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Pioneers of electric mobility: Lessons about transport decarbonisation from two bay areas

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ABSTRACT

Electric mobility has the potential to spearhead transport decarbonisation. While there is a vast literature on the potential benefits of electric vehicles (EVs) towards sustainability and national policies of EV adoption, regional and local polices are often overlooked. Hence, this paper aims to capture lessons learned from two bay areas, namely the Guangdong-Hong Kong-Macau Greater Bay Area (GBA) in China and the San Francisco Bay Area (SFBA) in the United States. These two regions are pioneers in electric mobility within the two largest economies of the world. An integrative methodology of transport decarbonisation and backcasting analysis are applied to analyse the progress achieved so far (2000–2018) and to project future carbon reduction potentials (2019–2050). Regional and local transport CO_2 emissions are estimated by a distance-based approach. The results illustrate that electric mobility has led to carbon reductions of 1.73 Mt CO_2 and 0.25 Mt CO_2 in 2018 in GBA and SFBA respectively, contributing to a relative decoupling status in both regions ($e = 0.85$ & $e = 0.14$). Intra-regional variability in decoupling status is observed, with stronger spatial variations in GBA. The backcasting analysis suggests that the EV share needs to reach almost 100% before 2035 so that the 450 Delayed Action vision can be achieved. This requires a proactive policy package of cleaner electricity with emissions performance standards, EV sales mandates, expanded public charging infrastructure, and a range of measures to incentivize EV market uptakes. Major driving forces of decoupling, including vehicle kilometre travelled, public transport share, and regional/local EV policies, are also identified and discussed.

1. Introduction

Electric mobility, or *electromobility*, can become a global strategy to spearhead transport decarbonisation and mitigate climate change. Compared with the traditional “avoid” and “shift” strategies only, electric mobility not only has higher carbon reduction potentials (Casals et al., 2016; Qiao et al., 2019; Wu et al., 2019) but is also more feasible with potentially greater co-benefits, ranging from increased energy security (Skerlos and Winebrake, 2010; Stephan and Sullivan, 2008), reduced air pollution and improved public health (Buekers et al., 2014; Gai et al., 2020; Lin et al., 2020), enhanced cost-effectiveness (Markel and Simspon, 2007; Peterson and Michalek, 2013), and stimulation of economic growth (Haddadian et al., 2015; Li et al., 2018; Qiao et al., 2019). Although the actual benefits and co-benefits are context-specific, electric mobility can act as an impetus in promoting comprehensive sustainability (i.e. social, economic and environmental) and pave the way to long-term decarbonisation and carbon neutrality (Brown et al., 2021; IEA, 2020; SDSN, 2020).

While electric mobility seems to offer significant opportunities, a multitude of empirical obstacles still exist. Global sales of electric vehicles (EVs) reached a record high of 3.2 million and the total sales exceeded ten million in 2020 (EV-Volumes, 2021). As of 2019–2020, Europe, China and US are the three markets with the largest sales of EVs (over 3 million sales), with China, USA and Germany being the three largest markets in 2020 (EV-Volumes, 2021). Nevertheless, EVs accounted for less than 3% of total car sales and around 1% of the global stock only in 2019 (IEA, 2020). For consumers, limited charging infrastructure availability (Biresselioglu et al., 2018; Steinhilber et al., 2013; Tal et al., 2020) and high upfront purchase costs (Azadfar et al., 2015; Axsen et al., 2013), combined with psychological parameters such as

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low awareness and scepticism (Burgess et al., 2013; Hardman et al., 2020), anxiety in EV charging (Franke et al., 2012) and a lack of perceived control (Afroz et al., 2015), could have led to fewer purchases. For automakers, the higher production cost, weight, and size of batteries as well as the reluctance from car dealers further slowed EV market development (O'Neil et al., 2019).

To facilitate the development of electric mobility, a wide range of policy choices are available. At the super-national level, international climate change commitments (i.e. Paris Agreement) and technological breakthroughs in EV technology (i.e. driving range, battery performance, and safety) can be encouraged. In addition, national policies may include vehicle purchase subsidies, investment in research and development (R&D) of the EV industry, performance targets on greenhouse gases (GHG), tightening of vehicle emission standards, and a transition to renewable energies. Regional policies to stimulate EV uptake may include regional sales mandate to automakers, further fiscal incentives for vehicle purchase, electric utility investment in charging infrastructure, and investment in hydrogen stations. At the local scale, complimentary EV parking, charging discounts, the use of priority lanes, free access to low-emission zones, and the electrification of public transport fleet can also be implemented.

2. Literature review

Given the above context, electric mobility has become an important field in sustainable transport research. Notwithstanding, there are two major research gaps. Firstly, there is insufficient research on the actual reduction of road transport carbon emissions in regions with rapid EV development over the past decade. In general, it is well recognized that EVs can reduce well-to-wheel carbon emissions when the electricity mix is clean enough (Woo et al., 2017; Rahman et al., 2021). However, as indicated by a comprehensive review of 239 articles related to EV adoption (Kumar and Alok, 2020), empirical evidence on the actual environmental benefits of EV policies is still limited. For instance, Ruggieri et al. (2021) analysed the ways that electric mobility policies (supported by other land-use and energy polices) have reduced air pollutants in six European cities with rapid EV development from 2016 to 2019. Some literature has analysed the trend of transport decarbonisation in different countries by applying aggregated data of transport CO_2 at a national level with an analytical timeframe of over 20 years. Overall, these global studies indicate that progress towards transport decarbonisation has been slow and divergent in the past three decades (Tapio et al., 2007; Loo and Banister, 2016). In relation, electric mobility policies were associated with periods of decoupling of transport carbon emissions at selected countries (Loo et al., 2020; Tsoi et al., 2021). Still, there are significant spatiotemporal variations of decarbonisation within national boarders (Wang et al., 2017; Wang and Wang, 2019) largely due to different socioeconomic status and policy contexts. Since EV development can vary substantially across cities and regions in a large country, a regional based decoupling analysis is required to provide empirical evidence on electric mobility in transport decarbonisation (i.e. actual reduction of road transport carbon emissions and intensities).

Moreover, while there is a growing literature on the role of government policies in promoting electric mobility (Hardman, 2019; Sperling, 2018; Wu et al., 2021), regional policies in upscaling electric mobility are overlooked. Typically, papers have examined government policies towards electric mobility from a global/national perspective: international (Leurent and Windisch, 2011; Hardman et al., 2017; Lieven, 2015; Rietmann and Lieven, 2019; Wang et al., 2019; Zimm, 2021), Europe (Cansino et al., 2018; Münzel et al., 2019) and the Nordic region (Kotilainen et al., 2019). These studies suggest that national fiscal incentives (i.e. purchase subsidies and tax rebates), R&D in EV and battery technology and charging infrastructure measures (i.e. subsidies and public funding) are pivotal. Climate change policies, national goals and strong industrial policies are also identified (Dijk et al., 2013; Zimm, 2021). Some studies have employed scenario-based analysis to illustrate how various policy instruments and different levels of interventions can affect market uptake (Liu and Xiao, 2018; Wolinetz and Axsen, 2017), but they do not integrate regional and local policies into a holistic framework. Essentially, early pioneers usually start their business at a local scale; and electric mobility is eventually scaled up when there are enough policy measures to alleviate the lock-in effects of the incumbent technologies under a favourable regime at the wider regional and national level. This suggests that electric mobility needs to be examined at different spatial scales. It is recognized that a lag time exists for radical innovations such as EVs to enter the socio-technical regime (Collantes and Sperling, 2008). Essentially, regional and local efforts are as important as national policies in transition to EVs (Sperling et al., 2020).

To address the above research gaps, this paper first examines transport decarbonisation in the two bay areas of significant EV development between 2000 and 2018. These two bay areas – The San Francisco Bay Area (SFBA) and Guangdong-Hong Kong-Macau Greater Bay Area (GBA) – are EV market leaders in the two largest economies of the world, that is, the United States and China respectively. An analysis of changes in regional road CO_2 emissions in the two regions will provide valuable insights and lessons which can have higher relevancy in understanding the transport carbon reduction capability of electric mobility within specific contexts. In addition, this study applies a backcasting methodology to evaluate policy measures in achieving long-term carbon reduction targets by 2050 in the two regions. For electric mobility to become a global strategy of long-term transport decarbonisation, a coherent set of policies from the national, regional, and local scales is necessary and is analysed from the two bay areas.

3. Research methodology

Fig. 1 illustrates the analytical framework in this study. To begin with, the transport decarbonisation analysis is conducted between 2000 and 2018 by considering local-regional economic indicators (i.e. real GDP). Next, a backcasting analysis is conducted for the period between 2019 and 2050. Supporting both analyses is the data of local and regional road transport CO_2 emissions based on several important indicators on transport activities, fuel carbon intensity, and the amount of EV stock.

3.1. Study areas

GBA and SFBA are selected as study areas because these two regions are pioneers in electric mobility within the two largest economies of the world (i.e. China and US). China is one of the global leaders in EV development, with national investment in R&D of ZEVs, ambitious goals for EV deployment & air quality improvement, as well as strong fiscal incentives. GBA, situated in the Guangdong Province of China, has been one of the earliest core pilot regions of electric mobility. It is also where the headquarter of the largest EV manufacturer in China (also the leading battery-maker), BYD, is located. Regional policies in public transport fleet electrification and local monetary incentives are implemented. In the US, national EV-related policies mainly include GHG performance standards and vehicle purchase incentives, while regional policies vary across each state. SFBA, located in California State, has been one of the most successful regions of EV development. It is the home to Tesla, the first EV original equipment manufacturer (OEM) in the world. SFBA is also an affluent region and home to the Silicon Valley which embraces new technology. The regional government has shown a strong commitment to promote EV development by fiscal measures, parking and charging incentives, and outreaching programmes. Nationally, China has much stronger ZEV policies than the US in terms of air quality, energy security, industrial polices, and GHG reduction. Regionally, California has a similar level of commitments to ZEVs as China. The above transport decarbonisation polices are highly relevant to Sustainable Development Goal (SDG) 11 by improving air quality, SDG 7 by enhancing energy efficiency, and SDG 13 by reducing carbon

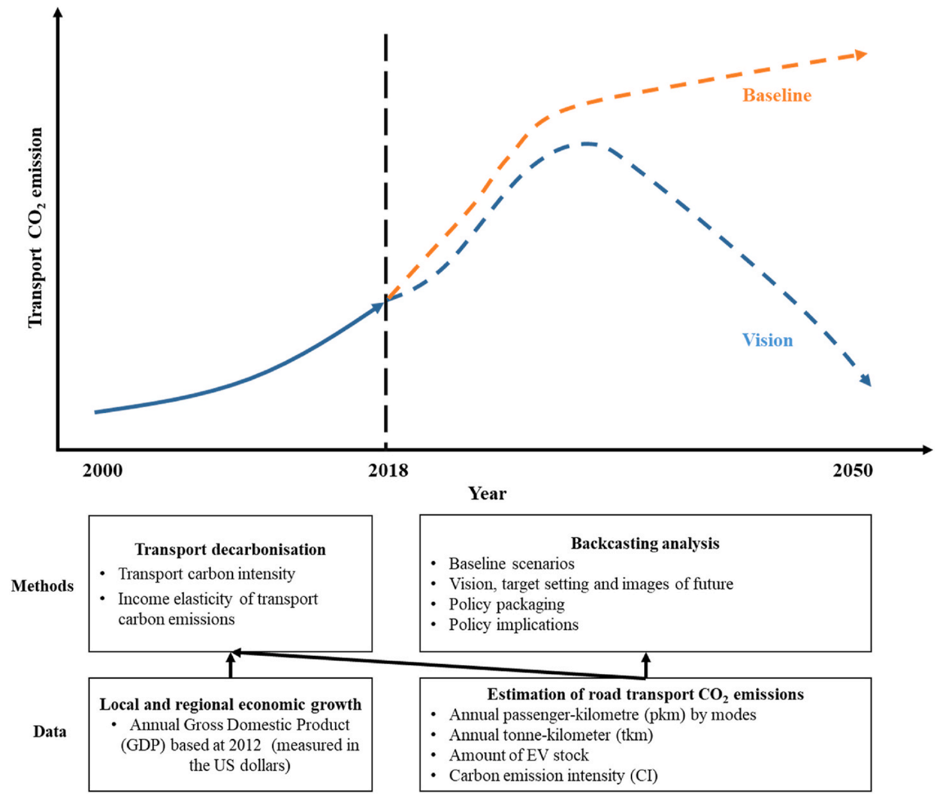

Fig. 1. The analytical framework.

emissions.

Figs. 2 and 3 depict the population density and the percentage of light-duty EVs at each local administrative entity of GBA and SFBA respectively in 2018. GBA comprises of nine municipalities and two special administrative regions in Guangdong Province whereas SFBA comprises of nine counties in the state of California. GBA has been undergoing significant development in electric mobility. In 2019, the top five cities with the highest number of electric vehicles in China were Shanghai, Beijing, Shenzhen, Hangzhou and Guangzhou. Two (Shenzhen and Guangzhou) are in the GBA. Shenzhen is the first city in the world that fully electrified its city buses with a fleet size of 16,000 in 2017 (IEA, 2018) and almost transformed all taxis fleet to full electric models by 2019 (Li et al., 2019). SFBA is the leading region of North America in EV market development. In 2018, California had a market share of EVs of 7.8%. San Francisco and San Jose[1] are the top two most populous cities in the region, with EV market shares of 12 percent and 20 percent, respectively, in 2018 (Bui et al., 2020). As of 2019, the top three counties in the SFBA with the highest percentage of light-duty EV stock are Santa Clara (4.87%), Marin (4.06%) and Alameda (3.72%). Apart from the development in private cars, there is also rapid development in electric mobility of public transit (i.e. electric buses), ride-hailing services, and electric bikes/scooters (CEC, 2021; SFMTA San Francisco Municipal Transportation Agency, 2019).

3.2. Estimation of road transport CO_2 emissions

Measuring the total road transport CO_2 is a major methodological challenge at the regional scale. There are seldom official disaggregated data (i.e. both spatial and sectoral) of transport CO_2 emissions. Distance-based and fuel-based measurements are commonly used to estimate transport emissions. Following Loo and Li (2012, 2016), a distance-based approach comprising of three indicators – passenger-kilometre travelled (pkm), tonne-kilometre travelled (tkm) and carbon intensity (CI) per pkm and tkm – is adopted. Since CI differs across transport modes, the volume of road transport CO_2 emissions is estimated by:

$$RC_{i,t} = \sum_{kn}(pkm_{i,kn,t} \times pci_{i,kn,t}) + \sum_{n}(tkm_{i,t,n} \times tci_{i,t,n}) \quad \text{(Eqn. 1)}$$

where $RC_{i,t}$ is the road transport CO_2 emissions of local entity i in year t; $pkm_{i,kn,t}$ indicates the passenger-kilometre of sub-mode k *and* engine type n in local entity i in year t; *pci* indicates the passenger-transport carbon intensity; *tkm* indicates the road tonne-kilometre and *tci* is the carbon intensity of trucks. In this study, passenger modes include private cars, motorcycles, taxis (or demand-response) and city buses. Trucks are the only mode in road freight transport. Due to data unavailability, we do not further disaggregate trucks into light-duty and high-duty vehicles. Moreover, all vehicles are internal combustion vehicles (ICVs) in the two regions before 2010. The indicators and sources of variables for deriving the estimated road transport CO_2 are summarised in Appendix 1.

3.2.1. Annual transport activities

Data on mode-specific pkm at a county or a city level are not officially available in both bay areas. To generate the best estimates of annual sub-mode pkm, several important parameters are required, which can be illustrated by the equation below:

$$pkm_{i,k,t} = VKT_{i,k,t} \times VEH_{i,k,t} \times OR_{i,k,t} \quad \text{(Eqn. 2)}$$

where $pkm_{i,k,t}$ represents the annual passenger-kilometre of sub-mode k in local entity i in year t; $VKT_{i,k,t}$ represents the annual per-vehicle vehicle-kilometre travelled; $VEH_{i,k,t}$ represents the number of motor vehicles and $OR_{i,k,t}$ represents the average occupancy rates. Due to data

[1] San Jose is considered part of the SFBA in this study as it is a city of Santa Clara County. The city is also part of the Association of Bay Area Governments (https://mtc.ca.gov/about-mtc/what-mtc/nine-bay-area-counties).

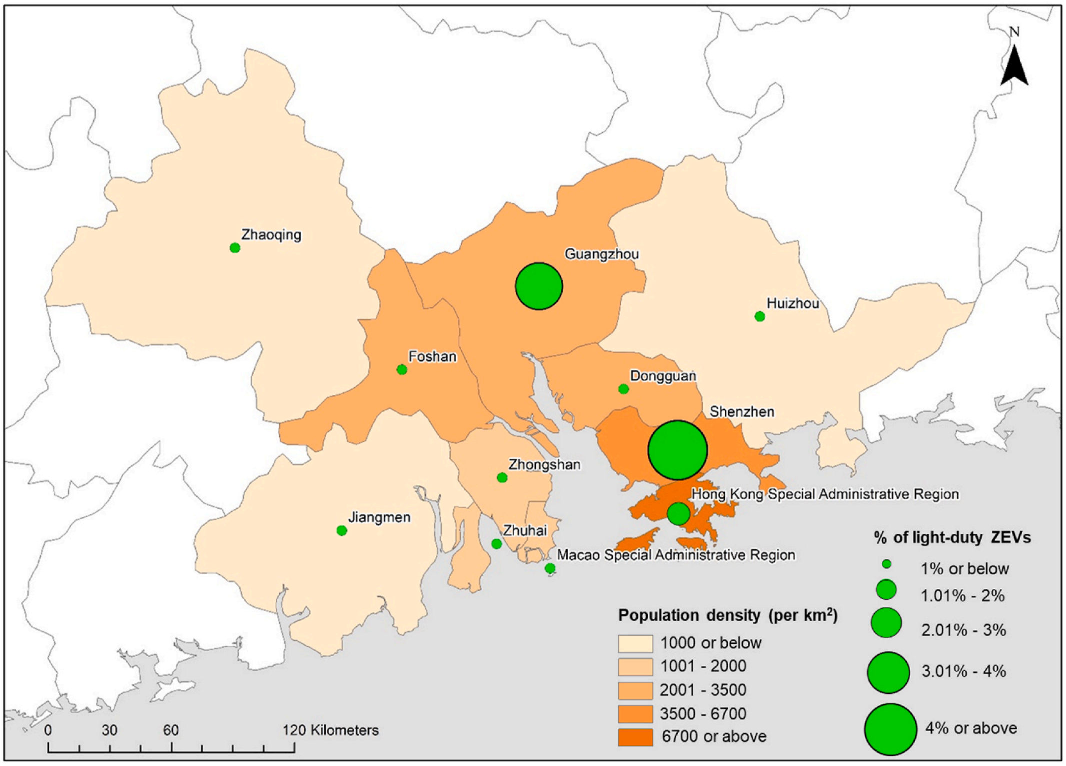

Fig. 2. Electric mobility development in the Greater Bay Area (GBA).

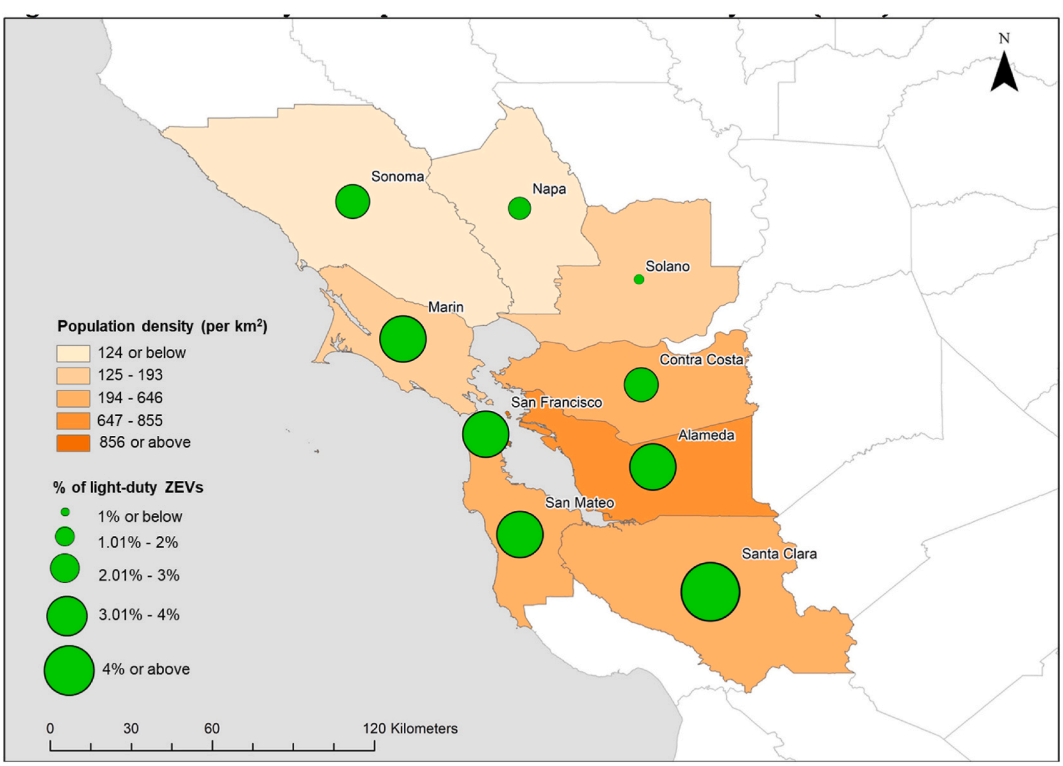

Fig. 3. Electric mobility development in the San Francisco Bay Area (SFBA).

availability issues, the calculation of pkm across different cities in GBA and SFBA is slightly different. The full procedures are explained in Appendix 2a. As for road tkm, annual road tkm is available in local statistical yearbooks of the nine municipalities in the GBA. Data for Hong Kong SAR and Macau SAR are estimated based on annual VKT by trucks and annual throughput. In SFBA, annual road tkm at the county level is estimated based on the state-level statistics in the Freight Analysis Framework (FAF) Version 4 (CTA, 2019). The full procedures are provided in Appendix 2b.

3.2.2. EV stock

Then, the number of EVs in the local area and the region is obtained. In this study, we do not further distinguish the different types of EVs. The figures in the SFBA are extracted from CARB (2021), which records the number of all types of EVs and the total registered vehicles in the region. Yet, no consolidated databases of EVs are available in the GBA. Hence, the figures are extracted from the policy archives from the open portals of the eleven local governments.

3.2.3. Carbon emission intensity (CI)

Next, the carbon emission intensity (CI) by each mode is estimated. For ICVs, we apply the data of average CO_2 per pkm based on international experience (Loo and Li, 2012). The corresponding figures of taxis, buses, private cars and motorcycles (of ICVs) in the 2000s, measured in g/pkm, are 145, 59, 112 and 56 respectively. For EVs, the CI (g/pkm) in the GBA are 75.4, 30.7, 58.2 and 29.1 respectively, considering that the regional-specific carbon footprint (based on the power mix) for a BEV in Guangdong Province is 48% lower when compared to ICVs (Wu et al., 2019). The corresponding values in the SFBA are 59.5, 24.2, 46.2 and 23.0, which was estimated based on the average of 55% reduction of annual emissions per EV in California (AFDC, 2019).

3.2.4. General income elasticities of transport CO_2 emissions

Finally, we examine the general relationship between negative transport externalities and economic growth (Loo and Banister, 2016; Loo et al., 2020; Tapio et al., 2007). In essence, it is measured by the income elasticity of a negative transport externality (*e*), as follows:

$$e = \frac{\Delta nte}{\Delta y} \quad \text{(Eqn. 3)}$$

where Δ *nte* indicates the percentage change of a negative transport externality and Δ *y* represents the percentage change of income. In this study, *nte* is represented by the annual CO_2 emissions in the road transport sector (including both passenger and freight) and *y* is the real GDP measured in US dollars (based 2012). The study period is further divided into four sub-periods, that is, 2000–2005, 2005–2010, 2010–2015, and 2015–2018.2020 cannot be used as the latest data available are for 2018. The real GDP statistics were consolidated from local statistical yearbooks/databases and transformed to a base year of 2012. To allow a consistent comparison, all data are calculated in US dollars.[2] When CO_2 is declining and GDP is rising, the income elasticity is negative. A higher absolute income elasticity (strong absolute decoupling) denotes a better scenario of more rapid transport decarbonisation. When both CO_2 and GDP are increasing, a lower but positive income elasticity (weak relative decoupling) denotes a better scenario that transport carbon did not increase as fast as the GDP. By examining the regional dynamics of transport carbon intensities and income elasticities, one aims to understand the transport decarbonisation progress in the two bay areas over the last two decades.

3.3. Backcasting analysis

To understand how EV policy measures can contribute to transport decarbonisation, a backcasting analysis is conducted. The essence of backcasting is to analyse and identify the necessary conditions to materialise the normative viewpoints or targets of possible futures (Dreborg, 1996; Gerus and van Wee, 2000). Based on previous studies in backcasting in transport carbon emissions (Banister and Hickman, 2013; Hickman et al., 2011), there are three fundamental steps. They are (i) baseline and target setting, (ii) policy packaging and (iii) appraisal. In this study, we only focus on the first two steps because the primary objective is to examine the potentials of EV policies in paving the way to the long-term vision of transport decarbonisation.

[2] The conversion rate of USD to RMB is 1–6.8. The conversion rate of USD to HKD is 1–7.8.

3.3.1. Baseline, targets and images of future

The first step is to develop a baseline for the study period (i.e. 2000-2050) and define the most desirable futures. In a typical backcasting analysis, the long-term vision is generally developed by experts, policymakers and other stakeholders through face-to-face interviews or focus groups (Soria-Lara and Banister, 2018). With an aim to examine electric mobility as a global transport decarbonisation strategy, this study adopts common visions envisaged by international researchers in electric mobility. Two visions were considered. The first vision was developed by the recent the Partnership on Sustainable Low-carbon Transport (SLoCaT) (Gota et al., 2016) that a 64% reduction of CO_2 emissions when compared to the business-as-usual scenario (BAU) by 2050 is required to meet the 2-degree Celsius scenario (2DS). The second vision is to reduce CO_2 by 60% when compared with the 2010 baseline, which is identical to the **450 Delayed Action Scenario**[3] stated in Marchal et al. (2011). Given that the latter is more ambitious, we have chosen to focus on the latter.

A BAU scenario is developed to illustrate the trajectory of transport CO_2 in *status quo*, assuming that the other variables of economy, population and transport remain stable and consistent. To reflect the variability of the baseline scenario, a conservative and an optimistic baseline are developed to project the CO_2 emissions from 2019 to 2050. The conservative BAU scenario (BAU) assumes that the EV share will remain stable until 2050,[4] whereas the optimistic scenario ($BAU_{6\%}$) assumes that there is an annual growth of EV sales by 6%,[5] capturing the more macroscale impacts of technology diffusion. This study assumes that the average VKT per vehicle,[6] emission factor of ICVs, and occupancy rates of all modes remains the same throughout the projection period. The only variations are the total number of vehicle stock and share of EVs. For the number of vehicle stock, it is suggested that China will continue to have significant car growth in the near future. The growth factors of cars, buses and trucks are applied based on the Gompertz forecast model in Huo and Wang (2012). The figures are comparable to other national forecasts (Lu et al., 2018) and a recent provincial study based in Guangdong (Ma et al., 2019). In the SFBA, the projected vehicle stock is extracted from the fleet database (CARB, 2021). The backcasting analysis separates passenger and freight transport because the policy instruments and their associated impacts in increasing the market share of EVs can be different. With the baseline, images of future can be developed. Two trajectories that achieve the two aforementioned visions are developed. In this study, since our focus is primarily on EV development, a techno-optimism vision of rapid EV uptake and breakthrough in vehicle and battery technology is envisaged. The EV share is modelled in logistic growth (Rietmann et al., 2020) for these two trajectories. Essentially, there can be a wide range of different key drives in governing our future (Hickman et al., 2011; Loo, 2018).

3.3.2. Policy packages

The next step is to develop various policy packages to achieve the desirable futures. Each policy package consists of different policy instruments. Policy instruments not related to electric mobility are not

[3] The 450 Delayed Action scenario assumes that large number of additional initiatives need to be made after 2020 to "catch up" the delayed progress.

[4] In the SFBA, the BAU scenario follows the estimates from the inventory database of EMFAC 2021 (CARB, 2021). In the GBA, it is assumed that the EV share also follows the growth rate of EV share as in the SFBA.

[5] This assumption is rooted from around 6% increase in EV sales worldwide between 2018 and 2019 (IEA, 2020).

[6] In China, it is estimated that the private cars have an average of 12,000–13,000 annual kilometre travelled per vehicle in 2030 and 2050 (Huo et al., 2007), which is similar to the recent case.

considered because this study focuses on the potentials of electric mobility in transport decarbonisation. Due to limited data and the shorter timeframe of EV development, policies targeting trucks are not analysed separately. Essentially, to evaluate the required policy instruments, we need to know the effects of such measures in affecting EV uptake. To date, only a few policy instruments are found to have significant associations with EV uptake in both national and global studies. They include (i) direct financial incentives (e.g. direct subsidy, tax breaks and fuel discount) (Hardman et al., 2017; Soltani-Sobh et al., 2017; Wee et al., 2018), (ii) vehicle performance standards (Hardman and Tal, 2016), (iii) sales mandates (Olson, 2018), (iv) density of chargers (Lee et al., 2019; Li et al., 2020; Sierzchula et al., 2014) and (v) traffic regulations (e.g. free parking, priority licensing and use of HOV lanes) (Jenn et al., 2020). Essentially, both financial and non-financial measures can be vital to EV adoption (Rietmann and Lieven, 2019; Wang et al., 2017; Wang et al., 2019). As this study aims at analysing the regional development of electric mobility, only regional-local policies are included and evaluated. Five sets of policy measures are considered. The first four are targeting at charging density, monetary incentives, driving range, and traffic regulations. We apply the estimates from a structural equation model (SEM) in a global study of 20 countries/areas (Rietmann and Lieven, 2019), where the standardised coefficients of charging density, monetary incentives, and traffic regulations are 0.32, 0.27 and 0.37 respectively. It is also found that driving range has a significantly positive relationship (=0.17) (Li et al., 2020). The estimated impact of these policy measures on EV market share is summarised in Table 1. Finally, the emission factor of EVs is considered as it indicates the level of upstream carbon emissions[7] (i.e. electricity generation). Three policy packages are developed with different weighting of the five sets of policy measures in different scenarios.

(a) **A balanced approach (PP1)**: This policy package integrates balanced shares of policy measures in enhancing charging density, traffic regulations, and driving range. A weight of 1:1:1:1 is suggested.
(b) **A charger-oriented approach (PP2)**: This policy package assumes that there is a significant increase of charging density in the region. A moderate level of traffic regulations is implemented. There is a small improvement in the monetary incentives and driving range. A weight of 5:3:1:1 is used.
(c) **A clean electricity approach (PP3)**: This policy package envisages a more ambitious upstream carbon emissions of EVs (i.e. electricity generation). As both regions aim at having nearly all electricity mix from renewable power resources, this study assumes a 95% reduction of emission factor of EVs (at the 2018 level) by 2050. In this package, only charging density, driving range and traffic regulations are considered. A weight of 2:1:1 is tested.

Table 1
Impacts of policy measures on EV market share.

	Measurement unit	Effect of per unit increase in EV market share (%)
Charging density[a]	1 station/road km	Increase 0.59%
Monetary incentives[a]	USD $1000	Increase 0.41%
Driving range[b]	1 percent increase	Increase 0.48%
Traffic regulations[a,c]	0.1 point	Increase 0.41%

[a] Rietmann and Lieven (2019).
[b] Li et al. (2020).
[c] In their study, they used "scores" to represent to relative magnitude of traffic regulations in the country. A higher point, for example, indicates a free use of EVs for parking, bus lanes, toll roads, public areas and domestic ferries. A full coverage of traffic regulations across the country also infers a higher score.

[7] This study only considers operational emissions (tank to wheel) but not the lifecycle emissions.

4. Results

4.1. Transport decoupling of two bay areas between 2000 and 2018

Table 2 depicts the road transport CO_2 emissions (in million metric tons, or Mt) in both bay areas. For the GBA, road transport CO_2 has increased greatly in absolute terms; it recorded almost a quadruple increase in the past two decades. The rapid economic development of Pearl River Delta (PRD) since 2000s, in particular the Shenzhen metropolitan area and the peripheral cities (e.g. Guangdong, Dongguan and Foshan), where export-oriented industries have drastically stimulated both passenger transport and freight logistics, can be an important factor. On the contrary, SFBA has demonstrated a relatively stable trend of transport CO_2 emissions. The SFBA has higher CO_2 emissions than GBA at the first period (2000–2005); then, it has actually risen by 6.8% till 2018 with a slight decline in 2010. Significant contribution was found in the counties of Alameda and Santa Clara (over half of the CO_2 emissions), where important cities like San Jose, Oakland and Fremont are located.

When comparing the estimated road transport CO_2 savings brought by electric mobility, the GBA obtained a reduction of 0.33 Mt of CO_2 in 2015 and 1.73 Mt in 2018. The figures for SFBA were 0.1 Mt and 0.25 Mt respectively. In the GBA, Shenzhen has dominated the CO_2 reduction in 2018 (1.06 Mt), followed by Guangzhou and Dongguan. In the SFBA, the largest reduction was found in Santa Clara (0.09 Mt), followed by Alameda and San Mateo. For the composition of CO_2 emissions in road passenger and freight transport at the end of the study period, the GBA generated 42.1 Mt CO_2 (56.3%) and 32.74 Mt CO_2 (43.7%) respectively in 2018. The corresponding figures for SFBA were 17.45 (73.3%) and 6.35 (26.7%). In the GBA, there is a 5-time and 6-time increase of CO_2 emissions for passenger and freight transport between 2000 and 2018. In the SFBA, CO_2 emissions of passenger transport has increased by 10.1% and that of freight transport dropped by 0.7%.

Table 3 illustrates the daily passenger-kilometre per capita. Generally, the US has a much higher daily pkm per capita due to more extensive car travel. There is a 2.5-time difference between both regions in 2018. For the GBA, the personal daily pkm has also increased significantly by 2.7 times region-wide, with the highest increase in Dongguan, Zhuhai and Zhaoqing. For the SFBA, the daily pkm per person has remained stable with a slight decline by 1.92%. Only Napa, Solano and Sonoma have recorded by a 3–7% increase, whereas the largest decline is found in San Francisco by 11%. Table 4 shows the road transport emissions per converted pkm to better capture the spatial variations of emission intensity. In general, the SFBA has a higher emission intensity possibly due to the more extensive car travel in the region. Overall, there are significant variations at the local scale in both bay areas.

Table 5 illustrates the road transport CO_2 intensity per million real GDP based 2012. The cells in green indicate a **decrease of transport CO_2 intensity** compared to the previous period. In other words, the green cells are favourable signs of transport decarbonisation. Significant spatial variations are found within GBA. In 2018, the highest CO_2 intensity was found in Jiangmen (102.83 ton/million real GDP), followed by Huizhou and Zhongshan. The best performing areas were Macau SAR (7.18 t/million real GDP), followed by Hong Kong SAR and Shenzhen. Cities of significant economic growth dominated by tertiary economic sectors (e.g. Hong Kong SAR and Macau SAR) and some new metropolitan areas (e.g. Guangzhou and Shenzhen) were associated with declining carbon intensities in recent years (i.e. 2015 and 2018). The

Table 2
Road transport CO_2 emissions (Mt CO_2).

	Current					Without EM		Estimated CO_2 savings (2018)
	2000	2005	2010	2015	2018	2015	2018	
Greater Bay Area (GBA)								
Dongguan	1.03	1.98	3.60	6.06	8.86	6.10	8.97	0.12
Foshan	1.60	2.64	4.48	7.27	9.36	7.29	9.45	0.10
Guangzhou	2.99	5.52	11.40	18.41	20.29	18.43	20.64	0.35
Hong Kong SAR	3.75	3.72	3.78	3.96	4.04	3.97	4.05	0.01
Huizhou	0.65	0.93	1.72	3.46	5.13	3.47	5.16	0.02
Jiangmen	0.64	1.43	2.57	4.15	4.61	4.15	4.63	0.02
Macau SAR	0.24	0.27	0.31	0.39	0.39	0.39	0.39	0.00
Shenzhen	1.30	2.98	9.35	12.56	12.55	12.78	13.61	1.06
Zhaoqing	0.43	0.77	1.20	2.05	2.62	2.05	2.62	0.00
Zhongshan	0.63	0.99	1.66	3.57	4.51	3.59	4.55	0.04
Zhuhai	0.36	0.58	1.09	1.89	2.48	1.89	2.50	0.02
Regional	**13.63**	**21.81**	**41.18**	**63.76**	**74.84**	**64.09**	**76.57**	**1.73**
San Francisco Bay Area (SFBA)								
Alameda	5.94	5.98	5.50	6.12	6.18	6.15	6.25	0.06
Contra Costa	2.84	3.04	2.81	3.13	3.27	3.14	3.30	0.03
Marin	0.90	0.89	0.85	0.92	0.93	0.93	0.95	0.01
Napa	0.46	0.47	0.44	0.49	0.53	0.49	0.53	0.00
San Francisco	1.00	0.94	0.89	0.97	0.99	0.98	1.00	0.01
San Mateo	2.25	2.02	1.92	2.20	2.29	2.21	2.32	0.03
Santa Clara	5.64	5.28	5.17	5.83	5.98	5.87	6.07	0.09
Solano	1.67	1.80	1.68	1.86	1.96	1.86	1.97	0.01
Sonoma	1.55	1.57	1.48	1.64	1.68	1.64	1.69	0.01
Regional	22.24	21.99	20.73	23.16	23.81	23.26	24.06	**0.25**

Table 3
Daily passenger-kilometre per capita (pkm per person).

	2000	2005	2010	2015	2018
Greater Bay Area (GBA)					
Dongguan	4.29	8.93	10.71	16.82	25.58
Foshan	8.98	11.75	12.99	17.61	20.93
Guangzhou	7.10	11.05	11.75	13.24	13.39
Hong Kong SAR	10.96	11.01	11.05	11.41	11.32
Huizhou	3.57	6.77	7.97	11.76	16.17
Jiangmen	6.11	11.22	16.76	23.66	20.30
Macau SAR	9.85	11.18	12.53	13.66	13.20
Shenzhen	4.34	8.33	13.11	19.28	16.85
Zhaoqing	3.43	6.11	8.57	12.42	15.12
Zhongshan	7.27	9.52	10.33	16.11	22.36
Zhuhai	5.44	8.61	12.80	20.96	26.50
Regional	**6.51**	**9.67**	**11.75**	**15.88**	**17.58**
San Francisco Bay Area (SFBA)					
Alameda	61.86	61.99	54.94	57.57	61.01
Contra Costa	58.92	58.01	51.94	54.44	57.17
Marin	77.43	76.57	70.43	74.07	77.69
Napa	74.38	73.71	66.13	71.06	76.73
San Francisco	31.13	29.83	26.57	27.51	27.70
San Mateo	59.45	53.73	48.11	53.23	57.21
Santa Clara	59.58	56.71	51.63	54.73	58.06
Solano	60.73	63.99	58.81	62.26	65.27
Sonoma	53.83	53.51	48.48	51.58	54.70
Regional	**57.30**	**55.96**	**50.35**	**53.25**	**56.22**

Table 4
Daily road transport emissions per converted pkm (g/cpkm/day).

	2000	2005	2010	2015	2018
Greater Bay Area (GBA)					
Dongguan	29.77	40.73	43.30	49.56	56.52
Foshan	31.28	31.27	30.94	32.23	33.05
Guangzhou	27.55	25.81	22.82	20.26	19.80
Hong Kong SAR	26.63	26.87	28.06	29.45	29.75
Huizhou	21.40	29.93	28.16	26.51	27.73
Jiangmen	42.90	34.07	32.45	31.28	28.81
Macau SAR	29.00	31.57	33.42	35.16	33.93
Shenzhen	33.19	39.08	25.30	31.02	26.59
Zhaoqing	26.52	29.12	31.34	30.51	34.36
Zhongshan	29.30	30.09	30.34	25.51	29.48
Zhuhai	25.00	28.74	28.96	30.74	34.49
Regional	**28.38**	**30.18**	**27.22**	**27.26**	**27.41**
San Francisco Bay Area (SFBA)					
Alameda	31.25	30.88	31.27	31.60	33.99
Contra Costa	48.95	44.98	47.09	47.15	49.47
Marin	58.87	56.92	56.64	55.64	59.15
Napa	51.81	52.96	52.55	52.60	50.34
San Francisco	86.84	87.96	84.67	88.37	89.95
San Mateo	42.80	41.61	40.10	41.74	43.96
Santa Clara	39.42	40.20	39.49	39.40	41.63
Solano	29.92	29.95	29.99	29.88	30.56
Sonoma	33.64	33.38	33.38	32.90	33.88
Regional	**38.27**	**37.69**	**37.81**	**37.99**	**40.04**

Note: Converted pkm is calculated by summing up the pkm and tkm, with 1 tkm = 10 pkm (Loo and Banister, 2016).

more manufacturing-based cities (e.g. Dongguan, Foshan and Zhongshan), however, have been undergoing significant growth of carbon intensities. As for the SFBA, the regionwide transport CO_2 emissions have demonstrated a consistent trend of decline, with an overall drop by 43.8%. In 2018, the highest CO_2 intensity was found in Solano (84.01 t per million real GDP), followed by Sonoma and Alameda. The best performing county was San Francisco (5.67 ton per million real GDP), followed by Santa Clara and San Mateo. Although there are huge spatial discrepancies, almost all counties in SFBA have a stable decline in carbon intensities, with the largest reduction in Santa Clara by 62.1%.

Finally, Table 6 presents the income elasticities of transport CO_2 emissions of each local municipality/county of the two bay areas in the four study periods. Dark green cells denote the most desirable state of income growth but declining transport CO_2 (absolute decoupling), while light green cells denote a positive increase of transport CO_2 at a rate lower than the GDP growth (relative decoupling). Over time, the GBA only achieved relative weak decoupling with income elasticity lower than one ($e = 0.85$) in the most recent period. Again, huge spatial variations are observed. In the earlier periods (2000–2005; 2005–2010), around two-thirds of the cities achieved relative decoupling. In the recent decade (after 2010), a lot of the second-tier cities (e.g.

Table 5
Road transport CO_2 intensity (t CO_2 per million real GDP in USD based 2012).

	Current					Without EM	
	2000	2005	2010	2015	2018	2015	2018
China Greater Bay Area (GBA)							
Dongguan	74.92	57.04	55.27	63.17	73.58	63.50	74.55
Foshan	88.79	68.66	55.02	57.45	59.45	57.61	60.07
Guangzhou	66.32	63.81	69.63	69.49	62.31	69.56	63.38
Hong Kong SAR	23.28	18.67	15.59	13.98	13.05	14.00	13.09
Huizhou	100.07	78.69	67.24	74.06	85.10	74.30	85.48
Jiangmen	82.41	115.38	112.41	115.80	102.83	115.80	103.19
Macau SAR	15.95	10.69	7.26	7.82	7.18	7.82	7.21
Shenzhen	32.38	34.64	57.87	48.92	38.28	49.77	41.51
Zhaoqing	89.87	92.41	68.09	68.55	74.23	68.55	74.24
Zhongshan	102.64	65.80	57.47	76.00	79.04	76.48	79.75
Zhuhai	65.11	55.36	57.82	62.11	62.93	62.11	63.37
Regional	**38.96**	**38.86**	**45.06**	**48.46**	**47.20**	**48.71**	**48.30**
San Francisco Bay Area (SFBA)							
Alameda	75.29	65.91	59.13	53.44	47.32	53.66	47.80
Contra Costa	43.21	39.46	39.91	44.00	42.21	44.15	42.54
Marin	55.59	51.66	51.54	48.26	44.64	48.52	45.23
Napa	64.57	59.03	56.70	53.07	52.68	53.21	52.99
San Francisco	10.90	10.26	9.19	7.27	6.08	7.31	6.16
San Mateo	42.78	36.32	31.12	25.54	21.78	25.67	22.06
Santa Clara	49.78	40.11	29.96	23.15	18.89	23.30	19.16
Solano	118.04	103.62	91.20	88.02	84.01	88.15	84.32
Sonoma	76.38	71.00	66.58	63.31	58.81	63.46	59.14
Regional	**48.38**	**42.99**	**37.08**	**31.61**	**27.21**	**31.75**	**27.49**

Note: Measured in the US dollars. US dollar to RMB dollar (USD 1= RMB 6.8). US dollar to HKD dollar (USD 1= HKD 7.8). Shaded cells denote decrease in transport CO_2 intensity.

Table 6
Income elasticities of transport CO_2 emissions.

	2000-2005	2005-2010	2010-2015	2015-2018	**Changes** (2018 vs 2000)
Greater Bay Area (GBA)					
Dongguan	0.60	0.93	1.45	1.81	↓
Foshan	0.57	0.62	1.12	1.18	↓
Guangzhou	0.92	1.19	0.99	0.45	→
Hong Kong SAR	-0.04	0.08	0.28	0.21	↓
Huizhou	0.53	0.73	1.22	1.66	↓
Jiangmen	2.06	0.94	1.08	0.44	↑
Macau SAR	0.21	0.22	1.62	0.06	→
Shenzhen	1.13	2.43	0.58	-0.002	↑
Zhaoqing	1.07	0.50	1.02	1.55	↓
Zhongshan	0.39	0.74	1.84	1.23	↓
Zhuhai	0.68	1.10	1.20	1.06	↓
Regional	0.99	1.41	1.25	0.85	→
San Francisco Bay Area (SFBA)					
Alameda	0.04	-3.12	0.49	0.07	→
Contra Costa	0.41	0.88	11.01	0.51	→
Marin	-0.23	1.05	0.53	0.13	↓
Napa	0.22	3.15	0.57	0.91	→
San Francisco	-20.39	-1.07	0.25	0.07	↓
San Mateo	-1.95	-0.43	0.36	0.19	↓
Santa Clara	-0.39	-0.07	0.28	0.10	↓
Solano	0.35	-1.24	0.73	0.51	→
Sonoma	0.12	-13.88	0.66	0.25	→
Regional	**-0.10**	**-0.61**	**0.38**	**0.14**	↓

Note: ↑ denotes the improvement in decoupling status in the last period (2015-2018) when compared to the earliest period (2000-2005). ↓ and → represent the decreasing trend and no change.

manufacturing) have deteriorated to coupling with an absolute increase in transport carbon at a rate higher than income growth, possibly because of the rapid industrial development and trade. Hong Kong SAR and Macau SAR have remained rather stable in relative decoupling. In the latest period, Shenzhen achieved absolute weak decoupling (the best scenario of transport decarbonisation). As for the SFBA, the regional income elasticity of transport CO_2 emission status shows a clear pattern, with absolute decoupling (dark green) before 2010 but relative decoupling (light green) after 2010. The region and all counties managed to achieve relative decoupling in the final period ($e = 0.14$). The most distinctive period was between 2005 and 2010, where two-thirds of the counties experienced absolute decoupling. Overall, the core region of economic development (San Francisco, San Mateo and Santa Clara) seems to be performing better with at least two periods of absolute decoupling.

4.2. Backcasting analysis

In this section, we try to visualise the pathways towards transport decarbonisation in the two bay areas. To reiterate, the 450 Delayed Action vision of a 60% reduction of CO_2 emissions when compared to the 2010 level indicates the more ambitious decarbonisation target. Hence, we shall focus on the combination of policy measures required for achieving this target. For the GBA, this suggests an extremely ambitious target to reach the deep decarbonisation targets of 9.24 Mt and 7.2 Mt of CO_2 (i.e. 60% below the 2010 level) for passenger and freight transport respectively. Fig. 4 illustrates the backcasting results of passenger transport in the GBA. For passenger transport to achieve the target, there are several fundamental conditions. By 2050,

- All public transport including buses and taxis need to be 100% electric;
- The CO_2 emission factor of EVs needs to be reduced by at least 85%;
- Achieving 99% of EV share out of the total car stock, which is equivalent to an average annual growth rate of private car sales/ replacement by 11.1%;
- EV market share (the ratio of EV sales to total car sales) needs to reach 100% by 2031.

It is noted that electrifying all road vehicles alone will not achieve the decarbonisation targets as it will only lead to a moderate reduction to around 60 Mt CO_2. Enhancing the renewable mix in electricity and stimulating market uptake are paramount. The associated policy packages to achieve the target are summarised in Fig. 4. For **PP1** (balanced), charging density needs to increase by 50 stations per road km and a substantial provision of monetary incentives (USD 50,200) is required. For **PP2** (charger-oriented), charging density needs to increase by 94 stations per road km which can potentially contribute to a reduction of CO_2 by 18.40 Mt. For **PP3** (clean electricity), there is a reduction of emission factor by 95% (2.91 g/pkm for cars), and increasing 92 charging stations per road km is expected. Overall, the policy initiatives including boosting EV adoption and providing clean electricity are very ambitious.

For the SFBA, the 450 Delayed Action vision also suggests highly ambitious targets to reach deep decarbonisation at 5.86 Mt and 2.4 Mt of CO_2 (i.e. 60% below the 2010 level) for passenger and freight transport, respectively (Fig. 5). Again, there are several fundamental conditions. By 2050,

- All public transport including buses and taxis need to be 100% electric;
- The CO_2 emission factors of EVs need to be further reduced by at least 50%;
- Achieving 92.2% of EV share out of the total car stock, which is equivalent to an average annual growth rate of private car sales/ replacement by 9.38%;
- EV market share (the ratio of EV sales to total car sales) needs to reach 98% by 2035.

Cleaner electricity generation and more efficient electricity transfer are anticipated. The associated policy packages to achieve the target are summarised in Fig. 5. For **PP1** (balanced), charging density need to increase by 45 stations per road km and driving range needs to improve by 45 percent to reduce the CO_2 by 3.02 Mt. For **PP2** (charger-oriented), the charging density needs to increase significantly by 85 stations per road km that can reduce over 3.1 Mt of CO_2. The level of traffic regulation needs to increase by 5 points. For **PP3** (clean electricity), there is a reduction of emission factor by 95%, and increasing 66 charging stations per road km is expected. With the almost completely carbon-free electricity mix, the share of EV stock needs to achieve a minimum of 75%, and the market share needs to reach 80% by 2034.

5. Discussion

5.1. Main drivers for transport decoupling

5.1.1. Regional transport decoupling

The transport decarbonisation analysis indicates that transport decoupling has happened in GBA and SFBA. In the GBA, relative coupling happened during 2005–2015 and relative decoupling was achieved during 2015–2018. There are several possible driving factors. The relative coupling status during 2005–2015 can be attributed to the rapid motorisation in the region. The number of registered motor vehicles increased by 123% and 91% in the periods of 2005–2010 and 2010–2015 respectively, and the pkm increased by 46.8% and 41.5%. In contrast, decoupling took place in the latest period (2015–2018) partly because of slower growth rates of motor vehicles (17%) and pkm (18.1%). Moreover, the average VKT per vehicle also decreased by 33.9% in the past decade, as mostly favoured by more compact city development and improving accessibility in the core Shenzhen metropolitan area. The findings here align with the regional decoupling studies (Wang and Wang, 2019; (Xu et al., 2021)) that Guangdong Province has experienced expansive coupling in earlier periods followed by weak decoupling, which suggests that economic development and population growth have been the major driving forces. Also, the regional trading economy has become more mature with a steadier growth rate of tkm (17% in 2015–2018 when compared to 154% in 2005–2010). Moreover, the higher energy intensity in fuel consumption from fossil fuels has also led to transport coupling in CO_2 emissions in earlier

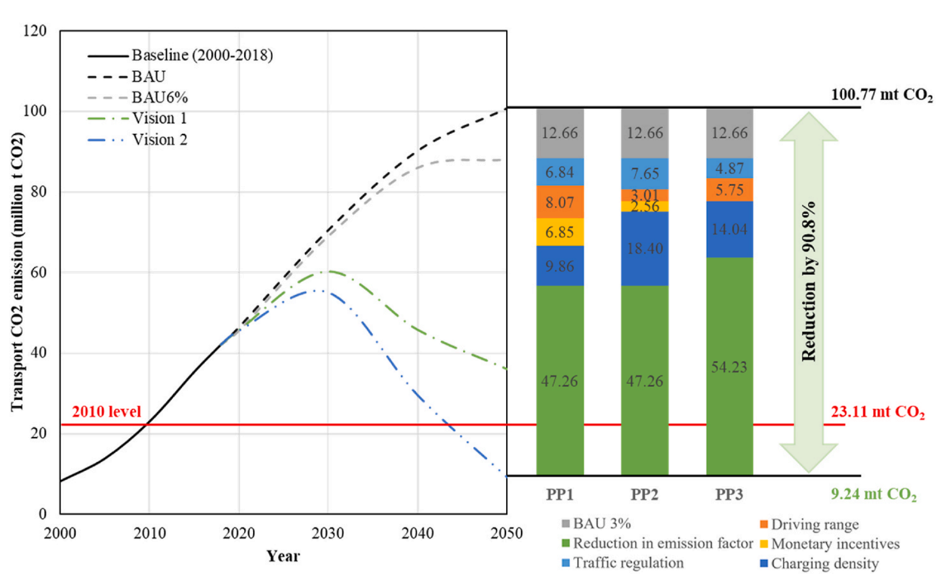

Fig. 4. An illustration of policy potentials in achieving the target of 60% reduction of transport CO_2 in the GBA compared with the 2010 baseline.

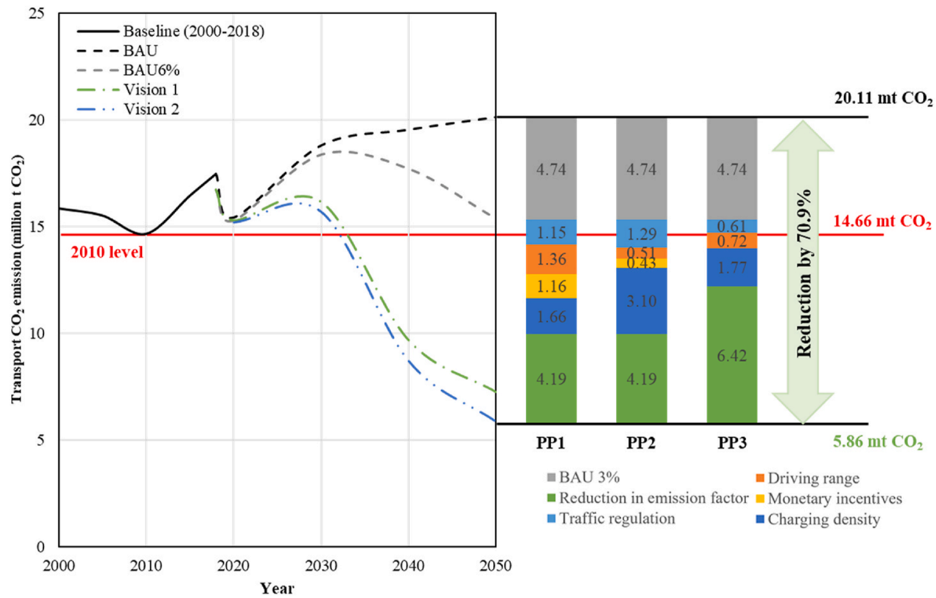

Fig. 5. An illustration of policy potentials in achieving the target of 60% reduction of transport CO_2 in the SFBA compared with the 2010 baseline.

periods (Wu et al., 2018). In addition, the surge of EVs and electrified public transport fleet after 2015 were favourable factors. When compared the regional decoupling status in GBA to the national trend, most decoupling studies (Liu and Feng, 2020; Song et al., 2019; Loo et al., 2020) demonstrate that China has maintained relative decoupling at the national level since 2005. Yet, highly uneven spatial variations across different regions were detected (Wang and Wang, 2019).

In the SFBA, decoupling has been consistent over the past two decades, with absolute decoupling followed by relative decoupling. In general, there is a strong relationship between the decoupling status and the annual total VKT travelled by private vehicles. In the earlier two periods with absolute decoupling, the regionwide VKT decreased by 2% and 6% respectively, while the increased by 13% and 7% in the latter two periods largely explained why the region could only achieve relative decoupling after 2010. Also, the share of road public transport still remains low in the region, which only accounts for 1–2% of the total pkm. The decoupling performance was the best in 2005–2010, as private vehicle VKT dropped to the lowest level largely due to a slower economic growth after the global economic crisis in 2008. This regional trend also largely conforms to the national decoupling trend in the US (Tsoi et al., 2021). Moreover, the findings tally with Neves and Marques (2021) that strong decoupling in transport was only achieved during 2010–2012 as a positive result of the regulation policy on emission standards to vehicles sold since 2009. Similar findings of the impact of regulation are illustrated by Rhodes et al. (2021). Overall, car mileage and economic development seem to be the most significant factors in affecting transport decoupling in the US. Despite the growth of EVs in the region, the energy intensity effect is offset by the increase in total VKT, hence failing to achieve the absolute decoupling status.

While population and economic structure have a strong impact on transport decoupling, fuel efficiency and energy intensity are also determining factors of decoupling, as empirically observed in China (Wu et al., 2018), Cameroon (Engo, 2019), Pakistan (Raza and Lin, 2020), the US (Neves and Marques (2021). Clearly, electric mobility, combined with low carbon intensity of electricity, can drive absolute transport decoupling. If we just focus on the latest periods, the regional policies of electric mobility can be an explanatory factor in helping both regions to achieve transport decoupling. Firstly, both regional governments have clear visions and multi-sectoral policy objectives in transport decarbonisation. They envisage long-term decarbonisation through the wider adoption of EVs that aligns with national decarbonisation blueprints and promote regional environmental sustainability (GO of Guangdong Province, 2012; State of California, 2013). The objectives are highly comprehensive, including (i) R&D in EVs, battery and components, (ii) enhancing consumer awareness, (iii) facilitating EV industrialisation and investment and (iv) densifying charging infrastructure. Overall, the objectives move beyond the “vehicle”, and cover the supply chain, consumer preferences and market mechanisms. Secondly, both regions have made significant progress towards decoupling largely because they have established quantifiable targets in EV sales corresponding to the objectives in the next 10–15 years and have formulated thematic action plans. Specific targets were set to 1.5 million zero-emission vehicles by 2025 in the SFBA (State of California, 2018a) and accumulated sales of 5 million by 2025 in the GBA (GO of Guangdong Province, 2012). Thirdly, cohesive institutional frameworks have enhanced the effectiveness of boosting EV development in both regions in the latest period. There is a multi-stakeholder approach which includes members from government officials, industry, consumers and scholars. Both regions have strong institutional coordination of major task divisions in local municipal governments. A clear top-down approach is adopted in GBA, with the policy vision from the State Council realised at the local scale by the pilot cities programmes. For the SFBA, a collaborative platform was set up for exchanging experiences in promoting EV adoption in local communities. Policy examples are illustrated in Appendix 3. In short, having a clear vision and multi-instrumental objectives are required for effective transport decarbonisation (Tsoi et al., 2021). Also, recent findings from Moradi et al. (2021) suggest that promoting EV & PHEV can potentially lead to substantial carbon savings but it needs to be supported by other pricing measures (i.e. price of gasoline).

5.1.2. Local transport decoupling

Despite the regionwide decoupling progress, the decoupling status varies across different cities, suggesting that some local policy mechanisms might have also affected their decoupling status. In the GBA, spatial variations are much stronger. Guangzhou, Hong Kong SAR and Shenzhen are the three best cities that achieved two consecutive decoupling periods (2010–2015; 2015–2018). On one hand, the growth rates of motor vehicles of these cities are the lowest (2.1%–18.8%) when compared to the other major cities (45.7%–85.5%). The development of metro rail system and a higher share of public transport is also an essential factor of decoupling (i.e. 31-62% of bus pkm). For the SFBA, local variations are smaller, as the increase of vkm among the nine counties is relatively similar, ranging from 13% to 28% during 2010–2018. Counties with a larger magnitude of decoupling are mainly in the core regions of SFBA, including Alameda, San Francisco and Santa Clara. Indeed, electric mobility can also largely explain the local variations of decoupling. The EV shares of these cities are higher than their counterparts. In GBA, Shenzhen, Guangzhou and Hong Kong SAR ranking the top three cities in EV adoption (1.7–6%). In SFBA, the best performing counties are also having a higher EV share of 2.5–3.3% whereas the others only attain 1.1–2.8%.

Focusing on these better performing regions, several local electric mobility policies have acted as the driving forces for decoupling in the most recent period (2015–2018). Firstly, these cities have provided local monetary incentives in aspects such as utilities, parking and charging station installation, building on top of the general fiscal incentives promoted nationwide in the US (Wee et al., 2018) and China (Wu et al., 2021). Shenzhen has free street parking for EVs in the first hour; and the City of San Jose (Santa Clara) has free parking at parking metres and selected parking slots. Charging rates, if publicly available, are either entirely complimentary (Hong Kong & Macau), capped at a fixed rate (Shenzhen, Guangzhou, Santa Clara) or discounted at off-peak hours (Alameda). To illustrate, Shenzhen has a fixed charging rates of 0.45 yuan per kWh and Alameda has fixed rate of $0.06 per kWh or $15 per vehicle per month (ALP, 2018). Also, grants for installing charging infrastructure are provided by some local governments (e.g. Shenzhen and Santa Clara).

Secondly, these cities have better local governance in promoting EVs. In the GBA, Shenzhen has achieved absolute decoupling recently possibly because it has been selected as a pilot city with strong horizontal integration among different government authorities in promoting EV development. For example, a joint-departmental committee in implementing NEV policies has been established by multiple departments of transport, environment, urban planning, police departments and district offices (Shenzhen Government, 2009). In the SFBA, strong cooperation among different local governments is observed, as JPC facilitates coordination among different local government hierarchies (i.e. counties and cities) and adopts a more information-led and market-oriented approach to consolidate best practices of local governments (Brown et al., 2010).

Thirdly, the best-performing local areas have streamlined R&D in EV production and sales. In the GBA, there is relatively strong assistance from the government. Shenzhen, in particular, provides clear initiatives in (i) facilitating coordination between tertiary institutes, innovation and technology organisation and other local enterprises, (ii) injecting funding in upgrading laboratories and the industrial base, and (iii) developing pilot tests and developing strong branding in both local and foreign markets (Shenzhen Government, 2015). In comparison, the SFBA tends to have a more market-oriented approach. Some governments provide local firms with R&D subsidies to better access the resources of particular facilities and knowledge, which is largely beneficial to the small and medium-sized business in innovation without sufficient start-up capital (BAAQMD, 2013a). The R&D has been rather mature in upstream activities (e.g. energy), manufacturing of components and vehicles, charging infrastructure, and downstream activities (e.g. recycling) (BAQAMD, 2013b).

Finally, an observation that partly explains cities of better decoupling is the local emphasis on electrifying the public transport fleet. Almost all cities in the GBA (including both SARs) have started pilot projects in electric buses. Some pilot projects are also found in taxis and government vehicles (e.g. police vehicles). In Shenzhen, the ambition in developing a multi-actor business public transport model with governments, power suppliers, manufacturers, fleet operators and transmission system corporations has stimulated innovations from the private sectors and ease the financial pressure of local governments (Li et al., 2016). In SFBA, there are plenty of electric vehicle demonstration programmes. For example, Alameda-Contra Costa Transit District initiated a first demonstration project of fuel cell electric buses (FCEBs) which has made trials for three fuel cell buses (Chandler and Eudy, 2007). In Santa Clara and San Mateo, the Zero Emission Bay Area (ZEBA) demonstration project has implemented 12 fuel cell electric buses and two hydrogen fuelling stations, and throughout the trials a lot of challenges were identified and addressed, including durability, cost, range and fuel economy (Eudy and Post, 2014).

5.2. *Policy implications from the backcasting analysis*

The backcasting analysis clearly shows that provocative EV strategies are needed to achieve the 450 Delayed Action transport decarbonisation targets. When comparing the two bay areas, GBA needs to accelerate the EV adoption rate and enhance the electricity emissions performance standards significantly. In the SFBA, with the increasing clean source of electricity mix, there can be a huge potential in further promoting EV through increasing charging density. On the contrary, China has faced significant barriers in decarbonisation because of the higher pollutant emission factors. As suggested, while China will reach a 50% EV share of the car inventory in 2035, CO_2 emissions will grow by 54.2% (Rietmann et al., 2020). The concerns about the energy mix are also serious (Li et al., 2019). Overall, our findings suggest that an integrative policy package of reducing VKT and significantly enhancing energy mix would be essential to support electric mobility. Similar to the findings of European Federation for Transport and Environment (2018), merely increasing the EV adoption rate would not be sufficient for transport decarbonisation. Also, more policy is needed to consider the lifecycle GHG emission of EVs, which are not integrated in the framework if they also need to be “clean” enough to support decarbonisation. There have been some efforts, though it requires stronger regulation and promotion in clean battery and clean manufacturing.

Both bay areas have demonstrated strong ambitions to achieve carbon neutrality by around 2050, but the spatial variations of decarbonisation suggest that more context-specific and complimentary measures should be implemented at the regional and local scales. In the GBA, the Guangdong Province was selected in 2010, by the national government, as one of the seven earliest pilot regions for achieving carbon neutrality, with Guangzhou, Shenzhen and Zhongshan listed as pilot cities (DoEE, 2021). The national government has established a clear goal of achieving carbon neutrality in 2060. Aligning to this, Guangdong Province is committed to stabilise carbon emissions by 2035, with renewable energy mix increasing to 29% (composing nuclear) by 2025 and a carbon trading mechanism well-developed within the GBA (GO of Guangdong Province, 2021). Hong Kong SAR has an even more ambitious target to reach carbon neutrality by 2050 and decrease the carbon intensity by 65–70% compared to the 2005 baseline (Environment Bureau, 2017; HKSAR Government, 2020). With the strong spatial variations of transport decarbonisation and economic contexts, more regional-local policy measures need to be implemented. In the SFBA, the State of California has established a major goal of net zero transportation emissions by 2045, followed by supporting goals such as 100% zero emission vehicles (ZEVs) sales by 2035 and clean electrical grid by 2045 that target at 1.5 °C increase (Energy and Environmental Economics, 2020; State of California, 2018b). These goals are significantly higher than the national goals of the US (achieving net zero emissions by 2050) and will reflect a need for stronger compensating policies to overcome the challenges. It is also noteworthy that the ZEV sales mandate is an important supply-side policy that can offer potentials in stimulating electric mobility on top of other demand-side and energy policies. More research is needed to evaluate its impacts and potential synergies on increasing EV share.

6. Conclusion

This study investigates the role of electric mobility in the transport decoupling progress of the GBA and SFBA over the past two decades (2000–2018). There are several limitations in this study. Firstly, only well-to-wheel emissions are considered in estimating transport carbon emissions. Lifecycle CO_2 emissions from car manufacturing, batteries production, and batteries recycling are not evaluated which may not reflect the full picture of environmental impacts of EVs in transport decoupling. Hence, the decoupling status achieved may have been overestimated. Further research can conduct lifecycle assessment (LCA) of EVs in decoupling and backcasting analysis, as the environmental impacts from EV production can be 60% higher than ICEs (Qiao et al., 2017). Secondly, due to data unavailability at the regional scale, it is assumed that the emission factors of ICEs have maintained stable throughout the study period. Decoupling effects due to the potential improvement in fuel efficiency may not be fully captured. Also, to maintain consistency in the analysis for both regions, average emission factors for EVs are applied without further differentiating EV types (BEVs & PHEVs) due to the lack of data in the GBA. Thirdly, the visions for the desirable future are extracted from the quantified targets stated in international reports. Though these visions are formulated by international experts in the field which can serve as a good reference point to start, more research is needed to develop multiple targets based on updated international commitments and different national contexts. Conducting Delphi interviews with relevant stakeholders can help generate multiple visions and define a wider range of policy measures (Tuominen et al., 2014; Soria-Lara and Banister, 2017). Finally, freight transport is not considered in the backcasting analysis which suggests that more policy measures to promote sustainable freight and logistics can help realise the predefined targets.

In summary, the regional decarbonisation and backcasting analysis highlight several important policy insights. Firstly, some progress in transport decarbonisation in road transport has been achieved in both bay areas. GBA has improved its decoupling status from relative coupling (2005–2015) to relative decoupling (2015–2018), whereas SFBA has achieved absolute decoupling in the earlier period (2000–2010) followed by relative decoupling (2010–2018). Vehicle-kilometre travelled, public transport share, fuel and energy intensity and economic development are found to be significant drivers for transport decoupling in both regions. Both regions have experienced a better decoupling status through electric mobility. An integrated policy planning and implementation approach is implemented to boost EV adoption. Clear vision, quantifiable targets and a well-established institutional framework are key policy factors. Secondly, from the local perspective, some cities in the GBA (Guangzhou, Hong Kong SAR & Shenzhen) and SFBA (Alameda, Santa Clara & San Francisco) perform better because these cities are able to provide diversified local monetary incentives, stimulate public transport electrification, streamline R&D in EV industry and integrate different policy actors. Thirdly, it is noteworthy that there are limited regional impacts on the supply side as indicated by the high dependency of both bay areas in the goals set by the national level. Hence, national leadership and investment in EV R&D seem particularly important. Finally, there needs to be a very proactive and comprehensive electric mobility strategy to achieve the desirable futures. Apart from boosting EV uptake through subsidies, enhancing charging density and traffic regulations seem to offer significant potentials in accelerating the decarbonisation progress. Also, reducing the carbon intensity is a prerequisite, not a choice. The composition of renewable power mix and electricity efficiency of vehicles are duly critical. More research is also needed to explore the policy synergies of different EV instruments. The co-benefits and conflicts generated by EV policies and other transport decarbonisation initiatives (i.e. such as avoid and shift strategies) is also critical to effective decoupling.

CRediT authorship contribution statement

Ka Ho Tsoi: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Validation. **Becky P.Y. Loo:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Gil Tal:** Methodology, Funding acquisition, Writing – review & editing. **Daniel Sperling:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Data sources of estimating road transport carbon emissions

Variables	Modes	Public data sources
Greater Bay Area (GBA), China		
The nine municipalities in mainland China		
Road passenger transport		
• Annual VKT per vehicle	Private cars, motorcycles, taxis and city buses	Loo and Li (2012)
• Number of motor vehicles		Annual statistics yearbooks [1]
• Average occupancy rates		Loo and Li (2012)
• Carbon intensity (per pkm)		Loo and Li (2012)
Road freight transport		
• Annual tkm	Trucks	Annual statistics yearbooks from municipalities[1]
• Carbon intensity (per tkm)	Trucks	EEA (2017)
Hong Kong Special Administrative Region (HKSAR)		
Road passenger transport		
• Annual VKT	Private cars, motorcycles, taxis and buses	Transport Department (2000-2019)
• Average occupancy rates	All modes	Transport Department (2012)
• CI per pkm	All modes	Loo and Li (2012)
Road freight transport		
• Annual VKT	Trucks	Transport Department (2000-2019)
• Annual ton/load factor	Trucks	CSD (2000–2019)
• CI per tkm	Trucks	EEA (2017)

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(*continued*)

Variables	Modes	Public data sources
Macau Special Administrative Region (MCSAR)		
Road passenger transport		
• Annual VKT	All modes	Zhang et al. (2016)
• Average occupancy rates	All modes	No data [2]
• Carbon intensity (per pkm)	All modes	Loo and Li (2012)
Road freight transport		
• Annual VKT	Trucks	Zhang et al. (2016)
• Annual ton/load factor	Trucks	SCS (2020)
• CI per tkm	Trucks	EEA (2017)
San Francisco Bay Area (USA)		
Road passenger transport		
• Annual VKT per vehicle	Private vehicles	CARB (2021)
• Vehicle stock	Private vehicles	CARB (2021)
• Average load factor	Private vehicles	FHWA (2018)
• Passenger-miles travelled	Taxis and buses	FTA (2019)
• CI per pkm	All modes	Loo and Li (2012)
Road freight transport		
• Annual tkm	Trucks	CTA (2019)
• CI per tkm	All modes	EEA (2017)

Note 1: The statistical year books are extracted from the nine municipalities in the GBA (Dongguan Municipal Statistical Bureau; Foshan Municipal Statistical Bureau; Guangzhou Municipal Statistical Bureau; Huizhou Municipal Statistical Bureau; Jiangmen Municipal Statistical Bureau; Shenzhen Municipal Statistical Bureau; Zhaoqing Municipal Statistical Bureau; Zhongshan Municipal Statistical Bureau; Zhuhai Municipal Statistical Bureau, 2000–2019). Note 2: There is no official nor estimated data. Hence, the average occupancy rates are assumed to be similar to the nine provinces in GBA.

Appendix 2a. Detailed procedures of pkm calculation in GBA and SFBA

	VKT	VEH	OR
Nine municipalities in mainland China (GBA)	Data of average per-vehicle sub-mode VKT (city buses, taxis, private cars and motorcycles) between 2000 and 2009 were extracted from several studies of transport CO_2 estimations in China (He et al., 2005; Wang et al., 2006; Loo and Li, 2012). The corresponding figures are 71,175 km, 34,000 km, 18,000 km, and 10,000 km. VKT in other years were estimated based on the elasticities of mode-specific VKT to income growth between 2000 and 2009. Annual VKT is correlated to economic activities (Huo et al., 2012; Liu et al., 2017).	The number of motor vehicles of the four transport modes are extracted from the annual statistical yearbooks of each municipality (refer Appendix 1).	Occupancy rates for different modes are extracted from Loo and Li (2012), which are 1.1 for taxis, 16 for city buses, 1.3 for private cars and 1.2 for motorcycles.
Hong Kong SAR (GBA)	Annual total modal VKT are available in the annual transport digests (Transport Department, 2000-2019).		Average occupancy rates are derived from annual traffic census (Transport Department, 2012).
Macau SAR (GBA)	Total annual VKT by mode is extracted from a local study (Zhang et al., 2016).		Due to data unavailability, it is assumed that the average load factors are similar to Hong Kong.
Nine counties in California (SFBA)	Annual total passenger-miles of road public transport can be directly extracted at a county level (FTA, 2000–2018). These data are converted to annual total pkm by modes (i.e. buses and taxis).		
	For private modes, daily vehicle-mile travelled is available at the county level (CARB, 2021) and is then converted to annual total pkm.		The occupancy rate for private cars is 1.7 (FHWA, 2018).

Appendix 2b. Detailed procedures of tkm calculation in GBA and SFBA

Nine municipalities in mainland China (GBA)

- Annual tkm is available in local statistical yearbooks of the nine municipalities in the GBA

Hong Kong SAR (GBA)

- Annual tkm is estimated based on the product of annual VKT by trucks (Transport Department, 2000–2018) and annual throughput (measured in tons) (CSD, 2000-2019).

Macau SAR (GBA)

- Annual tkm was estimated based on the product of annual VKT by trucks (Zhang et al., 2016) and annual throughput (measured in tons) (SCS, 2020).

Nine counties in SFBA

- Annual tkm is estimated on the state-level statistics (i.e. California) in the Freight Analysis Framework (FAF) Version 4 (CTA, 2019).

- They are disaggregated into county-specific estimates similar to the methodology by Aly and Regan (2009), where the disaggregated factor is the ratio of total truck vehicle mile travelled in a county to the total sum in the California State.
- For the sake of consistency, all units are standardized as tkm.

Appendix 3. Regional electric mobility policies in GBA and SFBA

	GBA	SFBA
Action plans	The Guangdong Province has delineated a holistic set of tasks. The major components are more technology and innovation oriented. The core components include (i) breakthrough in energy-saving technology, (ii) establishing a scientific-based industry layout, (iii) promoting application by pilot projects, (iv) developing charging facilities and (v) developing a system for battery utilisation and recycling (GO of Guangdong Province, 2012).	The state of California has devised a more market-driven and consumer-oriented action plan. There is clear task delineation among policy actors. The four core objectives are (i) completing needed infrastructure, (ii) expanding consumer awareness and demand, (iii) transforming fleets, and (iv) growing jobs and investment in the private sector (State of California, 2013).
Institutional framework	To scale up the local development of EVs from a city level, the regional government (i.e. Guangdong Province) established a joint-departmental cooperation mechanism, supported by the Development and Reform Commission, to execute 32 policy initiatives in the entire region (GO of Guangdong Province, 2018). In the SFBA	The Bay Area Plug-in Electric Vehicle Coordinating Council (EV Coordinating Council), managed under the Bay Area's Joint Policy Committee (JPC), is a staff-level platform (typically three conferences a year) to share the experiences of implementing electric mobility supported policies and enhance EV adoption in local communities (BAAQMD, 2013b).
Fiscal incentives	Local municipalities are mainly responsible for offering direct subsidies. Subsidies are given to new EV purchase according to driving range, ranging from 35,000 to 60,000 *yuan* between 2013 and 2015. The initial arrangement for the ratio of subsidies between the central government and local government is 1:1, but it was later decreased to 1:0.5 in 2016 and should not exceed 60 percent of its selling price (GPDRC, 2018).	There are various types of subsidies at the state and regional level. Direct incentives include the California's rebate programme (CVRP), which is a state-level initiative providing USD 1,500 (PHEVs) and 2,500 (BEVs) for eligible models and covers qualified light-duty fleet vehicles (CSE, 2020; State of California, 2013).

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