Design and Selection of Government Policies for Electric Vehicles Adoption: A global perspective

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Abstract

Regardless of increased attention in electric vehicles (EV) market expansion, the actual penetration of EVs remains low globally. Almost all major OEMs have announced investment plans to ensure that EVs constitute a major, if not complete, chunk of their product portfolios. On their part, governments worldwide (e.g., China, Poland, India, USA, etc.) have used various policy measures to facilitate EV adoption. In this paper, we study how incentives offered in terms of subsidy and differential taxation schemes could increase the market penetration of EVs. We analyze different models under uniform and differential taxation policies with and without subsidy, using a non-cooperative game-theoretic approach. Our analysis reveals that the government can follow any of the three tax-subsidy mixes that could maximize social welfare, i.e., differential taxation with and without subsidy, and identical tax with a subsidy. Surprisingly, the manufacturer's profit, the government's income, and consumer surplus for these three models are also the same and are better than the other two models depending on the consumer's green sensitivity, i.e., for higher green sensitivity, these three models can provide a win-win outcome. From an environmental perspective, levying tax on gasoline vehicles (GV) without subsidy to the manufacturer minimizes the overall environmental impact. In contrast, levying the same tax for both types of vehicles without subsidy to the manufacturer generates the maximum overall environmental impact. Furthermore, an increase in the unit environmental impact of vehicles attracts higher taxes. We portray that the increase in the cost-difference between EV and GV increases GV demand and is detrimental for EV acceptance. In addition, multifaceted insights are drawn for manufacturers and policymakers to envisage electric mobility. We extend our models and show that our main results hold under the implementation of mandate on EV manufacturers under subsidy and non-subsidy model, and inclusion of hassle cost for consumers due to lack of infrastructure in terms of charging facilities and maintenance.

Keywords: Electric vehicles, taxation, subsidy, social welfare, environmental impact.

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1. Introduction

1.1. Background and motivation

Increasing greenhouse gas (GHG) emission is a key global concern among policymakers, academicians, and environmentalists, as emissions continue to grow at a rate of 1.6% in 2017 and are projected to grow further (Washington Post, 2018). Specifically, the transportation sector alone accounts for about 23% of global GHG-related emissions, and the same is projected to surge up to 50% by 2050 (Bunsen et al., 2018). For instance, in countries like the USA, its share is even higher – accounting for 28.9% of

GHG emissions in 2017 (Bunsen et al. 2018). The internal combustion engine-based gasoline vehicles (GVs) majorly dominate the current transportation system. However, of late, electric vehicles (EVs) have emerged as a more efficient alternative, with zero tailpipe emissions, and even better well-to-wheel efficiencies, i.e., total energy consumption in their lifecycle (Shao et al. 2017; Zhang and Huang, 2021). Consequently, stakeholders have been trying to get a nuanced and multifaceted understanding of issues related to electric mobility.

Over the years, EVs have been gaining traction among environmentally aware consumers; thus, they have witnessed a surge in sales (Smith et al., 2017). In 2020, the global fleet of EVs hit the 10 million sales targets, an increase of 43% from the 2019 level (IEA, 2021). Regardless of this growth, the global penetration of EVs remains low as compared to conventional vehicles. The same can be established by the fact that China, despite having the highest EV sales in 2020, only had 5.7 % of the EV market share (IEA, 2021). Having said this, one needs to bear in mind the challenges for EV adoption. These could range from lack of charging infrastructure, range anxiety (apprehension about the short driving range of EVs), resale anxiety (worry related to the future value of EVs), absence of adequate incentive policies leading to huge upfront purchasing costs of EVs, lack of stringent emission regulations, bounded rationality (not being able to compute the future cost saving through the purchase of EV due to lack of information), among others (Lim et al. 2015, Masmoudi et al., 2018 and Hiermann et al. 2019). Herein, it is also important to note that consumers buy EVs for multiple reasons, including performance, technology, environmental benefits, symbolic motivations, lower operational costs, etc.; however, many of them primarily focus on the financial benefits only (Hardman et al. 2019).

In order to remove such barriers, governments worldwide have been using various policy levers in the form of taxation and incentives (Axsen and Wolinetz, 2018 and Chemama et al., 2019). Financial incentives, if appropriately designed, could possibly balance out the cost differential between EV and GV, which in turn could become the most important driver for customers to buy an EV (Lévay et al., 2017). Additionally, to deal with the high upfront cost of EVs relative to GVs, governments worldwide have used different policy interventions like subsidizing both EV consumers and manufacturers while taxing GV customers heavily (Lévay et al., 2017 and Chakraborty et al., 2021). Specifically, the UK government, for instance, proposed a £1.3 billion plan for boosting the demand for EVs across the UK, which includes providing consumer subsidy for EV purchases, and setting up sufficient charging stations across the nation (Financial Times, 2020). Furthermore, Chinese firms like BYD and BAIC Motors have received subsidies from the Chinese government to boost the production of plug-in vehicles (Reuters, 2017). Moreover, the Indian government has also decided to slash the Goods and Service Tax on EV purchases from 12% to 5% and also provide additional tax benefits for EV purchases, thereby reducing the price differential between an EV and a GV (Economic Times, 2019). In countries like Norway, policies such as exemption of EVs from Value Added Tax, registration tax, and annual circulation tax are in place (EEA, 2019). However, despite some countries either providing subsidies for EVs or taxing the purchase of GVs, other countries like Poland don't have any specific policy for stimulating EV demand in terms of levying taxes or providing subsidies (EEA 2019).

Table 1: Current practices in terms of incentive mechanism and regulations for EVs adoption around the world

Policy Intervention(s) Based Models	Description	Current Practice in Countries
Same Tax, No Subsidy (STNS Model)	When the government does not distinguish between an EV and a GV while imposing the green tax, and ends up levying the same green tax on both purchases. In addition, the government also doesn't provide any subsidy either to the EV customer or the manufacturer.	Poland[1]
Same Tax and Subsidy (STS Model)	Identical tax being levied on both EV and GV. However, the difference herein is that the government does extend a subsidy to EV manufacturers to boost production.	China[2] extended the subsidy support for EVs for two years due to the Covid-19 pandemic.
Differential Tax, and No Subsidy (DTNS Model)	The government imposes differential taxes for EV and GV purchases but doesn't provide any subsidy to EV manufacturers or consumers.	India[3] (Economic Times, 2019).
Tax on GV, No Subsidy (TGNS Model)	In this special case of DTNS, the government taxes the GVs, while the EVs are tax exempted. However, no subsidy would be provided to either the EV manufacturer or the consumer.	Norway and Sweden[4]
Tax on GV and Subsidy (TGS Model)	In this case, the government taxes the GVs while the EVs are exempted. Additionally, subsidies are given to EV manufacturers.	As a combination of policies in Norway and China

These five models are considered based on the prevailing tax-subsidy mix available in the different countries. For example, when the government does not provide any incentives for EV consumers as well as EV manufacturers, indicating no policy support from the government to boost EV adoption. Countries like Poland are following such a model. Here, the government is indifferent between an EV and GV consumers as well as manufacturers and thus considered as a model for the study. Another case is when the government, which is indifferent between an EV and GV consumers, levies the same taxes on both consumers but provides an incentive to EV manufacturers to boost the EV supply. Such models are in use in a few provinces of China. The business model behind such a case is to boost the supply side of the EV and thus be able to create a better EV supply chain.

[1] https://www.eea.europa.eu/data-and-maps/indicators/main-anthropogenic-air-pollutant-emissions/eea-2011 [accessed 19 August 2021]
[2] https://news.mit.edu/2021/chinas-transition-electric-vehicles-0429 [accessed 19 August 2021]
[3] https://www.forbes.com/sites/meghabahree/2019/03/09/india-offers-1-4-billion-in-subsidies-to-support-the-domestic-electric-vehicle-industry/#56acb6ce610a [accessed 28 August 2021]
[4] https://theicct.org/publications/poland-electric-passenger-car-market-sept2020 [accessed 19 August 2021]

On the other hand, the Indian government levied 28% goods and service tax (GST) for GV consumers, whereas GST is only 5% for EV consumers. Such tax incentives help to reduce the differential price in the upfront cost between an EV and a GV and directly help the EV consumers. Hence, it is essential to study the impact of this model in comparison to other models used in different countries.

Further, there are countries like Norway, where the government imposes multiple taxes on GV consumers, whereas EV consumers are tax exempted. Here again, the focus is on EV consumers rather than the EV manufacturers to deter prospective consumers from buying a GV with the imposition of multiple taxes. Such models have effectively supported EV adoption in many countries like Norway, Sweden and hence its comparison with other models may provide us important insights. Lastly, there are a few cases where the government supports both EV consumers as well as EV manufacturers. More specifically, the government imposes taxes on GV, whereas EVs are tax-exempted. Additionally, it also provides incentives to EV manufacturers to support the EV supply in the market. Such scenarios are the combination of policies used in China and Norway. In this case, the government invention is maximum in terms of supporting both EV consumers and the manufacturers. Consequently, this model may negatively impact the government revenue compared to other models and is thus included in our study.

Furthermore, we also gathered the latest developments in various countries related to EV subsidies and tax incentives. For example, as a recent development in the US, where the current administration will drive EV demand with "point-of-sale incentives" to support EV deployment (Washington Post, 2021). The purpose of these incentives is to lower the EV price and to make it more affordable for EV consumers. A recent article in Forbes highlighted the role of government policies in the successful adoption of EVs in Norway (Forbes, 2021). One of the major reasons stressed for the higher adoption of EVs is the government policy and incentives for EV purchasers. Norway exempted multiple taxes on EVs to reduce its price with its GV counterparts. In contrast, they raised taxes on conventional cars in terms of pollution tax, which further helps the EV adoption. As these incentives create a burden on the government's revenue, countries like China have reduced the direct subsidy to EV consumers and facilitated incentives to EV manufacturers (MIT News 2021 and IEA, 2021).

Summarising these latest developments, the five models in our study adequately capture the various scenarios available in different countries to support both demand and supply sides related to EVs. It is to be noted that these models can also be looked at from the lenses of both consumers' perspectives as well as the manufacturer's perspectives. From the consumer perspective, we have included those cases where consumers are receiving any additional tax benefits while purchasing an EV over a GV. The models DTNS, and TGNS, aim to provide incentives to EV consumers only and are thus included under the ambit of models addressing *consumer perspectives*. Further, from the manufacturer's perspective, the subsidy is provided to automobile manufacturers for producing EVs to improve the supply side. Hence, we consider two possible cases, i.e., STS and STNS, where the government provides subsidy or no subsidy to the automobile manufacturer for producing EVs respectively.

1.2. Research gap

There is a considerable amount of research on EVs, including the positive impacts of EVs usage (Shao et al. 2017 and Zhang and Huang, 2021), key challenges for EVs adoption (Masmoudi et al., 2018 and Hiermann et al., 2019), financial incentives for the faster EVs adoption (Lévay et al., 2017 and Chemama et al., 2019). However, few prior studies have analytically examined the impact of mixed policy interventions (e.g., taxation-subsidy mix) for boosting the EVs adoption. Due to varied policies, mixed policy interventions may have a different impact on the consumers, manufacturers, and finally on the government. Hence, it is necessary to evaluate which model is better off in different scenarios from the government and the manufacturer's perspectives. We compare the outcomes of these type of models and generate additional insights for manufacturers and governments to create a conducive EV ecosystem.

From the discussion above and the models listed in Table 1 earlier, it is evident that different countries have been using various policy measures like consumer or manufacturer subsidy/taxes to boost EV sales. However, the question of what could be the basis of deciding such a taxation-subsidy mix remains. This, in turn, motivates us to delve deeper into various forms of non-recurring financial policy instruments and make pragmatic decisions. Herein, it may be noted that our focus primarily revolves around 'non-recurring financial incentives'; in other words, subsidies or one-time taxes for speeding up EV adoption. Hence, we do not consider any recurring financial incentives such as highway lane access, access to infrastructure, free parking, etc. (Münzel et al., 2019).

1.3. Research questions & framework

Motivated from real-world policy interventions and regulation, we characterize the optimal price, demand, manufacturer's profit, and consumer surplus under a monopoly market structure. We study social welfare, which consists of manufacturer's profit, total green tax, the subsidy provided, overall environmental impact, and consumer surplus. By comparing the findings of the five models listed in Table 1, we try to answer the following research questions:

1. *What is the optimal green tax and subsidy mix for maximizing social welfare?*
2. *How do different tax and subsidy modes influence the demand for GVs and EVs, social welfare, consumer surplus, vehicle price, and government expenditure?*
3. *How does the unit environmental impact of EVs and GVs affect the government's policies in choosing the subsidy and green tax mix?*
4. *How does the green sensitivity of customers influence the demand of the vehicles, overall environmental impact, the green tax and subsidy mix, and social welfare?*

To answer the above research questions, we consider a single manufacturer in the automobile sector who sells both EVs and GVs. The government decides the subsidy and green tax to maximize social welfare. At the same time, the manufacturer chooses the optimal price of EVs and GVs to maximize its profits. We start with a generalized model and then study five different combinations of green tax and subsidy mix, policy decisions based on the prevailing scenarios, and the various policy instruments employed by different countries. The basic model framework of our study is shown in Figure 1.

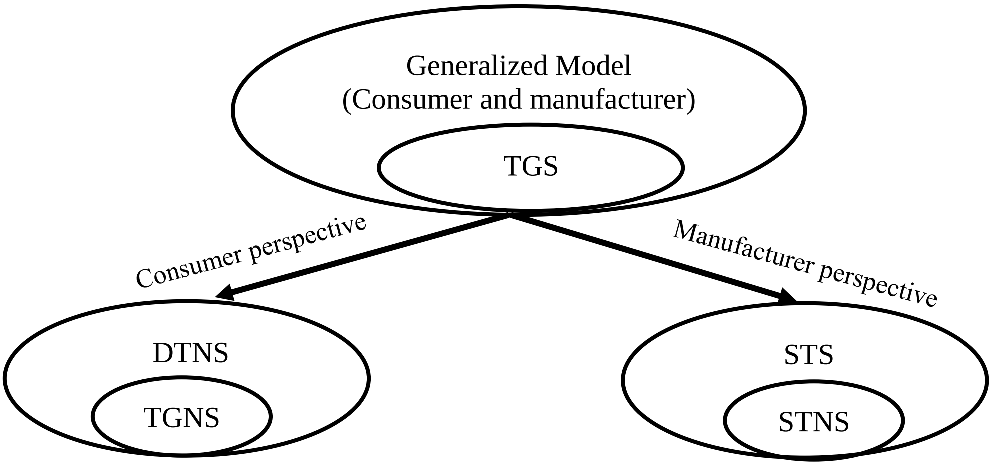

Figure 1. Basic Model Framework

1.4. Contributions and key findings

Previously, researchers have studied the effectiveness of financial incentives (e.g., subsidies) as a strategy to improve adoption (Jenn et al. 2018 and Deuten et al. 2020). Some studies explore the impact of indirect incentives such as exemption from registration and annual taxes (Lévay et al., 2017) and sales tax exemption (Gerlagh et al., 2018). Interestingly, the literature shows that incentives offered can have a mixed impact (positive as well as negative) on EV adoption. For instance, offering rebates and tax credits can positively affect EV sales (Jenn et al. 2018). However, in another study, Deuten et al. (2020) find that instead of incentives, strong penalty norms (for manufacturers not adhering to emission regulations) can be a better instrument for promoting EVs in some scenarios. As per our knowledge, none of the earlier studies had jointly analyzed the role of emission taxation and subsidies policy based on adoption. Considering that a joint policy instrument can be an optimal strategy to facilitate EV adoption is imperative.

A few recent studies dealt with consumer or manufacturer subsidies from different perspectives (Bian and Zhao, 2020 and Bian et al., 2020). However, their limitations include manufacturer competition, market response in line with emissions, consumer environmental concern, consumer heterogeneity, and different market segmentation, which we try to examine in our current paper. This paper differs significantly from previous studies and contributes to the literature in multiple ways. We show that multiple combinations of green tax and subsidy mix can be equally viable as alternatives for maximizing social welfare and minimizing the overall environmental impact. Additionally, we further explore the impact of the implementation of mandate on EV manufacturers under subsidy and non-subsidy model and inclusion of hassle cost on consumers for EVs adoption.

Our analysis reveals that the government can follow any of the STS, DTNS, or TGS models to maximize social welfare. The remaining two models, i.e., STNS and TGNS, produce lower social welfare. We also note that higher taxes on either of the vehicle types reduces the demand for that vehicle, while subsidies help in increasing the demand (as in the case of EVs). Further, manufacturer profit, government income, and consumer surplus for the Model DTNS, STS, and TGS are equal and better off compared to the other two models depending on the consumer's low carbon awareness (green-sensitivity). Model TGNS generates minimum environmental impact from an environmental perspective, whereas the Model STNS produces the highest environmental impact. Moreover, an increase in the environmental impact of EVs and GVs is liable for higher green taxes for both types of vehicles. Additionally, increases in GV’s environmental impact facilitate higher subsidies for manufacturers to produce EVs. From the cost perspective, an increase in relative cost-coefficient enhances the demand for GVs and lowers the demand for EVs.

The rest of the paper is organized as follows. Section 2 presents the review of the literature. Section 3 illustrates the model description. The analysis of a generalized model is carried out in Section 4, and illustrative models are presented in section 5. Section 6 presents the discussion, and section 7 concludes the study with research directions. All proofs are relegated to the 'Online Appendix'.

2. Literature Review

Our work lies within the umbrella of research on sustainable product adoption-related decisions, associated manufacturing decisions, and the role of various policies and regulations in the adoption of sustainable products.

2.1. Incentives, product adoption, and pricing decisions

The impact of sustainability on production decisions is an important field of study which has been explored earlier along various dimensions (Cai and Choi, 2021). For example, Jenn et al. (2018) evaluate the effect of financial incentives on EV adoption in the United States. They find that for every $1000 offered as a rebate and tax credit, the average EV sales increase by 2.6%. Deuten et al. (2020) analyzed the past and future EV share in Norway and found that only strong incentives (penalties for the manufacturer for not adhering to emission targets and emission taxes for consumers) result in a higher share of EVs. On the contrary, Fan et al. (2020) analyse the optimal pricing strategies and the role of government policies for EVs in the presence of technology spillover. They show that the technology spillover in a domestic market can negatively impact the manufacturer's and government's optimal decisions. Hence, the literature provides both facets of the financial incentive influence on EV sales.

Policies such as the government's subsidy schemes and taxation policies are two key instruments that influence the rate of adoption of green technologies, including EVs (Krass et al., 2013; Alizamir et al., 2016 and Chemama et al., 2019). Subsidies do have a positive impact on EV adoption; simultaneously, imposing emission-related taxes discourages the use of GVs, while promoting EVs (Gerlagh et al., 2018 and Chakraborty et al. 2021). In the case of the production of GVs as compared to EVs, researchers have studied the impact of green taxes on supply chain decisions (Hammami et al., 2018 and Ma et al., 2018) and regulations related to carbon emissions (Zhang and Huang, 2021). Shao et al. (2017) examined the automobile market under monopoly and duopoly structures. Their study focused on the impact of pricing discounts, incentive schemes, and subsidies on EV buyers. Their findings showed that the consumer surplus and social welfare are similar under two incentive schemes. Zhu et al. (2021) analyze a cooperative and competitive game-theoretic model between the transportation network company and the government. In a cooperative model, the government provides subsidy support to the public transit rides, and findings show that a socially optimal subsidy level may exist. Liu et al. (2021) used a logit-based stochastic user equilibrium model to analyze optimal locations and electricity prices for dynamic wireless charging links of EVs to minimize social costs under budget constraints. They find that the social planner can reduce the total social costs by reducing maintenance expenses of charging facilities for sharing more accurate travel and charging information. Though we study the incentives mechanism in terms of subsidy to the manufacturer on EVs production, our study is different in focussing on the combined role of taxation and subsidy policies on EV adoption to create a viable EV ecosystem by considering key stakeholders (i.e., the automobile manufacturer selling both EVs and GVs, the government, and consumers). The government decides the optimal level of taxes and subsidies to maximize social welfare, consisting of producer profit, revenue loss/gain, and total environmental impact.

In addition to subsidies, the government often promotes EVs by providing indirect financial incentives to buyers. These financial incentives could be exempt from registration and annual taxes (Lévay et al., 2017) and sale tax exemptions. Similarly, to penalize the usage of GVs, the taxes could be in the form of higher registration taxes, increased fuel taxes, or higher road taxes, to name a few (Gerlagh et al., 2018). Recent literature explores government's penalty schemes in various context (e.g., cyber security (Luo and Choi, 2022). Therefore, designing and deploying such policy mechanisms makes EVs a more attractive option for manufacturing firms and consumers (Kuppusamy et al., 2017 and Bian et al., 2020).

2.2. Policy regimes and welfare considerations

A different stream of literature has also focused on how a mix of taxes and subsidies can influence production decisions. Raz and Ovchinnikov (2015), for instance, showed that the use of only consumer subsidy could lead to welfare loss; however, a joint strategy, i.e., subsidy coupled with tax, could possibly coordinate the network. Taylor and Xiao (2017) found that subsidies have a non-trivial relationship with consumers' product awareness in commercial and non-commercial channels. Ma et al. (2021) studied the impact of government regulations and investment in green emission reduction technologies (GERT) on supply chain members' decisions under cooperative and non-cooperative settings. They show that a higher emission reduction subsidy leads to increased GERT investment and profitability. On the other hand, emission reduction standards nullified the effect of subsidy leading to the decreased manufacturer’s profit.

Some other studies used analytical models to analyze the influence of subsidy, green tax, or price discount-based schemes on EVs adoption (Luo et al. 2014; Shao et al., 2017; Chemama et al., 2019). Zhang and Huang (2021) analyzed the manufacturer’s decision to produce fuel vehicles and EVs under two subsidy schemes - the consumer subsidy (CS) and the R&D subsidy (RS). They show that the subsidy programs can lead to the reduction in carbon emission if and only if the manufacturer produces both fuel vehicles and EVs. They also derive the condition under which offering the CS can be an optimal policy for both the social planner and the manufacturer. Yoo et al. (2021) studied a combination of product service platforms in the context of EVs by analyzing three scenarios: integrated case, a partnership between the manufacturer and the service provider case, and the case where the service provider operates independently. They show that under government subsidy and high service fees, integrated cases outperform the other two cases. However, under low subsidy and low sensitivity to a service fee, the other two cases perform better than the integrated case. Different from them, motivated from real-world scenarios, we primarily focus only on the manufacturing subsidy along with various taxation policies.

2.3. Integrating policies, product adoption, and welfare

Recently, a few papers have sought to integrate these disparate themes to provide a more coherent and holistic treatment. For instance, Bian and Zhao (2020) investigated the impact of emission abatement subsidies and emission tax policies. From a supply chain perspective, they find that both the manufacturer and the retailers gain more from the subsidy rather than the tax policy. From a social welfare point of view, increasing competition improves social welfare under the tax policy rather than a subsidy policy. Their study focused on the retailer competition and suggested manufacturer competition as a part of their limitations. In another study, Bian et al. (2020) compared consumer and manufacturer subsidies to find that consumer subsidies yield lesser abatement and higher consumption quantity. Further, consumer subsidy produces higher social welfare compared to the manufacturer subsidy under certain conditions. Their limitations include manufacturer competition and unit emission related to the product, which we will capture in our current study. Further, this study talks only about subsidies, whereas we capture both subsidies and taxation with respect to manufacturers and consumers. Thus, in line with their future research directions, we have planned our current study to understand the manufacturer competition for green production adoption like EVs. Additionally, they also mention other limitations like market responses to emission reductions and consumer environmental concerns and call for future research addressing them. We capture these aspects also in our model formulations. Finally, Bian et al. (2020) highlighted their limitations regarding consumer heterogeneity and different market segmentation, which are also being captured in our modelling.

2.4. Summary and positioning

This study primarily analyses different combinations of subsidy and taxation instruments used by the governments to facilitate EV adoption. We examine the impact of different combinations on overall social welfare. By considering both these streams of literature together, to the best of our knowledge, our study is the first to model the combined impact of differential and uniform taxes, whereby the role of subsidies on EV adoption is focused on decreasing greenhouse gas emissions. In short, we derive the government's optimal taxation and subsidy strategy to optimize total social welfare. The summary of relevant works highlighting the research gaps is summarised in Table 2.

Table 2: Key literature related to our context

Study	Journal name	Area (type of supply chain)	Objective function	Taxes/ carbon cap	Subsidy/incentives (consumer)	Subsidy (Manufacturer/retailer)	Manufacturer competition	Consumer green sensitivity/ awareness	Consumer heterogeneity (Market segmentation)	Per unit environmental impact of products (e.g., EV, GV)	Remarks
Sierzchula et al. (2014)	EP	EV	EV Market share		√						Cross-country study
Cohen et al. (2016)	MS	Green	SW(CS,P, GR)		√						Focus on uncertainty
Shao et al. (2017)	EJOR	EV	SW(CS,P, EI)		√		√	√	√	√	Subsidy and price discount
Qi et al. (2017)	JCP	Generic	Profit	√							Centralize-decentralize
Bian et al (2018)	TRE	Generic	SW (CS, P, EI)	√			√				Centralize-decentralize
De Giovanni (2018)	EJOR	Closed-loop	Profit			√					Competing retailers, recycling case
Yu et al. (2018)	MSOM	Home appliance	SW (CS, P)		√	√	√				Consumer vs. manufacturer subsidy
Chemama et al. (2019)	MS	Solar	SW(CS,P, E,GR)		√						Dynamic subsidy over time
Taylor and Xiao (2019)	POM	Donor	Utility and subsidy		√			√	√		Profit maximizing intermediaries
Fan et al (2020)	TRE	EV	SW(P,CS)	√	√		√				Technology spill over
Bian et al. (2020)	EJOR	Green	SW(CS,P, GR)		√	√		√			Green technology investment
Bian and Zhou (2020)	EJOR	Generic	SW(P,CS, abetment cost, EI)	√		√					Retail competition and policies
Guo et al. (2021)	TRE	Generic	SW(CS,P, GR)		√		√				Manufacturer vs. supplier subsidy
Kumar et al. (2021)	TRE	EV	SW (P,CS, EI)		√		√		√		Charging infrastructure
Ma at al. (2021)	TRE	Generic	Profit			√		√			Subsidy vs. reduction standards
Zhang and Huang (2021)	TRE	EV/Hybrid	Profit		√			√	√		Manufacturer product line decisions
Zhu et al. (2021)	TRE	Public Transit	SW (CS, P)		√				√		Socially-optimal subsidy
Present study		EV	SW(CS,P, EI,GR)	√	√	√	√	√	√	√	
Note	*TRE= Transportation Research Part E, MS=Management Science; EJOR= European Journal of Operation Research; SW=Social welfare, CS=Consumer surplus, EI=Environmental impact, GR=Government revenue, E=Externality, EB= Environmental benefits; IJPE=International Journal of Production Economics; MSOM= Manufacturing & Service Operations Management, EP= Energy Policy, P=Profit.*										

3. Model Description

We consider a manufacturer selling both GVs, and EVs in the passenger vehicle market. The manufacturer incurs a per-unit cost c and κc ($\kappa > 1$) for producing GV and EV, respectively. The government may impose a green tax on the consumers for the purchase of EVs and GVs, which are given by T_e and T_g, respectively. The manufacturer may also receive a government subsidy, R, for manufacturing EVs. We model the interactions between the manufacturer and the government in the form of a non-cooperative sequential game. We have considered the government as the Stackelberg leader while the manufacturer acts as the Stackelberg follower. In our non-cooperative game model, the government decides the green tax (T_g, T_e) and subsidy R (as the case may be) to maximize social welfare. The manufacturer decides upon the optimal prices p_g and p_e for GVs and EVs, respectively, based on green tax rates and subsidies provided. Figure 2 describes the decision timeline for each firm.

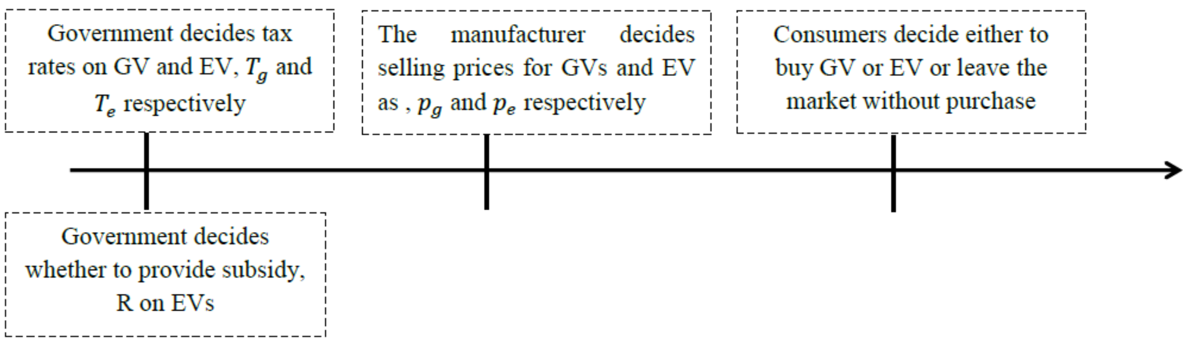

Figure 2. Decision timeline

The model has been developed considering a few assumptions. First, we assume that the consumers in the market are strategic and utility-maximizing (Zhang et al., 2021), i.e., ones who decide the vehicle to purchase depending upon their relative surplus. In addition to the relative prices of the vehicles, consumers' relative surplus also depends upon their information on green tax. The valuation of a consumer for the services of a vehicle is θ, which is uniformly distributed in the spread of 0 to 1 with a total mass of 1. Second, the manufacturer does not know the exact valuation of a particular consumer; therefore, it cannot price discriminate among consumers. However, the distribution of consumers' valuation is common knowledge. Further, consumers are heterogeneous in terms of valuations, along with the market size being normalized to 1. The same has been studied widely, even in other streams of literature (Srivastava and Mateen, 2020). Third, each consumer buys one vehicle and leaves the market immediately after purchase or remains inactive, depending upon his utility. Fourth, consumers’ low carbon awareness makes EV valuations more than GV, and in the absence of it, consumers are indifferent between a GV and an EV regardless of vehicle technological specifications. Finally, EV has a lower environmental impact compared to GV due to low carbon emissions, i.e., $i_e < i_g$ (MacKay, 2008). As mentioned previously, we have considered five different prevailing scenarios of green tax and subsidy; they have been covered in detail in the subsequent section.

4. Generalized Model Development

In the generalized model, the government levies different green taxes on EV and GV consumers and also provides a subsidy to the manufacturer for EVs. Hence, the government supports both EV customers as well as the manufacturer for EVs in this case. Here, optimizing three variables at the government level is analytically intractable. Thus, based on actual prevailing scenarios, we observe a mix of these policy instruments in different countries and thus, develop five different models.

In this section, we formulate a generalized model where the government imposes green taxes (T_e, T_g) on consumers for the purchase of both EV and GV, respectively, while the manufacturer receives a subsidy, R on every unit of production of EV. The manufacturer sells both types of vehicles at prices, p_e, and p_g, respectively. We assume that consumers are heterogeneous in terms of their valuation of the vehicles. We use "θ" to represent the valuations of the services provided by a vehicle for the GV consumers. Here, it is important to mention that EV consumers will also receive the same valuations "θ" from the vehicle if we ignore the green utility of the EVs. However, EVs are supported for environmental friendliness (a lower carbon footprint) and hence offer a green utility to EV consumers. This green utility is an additional utility received by an EV consumer in comparison with GV consumers. To model this extra green utility, we use consumers' low carbon awareness, denoted by δ. Thus, when GV consumers received a utility θ from the GVs, an EV consumer will receive a utility $\theta + \theta\delta$, here $\theta\delta$ is the additional utility received by an EV consumer due to EVs environmental benefits. A few recent studies used such additive utility models for depicting the additional utility of EVs to the EV consumers in comparison to the GV consumers (Shao et al., 2017; Kumar et al., 2021).

Therefore, for any given prices (p_e, p_g), and taxes (T_e, T_g), if a consumer receives utilities U_e, U_g and, U_r from her decision of either buying an EV or a GV or to remain inactive respectively, then we can write the consumer's utility functions as follows:

$$U_e = (1 + \delta)\theta - p_e - T_e, \tag{1}$$

$$U_g = \theta - p_g - T_g, \tag{2}$$

$$U_r = 0. \tag{3}$$

Let θ_e be the threshold utility of a marginal consumer who is indifferent between buying a GV and EV; in other words, all the consumers having a valuation, $\theta > \theta_e$, would prefer to buy EVs. Therefore, at such an indifferent point, $U_g(p_g, T_g) = U_e\,(p_e, T_e) \Longrightarrow \theta_e = \frac{p_e - p_g + T_e - T_g}{\delta}$. Similarly, let θ_g be the threshold valuation for consumers who are indifferent between buying a GV or not buying at all and leaving the market without purchasing any vehicle. Thus, at such an indifference point, $U_g(p_g, T_g) = U_r \Rightarrow \theta_g = p_g + T_g$. Therefore, a consumer segment with $\theta \in (\theta_e, 1]$ would prefer to buy an EV, and consumer segment with $\theta \in (\theta_g, \theta_e)$ would prefer to purchase a GV, while consumer segment having $\theta \in [0, \theta_g)$ would leave the market without any purchase (see Figure 3).

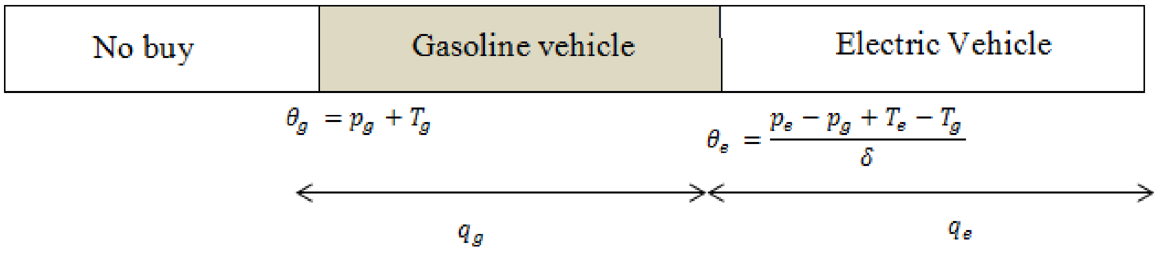

Figure 3. Description of valuations bound for EVs and GVs purchasing decision

Thus, the demand function for the EV can be derived as $q_e = \int_{\theta_e}^{1} \frac{1}{1-0} d\theta = \frac{\delta - p_e + p_g - T_e + T_g}{\delta}$. Similarly, the demand function for GV will be $q_g = \int_{\theta_g}^{\theta_e} \frac{1}{1-0} d\theta = \frac{(p_e+T_e)-(1+\delta)(p_g+T_g)}{\delta}$. For the given demand function for both vehicles, EVs and GVs, the manufacturer maximizes its total profit function, π_m by deciding the market prices, p_e and p_g as follows:

$$\pi_m = (p_e - \kappa c + R)q_e + (p_g - c)q_{g.} \tag{4}$$

Next, we calculate the consumer surplus following the works of Gambardella et al. (2017), Hassin and Roet-Green (2017), and Shao et al. (2017). Consumer surplus (*CS*) is defined as the aggregate utility of all consumers participating in the market and formulated as below:

$$CS = \int_{\theta_e}^{1} U_e(\theta)d(\theta) + \int_{\theta_g}^{\theta_e} U_g(\theta)d(\theta) + \int_{0}^{\theta_g} U_r(\theta)d(\theta). \tag{5}$$

Here, we would like to highlight that how our model is different from the other models related to the differentiated products. The salient features of our model are linked to three factors which work together, viz. product differentiation, incentive structure, and single homing. At the first level, consumers in our model get an incremental utility on purchasing EVs, which is broadly a template which can be followed by any differentiated product set up as mentioned in the review comment (including EVs). At the same time, it may please be noted that the price differential between EVs and GVs is very significant. However, at the next level, we have a subsidy and differentiated taxes regime, which are much more specific in nature. Only a very small subset of differentiated products would fall in this bracket (for example, solar panels in some countries). An additional important factor that we have incorporated is single homing, that is a consumer buys only one type of product (note that this would not necessarily hold for products like solar panels).

Additionally, as mentioned earlier, the automobile sector alone accounts for about 24% of global GHG emissions and is projected to surge up to 50% by 2050 without any interventions (IEA, 2018, 2021). Thus, we need to understand its adoption dynamics and modelling more specific to EV-GV market. For instance, the upfront cost of EVs is substantially high in comparison with its GV counterparts. We model this as a cost coefficient (*k*), which shows the higher price of an EV relative to a GV based on the prevailing scenario. We analyse the choices not just at a firm level but also at the government and consumer level. Further, modelling the per unit environmental impact of both EVs and GVs is another unique point, which are directly linked with the automobile market. The government policies can be directly linked with environmental impact of both types of vehicles and cost-coefficient, which are already in use in few countries like France (IEA, 2021). Hence, it is imperative to understand which scenarios will generate higher social welfare and a better EV eco-system from societal perspectives. Once we combine all these features, we believe that the model development will become quite tailored to the study of EVs and GVs.

The next theorem provides expressions for the manufacturer's profit and consumer surplus.

Theorem 1: *For a generalized case: (i) The manufacturer's profit as a function of T_e, T_g, and R can be expressed as follows:* $\pi_m = \frac{(c\kappa-\delta)^2-2c\kappa(c+T_g-T_e+R)+\delta(c+T_g)^2+\delta(1-2T_e+2R)+(c+T_g)^2-2c(T_e-R)-2T_g(T_e-R)+(T_e-R)^2}{4\delta}$. *(ii) The consumer surplus can be expressed as follows:* $CS = \frac{(c\kappa-\delta)^2-2c\kappa(c+T_g-T_e+R)+\delta(c+T_g)^2+\delta(1-2T_e+2R)+(c+T_g)^2-2c(T_e-R)-2T_g(T_e-R)+(T_e-R)^2}{8\delta}$.

Proof: *All proofs are provided in the online appendix.*

In order to derive social welfare, we follow the social welfare definition of Varian and Varian (1992), as "*the social welfare function aggregates the individual utility functions to come up with a social utility*". Thus, social welfare is expressed as the summation of the manufacturer's total profits (π_m), consumer surplus (CS), total green tax collected from GVs ($T_g q_q$), and the EVs ($T_e q_e$), and total environmental impact ($EI = i_e q_e + i_g q_g$). The unit environmental impact of EV and GV is quantified as i_e and i_g, respectively, by following a similar approach as Agarwal et al. (2012). The expression for the social welfare (SW) function will be

$$SW = \pi_m + CS + (T_e - i_e - R)q_e + (T_g - i_g)q_g. \quad (6)$$

Replacing the optimal profit, CS, and optimal quantities, the expression for *SW* is reduced to the following:

$$SW = \frac{(c\kappa-\delta)^2-2c\kappa(c+T_g-T_e+R)+\delta(c+T_g)^2+\delta(1-2T_e+2R)+(c+T_g)^2-2c(T_e-R)-2T_g(T_e-R)+(T_e-R)^2}{4\delta} + \frac{(ck-\delta)^2-2c\kappa(c+T_g-T_e+R)+\delta(c+T_g)^2+\delta(1-2T_e+2R)+(c+T_g)^2-2c(T_e-R)-2T_g(T_e-R)+(T_e-R)^2}{8\delta} + \frac{(T_g-i_g)(c(\kappa-\delta-1)+T_e-T_g(1+\delta)-R)}{2\delta} + \frac{(T_e-i_e-R)(c(1-\kappa)+T_g-T_e+R)}{2\delta}. \quad (7)$$

Here, both differential taxation and subsidy aim to boost EV adoption only. Hence, we need to understand how different combinations of these policy instruments actually influence adoption decisions. Nevertheless, it may be noted that determining the three policy decision variables uniquely from the above expression is not possible owing to the redundant nature of two first-order conditions. Hence, we would focus on prevailing scenarios with two of these policy instruments. As discussed in the introduction section, governments worldwide use different taxation-subsidy mixes to facilitate EV adoption. We consider five illustrative models based on prevailing scenarios and analyze the benefits with respect to all stakeholders (i.e., government, manufacturer, and consumer) subsequently.

4.1. Tax on GV and Manufacturer Subsidy Model (TGS)

This model is a special case of generalized model putting, $T_e = 0$. Hence, in this model, we analyze the case where the government provides a subsidy R for the manufacturer to produce EVs as well as no green tax charged for EV consumers, i.e., $T_e = 0$. However, green tax on GVs is T_g. For example, in countries like Norway, policies such as exemption of EVs from Value Added Tax, registration tax, and annual circulation tax are in place, along with incentives for EV manufacturers (EEA, 2019). Moving the same way as discussed in the generalized model with putting, $T_e = 0$, we get the following theorem for optimal prices, demand quantities, profit, and consumer surplus for the present model.

Theorem 2*: Under the Model TGS:* (i) *The optimal prices for the EVs and GVs are;* $p_e = \frac{1+\delta+c\kappa-R}{2}$, $p_g = \frac{1+c-T_g}{2}$; *(ii) The optimal demand for the EVs and GVs are:* $q_e = \frac{T_g+R+\delta+c(1-\kappa)}{2\delta}$, $q_g = \frac{c\kappa-R-(T_g+c)(1+\delta)}{2\delta}$ *; (iii) The optimal profit for the manufacturer:* $\pi_m = \frac{R^2+{T_g}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g+R)+2\delta(R+1)+2cT_g}{4\delta}$; *(iv) The consumer surplus:* $CS = \frac{R^2+{T_g}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g+R)+2\delta(R+1)+2cT_g}{8\delta}$.

From theorem 2, we can infer that the price and demand of vehicles under the present scenario would depend upon green tax, subsidy, and relative cost coefficient 'κ'. Social welfare in this model can be derived from equation (6), as explained earlier, reducing thereby to the following equation in terms of green tax and subsidy.

$$SW = \frac{R^2+{T_g}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g+R)+2\delta(R+1)+2cT_g}{4\delta} + \frac{R^2+{T_g}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g+R)+2\delta(R+1)+2cT_g}{8\delta} - \frac{i_g\left(c(\kappa-\delta)-(\delta+1)T_g-c-R\right)}{2\delta} + \frac{T_g\left(c(\kappa-\delta)-(\delta+1)T_g-c-R\right)}{2\delta} - \frac{i_e\left(c(1-\kappa)+\delta+R+T_g\right)}{2\delta} - \frac{R(c(1-\kappa)+\delta+R+T_g)}{2\delta}. \quad (8)$$

The social welfare function (8) is jointly concave in T_g and R. Joint concavity can be established following the previous methodology using the Hessian matrix. Simultaneously, solving first-order conditions with respect to T_g and R gives $\widehat{T_g} = 2i_g + c - 1$ and $\hat{R} = \delta - c\kappa - 2i_e + 1$. The optimal value of social welfare can be derived by substituting the optimal value of green tax and subsidy, as mentioned below:

$$SW = \frac{(i_e-c)^2+2(i_g+c)^2+c^2(\kappa^2-2\kappa-1)-2c\kappa(i_e-i_g-\delta)+\left(\delta(1-2i_e)-2i_g i_e\right)}{2\delta}.$$

As we are considering green tax exemption and manufacturer subsidy here for EVs, their relationship with the other variables is explained through the following corollary.

Corollary 1: *(i) Higher environmental impact of GV (i_g) is liable for higher green tax on GVs. (ii) Subsidy for EV increases with a decrease in i_e and relative cost coefficient 'κ'. (iii) The consumer's low carbon awareness (δ) is positively related to the subsidy ($\hat{R}$).*

Corollary 1 illustrates that the government should levy higher green taxes for higher emitting GVs, and provide more subsidies for environmentally friendly EVs. Thus manufacturers, in this case, try to curtail the environmental impact of GVs and EVs to reduce the green tax and maximize the subsidy. Until now, we discussed subsidizing both EV consumers and the manufacturer for EVs; however, due to limited budget constraints, the government cannot subsidize both EV consumers and the manufacturer in many cases. Hence, we examine other scenarios as well.

4.2. Differential Taxes and No Subsidy Model (DTNS)

Here, the government charges different green taxes on EVs and GVs termed as T_e and T_g, respectively (where, $T_g > T_e$). For example, the Indian government has imposed different Goods and Service Tax rates for conventional GVs and EVs. For GVs, the Goods and Service Tax is 28 %, whereas it is only 5 % for EVs (Economic Times, 2019). However, the manufacturer doesn't get any direct subsidy for each unit of EVs produced. Following a similar approach, as explained in section 4, we derive the optimal decisions. Theorem 3 illustrates the demand, price, manufacturer profit, and consumer surplus functions of the DTNS Model.

Theorem 3*: Under the Model DTNS: (i) The optimal prices for the EVs and GVs are;* $p_e = \frac{1+\delta+c\kappa-T_e}{2}$, $p_g = \frac{1+c-T_g}{2}$. *(ii) The optimal demand for the EVs and GVs are:* $q_e = \frac{T_g-T_e+\delta+c(1-\kappa)}{2\delta}$, $q_g = \frac{T_e-(T_g+c)(1+\delta)+c\kappa}{2\delta}$. *(iii) The optimal manufacturer profit:* $\pi_m = \frac{T_e{}^2+(T_e-T_g)^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{4\delta}$. *(iv) The consumer surplus:* $CS = \frac{T_e{}^2+(T_e-T_g)^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{4\delta}$.

From Theorem 3, we can understand that the price and demand of vehicles under differential taxation schemes depend on green taxes, relative cost coefficient 'κ' as shown by corollary 3.

Corollary 2*: (i) The optimal price for EVs and GVs decreases as the green tax increases. Further, an increase in κ leads to an increase in the price of EVs. (ii) The demand for EVs decreases, and GVs increase as the cost coefficient (κ) increases.*

Corollary 2 suggests that lower taxes on EVs can facilitate EV adoption because the higher upfront cost of EVs is one of the major hindrances to their acceptance (Chakraborty et al., 2021). Further, demand for EVs is dependent on the 'κ' factor since higher κ means higher cost of EVs as compared to GVs. The relative increase in the cost of EVs affects their adoption due to their increased prices. This, in turn, may be attributed to the fact that price-sensitive consumers would prefer to buy GVs instead of EVs, which effectively cannibalizes the demand for EVs in the same market.

The expression for social welfare function for this model could be obtained by substituting R=0 in the expression (6) and could be rewritten as follows:

$$SW = \frac{T_e{}^2+(T_e-T_g)^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{4\delta} + \frac{T_e{}^2+(T_e-T_g)^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{4\delta} - \frac{i_g\left(c(\kappa-\delta-1)+T_e-T_g(1+\delta)\right)}{2\delta} + \frac{T_g\left(c(\kappa-\delta-1)+T_e-T_g(1+\delta)\right)}{2\delta} - \frac{i_e\left(c(\delta-\kappa)+T_g-T_e\right)}{2\delta} + \frac{T_e\left(c(\delta-\kappa)+T_g-T_e\right)}{2\delta}. \quad (9)$$

Simultaneously solving for the first-order conditions, $\frac{\partial SW}{\partial T_e} = 0$ and $\frac{\partial SW}{\partial T_g} = 0$, we get $\widehat{T_e} = c\kappa - \delta + 2i_e - 1$ and $\widehat{T_g} = 2i_g + c - 1$. Using optimal values of T_e and T_g, we get optimal social welfare as $SW = \frac{(i_e-c)^2+2(i_g+c)^2+c^2(\kappa^2-2\kappa-1)-2c\kappa(i_e-i_g-\delta)+\left(\delta(1-2i_e)-2i_gi_e\right)}{2\delta}$. It is essential for the government to comprehend the impact of i_e and i_g on the T_e and T_g, respectively, which we present through the following corollary.

Corollary 3*: Green taxes on EVs (T_e) and GVs (T_g) increase with an increase in the per-unit environmental impact of EV (i_e) and GV (i_g), respectively.*

Corollary 3 implies the role of environmental impact on deciding the government's taxation policies. These values of i_g and i_e can act as a relevant measure for the policymakers to decide green taxes on both GVs and EVs, maximizing social welfare thereof. The government, in its end, could discourage the production or usage of vehicles with a higher emission rate by charging higher green taxes. Many countries like India and France have been increasingly imposing stringent tailpipe emission regulations to envisage zero-or low-emission vehicles (Bunsen et al., 2018). Further, a consumer having higher environmental consciousness would prefer to buy an EV with a lower green tax.

4.3. Taxes on GV and No Subsidy Model (TGNS)

Here, we explore the scenario where the government provides no subsidy, R=0 to EV manufacturer and charges no green tax on EVs, i.e., $T_e = 0$. However, green tax on GVs remains, T_g. Following a similar approach, as explained in the generalized model, we derive the optimal decisions. Theorem 6 represents expressions for optimal prices, demand, profit, and consumer surplus.

Theorem 4*: Under the Model TGNS:* (i) *The optimal prices for the EVs and GVs are:* $p_e = \frac{1+\delta+c\kappa}{2}$, $p_g = \frac{1+c-T_g}{2}$. (ii) *The optimal demand for EVs and GVs are:* $q_e = \frac{T_g+\delta+c(1-\kappa)}{2\delta}$, $q_g = \frac{c\kappa-(T_g+c)(1+\delta)}{2\delta}$. *(iii) The optimal profit for the manufacturer:* $\pi_m = \frac{T_g{}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{4\delta}$. *(iv) The consumer surplus:* $CS = \frac{T_g{}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{8\delta}$.

Theorem 4 entails that imposing only a green tax on GVs can also boost the EV demand and consequently undermine the GV demand. However, an increase in relative cost coefficient (κ) increases the sales of GVs and reduces EVs sales. Thus, when no subsidy and green tax is available for EVs, then the manufacturer should try to reduce the price differential between EV and GV to enhance EV adoption. This model's social welfare can be derived from equation (6), as explained earlier, reducing thereby to the following equation in terms of green tax, as shown below:

$$SW = \frac{{T_g}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{4\delta} + \frac{{T_g}^2+c^2(\kappa-1)^2+\delta(T_g+c)^2-2c\kappa(\delta+T_g)+2\delta+2cT_g}{8\delta} - \frac{i_g(c(\kappa-\delta)-(\delta+1)T_g-c)}{2\delta} + \frac{T_g(c(\kappa-\delta)-(\delta+1)T_g-c)}{2\delta} - \frac{i_e(c(1-\kappa)+\delta+T_g)}{2\delta}. \qquad (10)$$

Social welfare function (10) is concave in T_g and the first-order condition with respect to T_g results, $\widehat{T_g} = \frac{c(1-\kappa)+2(i_g-i_e)+\delta(2i_g+c)}{\delta+1}$. The optimal value of social welfare can be derived by substituting the optimal value of green tax T as below:

$$SW = \frac{\begin{array}{c}(3c^2\delta\kappa^2+4c^2\kappa^2-6c\delta^2\kappa-8ci_g\delta\kappa+4ci_e\delta\kappa-8c^2\delta\kappa-6c\delta\kappa-8ci_g\kappa+8ci_e\kappa-8c^2\kappa+3\delta^3+4{i_g}^2\delta^2+8ci_g\delta^2)+\\ 4i_e\delta^2+4c^2\delta^2+6\delta^2+8{i_g}^2\delta-8i_ei_g\delta+16ci_g\delta-8ci_e\delta-4i_e\delta+8c^2\delta+3\delta+4{i_g}^2-8i_ei_g+8ci_g+4{i_e}^2-8ci_e+4c^2\end{array}}{8\delta(\delta+1)}.$$

4.4. Same Tax and Manufacturer Subsidy Model (STS)

In this model, we explore the impact of subsidy (R) for manufacturers producing EVs, while the government charges equal green tax for both categories of vehicles. A few countries use the manufacturer subsidy policy to facilitate EV production. For instance, Chinese firms like BYD and BAIC Motors receive subsidies from the Chinese government to boost the production of plug-in electric vehicles (Reuters, 2017). Thus, we consider manufacturer subsidy R for each unit of EVs sold and impose the condition of $T_g = T_e = T$ to capture a uniform taxation policy. Following a similar approach, as explained in the generalized model, we derive the optimal decisions, as listed below.

Theorem 5*: Under the Model STS: (i) The optimal prices for the EVs and GVs are:* $p_e = \frac{1+\delta+c\kappa-R-T}{2}$, $p_g = \frac{1+c-T}{2}$. *(ii) The optimal demand for EVs and GVs are:* $q_e = \frac{\delta+R+c(1-\kappa)}{2\delta}$, $q_g = \frac{c(\kappa-\delta)-T\delta-R}{2\delta}$. *(iii) The optimal profit for the manufacturer:* $\pi_m = \frac{(T-R)^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T+R)+2\delta(R+1)+2cT}{4\delta}$. *(iv) The consumer surplus:* $CS = \frac{(T-R)^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T+R)+2\delta(R+1)+2cT}{8\delta}$

From theorem 5, we can understand that the price, demand for vehicles under the same taxation scheme, and subsidy given to the EV manufacturer would effectively depend upon both green taxes and subsidy. We have the following inferences related to the above theorem as listed below.

Corollary 4: *(i) The optimal price for EVs decreases as the subsidy increases. (ii) The demand for EVs increases, and GVs decrease as the subsidy increases.*

Corollary 4 suggests that subsidy to EV manufacturers can also facilitate EV adoption because higher subsidy ultimately leads to less upfront price of EVs for consumers. Further, an increase in subsidy generates more demand for EVs and less demand for GVs, which would be desirable, and in line with existing literature (Breetz and Salon, 2018).

Social welfare under the government's same green tax policy for consumers, along with a subsidy for an EV manufacturer, is calculated in line with section 4, as expressed below, by substituting $T_e = T_g = T$ in (6).

$$SW = \frac{(T-R)^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T+R)+2\delta(R+1)+2cT}{4\delta} + \frac{(T-R)^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T+R)+2\delta(R+1)+2cT}{8\delta} - \frac{i_g(c(\kappa-\delta-1)-T-R)}{2\delta} + \frac{T((c(\kappa-\delta-1)-T-R))}{2\delta} - \frac{i_e((1-\kappa)c+\delta+R)}{2\delta} + \frac{T((1-\kappa)c+\delta+R)}{2\delta} - \frac{R((1-\kappa)c+\delta+R)}{2\delta}. \quad (11)$$

Solving the first-order conditions for SW, we get $\hat{R} = \delta - c\kappa - 2(i_e - i_g) + c$ and $\hat{T} = 2i_g + c - 1$. Using $\hat{R}$ and $\hat{T}$ in the SW (equation 11), we get the optimal value of social welfare function as

$$SW = \frac{(i_e-c)^2+2(i_g+c)^2+c^2(\kappa^2-2\kappa-1)-2c\kappa(i_e-i_g-\delta)+(\delta(1-2i_e)-2i_g i_e)}{2\delta}.$$

Referring to the optimal tax and subsidy function, we have the following corollary to represent the relationship with environmental impacts.

Corollary 5: *(i) Green tax on GV increases with an increase in i_g. (ii) The subsidy, R increases for the manufacturer (for EV) with an increase in i_g and decrease in i_e.*

Corollary 5 signifies that the government should increase the green tax on GVs when the environmental impact is higher. Further, the subsidy would also increase in such cases to facilitate EV adoption while undermining GV sales. Along with GV per unit environmental impact, subsidy also depends on the i_e, i.e., the higher the i_e, the lower is the subsidy. This is in line with the latest regulations (e.g., adoption of BSVI regulations in India by April 2020) to curtail tailpipe emissions by adopting lesser polluting vehicles and ultimately transiting to EVs. Along similar lines, many countries like France and China have increasingly imposed stringent tailpipe emission regulations to envisage zero- or low-emission vehicles (Bunsen et al., 2018).

4.5. Same Tax and No Subsidy Model (STNS)

In this section, we explore the scenario where the government charges equal green tax for both categories of vehicles, GVs, and EVs, while providing no subsidies for the manufacturer to produce EVs. It is a reference case because no tax incentives nor subsidy is provided for EVs; in other words, no government policies support them. For instance, consider Poland's case, which doesn't have any specific policy for stimulating EV demand in terms of either levying taxes or providing subsidies (EEA, 2019). Thus, in this case, $T_g = T_e = T$ and $R = 0$. As explained in section 4, we derive the optimal decisions following a similar approach, as shown in theorem 6.

***Theorem 6**: Under the Model STNS: (i) The optimal prices for the EVs and GVs are:* $p_e = \frac{1+\delta+c\kappa-T}{2}$, $p_g = \frac{1+c-T}{2}$. *(ii) The optimal demand for the EVs and GVs are:* $q_e = \frac{\delta+c(1-\kappa)}{2\delta}$,$q_g = \frac{c(\kappa-\delta)-T\delta}{2\delta}$. *(iii) The optimal profit for the manufacturer:*$\pi_m = \frac{T^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T)+2\delta+2cT}{4\delta}$. *(iv) The consumer surplus:* $CS = \frac{T^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T)+2\delta+2cT}{8\delta}$.

The findings of theorem 6 entail that an increase in green tax does reduce the optimal price of both EV and GV, as well as reducing the demand for GVs. In this case, social welfare may be derived from the explanation in equation (6), which reduces the following:

$$SW = \frac{T^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T)+2\delta+2cT}{4\delta} + \frac{T^2+c^2(\kappa-1)^2+\delta(T+c)^2-2c\kappa(\delta+T)+2\delta+2cT}{8\delta} - \frac{i_g(c(\kappa-\delta)-\delta T-c)}{2\delta} + \frac{T\big((c(\kappa-\delta)-\delta T-c)\big)}{2\delta} - \frac{i_e(c(1-\kappa)+\delta)}{2\delta} + \frac{T(c(1-\kappa)+\delta)}{2\delta}. \tag{12}$$

Solving the first-order of SW with *T* gives $\hat{T} = 2i_g + c - 1$. The optimal value of SW can be derived by substituting $\hat{T}$ as below.

$$SW = \frac{3c^2\kappa^2-6c\delta\kappa-4ci_g\kappa+4ci_e\kappa-6c^2\kappa+3\delta^2+4{i_g}^2\delta+8ci_g\delta-4i_g\delta-4i_e\delta+4c^2\delta-2c\delta+4\delta+4ci_g-4ci_e+3c^2}{8\delta}.$$

As we are assuming equal green tax for both types of vehicles, the government needs to understand the impact of i_g and i_e on the green tax. Here again, the green tax, *T* increases with an increase in the i_g and is independent i_e. This illustrates that if the government puts equal green tax for both types of vehicles, as explained in this case, then its green tax would depend only on the environmental impact of GVs. In other words, it will be independent of the per-unit environmental impact of EVs. Thus, a higher per-unit environmental impact of GVs would be liable for higher green tax. In this case, the manufacturers would try to curtail the environmental impact of GVs rather than EVs to minimize the green tax. Hence, this model does not facilitate EV adoption and is certainly not ideal for current scenarios.

These five models represent different combinations of green tax and subsidy available for both consumers and manufacturers. The optimal parameters of these models are summarized in table 3. The government acting as a leader maximizes social welfare in each case to get the optimal results, while manufacturers maximize their profits.

Table 3: Optimal decision variables under different models

Optimal decisions	**Model DTNS**	**Model STS**	**Model STNS**	**Model TGS**	**Model TGNS**
p_e	$\delta - i_e + 1$	$c(\kappa-1) - 2i_g + i_e + 1$	$\frac{c(\kappa-1)+\delta-2(i_g-1)}{2}$	$c\kappa + i_e$	$\frac{c\kappa+\delta+1}{2}$
p_g	$1 - i_g$	$1 - i_g$	$1 - i_g$	$1 - i_g$	$\frac{c\kappa+(1-2(i_{g+}c))(1+\delta)+2i_e}{2(1+\delta)}$
T_e	$c\kappa - \delta + 2i_e - 1$	$2i_g + c - 1$	$2i_g + c - 1$	0	0
T_g	$2i_g + c - 1$	$2i_g + c - 1$	$2i_g + c - 1$	$2i_g + c - 1$	$\frac{-c\kappa-(-2i_g-c)\delta+2i_g-2i_e+c}{\delta+1}$

R	NA	$c(1-\kappa)+\delta + 2(i_g - i_e)$	NA	$1 - c\kappa + \delta - 2i_e$	
$\boldsymbol{VS}$	A	A	A	A	$\frac{c\kappa+(1-2(i_{g+}c))(1+\delta)+2i_e}{2(1+\delta)}$
EI	$\frac{B}{\delta}$	$\frac{B}{\delta}$	$\frac{c(i_g-i_e)(\kappa-1)-(i_g+i_e)\delta-2i_g(i_g-c)\delta}{2\delta}$	$\frac{B}{\delta}$	$\frac{E+\Delta-2{i_g}^2+(4i_e-2c)i_g-2{i_e}^2+2ci_e}{2\delta(\delta+1)}$
$\boldsymbol{CS}$	$\frac{(\omega+\Theta+\Omega+\Gamma}{2\delta}$	$\frac{(\omega+\Theta+\Omega+\Gamma)}{2\delta}$	$\frac{\psi+Z}{8\delta}$	$\frac{(\omega+\Theta+\Omega+\Gamma)}{2\delta}$	$\frac{K^2c^2(4+\delta)+2\delta^2(2\chi^2+1)+\delta(8\chi^2-8i_e\chi+1)+(4\chi^2-8i_e\chi+4i_e^2)+Z}{4\delta(1+\delta)}$
$\boldsymbol{\pi_m}$	$\frac{(\omega+\Theta+\Omega+\Gamma}{\delta}$	$\frac{(\omega+\Theta+\Omega+\Gamma)}{\delta}$	$\frac{\psi+Z}{4\delta}$	$\frac{(\omega+\Theta+\Omega+\Gamma)}{\delta}$	$\frac{K^2c^2(4+\delta)+2\delta^2(2\chi^2+1)+\delta(8\chi^2-8i_e\chi+1)+(4\chi^2-8i_e\chi+4i_e^2)+Z}{8\delta(1+\delta)}$
$\boldsymbol{GI}$	$\frac{\Gamma+\xi}{\delta}$	$\frac{\Gamma+\xi}{\delta}$	$A(2i_g+c-1)$	$\frac{\Gamma+\xi}{\delta}$	$\frac{2}{-\frac{(c\kappa-2i_g\delta-c\delta-2i_g+2i_e-c)(c\kappa-i_g\delta-c\delta-i_g+i_e-c)}{\delta(\delta+1)}}$

Where, $\boldsymbol{A=(1-c-i_g);B=c(i_g-i_e)(\kappa-1)-({i_g}^2+ci_g-i_e)\delta-(i_g-i_e)^2;\ \psi=c^2\kappa^2-2c\kappa(c+\delta);Z=\left(4(i_g+c)^2-4(1-2i_g)-6c\right)\delta+c^2;\ \chi=(i_g+c);\ \omega=c^2\kappa^2+\delta^2-2c\kappa\left((c+\delta)-(i_g-i_e)\right);\ E=\left((2ci_g-ci_e)\delta+2ci_g-2ci_e\right)\kappa+(-2{i_g}^2-2ci_g+i_e)\delta^2;\ \Delta=(-4{i_g}^2+(4i_e-4c)i_g+(2c+1)i_e)\delta;\ \Theta=\left((i_g-c)^2+1-2i_e\right);\ \Omega=2i_g(c-i_e)+{i_g}^2;\ \Gamma=(i_e+c)^2;D=2(i_g+i_e-1)-\delta;\ \Gamma=c^2\kappa^2+(-2c\delta-3ci_g+3ci_e-2c^2)\kappa+\delta^2+(2{i_g}^2+3ci_g-3i_e+c^2+1)\delta;\xi=2{i_g}^2+(3c-4i_e)i_g+2{i_e}^2-3ci_e+c^2}$

As different countries use these models and thus might have different implications for the manufacturers, consumers, and the government. Outcomes of these five models vary and thus provide a base for the comparative assessment, which is a missing link in the literature. The comparison among these models does provide important insights for governments, policymakers, and manufacturers, and our next section highlights major findings.

5. Key Findings and Discussions

On the basis of the equilibrium results, we compare the performance of various policy mixes in terms of the manufacturer's profit, vehicle stock and price, environmental impact, government income, consumer and social welfare across models.

5.1. Manufacturer's profit

Table 3 indicates that manufacturer profit is equally better off under three scenarios (i.e., *DTNS*, *STS*, and *TGS*); however, the profit relationship between the other two models (*STNS*, *TGNS*) varies as stated in the following proposition.

Proposition 1*: The manufacturer profit under different models have the following order:* $\pi^{DTNS}=\pi^{STS}=\pi^{TGS}$, and, $\pi^{TGNS}>\pi^{DTNS}$, $\delta>c\kappa-1+\frac{2}{3}(i_e)$ *, however,* $\pi^{DTNS}>\pi^{STNS}$*, when* $\delta>c\kappa-c-\frac{2}{3}(i_g-i_e)$.

The increase in δ enhances the sales of EVs, and subsequently, the manufacturer generates higher profits for three models (*DTNS*, *STS*, and *TGS*). In *STNS* Model, the same taxes are charged for both types of vehicles, and no subsidy is separately offered to the manufacturer for EVs, indicating no favorable policy support for EVs. Thus, an increase in carbon awareness doesn't necessarily increase the profit of the manufacturer. Hence, it is expected that consumers' low carbon awareness, combined with other policy support, can make EV a lucrative alternative to GVs. This finding challenges the conventional wisdom that lower carbon awareness reduces the EVs sales (Okada et al., 2019). EVs sales can be improved by offering green taxation support/ or subsidy support when consumers' carbon awareness is low. This strategy can be helpful in countries like India, where people are less aware and price-sensitive at the same time.

Additionally, when green tax is imposed only for GV, and no tax or subsidy is provided for EV (Model *TGNS*), the demand for EVs can be expected to increase, while demand for GVs would decrease, which would subsequently improve the manufacturer profits. This outcome is subject to confirmation that the price difference between EV and GV is much lesser. Hence, when the government does plan to increase EV adoption by only imposing a tax on GV, it has to assure manufacturers that the price difference between EV and GV is much lesser than the tax imposed on GVs. Furthermore, when the government does go on to impose a different green tax for EVs and GVs and offers no separate subsidy to the EV manufacturer (Model *DTNS*), the optimal price of both EVs and GVs would increase, which in turn would strongly impact EV pricing with an increase in the price differential. Government policies could also consider compensating the price differential factor's impact on EVs by imposing a relatively lower tax on EVs in comparison to GVs (Chakraborty et al., 2021). This finding partially explains why the Indian government has reduced tax on EVs from 12% to 5% and offered tax benefits by exempting road taxes on EVs[5].

5.2. Vehicle stock

The vehicle stock comprises the number of vehicles sold, including both GVs and EVs. Mathematically vehicle stock is represented as, $VS = q_e + q_g$. The vehicle stock is the same for four models (*DTNS, STS, STNS, and TGS*), and it is different from *TGNS,* as illustrated by the following proposition.

Proposition 2*: The vehicle stock of different models has the following order:* $VS^{DTNS} = VS^{STS} = VS^{TGS} = VS^{STNS}$*, and* $VS^{TGNS} > VS^{DTNS}$ *for* $\delta < c\kappa + 2i_e - 1$.

It is quite interesting to note here that the *STNS* Model has the same vehicle stock as compared to the other three models and even generates lower profits. This may be explained by the fact that there haven't been any incentives offered for EVs either in terms of tax or subsidy, which effectively leads to lower profit margins for the manufacturer. Hence, policy support, like taxation or subsidy schemes, could help manufacturers to generate higher profits while creating a larger, conducive EV ecosystem.

[5] https://www.firstpost.com/tech/auto-tech/state-wise-ev-subsidies-in-india-a-handy-list-of-incentives-and-benefits-for-electric-vehicles-in-each-state-9952771.html [accessed 13 September 2021].

5.3. Environmental impact

The environmental impact indicates the environmental damage caused by all vehicles to the environment. Mathematically, environmental impact is calculated as $EI = i_e q_e + i_g q_g$. We have the following proposition for the environmental impact.

Proposition 3*: The environmental impact of the different models has the following order:* $EI^{DTNS} = EI^{STS} = EI^{TGS}$, $EI^{STNS} > EI^{DTNS}$, *and,* $EI^{DTNS} < EI^{TGNS}$.

Three models (*DTNS, STS*, and *TGS*) have an equal environmental impact, and it is lower than the other two models (*TGNS* and *STNS*) as defined above. Further, we see that environmental impact also influences the green tax and subsidy provided by the government and, subsequently, the upfront price of vehicles, for instance, on offering subsidies to manufacturers of EVs with the same level of green tax for both EV and GV (Model *STS*), the upfront price of EVs for consumers decreases. Lower the environmental impact of EV, higher is the subsidy offered to EV manufacturers, and lower is the green tax imposed on EV consumers. Thus, the demand for EVs increases, and demand for GVs decreases for further increase in subsidy, which goes on to facilitate EV adoption. This finding is in line with the previous literature (Breetz and Salon, 2018). On offering subsidies to EV manufacturers with green tax only imposed on GVs (Model *TGS*), the optimal price for EV decreases. An increase in the green tax reduces the price of GVs. Demand for EVs increases, and GVs decrease as the subsidy and/or green tax increases. The government should levy higher green taxes for polluting GVs and provide more subsidies for environmentally friendly EVs. In the context of green product development (GPD), Dong et al. (2019) and Bian et al. (2018) have arrived at a similar conclusion that a higher environmental tax leads to lower emissions. In comparison to other scenarios discussed, governments could also consider increasing EV sales significantly in this scenario by working out the subsidies for EVs and green tax for GVs. Such carrot and stick policies are being followed by many governments across the globe to promote sales of EVs. For instance, in India, under the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme, the government imposes higher green taxes on GVs and road tax exemption on EVs (50%-100%)[6] and offers other green tax benefits.

5.4. Government income

The government income is the net revenue generated from taxes minus subsidy. Mathematically, government income is calculated as $GI = T_g q_g + (T_e - R) q_e$. Comparative study reveals that the government income of three models (*DTNS, STS,* and *TGS*) are the same and different from the other two models. We have the following preposition regarding government income generated for all models under the given experimental setup.

[6]https://www.firstpost.com/tech/auto-tech/state-wise-ev-subsidies-in-india-a-handy-list-of-incentives-and-benefits-for-electric-vehicles-in-each-state-9952771.html [accessed 13 September 2021].

Proposition 4: *The government income of different models has the following order:* $GI^{DTNS} = GI^{STS} = GI^{TGS}$*, and* $GI^{STNS} > GI^{DTNS} > GI^{TGNS}$ *for* $\delta > c\kappa + 2i_e - 1$.

Here, we can say that the *STNS* Model is possibly the best model from a government income point of view. However, this model is not optimal when we consider other deliverables like manufacturer profit or overall environmental impact. Thus, we need to have a better measure to understand the model suitability under a given context like social welfare. However, countries where consumers are well aware, having developed charging and other infrastructure, and per capita income is higher can follow the *STNS Model* to maximize their income without much affecting EVs sales. For instance, Poland follows the STNS *Model*, which is not affecting growth in EVs sales. For example, the total EVs sales were 290 cars in the year 2015, which increased to more than 9500 EVs in the year 2020[7].

5.5. Social welfare

Social welfare is the aggregation of manufacturer profit, consumer surplus, government revenue, and environmental impact, as defined in equation 6. Hence, it provides a holistic idea about all models developed to measure the impact of EV adoption for the government as well as policymakers (Shao et al., 2017 and Chemama et al., 2019). We have the proposition below related to social welfare.

Proposition 5: *The social welfare of different models has the following order:* $SW^{DTNS} > SW^{STNS}$; $SW^{DTNS} > SW^{TGNS}$ *and* $SW^{DTNS} = SW^{STS} = SW^{TGS}$.

The comparative study of social welfare among five models indicate that social welfare is maximum when either differential tax is levied on the purchase of EVs and GVs with no manufacturer subsidy for EVs or identical green tax for both vehicles along with subsidy given to manufacturer for EVs or no tax on EVs along with subsidy given to manufacturer for EVs. However, social welfare is less when no subsidy is given to manufacturers for EVs along with either identical taxes for both types of vehicles or green tax for only GVs. Integrating these findings, we observe financial incentives like levying minimum green tax on EVs and/or maximum green tax on GVs along with subsidy schemes, which can maximize social welfare. Hence, this is a preferable policy from a government perspective and supports many government initiatives for providing financial incentives for EVs while levying higher taxes on GVs (Chakraborty et al., 2021).

5.6. Consumer surplus

Consumer surplus is an important yardstick to measure the total utility of all consumers participating in the vehicle market. We have the following proposition related to consumer surplus.

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[7] https://www.statista.com/statistics/1081299/poland-number-of-electric-passenger-vehicles/.[accessed 13
September 2021].

Proposition 6: *The consumer surplus of the different models has the following order:* $CS^{DTNS} = CS^{STS} = CS^{TGS}$ *and* $CS^{TGNS} > CS^{DTNS}$, *when* $\delta < c\kappa - 1 + \frac{2}{3} i_e$, and $CS^{STNS} > CS^{DTNS}$, when $\delta < c\kappa - c - \frac{2}{3}(i_g - i_e)$.

Proposition 6 indicates that the model *TGNS* has the highest consumer surplus in the given range of δ as defined above. Further, for lower values of δ, Model *STNS* outperforms Model *DTNS*; however, when δ crosses the threshold, then Model *DTNS* outperforms the Model *STNS*. The conditions shown in the above propositions are in terms of δ, however same condition may be explained in terms of other EV parameters like cost-coefficient (κ), or i_e, or i_g. Thus, we also examine the impact of these parameters on the model outcomes in the next section.

5.7. Vehicle prices

Vehicle prices act as an essential driver influencing consumer demand. Further, for EV adoption, higher EV prices have been identified as a major deterrent. Hence it is necessary to bring an analysis of the vehicle prices. We have the following proposition related to vehicle prices.

Proposition 7 (a): *The prices of the GVs across the different models have the following order:* $p_g^{DTNS} = p_g^{STNS} = p_g^{STS} = p_g^{TGS} > p_g^{TGNS}$.

Proposition 7 (b): *The prices of the EVs across the different models have the following order:* $p_e^{DTNS} > p_e^{STNS} > p_e^{STS}$ *is* $\delta > c\kappa - 2i_g + 2i_e - c$, *and* $p_e^{STS} > p_e^{TGS}$ *if* $i_g < \frac{1-c}{2}$ *with* $p_e^{TGS} > p_e^{TGNS}$ *if* $i_e < \frac{1+\delta-c\kappa}{2}$.

The above proposition indicates the role being played by consumers' low carbon awareness while affecting vehicle prices. For a higher value of consumers' low carbon awareness, the price of the EV becomes the highest under the DTNS model. Further, the unit environmental impact of the vehicles also plays a major role in influencing vehicle prices. For instance, if the unit environmental impact of both the vehicle types is high, the price of the GV is the lowest under the TGNS model. Proposition 7 leads us to the conclusion that for higher values of consumers' low carbon awareness, δ, the manufacturer's profit is the highest, the consumer surplus is the highest, and the social welfare is also the highest for these three models. Thus, the models DTNS, STS, and TGS yield win-win outcomes for the manufacturer, the consumer, and the government.

6. Numerical Experiments

Here, we compare the results obtained for all five models of taxation subsidy schemes and examine the relevant managerial implications. First, we investigate the relationship of consumer low carbon awareness (δ) on different outcomes like social welfare, consumer surplus, manufacturer's profit, environmental impact, government income, and vehicle stock in the subsequent subsections. The model parameters chosen satisfy the feasibility conditions across different models, and are given as: $c = 0.3$; $k = 1.3$; $i_g = 0.43$; $i_e = 0.40$. These model parameters are in line with the existing EV-GV market setup. For example, we have taken the relative cost component (κ) as 1.3, which is in line with extant literature and captures the higher cost of EVs when compared to GVs, attributable to high battery cost (Lévay et al. 2017; Shao et al. 2017). Similarly, the environmental impact of GV is higher than EV and is in line with MacKay (2008).

6.1. Impact of consumer low-carbon awareness

First, we analyze the impact of consumers' low carbon awareness on the manufacturer's profit and also validate the propositions. Figure 4 illustrates how δ influences the manufacturer's profit in all five models.

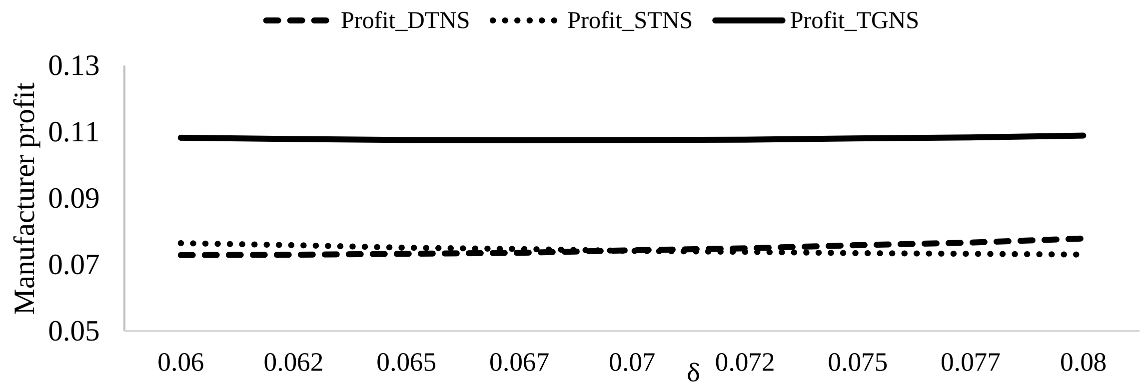

Figure 4. Impact of δ on the manufacturer profit

Figure 4 signifies that manufacturer profit is equal under three scenarios (i.e., *DTNS*, *STS*, and *TGS*); however, profit varies for the other two models (*STNS*, *DTNS*) depending on the δ as shown in proposition 1. Further, Figure 4 indicates that the profit of Model *TGNS* is the highest in the given range of consumer low carbon awareness in comparison to other models. The increase in δ improves the profit the manufacturer generates for three models (*DTNS*, *STS*, and *TGS*) due to higher EV sales. Next, we examine the vehicle stock (VS) variation along with consumer low carbon awareness in the given settings, as illustrated in Figure 5.

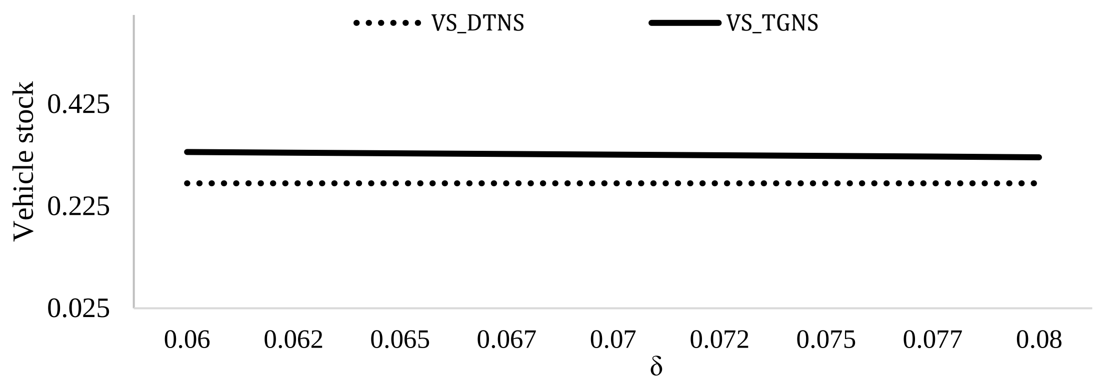

Figure 5. Impact of δ on the vehicle stock

The vehicle stock of one model (*TGNS*) is highest among all models for a lower range of consumer low carbon awareness, as defined in proposition 2, indicating that the *TGNS* Model is not a favourable option from a traffic point of view. However, the remaining four models generate the same vehicle stock, and thus other performance measures have to be evaluated before making the decision.

The comparative analysis of the overall environmental impact of models is presented in Figure 6. Three models (*DTNS, STS,* and *TGS*) have an equal environmental impact, and it is lower than the other two models (*TGNS* and *STNS*).

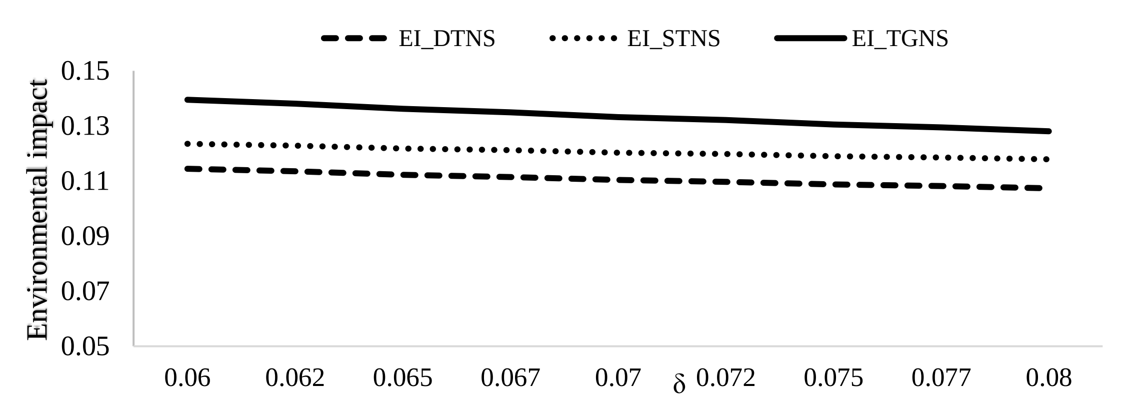

Figure 6. Impact of δ on the total environmental impact

Figure 6 states that the environmental impact is highest for the Model *TGNS* and lowest for the Models *DTNS, STS,* and *TGS* in the given range, as illustrated in proposition 3. Hence, the government may adopt any of these three models (*DTNS, STS,* and *TGS*) to minimize the overall environmental impact. Along similar lines, it is observed that environmental impact does decrease when the consumer's low carbon awareness increases. This is in line with extant literature, which supports that when consumers are more environmentally cautious, the overall environmental impact does decrease due to the adoption of greener products (Agarwal et al., 2012 and Okada et al., 2019).

Next is the government income, and its comparative study reveals that the government income of the three models (*DTNS, STS*, and *TGS*) are the same and different from the other two models. The impact of consumer low carbon awareness on government income under the given experimental setup is presented in Figure 7.

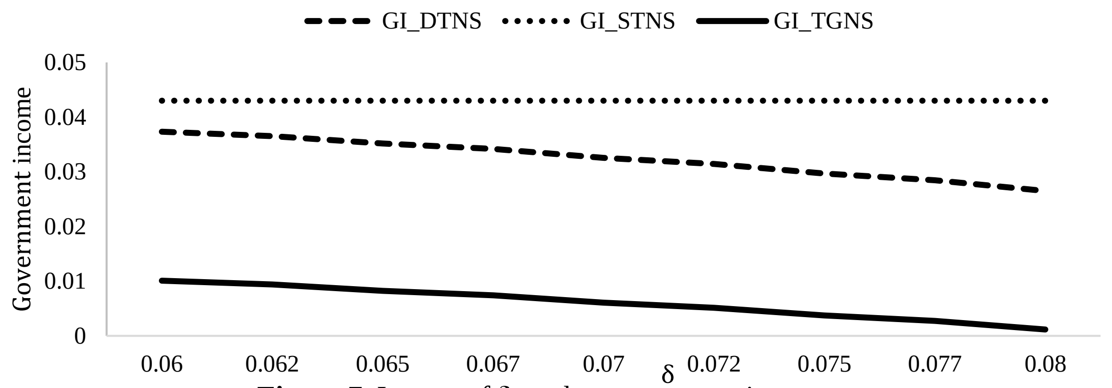

Figure 7. Impact of δ on the government income

We can infer from Figure 7 that higher low carbon awareness leads to lower government income in all models except *STNS* because of government incentives, which are offered in the form of tax or subsidy to facilitate EV adoption. However, the *STNS* Model has no impact on government income, mainly due to the lack of incentives in the form of tax or subsidy.

Social welfare is the aggregation of all stakeholder interests and hence provides a holistic idea about model performances and their impact on EV. The impact of consumers' low carbon awareness on social welfare under a given experimental setup is presented in Figure 8.

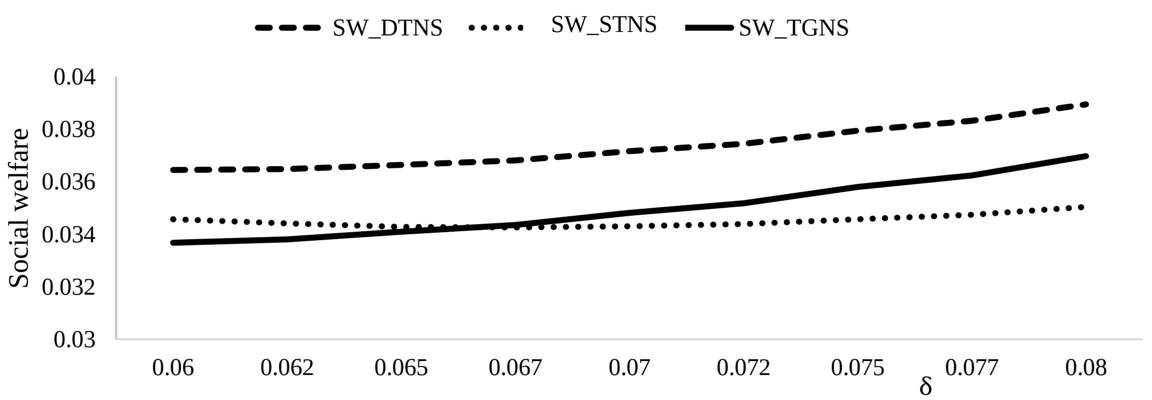

Figure 8. Impact of δ on the social welfare

Figure 8 states the variation of SW among models is in line with proposition 5 and shows that consumers' low carbon awareness positively influences social welfare. This can be explained by the fact that higher δ in coordination with incentive policies can lead to higher EV sales, manufacturer profit, lower environmental impact, and subsequently generate higher social welfare. In fact, many countries are making efforts to make consumers more sensitive to green products while attempting to create a conducive EV ecosystem (Okada et al., 2019).

Further, the consumer is influenced by behavioral factors like consumer low carbon awareness (Okada et al. 2019). It is crucial to envisage the relationship between a consumer's low carbon awareness vis-à-vis the consumer surplus, as shown in Figure 9.

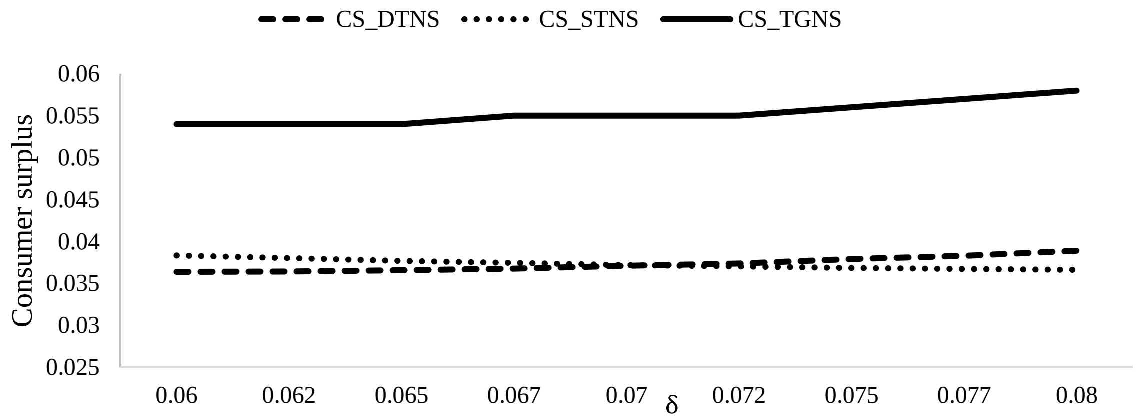

Figure 9. Impact of δ on the consumer surplus

Figure 9 states that the *TGNS* Model has a maximum consumer surplus among the five models; it is positively influenced by δ. Notably, three models (i.e., *DTNS*, *STS*, and *TGS*) have less consumer surplus while having maximum social welfare. Hence, models that are better for consumers may not necessarily be better for the government; there is a trade-off required based on prevailing scenarios.

6.2. Impact of vehicle environmental impact

In this section, we analyze how the environmental impact of a vehicle influences government policy decisions in terms of taxes and subsidies for different models. First, we examine the impact of i_g on the green tax of GVs for different models as shown in Figure 10. We consider δ as 0.07 to understand the influence of other parameters on the model outcomes.

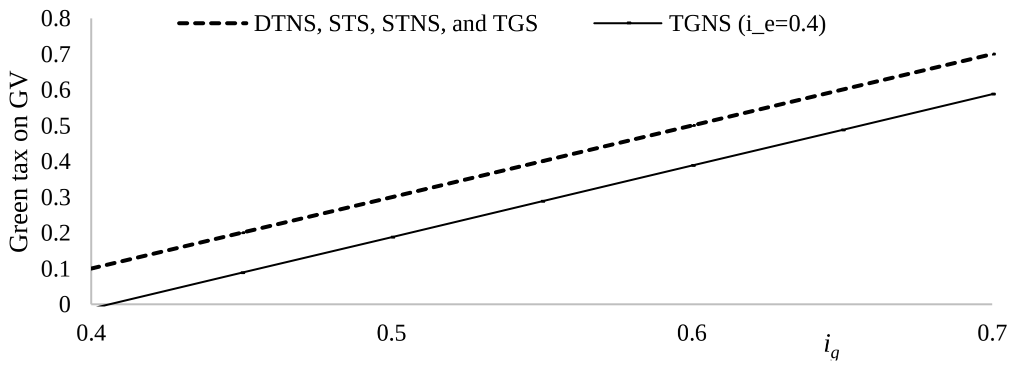

Figure 10. Impact of i_g on green tax (GVs) for different models

Figure 10 shows that four models (*DTNS*, *STS*, *STNS*, and *TGS*) are equally better-off in green taxes, and it increases with an increase in i_g. However, for model *TGNS*, the tax depends on both the environmental impact of EVs (i_e) and GV (i_g). We show variations with i_g by the x-axis and consider one level of i_e (i.e., 0.4) to understand its influence on the green tax of GVs. The figure indicates that green-tax, imposed on GV only and no subsidy provided to the manufacturer for EVs (model *TGNS*), attract less green tax on GV as compared to other scenarios and hence a recommended strategy for the manufacturers to produce GVs. Further, green tax on GVs increases with an increase in the environmental impact of GVs (i_g), and hence indirectly, it also impels the manufacturer to lessen the environmental impact of GVs. In similar lines, we analyze green taxes for EVs, as shown in Figure 11.

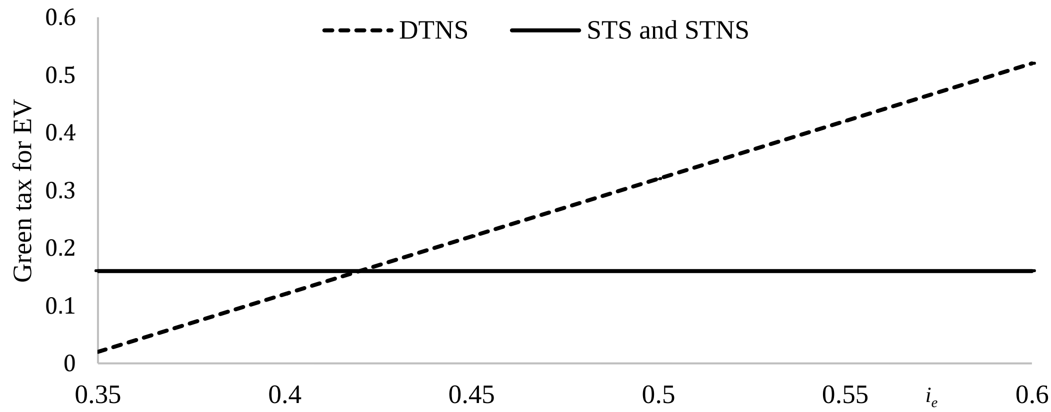

Figure 11. Impact of i_e on green tax for EV in different models

Figure 11 signifies that levying the same taxes on both types of vehicles, either in the presence or absence of manufacturer subsidy, is dependent only on i_g and is independent of i_e. Hence, for these two scenarios, the manufacturer's strategy is to focus on the GV environmental impact only, not EVs, to minimize the tax burden for the consumers. Counterintuitively, for model *DTNS*, the higher environmental impact of EVs is liable for more green taxes for the vehicles, whereas, for a lower value of i_e, model *DTNS* is preferable due to less green tax for EV consumers. Hence this cut-point is important for manufacturers to understand the green-tax burden for EV consumers and device policies accordingly. The importance of environmental impact is very crucial for designing an effective policy for EV adoption. Along similar lines, the European Commission set a target of a 15% reduction in CO_2 emissions by 2025 and a 30% reduction by 2030 (IEA, 2019).

6.3. Impact of cost-coefficient

The higher upfront cost is a major hurdle for EV adoption, as acknowledged in multiple studies (Chakraborty et al., 2021). Thus, it is imperative to understand how the higher cost of EVs influences government policy decisions, especially green taxes. We mapped this cost coefficient through parameter 'κ' and indicated that higher κ means more the cost of EVs. Figure 12 illustrates the green tax variations for EV and GV under the influence of varying κ for different models.

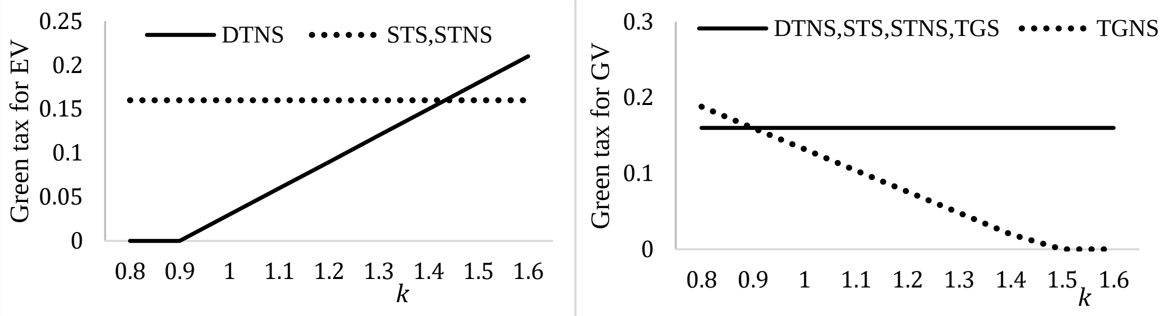

Figure 12. Impact of k on green taxes for different models

The higher κ leads to more taxes on EVs in the *DTNS* Model, which implies less adoption of EV in this case. Hence, the manufacturer needs to maintain κ closer to 0.9 to minimize tax on EVs. Counterintuitively, Models *STS* and *STNS* are independent of cost-coefficient 'κ', indicating that the cost of EVs has no influence on these two models' green tax estimations. Thus, in line with existing scenarios, where $\kappa > 1$ in most of the countries (IEA, 2019), it is preferable to follow *STS* and *STNS* Models to minimize the taxes on EVs. Additionally, it is important to mention here that model *TGNS* and *TGS* have no green tax for EV because these two models don't support any tax for EV.

Further, higher κ has no influence on the GV green tax of *DTNS*, *STS*, *STNS*, and *TGS* Models. It indicates that EV cost has no influence on the GV tax structure of these four models (*DTNS*, *STS*, *STNS*, and *TGS*). Counterintuitively, a higher EV price (i.e., higher κ) leads to lowering the green taxes on GV for Model *TGNS*. This is mainly attributed to the higher κ, which leads to less adoption of EVs, and hence most of the consumers would buy GVs only even though the green tax is imposed on GVs. According to a survey report by McKinsey, EVs often cost $12,000 more to produce than the GVs, increasing the production costs significantly and thus the final market price[8], leading to reduced sales. Consequently, to optimize social welfare, the government has to lower the green tax on the GVs for higher κ values.

6.4. Impact on social welfare

Lastly, we examine how various EV-related factors influence the government′s decisions of maximizing social welfare. Till now, we have done sensitivity analysis with various exogenous parameters like per unit-environmental impact of vehicles, consumers' low carbon awareness, and cost-coefficient. However, the influence of these exogenous variables on social welfare is yet to be explored. Three models, namely *DTNS*, *STS*, and *TGS*, maximize social welfare as compared to the other remaining models. Thus, we illustrate the social welfare curve of these three models (i.e., same SW, referring to proposition 5) under the influence of the environmental impact of GVs and EVs in Figure 13.

[8] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/making-electric-vehicles-profitable [accessed 08 September 2021].

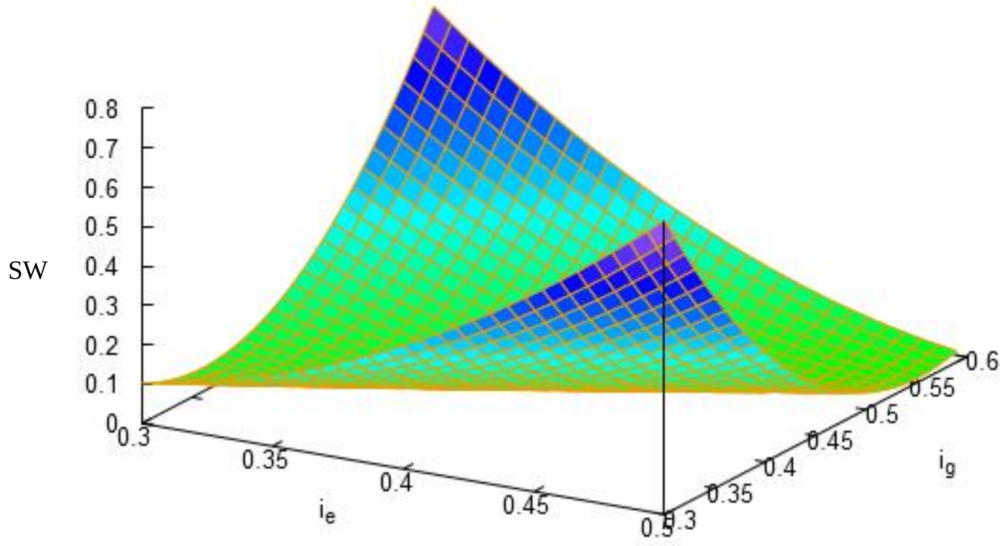

Figure 13. Impact of i_e and i_g simultaneously on social welfare

Figure 13 shows that social welfare maximizes for these three models (i.e., *DTNS*, *STS*, and *TGS*) in lower range values of i_e and mid-range values of i_g. Ironically, an increase in i_e can also improve the social welfare provided i_g must be in the lower range values. However, for higher range values of i_e, an increase in i_g reduces the social welfare. Hence, the government needs to align their taxes and subsidies to maintain i_e in the lower range and i_g may be in the mid-range to maximize the SW.

Further, we examine how SW varies with changes in the δ and κ for the best models from a societal point of view (i.e., *DTNS*, *STS,* and *TGS*), as shown in Figure 14. The SW is maximum in the lower range of κ because taxes on EVs are minimum in this range, leading to higher adoption of EVs and subsequently higher social welfare. Further, an increase in κ leads to a decrease in social welfare, which then increases slightly at a higher range of κ because of reduced GV taxes. This leads to more demand for GVs and thereby increases social welfare slightly. Additionally, in this range, a high cost of EVs and lower δ also lead to an increase in the demand for GVs.

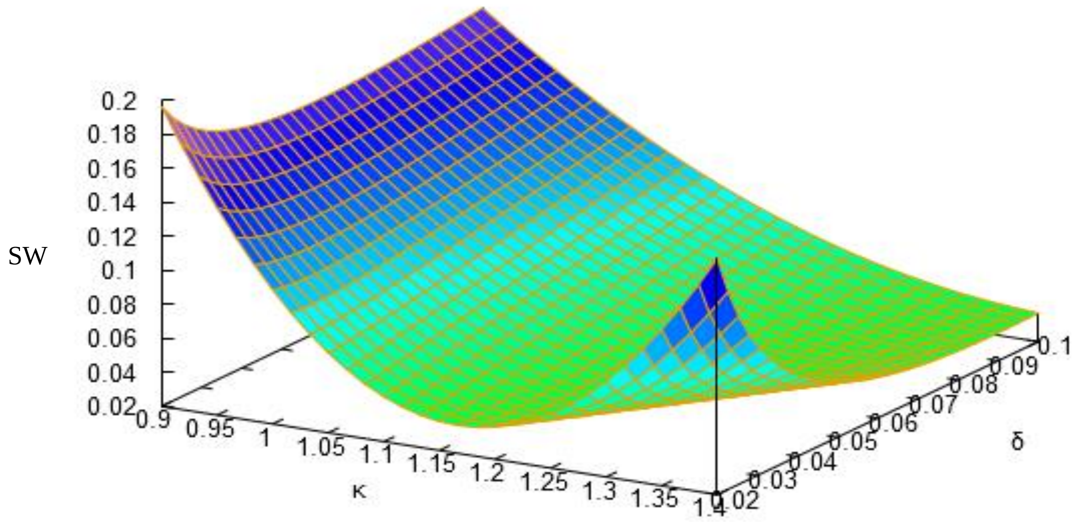

Figure 14. Impact of k and δ simultaneously on social welfare

7. Model Extensions

7.1. Impact of mandate on EVs sales

Recently, policymakers in China implemented the New Energy Vehicles (NEV) mandate, which phases out the subsidies and imposes a mandate on vehicle manufacturers. According to the new mandate, a certain parentage of all vehicles sold by the manufacturer must be EVs[9]. Similarly, California's Zero-Emission Vehicle (ZEV) mandate imposes a requirement to produce the necessary percentage of EVs for the manufacturers[10]. Therefore, in this extension, we attempt to explore the impact of the mandate on EVs sales, profitability, and social welfare.

Let ϕ be the faction of vehicles produced which must be battery operated and $(1-\phi)$ is the fraction of GVs produced by the manufacturer. Thus, the manufacturer's profit function can be written as: $max_{p_e,p_g}\,\pi_m = \phi(p_e-\kappa c)q_e + (1-\phi)(p_g-c)\,q_g$. We analyse the model and present our results in Proposition 7.1(a), which is shown in Online Appendix.

We find that with the mandate policy and no subsidy for the manufacturer, the sales of EVs drop due to the rise in the price of EVs. Thus, the manufacturer suffers in terms of profit loss and declining sales. The effect becomes more severe with an increase in ϕ and the elimination of incentives. Comparison of results with other models shows that the consumer surplus also reduces with the implementation of the mandate without any incentive. Findings partially explain why in China, total

[9]https://news.mit.edu/2021/chinas-transition-electric-vehicles 0429#:~:text=As%20a%20result%2C%20China's%20policymakers,year%20must%20be%20battery%2Dpowered [accessed 08 July 2021].
[10]https://www.transportpolicy.net/standard/californiazev/#:~:text=The%20California%20Zero%20Emission%20Vehicle,and%20plug-in%20hybrid [accessed 14 July 2021].

sales of EVs drop in the year 2021 after elimination of subsidy and implementation of the mandate, leading to price rise[11].

7.2. Impact of hassle cost on EV adoption

In emerging countries, one of the key concerns for the slow adoption of EVs is the scarcity of required infrastructure (e.g., charging stations or maintenance facilities)[12]. Thus, if a consumer decides to purchase an EV has to incur a hassle cost. In literature, the concept of hassle cost has been studied from different perspectives, including omnichannel retail operations (buy online versus pick-up-in store) (Gao and Su, 2017) and product return (moneyback guarantee versus hassle-free policy) (Hsiao and Chen, 2014, 2012). Following Gao and Su (2017), we derive the utility function for a consumer who chooses to buy an EV and incurs a hassle cost as h_e as $U_e = (1 + \delta)\theta - p_e - h_e - T_e$.

Analysis results show that the inclusion of hassle cost in the model does not alter the main results, and Model DTNS, STS, and TGS are still optimal and result in the same profit and income levels for the manufacturer and the social planner. However, the adoption rate, overall sales of EVs, profitability, and social welfare decrease significantly. The impact is more severe for the models with no subsidy and the same taxes on EVs and GVs. Therefore, consideration of hassle cost dilutes the effect of incentives in terms of taxation and subsidies.

8. Conclusion

There has been a mounting concern to reduce global GHG emissions; thus, governments in many countries are taking that added effort to facilitate faster penetration of EVs. Hence, it is imperative to understand EV adoption dynamics and modeling our paper more specific to EV-GV market. We analyse the choices not just at a firm level but also at the government and consumer level. Further, modelling the per unit environmental impact of both EVs and GVs is another unique point, which are directly linked with automobile market. The government policies can be directly linked with environmental impact of both types of vehicles, which are already in use in few countries like France, few provinces of China (IEA, 2021). Apart from modelling abovementioned specific EV-GV market scenarios, we have also explored prevailing subsidy and differentiated taxes regime, which are much more specific in nature. Only a very small subset of differentiated products would fall in this bracket (for example, solar panels in some countries). An additional important factor that we have incorporated is single homing, that is a consumer buys only one type of product (note that this would not necessarily hold for products

[11] https://news.mit.edu/2021/chinas-transition-electric-vehicles 0429#:~:text=As%20a%20result%2C%20China's%20policymakers,year%20must%20be%20battery%2Dpowered [accessed 08 July 2021].

[12] https://www.forbes.com/sites/daneberhart/2020/11/05/if-you-build-it-challenges-facing-electric-vehicle-infrastructure/?sh=226bf12c6dd0 [accessed 10 July 2021]

like solar panels). Combining all these features, our study become quite unique and yet impactful tailored to the electric mobility.

In this paper, we have analyzed the role of taxation and subsidy policies based on EV adoption to create a viable EV ecosystem. We considered three key stakeholders, i.e., the automobile manufacturer selling both EVs and GVs, the government, and consumers. The government decides the optimal level of taxes and subsidies to maximize social welfare, consisting of consumer surplus, producer profit, revenue loss/gain, and total environmental impact. Our analysis states that the government can use any three out of five scenarios to maximize social welfare. Additionally, a comparative study among these five models generates multifaceted insights for both governments and manufacturers. We also illustrate how the environmental impact of these vehicles, consumers' low-carbon awareness, and price differential factors actually influence the government and manufacturers' decisions and optimal policy decisions.

8.1. Policy and managerial implications

We highlight the managerial and policy implications for each model as follows:

8.1.1 Model STNS

For countries like Poland, where EVs and GVs are equally green taxed, and no subsidies are offered for the EV manufacturer, our results show that the green tax will depend solely on the per-unit environmental impact of GVs, and will be independent of the environmental impact of EVs. Companies would invest their resources in research and development to curtail the environmental impact of GVs rather than innovating on EVs to minimize their green tax on vehicles. Under this setting, the manufacturing companies are oriented to further improve the 'green efficiency' and effectiveness of GVs, as they influence consumer decisions and incentivize them from not switching to competing brands. Other than consumers who are intrinsically motivated (e.g., strong green orientation, ardent sustainability follower) to use EV, there is no incentive to adopt EV or dis-incentive not to adopt GV. Hence, this model shows that charging equal tax for both EVs and GVs (without subsidy for EV) is as good as not imposing any tax; neither of them transitioned the consumers from GV to EV. Therefore, having no specific policy for stimulating EVs demand in terms of green taxes or providing subsidies can be a successful model in countries where consumers are well aware, intrinsically motivated, and have a well-developed infrastructure for the use of EVs (e.g., Poland). For instance, Poland is experiencing continuous growth in EVs sales (e.g., nearly 10,000 EV cars were registered in the year 2020 compared to 290 cars in the year 2015[13]). On the other hand, in developing countries like India,

[13] https://www.statista.com/statistics/1081299/poland-number-of-electric-passenger-vehicles/.[accessed 13 September 2021]

sales of EVs are declining (irrespective of policy interventions in terms of reduced taxes and offering subsidies[14]) due to unawareness, lack of charging infrastructure, and lower per capita income.

8.1.2 Model STS

The upfront price of EVs for consumers decreases on offering subsidies to the manufacturers of EVs while levying the same green tax for both the EV and GV consumers. Lower the environmental impact of EV, higher is the subsidy offered to manufacturers of EV, and lower is the green tax imposed on EV consumers. The demand for EVs increases, and GV decreases for further increase in subsidy (Breetz and Salon, 2018), thereby facilitating quicker EV adoption. These findings partially support the policy interventions followed by countries like China. However, China has planned to eliminate the subsidy policy for EVs by 2020, which is now extended till 2022 due to a pandemic. Additionally, China has implemented a New Energy Vehicle dual credit system and provided 10-12% EV credits in the year 2019-2020 and planning to offer 14-18% credits in the year 2021-2023[15].

8.1.3 Model DTNS

When the government imposes a different green tax for EVs and GVs and offers no subsidies to EVs, the optimal price for EVs and GVs increases more for EVs when the price differential factor increases. Government policies could thereby consider compensating the price differential factor's impact on EVs by imposing a relatively lower tax on EVs as compared to GVs (Chakraborty et al., 2021) for its lower environmental impact. This possibly would facilitate an increase in EV adoption by stopping price-sensitive consumers from buying GVs as compared to EVs, which effectively pulls down the demand for EVs within the same market. In developing countries like India, where the price is a key driver for the consumers' purchase decision of EVs, the tax incentives can help in faster EV adoption. However, governments should also focus on developing charging infrastructure (India is providing subsidies for building charging stations, Kumar et al. 2021), educating customers, etc.

8.1.4 Model TGNS

For countries like Norway and Sweden, where green tax is imposed only for GV, and no tax or subsidy is provided for EVs, the demand for EVs can be expected to increase, and demand for GVs would consequently decrease. This outcome is subject to confirmation that the price difference between EV and GV is much lesser. Hence, when the government plans to increase EV adoption by only imposing a tax on GV, it has to ensure by involving manufacturers that the price difference between EV and GV is much lesser than the tax imposed on GVs.

[14] https://www.autocarindia.com/car-news/smev-cumulative-ev-sales-down-1941-percent-in-fy2021-420595 [accessed 13 September 2021]

[15] https://www.iea.org/reports/global-ev-outlook-2021/policies-to-promote-electric-vehicle-deployment. [accessed 13 September 2021]

8.1.5 Model TGS

On offering subsidies to manufacturers of EVs with green tax only imposed on GVs, the optimal price for EVs decreases. An increase in the green tax reduces the price of GVs. The government should levy higher green taxes for polluting GVs, and provide more subsidies for environmentally friendly EVs. Manufacturers should curtail the environmental impact of GVs and EVs to minimize green tax and maximize subsidy on vehicles. In comparison to other scenarios discussed, governments could also increase EV sales significantly in this scenario by working out subsidies for EVs and green tax for GVs. These findings partially support the mixed policy interventions followed by countries like China and Norway.

8.2. Future research

There are important avenues in this domain that future research can explore. For instance, dynamic decision-making in such scenarios could lead to different policy requirements for each period based on resource availability and constraints. Another direction of research may include consideration of the asymmetric cost information between government and manufacturers under a dynamic environment. One could possibly explore other constraints of EV diffusion like charging infrastructure, range anxiety, reoccurring financial benefits and model them in existing scenarios.

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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