (TCO). The gap becomes smaller when we compare levelized costs.

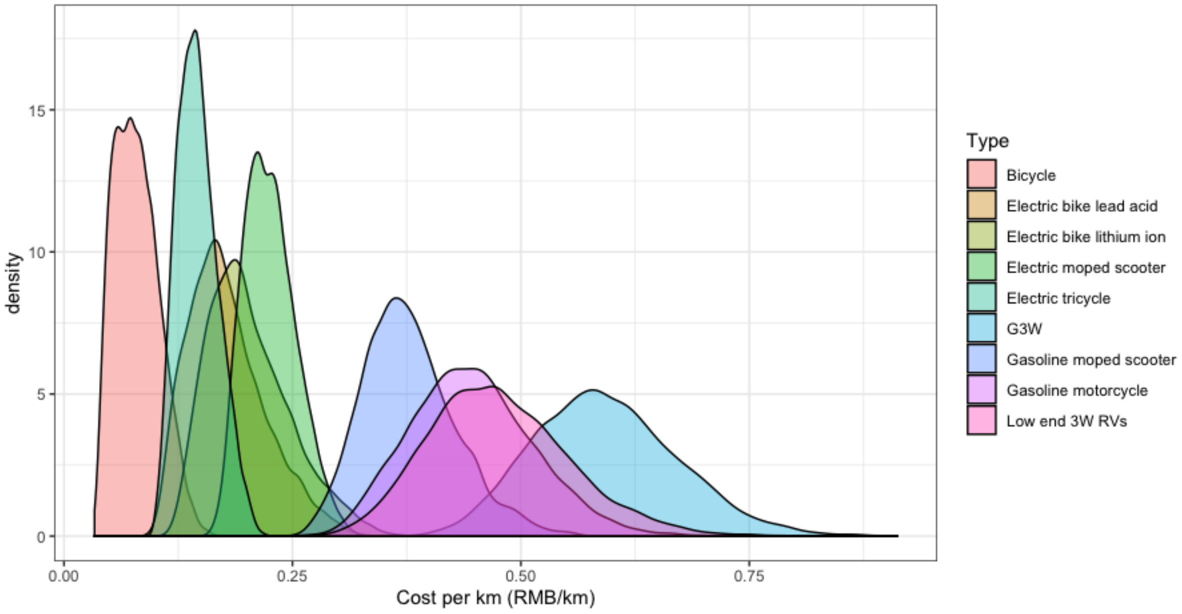

Figure 35 Levelized cost (cost per km) comparison for 2Ws and 3Ws.

Considering real-world travel intensities, gasoline/diesel vehicles have a less stochastic dominance over electric ones when the levelized cost is considered. The cost per km of owning a gasoline/diesel 2/3W is still double that of owning an electric 2/3W.

A Monte Carlo simulation of 4-wheeler total costs indicated that compact gasoline cars, large 4RVs, and compact BEV400 have similar total cost results, whereas the compact BEV300 falls behind compact gasoline, diesel, PHEVs, or BEV400, which could be expected since the BEV300 has no engine and smaller batteries. LSEVs (lead-acid batteries), LSEVs (Lithium-ion batteries), and Micro BEVs are the vehicles with the lowest total cost. As a result, gas- and diesel-powered vehicles generally represent a higher total cost of ownership than electric mobility solutions due to high purchase costs and fuel costs, whereas LSEVs are the cheapest vehicles due to their lower purchase costs, shorter annual travel distances, and lower electricity prices.

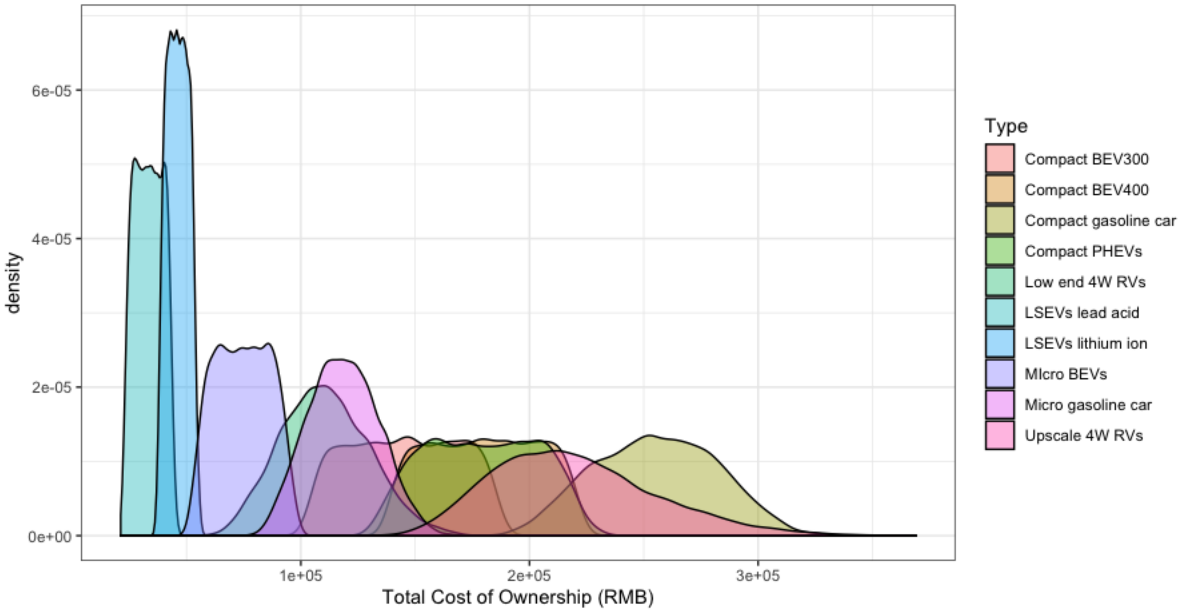

***Figure 36 TCO comparison of 4Ws**.*

Gasoline compact cars and upscale RVs tend to have a relative stochastic dominance over other options, whereas LSEVs are cheapest to own over the course of their lifetimes. In terms of total costs, there are numerous overlapping options in the middle, which indicates that it is not clearly better or worse to own different vehicles.

When considering the real-world driving profiles and vehicle lifetimes, there is no indication that there is a clear stochastic dominance for the levelized cost of 4-wheelers. However, the levelized cost of compact gasoline vehicles appears to have a relative stochastic dominance over all other electric vehicles. Compact BEV400s and compact PHEVs have very similar distributions. Furthermore, the long range of gasoline vehicles indicates a higher level of uncertainty in related variables. In terms of levelized cost, the compact gasoline vehicles/compact BEVs are stochastically more expensive to own than LSEVs and 3RVs as they belong to different classes of vehicles. A micro–BEV or a micro gasoline car has a slightly higher levelized cost than an LSEV. According to the overlapping of some curves, the levelized cost advantages are quite uncertain.

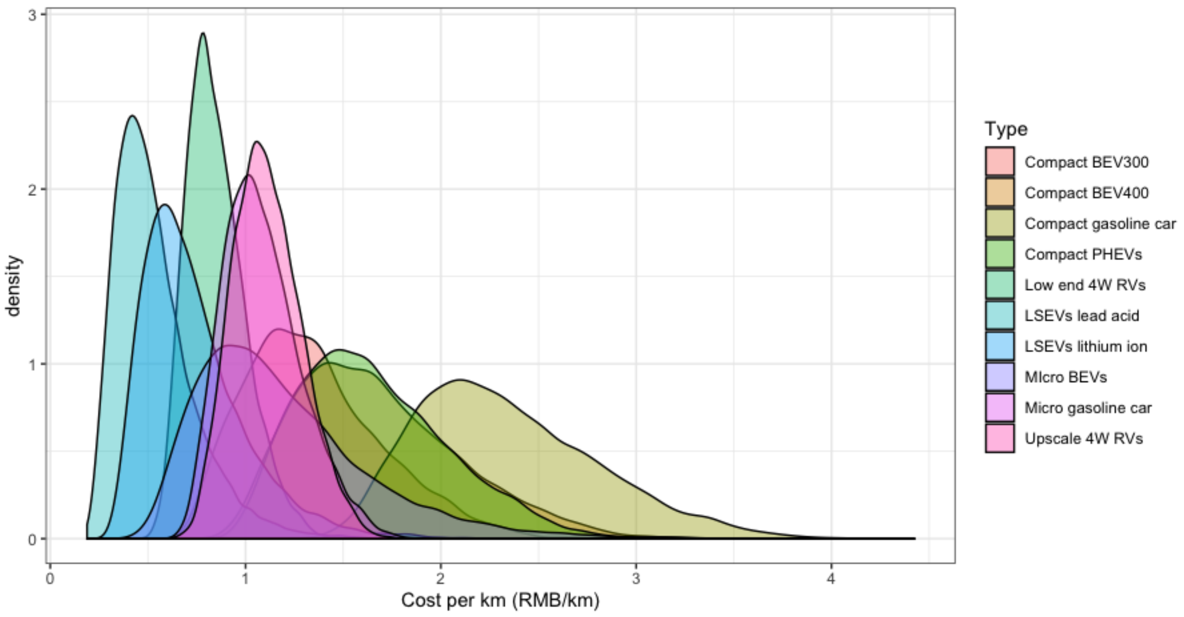

Figure 37 Levelized cost (cost per km) comparison for 4Ws.

In terms of real-world travel intensities, the stochastic dominance is diminishing, except for compact gasoline cars, for which the levelized cost is approximately 2-3 RMB/km. In addition, this chart demonstrates that switching from gasoline cars to other alternatives such as LSEVs, compact BEVs, PHEVs or micro BEVs will be cost-effective for consumers. Even so, there is no one type of vehicle that is clearly better or worse than another.

The general conclusion from these two figures is that gasoline modes typically have a higher levelized cost than the same-class low-end electric modes and diesel vehicles. In real-world driving profiles and lifespans, however, there is not necessarily a better or inferior option.

4.4 Conclusion

In the study, a comprehensive TCO analysis is conducted in order to better evaluate the cost of owning different vehicles. The study considers the different cost components and the key factors that influence both the total costs and the levelized costs. In addition, a Monte Carlo simulation is applied to better understand the variability of the costs. A total of 19 vehicle types are included in this study for the purpose of making the comparison more comprehensive, and several assumptions are made to simplify the modeling process.

Using two metrics (total cost and levelized cost), electric modes are found to be less expensive to own than their replacing counterparts, but the difference will be smaller if the real-world travel intensity is considered. The largest component of the cost for gasoline/diesel vehicles is the fuel cost, followed by the purchase cost, whereas the largest component for electric vehicles is the purchase cost. The comparison between lead-acid battery vehicles and lithium-ion battery vehicles reveals that the battery replacement cost accounts for a large share of both the total costs and levelized costs for lead-acid battery vehicles due to their shorter lifetime. Hence, switching from lead-acid LSEVs to lithium LSEVs is totally cost-effective and results in less pollution, higher battery capacities, etc.

This study has two major limitations, both of which may be improved in future studies. Firstly, fixing the holding years and including the vehicle residual values into the model will make the comparison fairer, and the model will be free of the assumptions I made on vehicle lifetimes. Secondly, the sensitivity analysis can be improved by adding the relative feature importance to the total cost and levelized cost. Thus, we may be able to identify the most important factors that influence the cost to own a vehicle, which can be utilized by policy makers as a means of promoting the purchase of cleaner vehicles.

CHAPTER 5 ENERGY AND EMISSIONS ANALYSIS

EVs have the great potential to reduce energy use and carbon emissions. However, the power of reducing carbon emissions depend on the electricity grid. There are various studies researching on the environmental impacts of EVs in China. Huo et al. in 2010 examined the fuel-cycle CO_2 emissions of EVs in China in both 2008 (current) and 2030 (future) periods and found out EVs do not promise much benefits in reducing CO2 emissions mainly because the majority of electricity was generated from coal in China (Huo, Zhang, Wang, Streets, & He, 2010). Zhou et al. compared the energy consumption and GHG emissions of PHEVs and BEVs with ICEVs on the level of the regional power grid in 2009, and found out that there were higher energy saving and GHG emissions reduction in central, southern and northwestern provinces compared with northern, northeastern and eastern provinces due to the higher share of coal-fired power in these regional grids (Zhou, Ou, & Zhang, 2013).

Huo et al. in 2014 also compared the fuel-cycle emissions of GHGs and air pollutants of EVs in China's and the U.S.'s six most populated and economically developed regions, and the results showed that EV fuel-cycle emissions depend substantially on the carbon intensity and cleanness of the electricity mix (Huo, Cai, Zhang, Liu, & He, 2015). Zhao et al. evaluated the life-cycle cost and emissions of BEVs in China and found out BEVs are not economically competitive compared with ICEVs in the Chinese market and BEVs likely will not be economically competitive in China before 2031 (X. Zhao, Doering, & Tyner, 2015). Qiao et al. in 2017 conducted the cradle-to-gate GHG comparison of BEVs and internal combustion engine vehicles (ICEVs) in China, and found out the GHGs of BEVs are 50% higher than ICEVs, with 20% of GHG increase caused by traction battery production, and suggest to improve manufacturing technique of traction battery production, vehicle recycling and energy structure optimization (Qiao, Zhao, Liu, Jiang, & Hao, 2017). Li et al. in 2019 assessed the emission reduction effects of EV adoption at different provinces by a well-to-wheel model, and the results show that the future potential for emission reduction is mainly from southern provinces due to their large market potential and availability of clean power (Li et al., 2019).

However, the energy and environmental impacts of low-speed vehicles such as LSEVs are not yet evaluated due to lack of data and interests. In this chapter, I will conduct a spatial analysis of the energy and emission impacts of different vehicle technologies, with a special focus on low-speed vehicles.

5.1 Methodology and data

I utilize life-cycle assessment (LCA) methods for evaluating energy use and greenhouse gas emission impacts by considering a vehicle's lifetime energy consumption and greenhouse gas emissions, which includes vehicle production, energy production, vehicle operation, and vehicle recycling.

Unfortunately, there are some limitations to conducting a full comparative LCA analysis due to the lack of information for some specific types of vehicles in our studies, such as the production phase and recycling phase of E2Ws, Gasoline Motorcycles, and LSEVs. Instead, I will focus solely on vehicle operation/TTW (tank-to-wheel). In terms of GHG emission analysis, I concentrate on the two main phases of the LCA analysis, namely energy production (well-to-tank phase) and vehicle operations (tank-to-wheel phase). Tank-to-wheel energy use and emission calculation for one vehicle is as follows:

$$Fuel_k^{TTW} = \sum_i \sum_j (Stock_i \times VKT_{i,j,k} \times FC_{i,j,k} \times density_k \times 10)$$

$$GHG_k^{TTW} = Fuel_k^{TTW} \times EF_k \times \frac{44}{12}$$

- *i* indicates different vehicle technologies such as E2Ws, LSEVs, or Gasoline Cars, etc.
- *j* indicates the vehicle age in years.
- *k* indicates fuel type, including gasoline, diesel and electricity.
- $Stock_i$ is the vehicle population for that vehicle technology.
- $VKT_{i,j,k}$ is the annual distance travelled (km).
- $FC_{i,j,k}$ is the fuel consumption rate per distance traveled (L/km or kWh/km).
- $Density_k$ is the density of fuel k (kWh/L or kWh/kWh).
- EF_k is the CO2 emission factor (kg/kWh).
- $Fuel_k$ (TTW) and GHG_k (TTW) are TTW fuel consumption (kWh) and CO2 emissions (g), respectively.

For well-to-tank phase, I will include the monthly average grid emissions rate for different electricity generation methods at each province, whereas I will not include the emissions resulting from fossil fuel production, due to the higher efficiency of fossil fuel production.

For different vehicle technologies, I have already collected data regarding vehicle VKTs, fuel consumption rates, and energy density as shown in previous chapters. As a result, calculating the energy consumption of different vehicle technologies is relatively straightforward. As part of the calculation of the GHG emissions, I obtained highly detailed data on the electricity grid emission rate in various provinces of China.

5.2 Vehicle energy efficiency and grid emission rate

Our calculations are at the individual vehicle level, but I consider a variety of driving profiles and vehicle performance for each technology. Since all variables related to vehicle technology are the same across provinces except for the provincial grid emission rate, the calculation of energy is at the technology level, whereas the measurement of GHG emissions is at the technology and province level.

In view of the high-resolution data for the grid emission rate in each province of China, a geospatial comparison is conducted in order to examine the different potentials in terms of reducing GHG emissions within the different provinces.

Figure 38 demonstrates the percentage of electricity generated with coal in each province. This provides some insights into the percentage of clean electricity produced in each province, since coal dominates the production of electricity using fossil fuels. A large percentage of China's electricity is generated by coal in the northern provinces. In contrast, most of the country's electricity is generated by hydropower in southern provinces, such as Sichuan and Yunnan. Beijing has reduced its coal-based electricity production to 0% since 2017. Beijing has ceased using coal-based generators and has become the first Chinese city to only produce electricity using renewable sources.

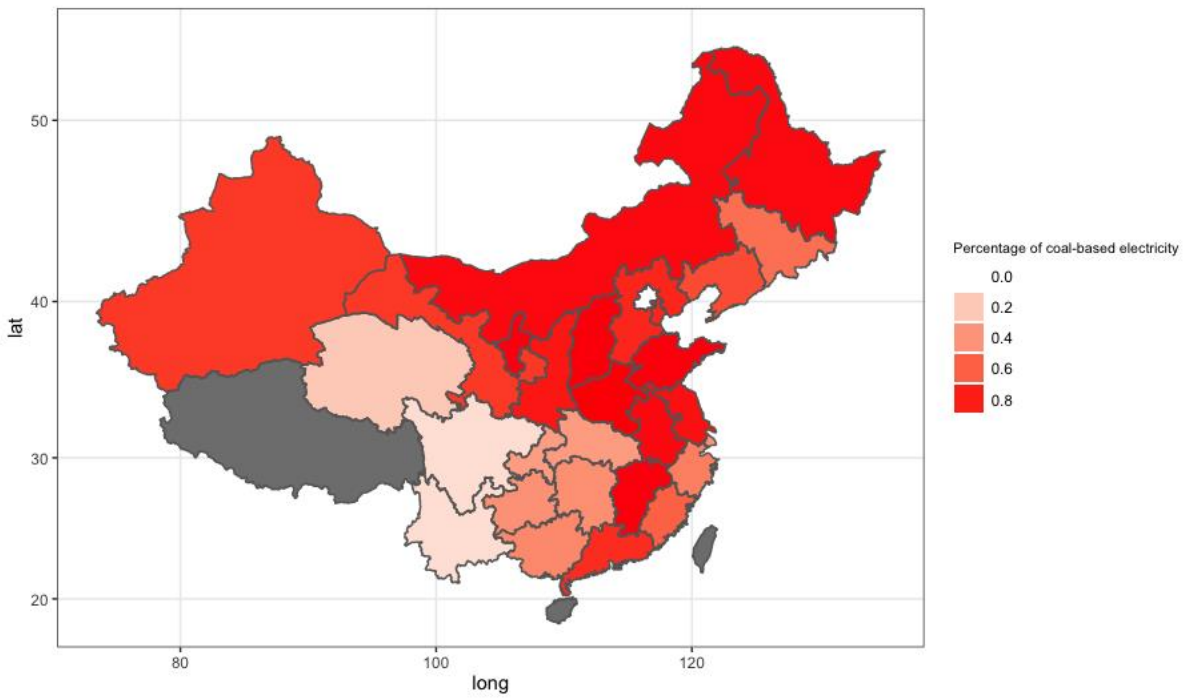

Figure 38 Percentage of electricity production with coal in each province.

The northern provinces of China have a very high percentage of coal generation due to their relatively richer coal resources, while most southern provinces, especially the southwestern provinces, such as Sichuan, Yunnan, Qinghai, which have plenty of hydropower or solar power to generate electricity. Data is not available for Tibet, Hainan and Taiwan. The data source is from the collaborator from MIT.

Figure 39 shows the difference in annual emissions between micro gasoline vehicles and LSEVs with lead-acid batteries. Given that I assumed that the emission factor for micro gasoline was similar across provinces, the plot below illustrates the potential reduction of GHGs when switching from micro gasoline vehicles to LSEVs, which is similar to the previous plot. Additionally, Qinghai, Sichuan, Yunnan, and Beijing have the highest reduction potential, whereas coal-based electricity generation has the lowest percentage. Conversely, Shandong, which is the largest LSEV market, has the lowest potential for reducing greenhouse gas emissions by switching from micro gasoline cars to LSEVs (lead-acid).

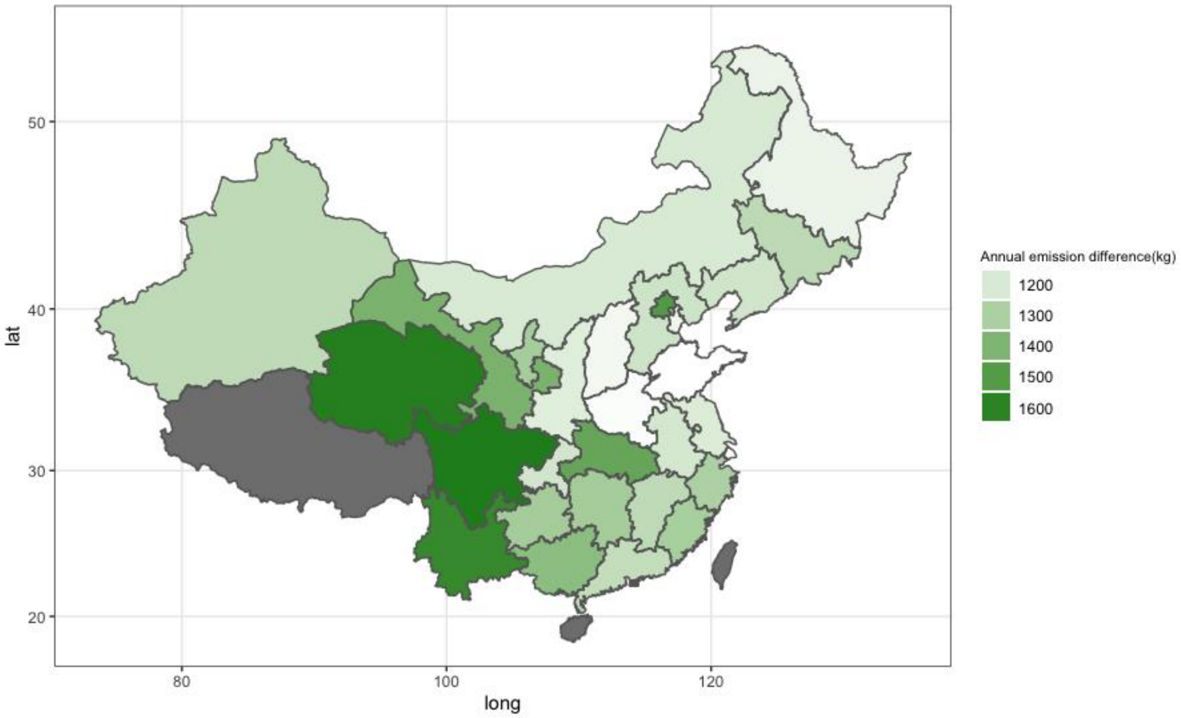

Figure 39 Annual emission difference (kg) between micro gasoline vehicle and LSEV (lead-acid).

Provinces such as Qinghai, Sichuan, Yunnan and Beijing have the largest potential of GHG reduction when switching from micro gasoline vehicles to LSEVs with lead-acid batteries, where these provinces have very low percentage of coal-based electricity generation. For provinces with large population of LSEVs such as Shandong, Henan, the potential of GHG reductions is the smallest. About annual over 1600kg GHG reduction can be achieved when switching one micro gasoline vehicle to a lead-acid LSEV in provinces with largest potentials.

In Figure 40, similar results can be observed with respect to Figure 39, since I am comparing micro gasoline cars with LSEVs that are powered by either lead-acid batteries or lithium-ion batteries.

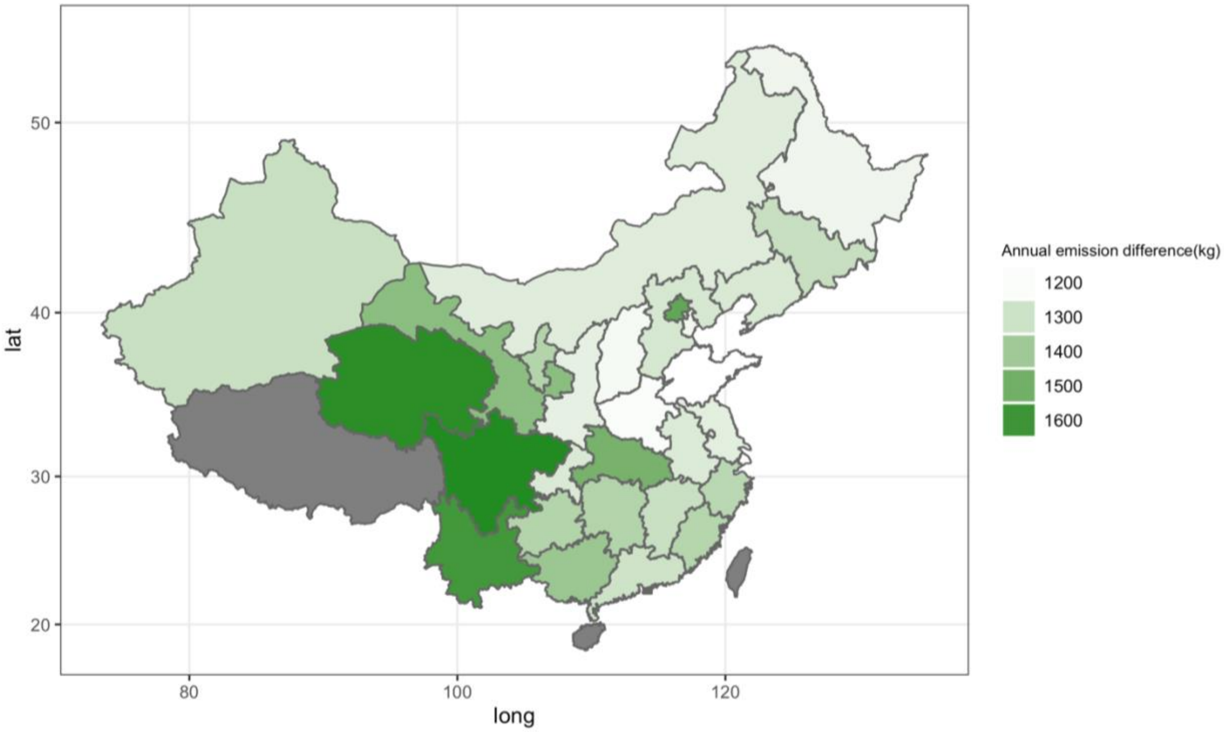

Figure* 40 *Annual emission difference (kg) between micro gasoline vehicle and LSEV (lithium-ion).

Provinces such as Qinghai, Sichuan, Yunnan and Beijing have the largest potential of GHG reduction when switching from micro gasoline vehicles to LSEVs with lithium-ion batteries, which are the same with the previous plot.

Figure 41 illustrates the potential reduction in greenhouse gas emissions in different provinces when switching from micro gasoline vehicles to micro BEVs. Micro BEVs have less potential for reduction than LSEVs due to their lower fuel efficiency. It is estimated that changing from one micro gasoline car to a micro electric vehicle could result in a reduction of approximately 1400 kilograms of greenhouse gas emissions per year.

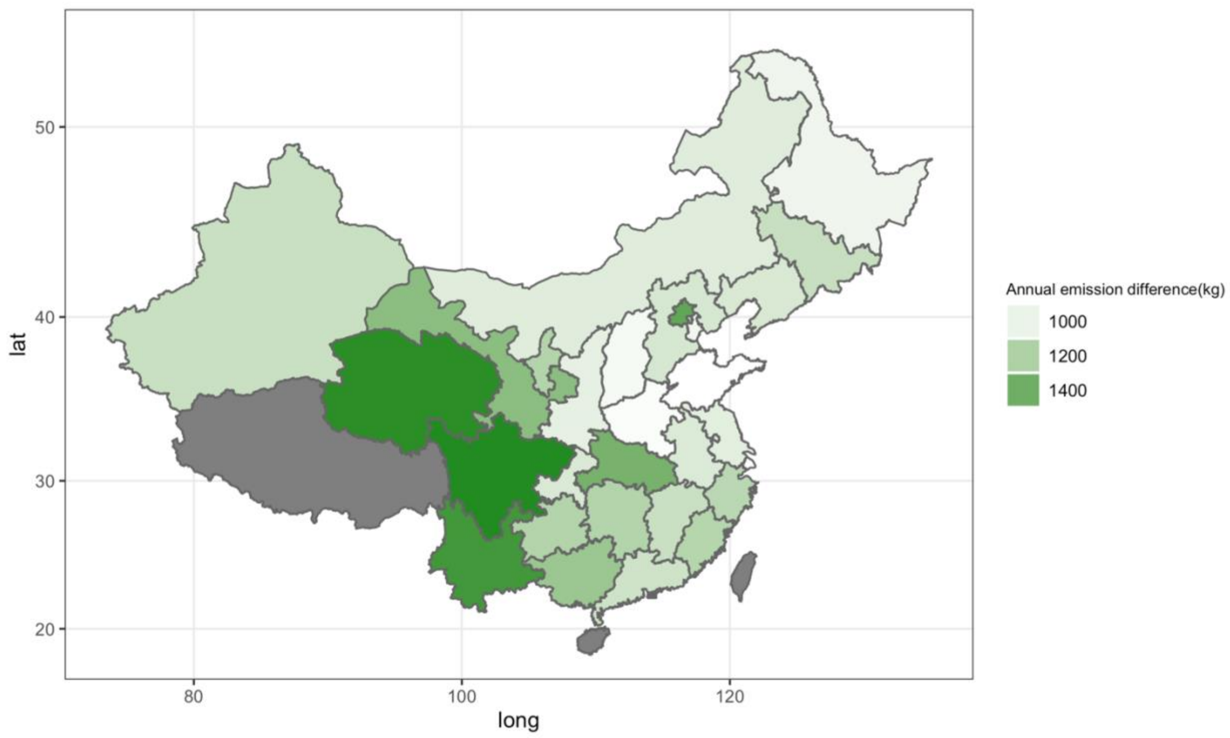

Figure* 41 *Annual emission difference (kg) between micro gasoline vehicle and micro-BEV.

The biggest GHG reduction still happens in provinces such as Qinghai, Sichuan and Yunnan, where the coal-based electricity has lowest percentage.

In Figure 42, you can see the potential annual reductions in GHG emissions when shifting from a compact gasoline vehicle to a BEV in various provinces. Both our gasoline and electric vehicles are larger, so the potential reduction is greater when compared to smaller vehicles in previous comparisons. In provinces such as Qinghai, Sichuan, and Yunnan, it is possible to reduce GHG emissions by over 2000kg annually.

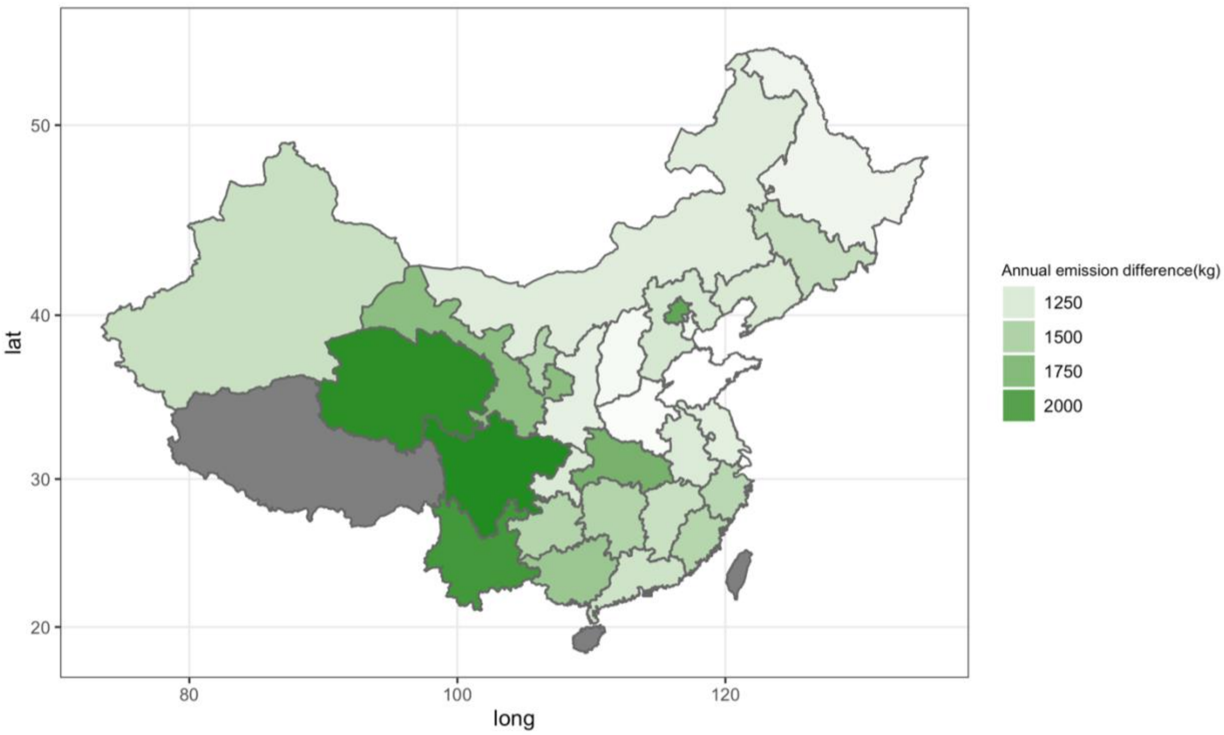

Figure* 42 *Annual emission difference (kg) between compact gasoline vehicle and compact BEV.

The biggest GHG reduction still happens in provinces such as Qinghai, Sichuan and Yunnan, where the coal-based electricity has lowest percentage.

Figure 43 shows the difference in annual GHG emissions between micro plug-in electric vehicles and LSEVs with lithium-ion batteries. Since they are all electric powered, the cleaner the grid is, the smaller the difference will be.

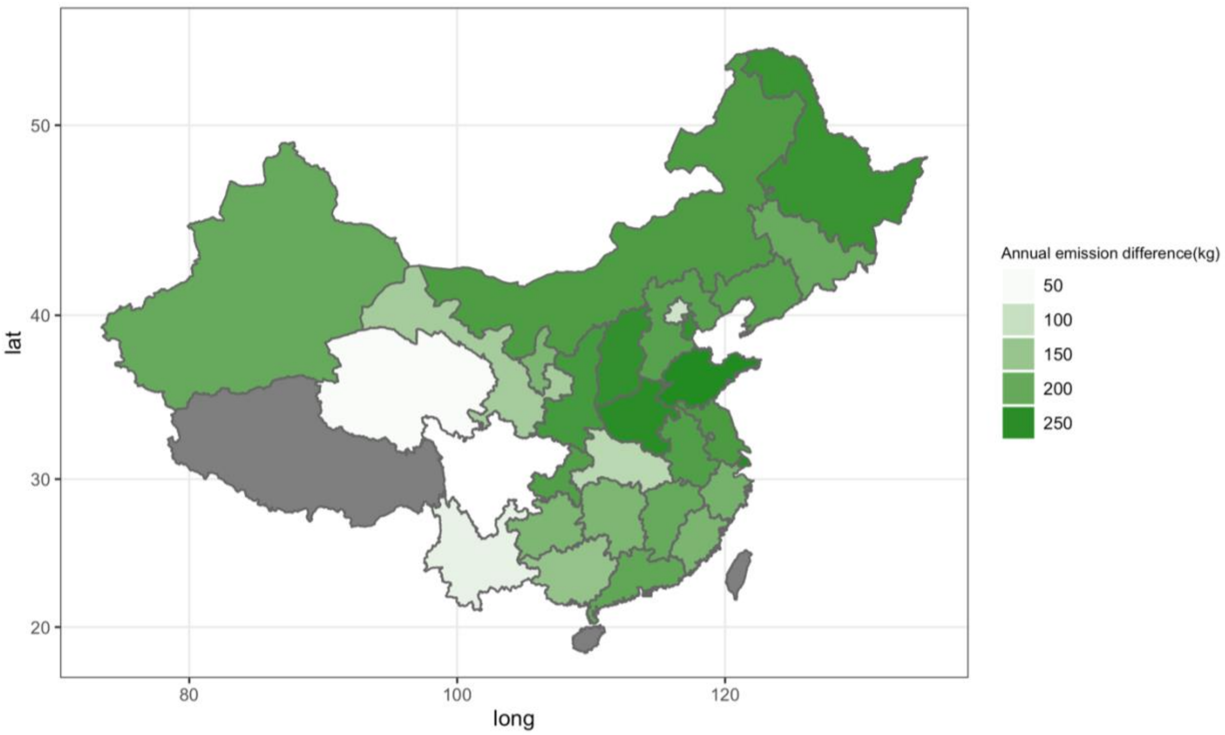

Figure* 43 *Annual emission difference (kg) between micro plug-in electric vehicle and LSEV (lithium-ion).

The minimal GHG reduction happens at provinces with lowest coal-based electricity percentage.

Figure 44 illustrates the annual emissions for two-three wheelers in different provinces. In the case of electric vehicles such as scooters, LSEVs, and electric bicycles, each province has different emission values due to different grid emission rates. The median line indicates the average emission level for all provinces. Considering that the emission grid for gasoline and diesel vehicles is the same across provinces, we can assume the emission values are also the same across provinces.

Diesel and gasoline vehicles have higher emissions than all other modes of transportation. A diesel-powered 3-wheel rural vehicle has very high annual emissions in comparison with all other modes. The main reasons for this are the extremely low fuel efficiency of diesel engines and the relatively high emission rates associated with diesel fuel.

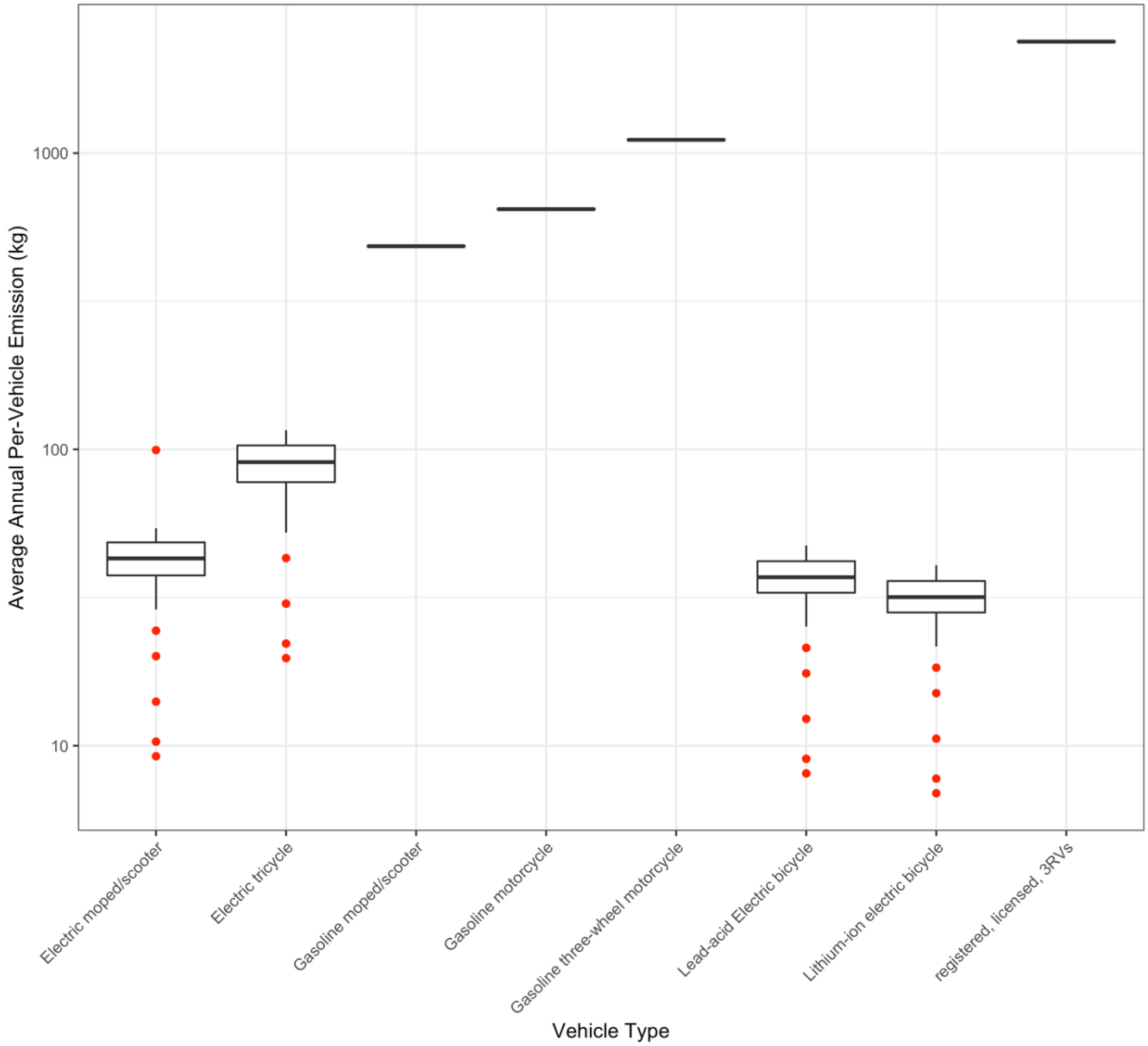

Figure 44 Annual per-vehicle emissions for two-three wheelers.

A diesel/gasoline vehicle have over 500kg annual GHG emission while the 3W RV has about 2400kg annual GHG emission. Electric 2/3 wheelers have very narrow range of emissions considering geospatial differences, and under 200kg annual GHG emission. The big GHG emission differences indicate that switching from gasoline motorcycles or diesel rural vehicles to electric 2/3 wheelers have a great potential of GHG emissions. ***Note that the y axis of the plot is log scaled for better visualization***

Figure 45 depicts the annual emissions for four-wheelers in different provinces. Due to the different grid emission rates, each province has different emission values for electric modes such as LSEVs, micro BEVs, and compact BEVs. The median line indicates the average emission values for all provinces. As I assume that the emission grid is the same across provinces for gasoline and diesel vehicles, the emission values will be the same across provinces. We can see that the low-end micro gasoline car has relatively low emissions owing to its small and efficient engine. Diesel vehicles, such as high- and low-end four-wheel rural vehicles, produce far more emissions than any other mode of transportation.

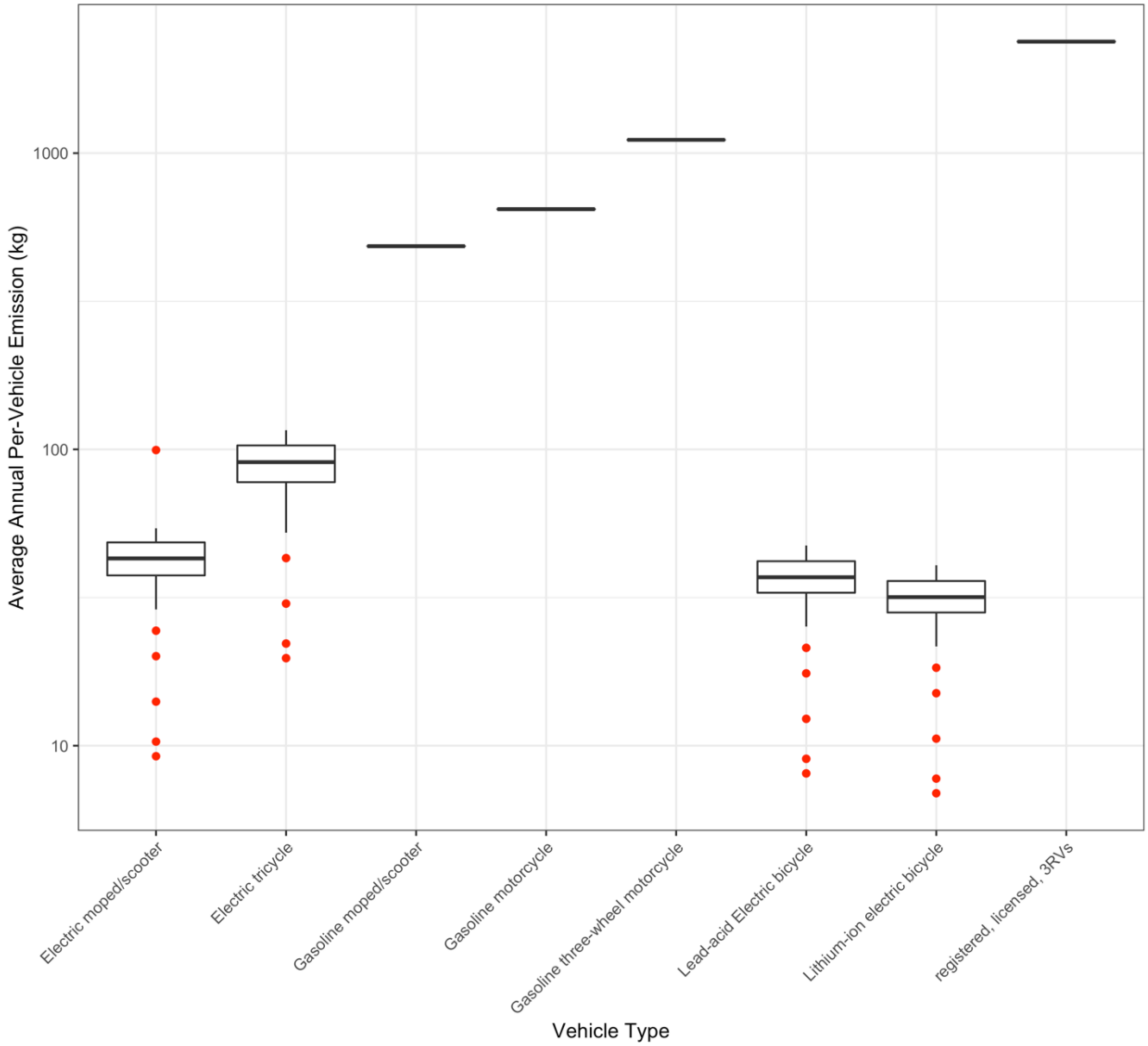

Figure* 45 *Annual per-vehicle emissions for four wheelers.

Most of the gasoline/diesel vehicles have the annual GHG emissions over 2000kg while upscale 4RVs have about 8000kg GHG emissions. The main reason for the very high GHG emissions for 4RVs is the low fuel economy of diesel engines and relatively lower fuel efficiency of diesel. For BEVs and LSEVs, the annual GHG emission is under 1000kg and LSEVs have lowest annual GHG emission compared with micro BEVs and compact BEVs. Switching from gasoline/diesel cars to PEVs or LSEVs will reduce the GHG emissions significantly. ***Note that the y axis of the plot is log scaled for better visualization***

5.3 Discussion

The purpose of this analysis is to examine the energy and emission differences between different types of vehicles based on both tank-to-wheel and electricity generation phases. In the light of our analysis, I conclude that E2Ws provide a great opportunity for reducing GHG emissions compared to their gasoline/diesel counterparts while gasoline motorcycles and rural vehicles produce significant GHG emissions. Our study also concludes that LSEVs and PEVs have great potential for reducing GHG emissions if they are substituted for gasoline and diesel vehicles. Geographically, provinces with lower coal-based electricity generation, such as Qinghai, Sichuan and Yunnan, have greater potential to reduce GHG, whereas provinces such as Shandong and Henan have smaller GHG reduction potential per vehicle.

We have learned that a greener grid enhances the benefits of GHG reduction associated with electrification. Thus, promoting the development of renewable electricity sources such as solar, wind, and hydropower could contribute significantly to reducing greenhouse gas emissions when vehicles become more electrified. Yet, to fully understand the GHG reduction potential of electric vehicles, a comprehensive analysis that includes the emissions resulting from the installation or construction of equipment such as solar panels, windmills, or hydroelectric plants is required.

The analysis has three limitations that can be addressed in future studies. To begin with, a more comprehensive lifecycle analysis (LCA) should be conducted to include phases such as vehicle manufacturing, energy production, operation, and end-of-life. By doing so, the comparison of emissions will be more accurate and can consider phases that may have large emissions, but which I did not consider in this study. Furthermore, if the vehicle inventories for different provinces could be collected, a more meaningful geospatial comparison could be made in order to identify candidates for electrification. Finally, in addition to GHG emissions, pollutants such as NO_x, HC, and SO_x can be included in the LCA analysis. These studies have not been performed in this dissertation due to time constraints and lack of data.

CHAPTER 6 CONCLUSIONS

This dissertation investigates the current state of the LSV market, the travel intensity of LSVs, particularly LSEVs, the total cost of ownership of LSVs compared to their counterparts, and the energy/emission analysis. As a result of these chapters, a more comprehensive understanding of LSVs is provided in terms of market status, policies, cost, and energy/emission aspects. This work has utilized several approaches including literature reviews, TCO modeling, Monte Carlo simulation, and tank-to-wheel emission modeling.

Some key findings include: 1) LSVs, including electrified/gasoline 2Ws, rural vehicles and LSEVs, experienced extraordinary growth in the last two decades due to factors such as technical, policy, economic factors, and the local/central government policies accelerated the adoption of electric LSVs but discouraged the use of gasoline/diesel LSVs. 2) LSEVs can provide similar mobility level of electric bikes, rural vehicles or motorcycles but can’t provide comparable mobility level of private passenger cars. 3) Electric modes are found to be less expensive to own than the gasoline and diesel counterparts in terms of total cost and levelized cost and switching from lead-acid LSEVs to lithium-ion LSEVs is cost-effective and more environmentally friendly due to the lower lifetime of lead-acid batteries and inefficient battery recycling. 4) Provinces with lower-based electricity generation percentage have greater potential to reduce GHGs when switching from fossil-fuel based vehicles to electric vehicles, and a greener grid can enhance the benefits of GHG reduction associated with electrification.

The findings of this dissertation indicate that the LSV market constitutes an important market that contributes significantly to energy consumption and emissions, providing daily transportation for many rural and urban residents. Additionally, it indicates that switching from gasoline/diesel vehicles to their electric counterparts would benefit both the environment and the economy. The market for LSVs should be adequately regulated and LSV users should be encouraged to become future PEV consumers through appropriate policy, monetary, and non-monetary leverages.

6.1 Areas of future studies

This research is one of the first to focus on understanding the future significance of LSVs as well as their travel, cost and energy/emission characteristics. Many interesting questions remain unanswered about LSVs that the author has not had the opportunity to answer, for example:

- Should LSEVs be regulated as motorcycles or as cars, or should a new category be created for them within the current system? How can we make better policy decisions so that LSEVs can better serve consumers without causing confusion on the roads?
- The ban on gasoline motorcycles and E2Ws in China: Why have some cities chosen to ban them rather than manage them?
- What are the best options for replacing rural vehicles that are used for agricultural production and cargo transportation? Would electric cars or trucks be suitable for agricultural use?
- How does the transition of ownership of different vehicles affect the use of electric vehicles? What will current users of E2W, motorcycles, and rural vehicles purchase to upgrade their mobility? What can be done to promote the purchase of electric vehicles?
- The cost per mile in Chapter 4 assume the same benefit for all the vehicles but other characteristics such as capacity, speed, range, weather resistance and other factors are not considered and not quantified in the cost comparison. Therefore, these factors would change the utility of each vehicle and influence consumers’ purchase behaviors.

- What is the total carbon emission reduction benefit of switching from gasoline/diesel to electric-powered vehicles?

6.2 Policy Discussions

Although electric LSVs have great advantages such as cost, convenience, energy efficiency, and emissions, they also have two negative externalities, namely traffic safety and lead-acid battery pollution. LSVs powered by gasoline or diesel have only cost advantages, but they are uncompetitive in terms of energy efficiency and emissions. The following policy recommendations are proposed for policy makers to mitigate the negative externalities of LSVs.

Stricter regulations and quality standards for LSVs

The introduction of stricter regulations on LSVs, such as their performance characteristics (maximum speed, curb weight), production quality standards, and emission and energy use standards might help address issues such as traffic chaos, safety concerns, and energy and emission disadvantages.

Convert lead-acid batteries for both E2Ws and LSEVs to lithium-ion batteries

Lead pollution is one of the major concerns for lead-acid batteries and this type of battery used to be cost effective. With the rapid development of lithium-ion battery technologies, the energy density and battery life have increased, while the cost per kWh has decreased. Switching from lead-acid batteries to lithium-ion batteries is not only environmentally friendly, but also economically feasible.

A cleaner electricity grid contributes to the reduction of greenhouse gases.

China's current grid is still coal-based in most northern provinces, which dampens the reduction of greenhouse gas emissions associated with transportation electrification. Therefore, increasing the availability of solar, wind, and hydroelectric power will accelerate the process of electrification.

Bibliography

Chen, Bo, & Midler, C. (2016a). The electric vehicle landscape in China: between institutional and market forces. *International Journal of Automotive Technology and Management*, *16*(3), 248.

Chen, Bo, & Midler, C. (2016b). Designing strategy for the globalisation of innovation: perspectives for foreign electric vehicle manufacturers in China. *International Journal of Automotive Technology and Management*, *16*(4), 436.

Chen, B. (2018). *Stratégies et Management de l'Innovation de Rupture dans les Pays Emergents: le cas du Véhicule Electrique en Chine* (Doctoral dissertation).

Cherry, C. R., Weinert, J. X., & Xinmiao, Y. (2009). Comparative environmental impacts of electric bikes in China. *Transportation Research Part D: Transport and Environment*, *14*(5), 281–290.

Cherry, Christopher. (2007, January). *Electric Two-Wheelers in China: Analysis of Environmental, Safety, and Mobility Impacts* (Doctoral dissertation).

Cherry, C. (2007). Electric bike use in China and their impacts on the environment, safety, mobility and accessibility.

China Automobile Dealers Association. (2020). *2020 China's Auto Market Almanac*. China Commercial Publishing House.

Fang, H., & Zhu, Y. (2015). Investigation on low-speed EV markets (低速电动汽车行业发展形势调查). *ANNUAL REPORT ON NEW ENERGY VEHICLE INDUSTRY IN CHINA (2015)*.

Guo, Y., Wang, J., Peeta, S., & Ch. Anastasopoulos, P. (2020). Personal and societal impacts of motorcycle ban policy on motorcyclists' home-to-work morning commute in China. *Travel Behaviour and Society*, *19*, 137–150.

Hao, H., Wang, M., Zhou, Y., Wang, H., & Ouyang, M. (2015). Levelized costs of conventional and battery electric vehicles in china: Beijing experiences. *Mitigation and Adaptation Strategies for Global Change*, *20*(7), 1229–1246.

Hao, X., Lin, Z., Wang, H., Ou, S., & Ouyang, M. (2020). Range cost-effectiveness of plug-in electric vehicle for heterogeneous consumers: An expanded total ownership cost approach. *Applied energy*, *275*, 115394.

Hou, C., Wang, H., & Ouyang, M. (2013). Survey of daily vehicle travel distance and impact factors in Beijing. *IFAC Proceedings Volumes*, *46*(21), 35–40.

Hove, A., & Sandalow, D. (2019). *ELECTRIC VEHICLE CHARGING IN CHINA AND THE UNITED STATES*. Columbia Center on Global Energy Policy.

Huo, H., Cai, H., Zhang, Q., Liu, F., & He, K. (2015). Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S. *Atmospheric environment*, *108*(108), 107–116.

Huo, H., Zhang, Q., He, K., Yao, Z., & Wang, M. (2012). Vehicle-use intensity in China: Current status and future trend. *Energy policy*, *43*, 6–16.

Huo, H., Zhang, Q., Wang, M. Q., Streets, D. G., & He, K. (2010). Environmental implication of electric vehicles in China. *Environmental Science & Technology*, *44*(13), 4856–4861.

JAMA. (2019). *2019 Japan Light Car Usage Survey Report*. JAMA.

Kimble, C., & Wang, H. (2013). China's new energy vehicles: value and innovation. *Journal of Business Strategy*, *34*(2), 13–20.

Ling, Z., Cherry, C. R., & Yang, H. (2019). Emerging mini electric cars in China: User experience and policy implications. *Transportation Research Part D: Transport and Environment*, *69*, 293–304.

Li, F., Ou, R., Xiao, X., Zhou, K., Xie, W., Ma, D., Liu, K., et al. (2019). Regional comparison of electric vehicle adoption and emission reduction effects in China. *Resources, Conservation and Recycling*, *149*, 714–726.

Massey, F. J. (1951). The Kolmogorov-Smirnov Test for Goodness of Fit. *Journal of the American Statistical Association*, *46*(253), 68–78.

MIIT. (2018). *Safety technical specification for electric bicycle* (Vol. GB17761-2018).

MIIT. (2021). *Battery electric passenger cars — Specifications GB/T 28382 (Draft for Comments).*

Ministry of Ecology and Environment. (2018). *Limits and measurement methods for emissions from motorcycles (CHINA IV). GB14622-2016.*

Ministry of Ecology and Environment of the People's Republic of China. (2006). *Limits and measurement methods for exhaust pollutants from diesel engines of tri-wheel & low-speed goods vehicles* (Vol. GB19756-2005).

National Automotive Standardization Technical Committee. (2004). *The Automobile Industry Development Policy and Road Traffic Safety Law*. *GB1589-2004*.

National Highway Traffic Safety Administration. (1998). *Federal Motor Vehicle Safety Standard 500*.

Ouyang, D., Zhou, S., & Ou, X. (2021). The total cost of electric vehicle ownership: A consumer-oriented study of China's post-subsidy era. *Energy policy*, *149*, 112023.

Ou, S., Lin, Z., Wu, Z., Zheng, J., Lyu, R., Przesmitzki, S., & He, X. (2017). A study of China's explosive growth in the plug-in electric vehicle market. *Knoxville TN*.

Qiao, Q., Zhao, F., Liu, Z., Jiang, S., & Hao, H. (2017). Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China. *Applied energy*.

Research and Markets. (2021). *China Low-speed Electric Vehicle (LSEV) Industry Report, 2020-2026*. Research and Markets.

Sperling, D., Lin, Z., & Hamilton, P. (2004). Chinese rural vehicles: An explanatory analysis of technology, economics, industrial organization, energy use, emissions, and policy.

Standardization Administration of China. (2017). *Technical specifications for safety of power-driven vehicles operating on roads* (Vol. GB7528-2017).

Teter, J. (2011). *The Power of Policy and the Future of Chinese Rural Vehicles* (Master thesis).

The European Parliament and the Council of the European Union. (2013). REGULATION (EU) No 168/2013 OF The European Parliament and the Council on the approval and market surveillance of two- or three-wheel vehicles and quadricycles. *Official Journal of the European Union*.

Tian, X., Wu, Y., Gong, Y., & Zuo, T. (2015). The lead-acid battery industry in China: outlook for production and recycling. *Waste management & research: the journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *33*(11), 986–994.

U.S. Federal Highway Administration. (2019). Highway Statistics 2019 - Policy | Federal Highway Administration. Retrieved December 20, 2021, from https://www.fhwa.dot.gov/policyinformation/statistics/2019/vm1.cfm

Wang, H., & Kimble, C. (2011). Leapfrogging to electric vehicles: patterns and scenarios for China's automobile industry. *International Journal of Automotive Technology and Management*, *11*(4), 312.

Wang, H., & Kimble, C. (2012). The low speed electric vehicle – china's unique sustainable automotive technology? In A. Subic, J. Wellnitz, M. Leary, & L. Koopmans (Eds.), *Sustainable automotive technologies 2012* (pp. 207–214). Berlin, Heidelberg: Springer Berlin Heidelberg.

Weinert, Jonathan X., Ma, C., Yang, X., & Cherry, C. R. (2007). Electric Two-Wheelers in China. *Transportation Research Record: The Journal of the Transportation Research Board*, *2038*(1), 62–68.

Weinert, J X. (2007). *The rise of electric two-wheelers in China: factors for their success and implications for the future*. University of California, Davis.

Zhang, Y., Chen, J., Li, X., & Zhong, M. (2019). Exploring logistics dispatcher's preference in electric tricycle related policies: The case of China. *Journal of Cleaner Production*, *230,* 835–843.

Zhao, F., Zhao, S., & Liu, Z. (2017). 中国低速电动车产业的现状, 问题与未来发展策略. *Chinese Journal of Automotive Engineering*, *7*(5), 313–320.

Zhao, X., Doering, O. C., & Tyner, W. E. (2015). The economic competitiveness and emissions of battery electric vehicles in China. *Applied energy*, *156*, 666–675.

Zhou, G., Ou, X., & Zhang, X. (2013). Development of electric vehicles use in China: A study from the perspective of life-cycle energy consumption and greenhouse gas emissions. *Energy policy*, *59*, 875–884.