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An Evolutionary Game Model for EV and Charging Station Adoption

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ABSTRACT

Electric vehicles and charging stations are pivotal tools in the endeavor to decarbonise the transportation system. The connection between the adoption of electric vehicles and the deployment of charging stations is widely recognised as a "chicken-and-egg" dilemma. This term describes a situation where the low adoption of electric vehicles impedes the installation of charging stations, and conversely, the limited availability of charging stations dampens drivers' enthusiasm to switch to electric vehicles. To gain insights into this intricate relationship between consumers' choices regarding electric vehicles and infrastructure investors' decisions on charging station expansion, this study employs an evolutionary game model. This model not only captures the dynamic interactions involved but also considers the internal and external factors that influence these decisions. Leveraging this model, this paper analyses the impact of incentive policies on the adoption rates of electric vehicles and charging stations.

Keywords: Electric vehicle, charging station, evolutionary game

NONMENCLATURE

Abbreviations	
EV	Electric vehicle
GV	Gasoline vehicle
CS	Charging station
GS	Gasoline station
Symbols	
c_{ev},c_{gv}	Purchasing costs of EV and GV
L_{ev},L_{gv}	Service life of EV and GV
C_{c0},C_{g0}	Construction costs of CS and GS
C_{ci},C_{gi}	*Annual* construction costs of CS and GS
L_{cs},L_{gs}	Service life of charging and gas stations
m_{ev},m_{gv}	Average annual miles of EV and GV
r	Discount rate
e_{ev},e_{gv}	Energy and fuel consumption rates of EV and GV
C_{cm},C_{gm}	Annual management and maintenance costs
c_e,c_g	Price per unit of electricity and gasoline

1. INTRODUCTION

Electric vehicles (EVs) and charging stations (CSs) are recognised as critical components to decarbonise transportation systems. Advancements in battery and charging technologies and supportive policies from governments are driving the transition from the current high-emission transportation system, dominated by gasoline vehicles (GVs) and gas stations (GSs), to a low-emission system reliant on EVs and CSs. Remarkably, the EV market is experiencing exponential growth, with sales surpassing 10 million units in 2022 [1]. However, the development of EV CSs is comparatively slow. This lag results in an imbalance between the demand for and supply of charging services and amplifies drivers' range anxiety, which in turn discourages drivers from adopting EVs.

The development of charging station infrastructure poses novel research challenges in the fields of energy and transportation. These challenges encompass various aspects, including the selection of optimal sites for charging station deployment [2], the design of charging station capacities [3], and the formulation of effective charging and management strategies [4]. Notably, several studies delve into the interplay between EVs and CSs adoptions. For instance, in [5], authors investigate the dynamic impacts of government policies and consumer preferences on the diffusion of charging network within the context of a small-world network. The effects of both static and dynamic

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subsidies are simulated. Ref. [6] studies the effects of multiple incentives on CSs deployment based on evolutionary analysis in complex network. In [7], an evolutionary game model of private charger installation from the perspective of the EV drivers and the property companies is built, and design incentive scheme to promote private charger installation. The existing literature on the relationship between policies and the adoptions of EVs and CSs offers valuable insights. However, a crucial knowledge gap persists, particularly in understanding how drivers interact with infrastructure investors in the presence of policy incentives. Filling this gap is necessary for promoting the decarbonisation of the transportation system. In this study, we aim to illustrate the dynamic interaction process between drivers and infrastructure investors, i.e., the interactive relationship between drivers' choices on EVs or GVs and infrastructure investors' investment decisions on CSs or GSs. This is captured by an evolutionary game framework. By modeling their payoff functions and constructing the evolutionary game model, the dynamic evolutionary processes of EV adoption and charging station deployment are revealed, and the impacts of incentive policies on EV and charging station deployment are analysed.

2. PROBLEM FORMULATION

2.1 Game description

The game contains two players: drivers and infrastructure investors. The infrastructure investors have two pure strategies: CSs or GSs. The drivers have two pure strategies: EVs or GVs. Let x represents the proportion of drivers that select EVs, while $1-x$ be the proportion of drivers that select GVs. Similarly, let y represent the proportion of investors who choose CSs, and $1-y$ is the proportion of consumers who choose the GSs.

2.2 Drivers' choice between EV and GV

The annual use cost of EV and GV are given by

$$\Psi_{ev}^{1} = U_d - p_e m_{ev} e_{ev} - (c_{ev} - S_1)\frac{r(1+r)^{L_{ev}}}{(1+r)^{L_{ev}}-1},$$
$$\Psi_{gv}^{1} = U_d - p_g m_{gv} e_{gv} - c_{gv}\frac{r(1+r)^{L_{gv}}}{(1+r)^{L_{gv}}-1},$$

where U_d represents the utility of buying a vehicle. p_e and p_g are the charging price ($/kWh) and refueling price ($/L). m_{ev} and m_{gv} represent the average annual miles of EV and GV, respectively. e_{ev} and e_{gv} represent the energy and fuel consumption rates of EV and GV, respectively. c_{ev} and c_{gv} are the purchasing cost of EV and GV, respectively. L_{ev} and L_{gv} are the service life of EV and GV, respectively. r is the discount rate. S_1 is the subsidy for EV purchasing provided by government.

2.3 Cost of infrastructure investor

The total cost of the stations includes construction cost, operation cost, and maintenance cost. The annual average construction costs of charging stations and gas stations are calculated using the life cycle method

$$C_{ci} = (C_{c0} - S_2)\frac{r(1+r)^{L_{cs}}}{(1+r)^{L_{cs}}-1},$$
$$C_{gi} = C_{g0}\frac{r(1+r)^{L_{gs}}}{(1+r)^{L_{gs}}-1},$$

where C_{c0} and C_{g0} are the initial construction costs of one CS and one GS, respectively. L_{cs} and L_{gs} refer to the assigned service life of charging and gas stations, respectively. The government can provide subsidy to the construction of CSs. The subsidy rate is S_2. The annual profit of the CS and GS can be calculated as

$$C_{co} = m_{ev} e_{ev}(p_e - c_e),$$
$$C_{gm} = m_{gv} e_{gv}(p_g - c_g),$$

where c_e and c_g refer to the purchasing price of electricity ($/kWh) and gasoline ($/L), respectively. Let C_{cm} and C_{gm} be the annual management and maintenance costs for CSs and GSs, respectively. The payoff function for infrastructure investor is represented by the net annual profit given by

$$\Phi_{cs}^{1} = C_{co} - C_{cm} - C_{ci},$$
$$\Phi_{gs}^{1} = C_{go} - C_{gm} - C_{gi}.$$

If one infrastructure investor chooses to build CS but the driver chooses EV, the driver's payment function is

$$\Psi_{ev}^{2} = -(c_{ev} - S_1)\frac{r(1+r)^{L_{ev}}}{(1+r)^{L_{ev}}-1},$$

and the infrastructure investor's payoff function is

$$\Phi_{gs}^{2} = -C_{gm} - C_{gi}.$$

On the contrary, If the infrastructure investor chooses to build CS but the driver chooses GV, the driver's payment function is

$$\Psi_{gv}^{2} = -c_{gv}\frac{r(1+r)^{L_{gv}}}{(1+r)^{L_{gv}}-1},$$

and the infrastructure investor's payoff function is

$$\Phi_{cs}^{2} = -C_{cm} - C_{ci}.$$

Payoff functions of drivers and infrastructure investors are summarised in Table 1.

Table 1 Game matrix.

		Infrastructure investor	
		CS(y)	GS(1-y)
Driver	EV(x)	Ψ_{ev}^1, Φ_{cs}^1	Ψ_{ev}^2, Φ_{gs}^2
	GV(1-x)	Ψ_{gv}^2, Φ_{cs}^2	Ψ_{gv}^1, Φ_{gs}^1

Denote the expected payoffs for drivers when choosing EV and GV are F_{ue} and F_{ug}, respectively. The expected payoffs when infrastructure investor choose CS and GS are F_{ic} and F_{ig}, respectively. The average expected payoff of drivers F_u and infrastructure investor $F_i$are calculated by

$$F_u = xF_{ue} + (1-x)F_{ug},$$
$$F_i = yF_{ic} + (1-y)F_{ig},$$

where

$$F_{ue} = y\Psi_{ev}^1 + (1-y)\Psi_{ev}^2,$$
$$F_{ug} = y\Psi_{gv}^2 + (1-y)\Psi_{gv}^1,$$
$$F_{ic} = x\Phi_{cs}^1 + (1-x)\Phi_{cs}^2,$$
$$F_{ig} = x\Phi_{gs}^2 + (1-x)\Phi_{gs}^1.$$

3. REPLICATOR DYNAMIC EQUATION

The basic principle of replicator dynamics (RD) can be summarised as follows: Within the bounded rational game group, the more stable strategy is gradually adopted by an increasing number of players, and the growth rate of players who choose this strategy equals the difference between the profit obtained when choosing this strategy and the average profit of the group [8]. The equation representing replicator dynamics is expressed as follows:

$$F(x) = \frac{dx}{dt} = \alpha x(u(x) - \bar{u}(x)),$$

where x is the proportion of players who choose a more stable strategy at time t. $u(x)$ and $\bar{u}(x)$ are the expected payoffs and the expected average payoffs obtained by the players, respectively. Here, we add a factor α that represents the sensitivity factor to the difference between the profit obtained when choosing this strategy and the average profit of the group. The RD equation of in this study is written as

$$\begin{cases} F(x) = \frac{dx}{dt} = \alpha x(F_{ue} - F_u), \\ F(y) = \frac{dy}{dt} = \alpha y(F_{ic} - F_i). \end{cases} \quad (1)$$

$$F(x) = \alpha x(1-x)\left(y\left(\Psi_{ev}^1 - \Psi_{gv}^2\right) + (1-y)\left(\Psi_{ev}^2 - \Psi_{gv}^1\right)\right),$$

$$F(y) = \alpha y(1-y)\left(x\left(\Phi_{cs}^1 - \Phi_{gs}^2\right) + (1-x)\left(\Phi_{cs}^2 - \Phi_{gs}^1\right)\right).$$

The equilibrium points of dynamic system (1) are (0,0), (1,0), (0,1), (1,1), and (x^*, y^*), where

$$x^* = \frac{\Phi_{cs}^2 - \Phi_{gs}^1}{\Phi_{cs}^2 - \Phi_{gs}^1 - \Phi_{cs}^1 + \Phi_{gs}^2},$$
$$y^* = \frac{\Psi_{ev}^2 - \Psi_{gv}^1}{\Psi_{ev}^2 - \Psi_{gv}^1 - \Psi_{ev}^1 + \Psi_{gv}^2}.$$

Next, we give the definition of evolutionarily stable strategy (ESS). It represents a stable strategy that cannot be successfully challenged by any alternative strategy in the population. Let $\pi(a, b)$ denotes the payoff obtained when playing strategy a against someone using the strategy b.

Definition: A strategy a is an ESS if and only if, for all other strategies $b \neq a$

1) $\pi(a|a) \geq \pi(b|a)$,
2) If $\pi(a|a) = \pi(b|a)$, then $\pi(a|b) > \pi(b|b)$.

The stability of equilibrium points can be determined though the Jacobian matrix approach.

Theorem 1: The equilibrium point (x, y) is an evolutionarily stable strategy if $det J|_{(x,y)} > 0$ andtr$J|_{(x,y)} < 0$.

The Jacobian matrix of the dynamic system is given by

$$J = \begin{pmatrix} \frac{\delta F(x)}{\delta x} & \frac{\delta F(x)}{\delta y} \\ \frac{\delta F(y)}{\delta x} & \frac{\delta F(y)}{\delta y} \end{pmatrix},$$

where

$$\frac{\delta F(x)}{\delta x} = \alpha(1-2x)\left(y\left(\Psi_{ev}^1 - \Psi_{gv}^2\right) + (1-y)\left(\Psi_{ev}^2 - \Psi_{gv}^1\right)\right),$$

$$\frac{\delta F(x)}{\delta y} = \alpha x(1-x)\left(\Psi_{ev}^1 - \Psi_{gv}^2 - \Psi_{ev}^2 + \Psi_{gv}^1\right),$$

$$\frac{\delta F(y)}{\delta x} = \alpha y(1-y)\left(\Phi_{cs}^1 - \Phi_{gs}^2 - \Phi_{cs}^2 + \Phi_{gs}^1\right),$$

$$\frac{\delta F(y)}{\delta y} = \alpha(1-2y)\left(x\left(\Phi_{cs}^1 - \Phi_{gs}^2\right) + (1-x)\left(\Phi_{cs}^2 - \Phi_{gs}^1\right)\right).$$

Theorem 1 can be used to determine whether the equilibrium point (x, y) is an evolutionarily stable strategy.

4. CASE STUDY

The construction costs of one CS and one GS are \$300,000 and \$260,000, respectively. The service life of both CSs and GSs are 10 years. The discount rate is 8%. The annual operation and maintenance costs of CSs and GSs are 5% of their construction cost, respectively. The prices of EVs and GVs are \$22000/vehicle and \$15000/vehicle, respectively. The grid electricity price and petrol price are 0.07 \$/kWh and 1.4 \$/L, respectively. The charging price is 0.21 \$/kWh and the refueling price is 1.72 \$/L. Both EVs and GVs have same annual operating mileage of 10,000 km. The electricity consumption of EVs is 0.2 kWh/km, and the gasoline consumption of GVs is 0.085 L/km. $\alpha = 0.0001$.

The results of stability analysis of equilibrium points is given in Table 2. We random generate 150 points ($0 \le x \le 1$, $0 \le y \le 1$), which represent different initial condition of the game model (1). The state trajectories with different initial conditions are shown in Figure 1. It can be observed from Table 2 and Figure 1 that both (0, 0) and (1, 1) are ESS. The equilibrium point (0, 0) signifies that all drivers opt for GVs, while all infrastructure investors select GSs. Conversely, the equilibrium point (1, 1) denotes that all drivers opt for EVs, and all infrastructure investors choose CSs. However, when the EV penetration rate and the number of CSs are both low, the system as a whole cannot spontaneously transition to a state with high EV adoption and CS availability. Therefore, incentives are required to facilitate and promote this transition.

Table 2 Stability of equilibrium points.

	Tr(J)	Det(J)	Stability
(0,0)	>0	<0	ESS
(0,1)	>0	>0	Unstable
(1,0)	>0	>0	Unstable
(1,1)	>0	<0	ESS
(x, y)	>0	>0	Unstable

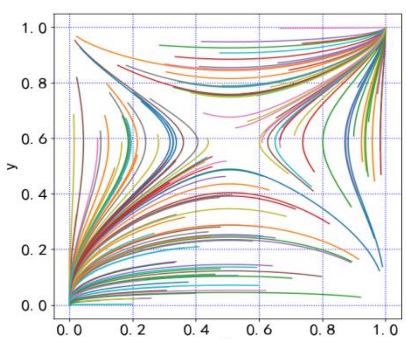

Fig. 1. State trajectories of system (1) under different initial conditions

Figures 2 and 3 exhibits the dynamics of x and y under different S_1 and S_2. Compared with GVs and GSs, EVs and CSs have higher initial investment costs that hinder their diffusion. The government needs to provide high incentives for their initial investment cost such that the current GVs and GSs based system can be transited to EVs and CSs.

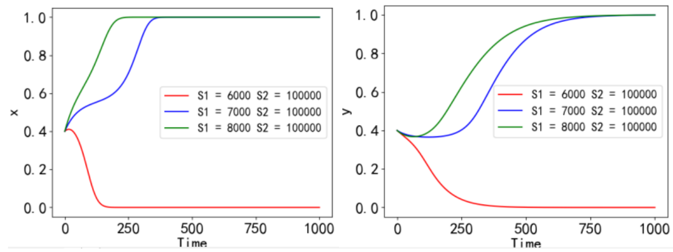

Fig. 2: dynamics of x and y with different S_1

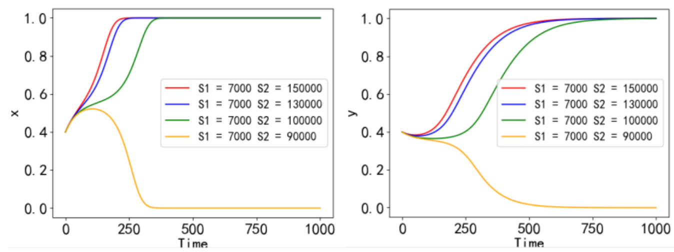

Fig. 3 dynamics of x and y with different S_2

5. CONCLUSIONS

In this study, we propose an evolutionary game model to capture the evolutionary dynamics of adoptions of EVs and CSs and explore the policy impacts on their diffusion. Future works include the model calibration, validation, and comparison with other models.

DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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