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Assessing the Impact and Cost-Effectiveness of Low-carbon transportation policies: A Case Study from Shenzhen City

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ABSTRACT

Using the Gompertz method and the elastic coefficient approach, we forecast vehicle ownership and GHG emissions under different low-carbon transportation policy scenarios, focusing on Shenzhen City as case study. We also factor in the learning curve associated with EV battery costs into our dynamic cost-benefit model. Scenario analysis reveals that Shenzhen's incremental car restriction policy decreased the number of cars by 18.7% in 2017 alone. By actively promoting EVs in a net zero carbon scenario, it's feasible that CO2 emissions might reach their peak as soon as 2020. Our cost-benefit analysis indicates that improving fuel economy policies for vehicles yields higher marginal abatement benefits. Although the initial push for EVs may result in elevated marginal abatement costs due to infrastructure investments, anticipated long-term reductions in battery costs, driven by economies of scale, could offset these costs, potentially even leading to net benefits.

Keywords: Low-carbon transportation policies, GHG emissions, scenario analysis, cost-effectiveness

NONMENCLATURE

Abbreviations

EV	Electric Vehicles
GHG	Greenhouse Gas
TTW	Tank-to-Wheel
WTW	Well-to-Wheel

1. INTRODUCTION

The transportation has been a significant contributor to global carbon emissions. Specifically, road transportation and motor vehicles have contributed substantially to these emissions [1-3]. The reduction of carbon emissions from vehicles holds significant promise for mitigating the deleterious effects of climate change. Many studies have highlighted various strategies for achieving this goal [4-8]. Overcoming these hurdles necessitates an integrated approach that takes into account various factors including energy system costs, policy trends, and market dynamics.

The current body of research has devoted significant attention to the mitigation of GHG emissions from vehicles, with promising results from varied strategies. Nonetheless, a discernible gap persists in providing localized strategies, especially at the city level, that can successfully implement low-carbon policies [9]. To bridge the identified research gap, our study aims to deliver a series of analyses on low-carbon policies for vehicles. Building on previous research [10-12], this study offers a city-level analysis of low-carbon policies' impact on GHG emissions, using vehicle ownership and use as a case study. Additionally, we analyze the cost-effectiveness of these policies, providing policymakers with insights to balance economic and environmental considerations. This model will be informed by the learning curve theory [13], which will help us to evaluate how the cost-effectiveness of the policies evolves as they become more mature and widespread.

2. METHODOLOGY AND DATA

2.1 Case information

Shenzhen is a vibrant, modern city located in southeastern China, serving as a major hub for innovation and technology. As the first Special Economic Zone established under China's "Reform and Opening" policy, it has transformed from a small fishing village into one of the country's fastest-growing cities in just a few decades. Shenzhen is also a leader in sustainable urban development and is at the forefront of China's push for

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new energy vehicles, boasting a fully electric public buses and taxis fleet. Its progressive policies and commitment to sustainable growth make Shenzhen an exemplary model for cities around the world aiming for a low-carbon future. This study takes the road transportation department of Shenzhen as the research object and selects 2017 data as the base year data. The data from 2018 to 2019 are used for the verification of forecast data, and the situation is predicted to 2050.

2.2 *Accounting methods for GHG emissions*

This study uses GHG emission "bottom-up" accounting model of transportation to calculate the GHG emissions of urban road transportation, based on our previous study [12].

2.3 *Analysis of factors affecting road transportation emissions and future trends*

The study involved comprehensive field research, which was facilitated by visiting many governmental departments in Shenzhen. Our predictions encompassed motor vehicle growth and associated energy usage. Additionally, we integrated potential impacts from upcoming policy documents into our model parameters.

2.3.1 Population and economic development

Based on "The 13th Five-Year Plan of Shenzhen for the Development of the Population and Social Enterprise" and the "Shenzhen Social Construction and Development Report (2016)", we anticipate that Shenzhen's resident population will reach 19.9 million by 2030, and will grow to approximately 25 million by 2050. When analyzing actual data from 2016 to 2018 and integrating information from the Shenzhen government's work report regarding the city's GDP growth rate for 2019 and 2020, we deduced that the average annual growth rate of Shenzhen's GDP from 2016 to 2020 hovered around 7.50%. We anticipate an average annual growth rate of 7% from 2020 to 2030. Post-2030, we expect this rate to decline by 0.5% every five years, reaching 5% by 2050. It's important to note that figures related to GDP and income in this study are adjusted to the constant 2015 prices.

2.3.2 The vehicle ownership

Prior studies [10,11] indicate that the growth trajectories of various vehicle types are influenced by distinct factors. Each type can be represented more accurately using hybrid modeling approaches to closely mirror real-world scenarios. Our research builds models and predictions for different categories of motor vehicles in Shenzhen using specific modeling techniques. The methodologies for projecting vehicle ownership are detailed in Table.1.

Table. 1 Projection of Vehicles

Vehicle type	Scenario	Prediction method
Cars	Unlimited car purchase scenario (counter factual scenario)	Gompertz model [12].
	Limited car purchase scenario	Elasticity coefficient method.
Buses and taxis		$VP_{t,j} = V_{t,j} \times P_t / 1000$ (1) Where $VP_{t,j}$ is the type j vehicles ownership in year t, and $V_{t,j}$ is the type j vehicles ownership per thousand people in year t.
Other Commercial Vehicles		Elasticity coefficient method.

2.3.3 Vehicle technology

Merging insights from the "13th Five-Year Plan" and considering potential policy directions for the promotion of new energy vehicles in Shenzhen, we establish two future scenarios: a Business-As-Usual (BAU) scenario and a Low-Carbon scenario. The distinctions between the two scenarios are laid out in Table.2.

Table. 2 Vehicle Technology Settings

Vehicle	Fuel	BAU scenario	Low-carbon Scenario
Bus/taxi	EV	100%	100%
PC	PHEV	10%	30% in 2050
	EV	10% in 2020, 50% in 2050	90% in 2050
HDT	LNG	1% in 2020, 10% in 2050	30% in 2050
	EV	1% in 2020, 10% in 2050	70% in 2050
MDT	EV	-	The same as HDT
LDT	EV	50%	100% from 2020
LDB	EV	7% in 2020, 50% in 2050	100% frm 2040
MDB	EV	-	The same as LDB
HDB	EV	-	70% in 2050

2.3.4 Fuel economy

We have defined two sets of fuel economy indicators: the BAU scenario and the Low-Carbon scenario. BAU Scenario (FE BAU): We operate under the assumption that the trends from 2010 to 2017 will persist, with no introduction of new policies influencing the changes in vehicle fuel economy. From 2015 to 2050, fuel consumption in light vehicles (comprising small passenger cars and light trucks) and in heavy vehicles (such as large passenger cars, big buses, and heavy trucks) will decline by 0.5% and 1% per 100 kilometers for gasoline, diesel, and natural gas vehicles respectively.

Low-Carbon Scenario (FE Low-Carbon): Referring to the "Energy-saving and New Energy Vehicle Technology Roadmap 2.0" released in 2020, It's anticipated to reduce further to 4.8 liters/100 kilometers by 2030. By 2050, we forecast that the fuel consumption of new passenger cars will stand at 4 liters/100 kilometers.

2.3.5 GHG emission factors and power structure

The GHG emission factors of motor vehicle fuel use include two parts, the upstream stage (from well to tank, WTT) and the downstream stage (from Tank to wheel, TTW) [12]. The two stages constitute the entire life cycle process (from well to wheel, WTW) of GHG emissions generated by the use of vehicle fuels

The electricity emission factor of the Southern Power Grid where Shenzhen is located will be reduced in the future with the continuous optimization of the power generation structure. According to the data from the China Southern Power Grid Corporate Social Responsibility Report over the years: The proportion of China Southern Grid’s thermal power generation decreased from 65.27% in 2007 to 49.3% at the end of 2017, which is far below the national average of 71.3% in 2017. Moving forward to 2050, with the objective of attaining cleaner electricity, the progression of the China Southern Power Grid can be delineated into two scenarios: Electricity BAU scenario (a certain proportion of thermal power generation): Considering the "lock-in effect" after energy infrastructure investment, it is predicted that there will still be some existing thermal power plants in the power sector in the future, although it can reduce the cost of social infrastructure investment and increase the utilization rate of existing coal-fired and gas-fired power plant assets, but the potential for emission reduction is limited. It is assumed that by 2030 and 2050, the proportion of non-fossil energy generation in China Southern Power Grid will reach 60% and 75%, respectively.

Electricity low-carbon scenario (high proportion of renewable energy): In the future, the electric power sector will generate multiple power from the power generation side, the grid side and the user side to increase the proportion of hydropower, wind power and solar power generation. Some coal-fired power plants may be phased out as soon as possible. Here we draw on the Sustainable Development Scenario of the International Energy Agency, which predicts that China’s thermal power generation will account for 23% of China’s thermal power generation and 77% of non-fossil energy power generation by 2040. We use this data for the power generation structure of China Southern Power Grid in 2035, and assume that by 2050, the proportion of non-fossil energy power generation will be 90%.

2.4 *Scenario settings*

This study adopts both path-oriented and goal-oriented approaches, segmenting future road transportation emissions in Shenzhen into four distinct scenarios: the BAU Scenario, the Unlimited Purchase Scenario, the Low-Carbon Development Scenario, and the Net-Zero Carbon Scenario. The policy frameworks and technological advancements inherent to each scenario, along with their corresponding interrelations with the previously mentioned parameter scenario configurations, are delineated in Table.3.

Table. 3 Scenario settings

Scenario	Policy and technology path	Correspondence with the above parameter scenarios
BAU scenario	Develop according to the "13th Five-Year Plan" Renewable energy promotion Promote new energy vehicles	Limited car purchase scenario Technology BAU scenario, FE BAU scenario, Electricity BAU Scenario
Unlimited purchase scenario	No incremental control policy for cars has been implemented after 2015 Renewable energy promotion Promote new energy vehicles	Unlimited car purchase scenario Technology BAU scenario, FE BAU scenario, Electricity BAU Scenario
Low-carbon development scenarios	On the basis of the BAU scenario, add: Significantly improve the fuel economy of passenger cars, trucks, and buses	Limited car purchase scenario Technology BAU scenario, FE low-carbon scenario, Electricity BAU Scenario
Net zero carbon scenario	On the basis of the low-carbon development scenario, add: Promoting 100% EV cars in phases Pure electric truck technology achieves a leap forward Greater efforts will be made to promote the use and consumption of renewable energy	Limited car purchase scenario Technology low-carbon scenario, FE low-carbon scenario, Electricity low-carbon scenario

Note: The assumptions of each scenario in terms of economy, population, passenger and freight travel are the same. The difference lies in the forecasts of policy and technological trends listed in the table.

2.5 *Emission reduction cost evaluation model*

The cost associated with carbon reduction in low-carbon policies can be defined as the total of changes in incremental capital costs, added operational and maintenance expenses, and shifts in fuel costs when compared to the BAU scenario, and MAC(Marginal Abatement Cost). The methods are based on our previous study [12]. Moreover, given the challenges in procuring direct manufacturing cost data for automobiles, we approximate the production cost of new energy vehicles using retail prices. We quantify the technological learning of BEVs by modeling their prices as a power-law function of cumulative production, utilizing the empirical learning curve approach [13].

3. RESULTS

3.1 *Vehicle Ownership*

In the unlimited purchase scenario, using 2014 as the base year, the Gompertz model was used to predict the number of passenger cars owned in the BAU scenario, excluding taxis. We then obtained the following prediction model for the number of passenger cars owned in Shenzhen, excluding taxis, in the future:

$$V_t = 400\times e^{-7.36\times\exp(-0.17X_t)},\quad R^2 = 0.979 \tag{2}$$

Shenzhen's policy to limit the increase in cars has achieved significant results. By comparing the number of motor vehicles in Shenzhen in the unlimited purchase scenario and the limited purchase scenario, as shown in Fig.1, in the unlimited purchase scenario, the number of passenger cars per thousand people in Shenzhen is still in a stage of rapid growth from 2006 to 2017. Under the influence of the car purchase restriction policy, the gap between the actual value and the theoretical value of the number of passenger cars per thousand people increased from 10 cars per thousand people in 2015 to 50 cars per thousand people in 2017, and it will quickly expand in the short term. In the long term, the gap will stabilize at about 267 cars per thousand people. In terms of vehicle population, as shown in Fig.2, under the influence of the purchase restriction policy, the number of passenger cars in Shenzhen decreased by 18.7% in 2017, and it is expected to decrease by 67.6% by 2050.

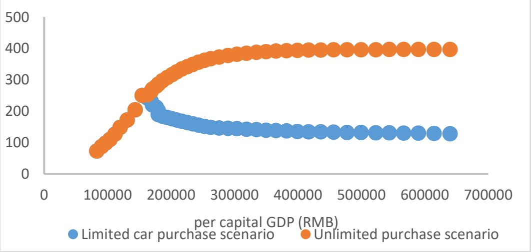

Fig. 1 The passenger cars per thousand people

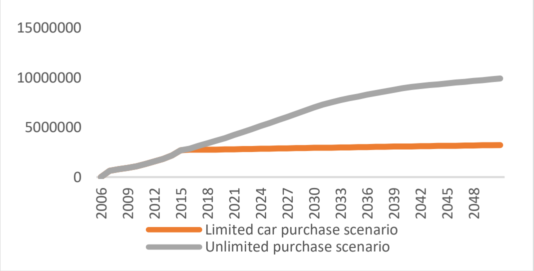

Fig. 2 Vehicle population under two scenarios

3.2 *GHG Emission Projections under Various Scenarios*

As depicted in Fig.3, Shenzhen's road transportation GHG emissions from the TTW perspective (excluding GHG emissions from electricity consumption of PHEVs and pure electric vehicles) for the period 2014-2050 are expected to increase at a declining rate, peaking in different years for each scenario, with varied reduction magnitudes. Specifically:

Under the unlimited purchase scenario, Shenzhen's road transportation GHG emissions (from the TTW perspective) peak around 2022 and remain high thereafter. The peak emissions have a 33.5% increase from 2014. Under the BAU scenario, with the continued implementation of road transportation carbon reduction policies and car volume control policies from the "Twelfth Five-Year Plan" and "Thirteenth Five-Year Plan", the GHG emissions peak around 2022 with the highest emissions which is 8.7% higher than in 2014.

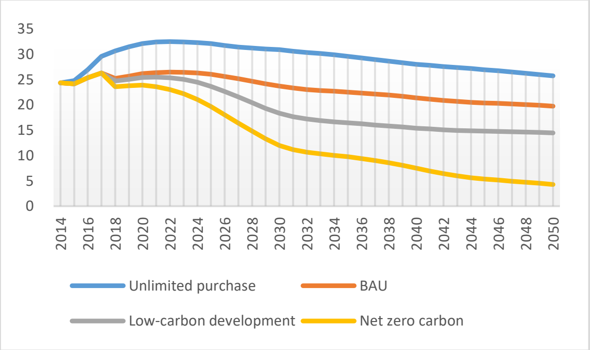

Fig. 3 TTW GHG for each scenario for 2014-2050 (MtCO$_{2e}$)

Under the low-carbon scenario, due to comprehensive reinforcement of fuel economy improvement policies for all types of fuel vehicles, the GHG emissions peak earlier, around 2017, an 8.0% increase from 2014. After peaking, emissions fluctuate until a second peak in 2021. From 2021 to 2030, the rate of GHG emission reduction gradually increases. As the potential for technological energy conservation reaches a bottleneck, the speed of GHG reduction slows down post-2030, with 2050 emissions at approximately 56.1% of the 2017 level and below 2014 level.

Under the net-zero carbon scenario, thanks to the significant increase in the market share of pure electric vehicles and the substantial reduction in the volume of fuel vehicles, GHG emissions peak around 2017 as well, reaching a peak. Post-peak, emissions fluctuate until a second peak in 2020. Afterward, GHG emissions rapidly decrease until 2050, when they drop below 5 MtCO$_{2e}$, only 16.2% of 2017 level and around 17.5% of 2014 level.

After taking into account GHG emissions from electricity and upstream energy consumption, the changes and peaking modes of GHG emissions from the

WTW perspective differ from those of the TTW perspective. The future GHG emissions from the WTW perspective are shown in Fig.4. Here, Shenzhen's road transportation GHG emissions are expected to increase at a declining rate and peak in different years for each scenario, with varied reduction magnitudes.

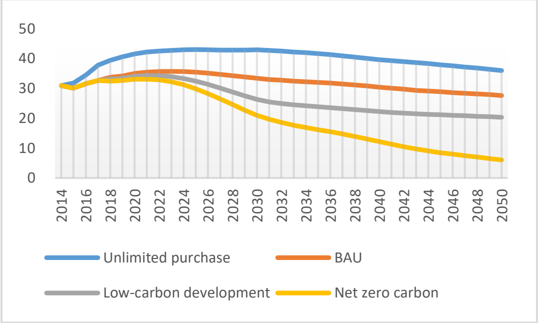

Fig. 4 WTW GHG for each scenario for 2014-2050(MtCO$_{2e}$)

3.3 *Cost-Benefit Analysis of Policies*

Through calculations, we analyzed the incremental investment costs, fuel savings benefits and MACCs of implementing each policy individually by separating the policies from the Low-carbon development scenario into “Promote EV cars policy” , “Promote EV rucks policy”, and “FE Low-Carbon policy”, as well as the policy combinations of the net-zero carbon scenario.

Looking at the incremental investment costs of the policies, as shown in Fig.5, in the short term (2018-2035), the cost of promoting pure electric commercial vehicle policy is relatively high, and the cost of improving passenger car fuel economy policy grows rapidly, but tends to stabilize in the long term. The cost of promoting pure electric passenger vehicle policy is significantly influenced by the technology learning curve, with costs first increasing and then decreasing. The incremental investment costs of the net-zero carbon policy combination scenario grow rapidly in the early stage and gradually decline after peaking around 2032.

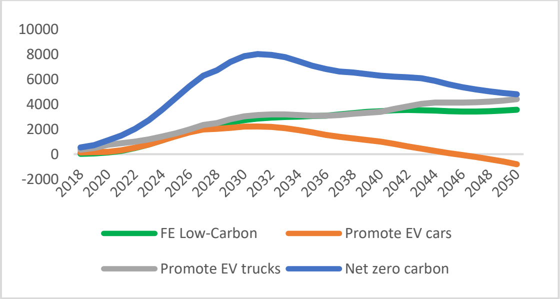

Fig. 5 Incremental investment cost of policy scenarios (MRMB)

The MACC charts, which evaluate policy GHG emission reductions from a WTW perspective, represents cumulative policy GHG emission reductions from 2018-2050 on the x-axis, and the value of the marginal emissions reduction cost on the y-axis. As can be seen from Fig.6 to Fig.7, the policy to improve the fuel economy of passenger cars yields a higher marginal emissions reduction benefit in the short term. The policy to promote new energy passenger cars has higher marginal emissions reduction costs in the short term due to infrastructure investments, but in the long term, due to the scale effects of technology learning and the constant decrease in the cost of electric vehicle batteries, the marginal emissions reduction costs gradually decrease and yield benefits. The policy to promote pure electric commercial vehicles has considerable marginal emissions reduction benefits due to its higher fuel-saving benefits offsetting investment costs. The net-zero carbon scenario, which combines the above three policies, has marginal emissions reduction benefits. The policy to improve fuel economy and the policy to promote pure electric vehicles have a hedging effect (the emission reduction of the policy combination < the total emission reduction of individual policies).

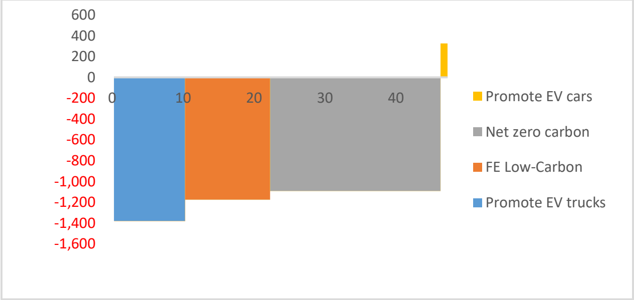

Fig. 6 MACC in 2025 (RMB/tCO$_{2e}$)

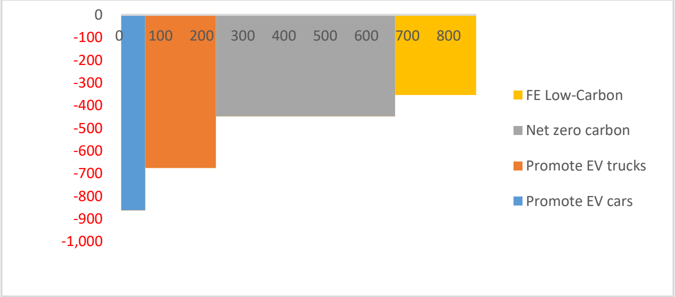

Fig. 7 MACC in 2050 (RMB/tCO$_{2e}$)

4. CONCLUSSIONS

In this study, using the Gompertz model and elasticity coefficient method, we made projections for vehicle ownership and associated carbon emissions across various scenarios. We integrated the technology learning curve of battery costs for new energy vehicles into a dynamic cost-benefit analysis, giving us the ability to gauge the cost-effectiveness and emission reduction potential of assorted low-carbon initiatives.

Our scenario analysis unveiled a sharp uptick in motor vehicle ownership, predominantly private cars, from 2015 to 2050 when considering an unrestricted purchase scenario. Remarkably, Shenzhen's vehicle increment limitation policy curbed the growth of passenger cars, slashing their numbers by 18.7% in 2017 relative to what would have been seen under natural growth. By actively promoting EVs in a net zero carbon scenario, it's feasible that CO2 emissions might reach their peak as soon as 2020. Our cost-benefit analysis indicates that near-term enhancements to fuel efficiency standards for passenger vehicles yield the most substantial marginal emission reduction benefits. Although championing new energy passenger vehicles initially incurs higher marginal costs due to necessary infrastructure development, the anticipated downward trend in battery costs, driven by economies of scale, could offset these initial expenditures. In the broader scope, policies advocating for new energy trucks hold promise for amplified fuel-saving revenues.

In summary, with the rapid development of the economy and the continuous increase in population, in order to reduce the GHG emissions from urban vehicles, Shenzhen should first persist in implementing control policies on the increase of vehicles, especially cars. Simultaneously, it should consider formulating or adjusting corresponding incentivizing financial and tax policies to encourage the research and development of new energy technologies and the promotion of new energy vehicles to reduce the direct TTW GHG emissions generated by vehicle use. From a WTW perspective, considering the GHG emissions generated by upstream fuel production, Shenzhen also needs to work together with the Southern Power Grid to vigorously develop non-fossil energy power generation and grid connectivity, reducing the WTT GHG emissions produced by upstream vehicle fuel production. This research offers invaluable guidance for decision-makers aiming to craft efficient and economically sound carbon-reducing strategies.

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