

ENVIRONMENTAL AWARENESS, SUBSIDIES AND TECHNOLOGICAL PROGRESS: EMISSION REDUCTION IN TRANSPORTATION FIRMS

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ABSTRACT. *This study develops a two-stage Cournot duopoly model in which the demand function is linear and influenced by firms' green goodwill. In the first stage, both firms decide whether to adopt emission abatement or not; in the second stage, they engage in quantity competition by simultaneously choosing output and green goodwill. The analysis reveals that the level of fixed green costs plays a pivotal role in the green transition of transportation firms, ultimately determining its success or failure. Moreover, we identify two potential pathways of green transition: either both firms adopt emission abatement, or the non-abating firm is eventually forced out of the market.*

Keywords: Environmental awareness, Green subsidies, Transportation firms, Carbon abatement, Green goodwill

1. Introduction. The urgency of addressing climate change has driven governments worldwide to implement policies aimed at reducing greenhouse gas (GHG) emissions, particularly carbon dioxide. The transportation sector plays a pivotal role in global GHG emissions and energy consumption, making its decarbonization a central element in tackling climate challenges. According to the International Energy Agency (IEA), the sector has been the world's largest energy consumer, with its GHG emissions nearly doubling between 1990 and 2019. As a critical component of China's national economy and a key area explicitly highlighted in the "new quality productive forces" policy, the green and low-carbon transition of the transportation industry is not only essential for fulfilling international climate commitments but also an inherent requirement for achieving high-quality development and building an efficient circulation system. China has integrated the "dual carbon" targets into its national macro-strategy, designating transportation and logistics as priority sectors in the *Action Plan for Carbon Peaking before 2030*.

We categorize the transportation sector into the following sub-sectors, each of which exhibits distinct characteristics and faces unique challenges in its green transition.

- 1) Road Transportation:** The promotion of new energy vehicles (NEVs) represents the most promising long-term pathway for emission reduction. China leads the world in the sales of zero-emission trucks (144,000 units in 2022) and the number of public

charging stations. Regarding technological trajectories, heavy-duty trucks are exploring multiple options, including battery-swapping electric vehicles and hydrogen fuel cell vehicles.

- 2) **Rail Transportation:** The low-carbon transition of the railway sector focuses on advancing electrification, increasing the share of electric locomotives in freight transport, and developing next-generation electric and new-energy locomotives.
- 3) **Shipping and Ports:** The shipping industry faces the daunting challenge of deep fuel decarbonization, with no single fuel demonstrating overwhelming advantages. Green methanol and green ammonia are considered feasible transitional fuels in the near term, as they offer relatively mature technologies and potential for large-scale production. However, limited supply capacity and high production costs remain significant constraints. As critical nodes in the maritime system, ports require electrification upgrades, including the construction of shore power facilities and the electrification of operational equipment. Nevertheless, the electrification of vertical handling equipment (e.g., quay cranes) encounters technological and practical barriers, with high costs and potential efficiency drawbacks compared to diesel-powered equipment.
- 4) **Air Transportation:** Aviation is one of the most challenging sub-sectors in transportation to decarbonize. Its primary pathway involves the expansion of sustainable aviation fuel (SAF) production and utilization, which serves as the main short-term strategy. However, SAF production falls far short of the 2030 decarbonization target (approximately 17.5 billion liters). In the long term, the industry is investing in the development of electric and hydrogen-powered aircraft, with small aircraft focusing primarily on electrification, while medium- and large-sized aircraft are expected to follow a diversified technological roadmap.

The green transition of transportation firms is not driven by a single force, but rather results from the combined effect of top-down governmental “push” policies and bottom-up market “pull” forces. Policy interventions are widely regarded as the primary driver of green transition in the transportation sector. Common policy instruments include carbon emission taxes, green subsidies, and public investment. Table 1 provides a comparative overview of these three policy instruments.

TABLE 1. Comparison of carbon taxes, green subsidies, and public investment

Policy instrument	Incentive mechanism	Advantages	Challenges
Carbon tax	Internalizes externalities by increasing the cost of emissions	Simple and direct; provides clear long-term price signals	May lead to industrial relocation and carbon leakage
Green subsidy	Promotes emission reduction by financially supporting green production	Accelerates green transition and supports emerging industries	Fiscal burden; potential for rent-seeking behavior
Public investment	Direct government investment in R&D and infrastructure	Promotes long-term technological progress and competitiveness	Sustainability of investment may be uncertain

Empirical and theoretical studies indicate that carbon taxes and green subsidies exert similar effects on firms’ green transition, despite their fundamentally different implications for government policy. For analytical tractability, this study focuses on green subsidies while abstracting from the direct effects of carbon taxes on transportation firms. This approach aligns with the recent trend in multiple countries, where governments have implemented various subsidy programs to encourage the purchase of new energy vehicles

by transportation enterprises. Moreover, our model incorporates public investment by the government to facilitate the societal green transition. Such investments not only reduce the variable green costs for transportation firms (e.g., the per-kilometer operating cost of electric vehicles relative to conventional vehicles) but also lower fixed green costs (e.g., government-funded public charging stations reduce the firms' need to build their own charging infrastructure).

Beyond policy-driven push factors, market forces generate significant endogenous pull for green transition. First, the growing demand from consumers and downstream clients for environmentally friendly services, reflecting heightened environmental awareness, directly incentivizes firms to adopt green practices. Second, Environmental, Social, and Governance (ESG) ratings have become a key metric for assessing corporate sustainability performance. Firms with strong ESG performance not only enhance brand reputation and attract more customers but also unlock new business opportunities. Finally, the green transition itself possesses substantial economic value. Studies indicate that by leveraging digital technology and innovation, logistics firms can optimize resource allocation, improve operational efficiency, and reduce costs, thereby generating tangible economic benefits.

For the sake of model simplicity, this study focuses on the aforementioned environmental awareness. We adopt the concept of *green goodwill* from André et al. [1] to measure the environmental content of services provided by transportation firms, which in turn influences consumer purchasing decisions. Laroche et al. [2] employ various statistical analyses to examine the demographic, psychological, and behavioral characteristics of consumers willing to pay a premium for environmentally friendly products, finding that an increasing number of consumers are willing to do so. Additional reports provide complementary evidence on green consumer behavior. For instance, in the United States, 51% of consumers are willing to pay higher prices for products with superior environmental quality, and 67% consider it essential to purchase environmentally beneficial products [3].

The modeling of consumer environmental awareness has a long tradition in the economics literature. For instance, Conrad [4] investigates the market implications of product differentiation when consumers take environmental attributes into account. García-Gallego and Georgantzís [5] study a vertically differentiated market in which conventional and green firms supply products with different environmental impacts, showing that environmental awareness campaigns may, paradoxically, reduce overall social welfare. Wen et al. [6] examine carbon abatement and pricing strategies in a duopoly setting with both emission trading schemes and consumer carbon awareness. Additional related studies can be found in [7, 8, 9, 10].

Recent studies on the transportation sector have increasingly emphasized carbon emission mitigation. For example, Wang et al. [11] review and synthesize recent methodological advances in dynamic traffic assignment models for environmentally sustainable road transportation, including traffic signal control strategies related to vehicle emissions and emission pricing mechanisms. Using panel data from 30 provincial-level regions in China spanning 2004-2019, Li et al. [12] empirically investigate the effects of public transportation development on carbon emission abatement and the associated transmission channels. Their results suggest that expanding the length of public transport networks and increasing the number of vehicles can significantly reduce carbon emissions. Despite this growing body of empirical and methodological research, theoretical analyses that employ game-theoretic frameworks to study the green transition of transportation firms remain relatively limited.

Krylatov and Zakharov [13] study competitive traffic flow allocation in green bus networks consisting of both green and non-green routes. They analyze the underlying competitive structure and propose a method for characterizing Nash equilibrium allocations

within the green subnetwork. Sheu [14] develops a reference-dependent Hotelling model to investigate airline competition in pricing and green transportation investment, as well as the associated financial performance under the EU Emissions Trading System. D'Alfonso et al. [15] formulate a duopoly model to examine the environmental effects of competition between high-speed rail and air transport, explicitly accounting for induced demand, service frequency, and high-speed rail speed.

By integrating data envelopment analysis (DEA) with a cooperative game framework, Omrani et al. [16] assess the energy efficiency of the transportation sector across 20 provinces in Iran. Chen et al. [17] examine the effects of government-mandated sustainable aviation fuel (SAF) policies on the heterogeneous strategic responses of full-service carriers (FSCs) and low-cost carriers (LCCs) competing within the same market. They develop a game-theoretic model that explicitly incorporates differences in service quality and cost structures, including fuel efficiency, between FSCs and LCCs. Sasahara et al. [18] introduce an incomplete-information “green” routing game to model strategic interactions among multiple logistics operators. In contrast to existing approaches, their model captures the trade-off between increased charging congestion delays arising from a higher penetration of electric vehicle (EV) trucks and higher pollution costs associated with continued internal combustion engine vehicle (ICEV) usage.

We consider a duopoly market in which the demand function is linear and influenced by firms' green goodwill. We develop a two-stage Cournot game¹: in the first stage, both firms decide whether to adopt emission abatement; in the second stage, they engage in quantity competition, simultaneously choosing output and green goodwill. Production costs are abstracted, and the cost difference between abating and non-abating firms arises from the green fixed and variable costs borne by abating firms. In addition, abating firms can receive green subsidies proportional to their emission abatement. The results indicate that the level of green fixed costs plays a pivotal role in the green transition of transportation firms, determining its success or failure. The managerial implication is that governments should assist willing firms in lowering their green fixed costs – through public investment or one-time subsidies – to facilitate societal green transition. Moreover, we identify two potential pathways for green transition: either both firms ultimately adopt emission abatement, or the non-abating firm is driven out of the market.

The structure of this paper is as follows. Section 2 develops a two-stage Cournot game incorporating firms' green goodwill and consumers' environmental awareness. Section 3 analyzes the equilibrium outcomes of the second stage under three possible scenarios. Section 4 examines the first-stage game, identifying four potential cases. Finally, Section 5 concludes the paper.

2. Model Setup. Consider a duopoly game in which two transportation firms (Firm 1 and Firm 2) provide transportation services. Let q_1 and q_2 denote the quantities of services (goods) supplied by the two firms, respectively, and let e_1 and e_2 represent the carbon emissions per unit of service provided by each firm.

The utility of the representative consumer depends not only on the quantities of services provided by the two firms but also on their respective levels of green goodwill. We define the green goodwill of firm i as

$$w_i = \frac{e_m - e_i}{e_m}, \quad (1)$$

where e_m denotes the maximum possible unit emission in the transportation industry (e.g., emissions per kilometer per kilogram of freight transported). The green goodwill w_i

¹This is a dynamic duopoly model, but it differs from oligopoly models that employ dynamical systems for modeling [19, 20, 21].

captures firm i 's effort to reduce carbon emissions during its operations. When $w_i = 1$, we have $e_i = 0$, meaning that firm i provides fully green transportation services, i.e., zero emissions. Conversely, when $w_i = 0$, we have $e_i = e_m$, implying that firm i 's emissions reach the maximum possible level in the industry. Based on the above construction, it follows that $w_i \in [0, 1]$.

To capture consumers' environmental awareness, we specify the representative consumer's utility function as

$$U_c = A(q_1 + q_2) - \frac{B}{2} (q_1^2 + q_2^2) - Cq_1q_2 + D(w_1q_1 + w_2q_2),$$

where $A, B, D > 0$, $C \geq 0$, and $B \geq C$. The above formulation follows Singh and Vives [22], who assume that the representative consumer's utility is quadratic in output and strictly concave in quantities, namely

$$U'_c = A(q_1 + q_2) - \frac{B}{2} (q_1^2 + q_2^2) - Cq_1q_2.$$

The parameter C reflects the degree of substitutability (or product differentiation) between the two goods. A larger C implies a higher degree of substitutability (i.e., lower product differentiation), whereas a smaller C indicates lower substitutability (i.e., greater product differentiation). In particular, when $C = B$, the two goods are perfect substitutes, while when $C = 0$, the two goods are independent.

Our utility function U_c incorporates consumers' preferences for firms' green goodwill. The parameter D measures the level of consumer environmental awareness, capturing the extent to which consumers value firms' efforts in reducing carbon emissions. Specifically, a higher D implies that consumers place greater importance on the environmental impact of carbon emissions. When $D = 0$, consumers are entirely indifferent to firms' green goodwill, and U_c reduces to the baseline utility function U'_c without green preferences.

Let p_1 and p_2 denote the service prices of the two transportation firms. The representative consumer determines the demand for each firm's service by maximizing consumer surplus, defined as

$$CS = U_c - (p_1q_1 + p_2q_2).$$

The first-order condition of this maximization problem is given by

$$\frac{\partial U_c}{\partial q_i} = A - Bq_i - Cq_{-i} + Dw_i - p_i = 0, \quad i = 1, 2.$$

It is worth noting that the second-order condition is always satisfied, since

$$\frac{\partial^2 U_c}{\partial q_i^2} = -B < 0, \quad i = 1, 2.$$

Consequently, the representative consumer determines the demand for the services provided by the two transportation firms through the following inverse demand functions:

$$p_i = A - Bq_i - Cq_{-i} + Dw_i, \quad i = 1, 2. \quad (2)$$

Moreover, we have $\frac{\partial p_i}{\partial w_i} = D$. This implies that, holding all else constant, an increase in w_i leads to a higher p_i when $D > 0$. In other words, consumers are willing to pay a higher price for transportation services offered by firms with greater green goodwill.

For the sake of analytical simplicity, we assume that the two transportation firms provide identical services, i.e., $B = C$. Furthermore, we normalize $A = B = C = 1$, so that the price function simplifies to

$$P(Q) = 1 - q_i - q_{-i} + Dw_i.$$

These simplifications allow us to focus on the impact of consumer environmental awareness on the outcomes of the game.

We assume that the government implements a green subsidy policy to promote the green transition of transportation firms, i.e., providing subsidies proportional to the firms' emission abatement. While it is difficult for the government to measure the exact reduction of each firm, we assume that it can reasonably estimate $e_m - e_i$, the difference between the maximum possible unit emission in the industry and the unit emission of firm i 's service. For example, in road transportation, this difference can be approximated based on the number of conventional and new energy vehicles owned by the firm.

Let S_i denote the subsidy per unit of emission abatement. Then the green subsidy received by firm i is given by

$$S_i(e_m - e_i)q_i = S_i e_m w_i q_i.$$

For notational simplicity, we define $s_i = S_i e_m$, which can be interpreted as the unit subsidy for fully clean transportation (zero emissions). Clearly, $s_i \geq 0$, so that the subsidy received by the exporting firm can be expressed as $s_i w_i q_i$. There is a rich literature on subsidy policies; see, e.g., [23, 24, 25].

Furthermore, we assume that the cost function of a non-abating firm is

$$C_i^N(q_i) = cq_i,$$

while the cost function of an abating firm is

$$C_i^A(q_i) = cq_i + rw_i^2 q_i + F,$$

where $c \geq 0$, $r > 0$, and $F \geq 0$. The term cq_i represents the production cost. To focus on the emission reduction aspect, we set $c = 0$ in the following analysis.

The cost function $C_i^A(q_i)$ captures two types of green costs: fixed and variable. The term $F \geq 0$ represents the firm's fixed green cost [26], and the plausibility of this assumption can be illustrated by numerous real-world examples. For instance, a non-abating firm that wishes to start reducing emissions must incur a one-time fixed cost to acquire the necessary equipment. Clearly, the government can reduce a firm's fixed green cost F through public investment.

The term $rw_i^2 q_i$ represents the variable green cost², which captures the additional cost required to achieve a green goodwill level w_i while providing q_i units of service using green technology. This cost varies with both w_i and q_i : it is linear in q_i (implying constant marginal cost with respect to quantity) and quadratic in w_i (implying increasing marginal cost with respect to green goodwill). It should be noted that r measures the level of variable cost that a firm must incur to provide green transportation. A lower value of r implies that firm i can achieve a given level of green goodwill w_i at a lower cost. Similarly, public investment by the government (e.g., funding green technology research at universities or research institutes) can reduce the variable cost level r for firms.

Consider a two-stage Cournot game (quantity competition). In the first stage, the two firms decide whether to adopt emission abatement (A) or not (N) based on expected profits. In the second stage, the firms engage in quantity competition in the market, simultaneously choosing output levels and green goodwill so as to maximize their respective profits. We analyze the game using backward induction.

3. The Second Stage. In this section, we examine in detail the three possible subgames that may arise in the second stage: (i) both firms choose not to abate, adjusting only output levels in response to competition; (ii) both firms choose to abate, determining

²For similar specifications of variable costs, see, e.g., [6, 27].

both their green goodwill and output levels so as to maximize firm profits; and (iii) only one firm abates while the other does not.

3.1. The case where both firms choose not to abate. If both firms choose not to abate, this is equivalent to setting their green goodwill levels to zero. Consequently, the profits of the two firms are given by

$$\Pi_1^N = (1 - q_1 - q_2)q_1, \quad \Pi_2^N = (1 - q_1 - q_2)q_2.$$

The first-order conditions for profit maximization are

$$\frac{\partial \Pi_1^N}{\partial q_1} = 1 - q_2 - 2q_1 = 0, \quad \frac{\partial \Pi_2^N}{\partial q_2} = 1 - q_1 - 2q_2 = 0,$$

while the second-order conditions always hold since

$$\frac{\partial^2 \Pi_1^N}{\partial q_1^2} = -2 < 0, \quad \frac{\partial^2 \Pi_2^N}{\partial q_2^2} = -2 < 0.$$

Hence, the profits of both firms are maximized at $q_1 = q_2 = 1/3$. In other words, if both firms choose not to abate, the Nash equilibrium of the second-stage game is

$$(\bar{q}_1^N, \bar{q}_2^N) = \left(\frac{1}{3}, \frac{1}{3}\right).$$

Further calculations show that at the Nash equilibrium $(\bar{q}_1^N, \bar{q}_2^N)$, the profits of the two firms are

$$\bar{\Pi}_1^N = \bar{\Pi}_2^N = \frac{1}{9}.$$

3.2. The case where both firms choose to abate. If both firms choose to abate, this implies $w_1, w_2 > 0$. In this case, the profits of the two firms are given by

$$\Pi_1^A = (1 - q_1 - q_2 + Dw_1)q_1 + sw_1q_1 - rw_1^2q_1 - F,$$

and

$$\Pi_2^A = (1 - q_1 - q_2 + Dw_2)q_2 + sw_2q_2 - rw_2^2q_2 - F.$$

Each firm i simultaneously chooses its green goodwill level w_i and output level q_i . For example, the first-order conditions for profit maximization of Firm 1 are

$$\frac{\partial \Pi_1^A}{\partial w_1} = (-2rw_1 + D + s)q_1 = 0, \quad \frac{\partial \Pi_1^A}{\partial q_1} = -rw_1^2 + Dw_1 + sw_1 - 2q_1 - q_2 + 1 = 0.$$

Similarly, the first-order conditions for Firm 2 are

$$\frac{\partial \Pi_2^A}{\partial w_2} = (-2rw_2 + D + s)q_2 = 0, \quad \frac{\partial \Pi_2^A}{\partial q_2} = -rw_2^2 + Dw_2 + sw_2 - 2q_2 - q_1 + 1 = 0.$$

Solving these first-order conditions yields

$$\bar{w}_1^A = \bar{w}_2^A = \frac{D + s}{2r}, \quad \bar{q}_1^A = \bar{q}_2^A = \frac{D^2 + 2Ds + s^2 + 4r}{12r}.$$

It can be verified that at $(\bar{w}_1^A, \bar{q}_1^A)$, the Hessian matrix of Firm 1's profit function is

$$H = \begin{bmatrix} -2r\bar{q}_1^A & -2r\bar{w}_1^A + D + s \\ -2r\bar{w}_1^A + D + s & -2 \end{bmatrix} = \begin{bmatrix} -2r\bar{q}_1^A & 0 \\ 0 & -2 \end{bmatrix}.$$

Since the leading principal minors of H satisfy $|H_1| = -2r\bar{q}_1^A < 0$ and $|H_2| = 4r\bar{q}_1^A > 0$, the matrix H is negative definite. Therefore, the equilibrium green goodwill $\bar{w}_1^A$ and output $\bar{q}_1^A$ indeed maximize Firm 1's profit. Similarly, it can be shown that at $(\bar{w}_2^A, \bar{q}_2^A)$, the corresponding Hessian is negative definite, ensuring that Firm 2's profit is also maximized.

Remark 3.1. According to the definition of w_i in (1), the equilibrium green goodwill satisfies $\bar{w}_i^A \in [0, 1]$. Therefore, the parameters must satisfy

$$\frac{D+s}{2r} \in [0, 1].$$

Since $D \geq 0$, $s \geq 0$, and $r > 0$, it follows that $\frac{D+s}{2r} \geq 0$ always holds. Accordingly, we refer to the set of parameters that satisfy the following conditions as feasible for this scenario:

$$D \geq 0, \quad s \geq 0, \quad r > 0, \quad F \geq 0, \quad \frac{D+s}{2r} \leq 1.$$

It is readily observed that an increase in either the consumers' environmental awareness D or the green subsidy rate s leads to higher equilibrium green goodwill for both firms, i.e., $\bar{w}_1^A$ and $\bar{w}_2^A$. The underlying mechanism is straightforward: a higher D raises the demand and price for services provided by firms with superior green reputation, thereby incentivizing emission reduction efforts; similarly, an increase in the green subsidy rate s enhances the profits of greener firms, encouraging environmentally friendly behavior. Moreover, reducing the parameter r through the development of green technologies also increases $\bar{w}_1^A$ and $\bar{w}_2^A$ (provided that D and s are not both zero), as it lowers the variable green costs and increases firms' green returns, further stimulating their willingness to adopt emission-reducing measures.

Regarding firms' output levels, we also find that an increase in consumers' environmental awareness D or the green subsidy rate s leads to higher equilibrium quantities, $\bar{q}_1^A$ and $\bar{q}_2^A$. Moreover, the expression for the equilibrium quantity can be rewritten as

$$\bar{q}_1^A = \bar{q}_2^A = \frac{\frac{D^2+2Ds+s^2}{r} + 4}{12},$$

which clearly indicates that a reduction in r also increases $\bar{q}_1^A$ and $\bar{q}_2^A$ (assuming D and s are not both zero). It can be observed that a firm's equilibrium green goodwill is positively correlated with its equilibrium profit, and parameter changes that enhance green goodwill simultaneously increase output. This relationship arises because, under the combined effects of consumers' environmental awareness D and the green subsidy rate s , higher green goodwill either raises the product price or increases the firm's subsidy income, thereby incentivizing higher output to capture greater profits.

Further calculations show that at the Nash equilibrium point $(\bar{w}_1^A, \bar{q}_1^A, \bar{w}_2^A, \bar{q}_2^A)$, the profits of the two firms are given by

$$\bar{\Pi}_1^A = \bar{\Pi}_2^A = \frac{(D^2 + 2Ds + s^2 + 4r)^2}{144r^2} - F.$$

It can be observed that the equilibrium profits of both firms increase with higher consumer environmental awareness D and higher green subsidy rate s , but decrease with higher fixed green cost F . Moreover, the above expression for the equilibrium profits can be rewritten as

$$\bar{\Pi}_1^A = \bar{\Pi}_2^A = \frac{\left(\frac{D^2+2Ds+s^2}{r} + 4\right)^2}{144} - F,$$

which implies that, ceteris paribus, the development of green technologies (i.e., a reduction in r) can also enhance the firms' green profits. These observations are consistent with intuition and provide clear managerial insights for corporate strategy and regulatory policy.

3.3. The asymmetric case. Consider the asymmetric case where the two firms choose different strategies. Suppose Firm 1 chooses not to reduce emissions while Firm 2 chooses

to adopt emission reduction. Their respective profits are given by

$$\Pi_1^{NA} = (1 - q_1 - q_2)q_1,$$

and

$$\Pi_2^{NA} = (1 - q_1 - q_2 + Dw_2)q_2 + sw_2q_2 - rw_2^2q_2 - F.$$

The first-order condition for Firm 1's profit maximization is

$$\frac{\partial \Pi_1^{NA}}{\partial q_1} = 1 - q_2 - 2q_1 = 0.$$

The first-order conditions for Firm 2's profit maximization are

$$\frac{\partial \Pi_2^{NA}}{\partial w_2} = (-2rw_2 + D + s)q_2 = 0, \quad \frac{\partial \Pi_2^{NA}}{\partial q_2} = -rw_2^2 + (D + s)w_2 - 2q_2 - q_1 + 1 = 0.$$

Obviously, q_1^{NA} maximizes Firm 1's profit because the second-order condition

$$\frac{\partial^2 \Pi_1^{NA}}{\partial q_1^2} = -2 < 0$$

always holds. Moreover, at $(\bar{w}_2^{NA}, \bar{q}_2^{NA})$, the Hessian matrix of Firm 2's profit is

$$J = \begin{bmatrix} -2r\bar{q}_2^{NA} & -2r\bar{w}_2^{NA} + D + s \\ -2r\bar{w}_2^{NA} + D + s & -2 \end{bmatrix} = \begin{bmatrix} -2r\bar{q}_2^{NA} & 0 \\ 0 & -2 \end{bmatrix}.$$

Since the leading principal minors satisfy $|J_1| = -2r\bar{q}_2^{NA} < 0$ and $|J_2| = 4r\bar{q}_2^{NA} > 0$, J is negative definite. Hence, the equilibrium green reputation $\bar{w}_2^{NA}$ and output $\bar{q}_2^{NA}$ indeed maximize Firm 2's profit.

Remark 3.2. For the asymmetric case considered in this subsection, we now examine the feasible parameter conditions. Similar to Remark 3.1, the equilibrium green reputation must satisfy $\bar{w}_2^{NA} \in [0, 1]$, which requires

$$\frac{D + s}{2r} \leq 1.$$

Moreover, since firms' outputs cannot be negative, i.e., $\bar{q}_1^{NA} \geq 0$, the feasible parameters must satisfy

$$\frac{4r - D^2 - 2Ds - s^2}{12r} \geq 0 \iff \frac{D + s}{2\sqrt{r}} \leq 1.$$

Hence, for the asymmetric case considered here, the feasible parameter conditions are

$$D \geq 0, \quad s \geq 0, \quad r > 0, \quad F \geq 0, \quad \frac{D + s}{2r} \leq 1, \quad \frac{D + s}{2\sqrt{r}} \leq 1.$$

Similarly to the symmetric case, an increase in consumer environmental awareness D , a higher green subsidy rate s , or the development of green technology (i.e., a reduction in r) leads to an increase in the equilibrium green reputation $\bar{w}_2^{NA}$ of the abating firm (Firm 2). Regarding output, it can be readily observed that in this asymmetric scenario, parameter changes affect the two firms differently: the output of Firm 2, $\bar{q}_2^{NA}$, increases with D or s , whereas the output of Firm 1, $\bar{q}_1^{NA}$, decreases. This occurs because, in an environment where consumers exhibit green preferences and the government provides green subsidies, an increase in D or s raises Firm 2's green reputation, thereby enhancing its per-unit profit and incentivizing higher production, while Firm 1 faces increased competitive pressure, resulting in a reduction of its output.

Moreover, in the asymmetric scenario, the two firms hold different market shares. Specifically, the market share of Firm 1 is given by

$$s_1 = \frac{\bar{q}_1^{NA}}{\bar{q}_1^{NA} + \bar{q}_2^{NA}} = \frac{4r - D^2 - 2Ds - s^2}{D^2 + 2Ds + s^2 + 8r},$$

while the market share of Firm 2 is

$$s_2 = 1 - s_1 = \frac{4r + 2D^2 + 4Ds + 2s^2}{D^2 + 2Ds + s^2 + 8r}.$$

It is evident that $s_1 \leq s_2$, indicating that the non-abating firm holds a smaller market share than the abating firm. This result is intuitive in the context of consumer environmental awareness and the presence of green subsidies. Moreover, we observe that increasing D or s , or reducing r , will further enhance the market share of the abating firm (Firm 2) while compressing the market share of the non-abating firm (Firm 1).

Further calculations show that, at the Nash equilibrium $(\bar{q}_1^{NA}, \bar{w}_2^{NA}, \bar{q}_2^{NA})$, the profits of the two firms are

$$\bar{\Pi}_1^{NA} = \frac{(4r - D^2 - 2Ds - s^2)^2}{144r^2}, \quad \bar{\Pi}_2^{NA} = \frac{(D^2 + 2Ds + s^2 + 2r)^2}{36r^2} - F.$$

It can be observed that increasing D or s , or decreasing r , raises the equilibrium profit of the abating firm (Firm 2) while reducing that of the non-abating firm (Firm 1), which is consistent with intuitive expectations.

Furthermore, although the output and market share of Firm 2 are not affected by the fixed green cost F , its profit is reduced by this fixed cost. This is intuitive because, in the second stage of the game, once the firm has already chosen to abate (and incurred the fixed green cost), F does not influence its strategic decisions. However, the fixed green cost F plays a crucial role in the firms' strategic choices in the first stage of the game, which will be analyzed in detail in the next section.

4. The First Stage. We now turn to the analysis of the first stage of the game. The payoff matrix for the two firms under different abatement choices is presented in Table 2, where each firm can choose to abate (A) or not abate (N). In each cell of the matrix, the first entry denotes the payoff of Firm 1, while the second entry denotes the payoff of Firm 2. The abatement choices of Firm 2 are listed across the top of the matrix, and those of Firm 1 are listed along the left side.

TABLE 2. Payoff matrix of transportation firms

Firm 1 ↓ Firm 2 →	N	A
N	$\bar{\Pi}_1^N, \bar{\Pi}_2^N$	$\bar{\Pi}_1^{NA}, \bar{\Pi}_2^{NA}$
A	$\bar{\Pi}_1^{AN}, \bar{\Pi}_2^{AN}$	$\bar{\Pi}_1^A, \bar{\Pi}_2^A$

The expressions for $\bar{\Pi}_i^N$, $\bar{\Pi}_i^A$, and $\bar{\Pi}_i^{NA}$ for $i = 1, 2$ have been provided in the previous section. It is straightforward to see that

$$\bar{\Pi}_1^{AN} = \bar{\Pi}_2^{NA}, \quad \bar{\Pi}_2^{AN} = \bar{\Pi}_1^{NA}.$$

Hence, all entries in the payoff matrix presented in Table 2 are now explicitly determined. To analyze the possible outcomes of the game, we define

$$\begin{aligned} \Delta_1 &= \bar{\Pi}_1^{NA} - \bar{\Pi}_1^A = F - \frac{(D+s)^2}{9r}, \\ \Delta_2 &= \bar{\Pi}_1^{AN} - \bar{\Pi}_1^N = \frac{(D+s)^2(D^2 + 2Ds + s^2 + 4r)}{36r^2} - F, \\ \Delta_3 &= \bar{\Pi}_1^A - \bar{\Pi}_1^N = \frac{(D+s)^2(D^2 + 2Ds + s^2 + 8r)}{144r^2} - F. \end{aligned} \tag{3}$$

We can establish the following results.

Theorem 4.1. *Assume that $\Delta_i \neq 0$ for $i = 1, 2, 3$. Then, the first-stage duopoly game admits only the following four possible cases:*

- **C1:** $\Delta_1 < 0$, $\Delta_2 > 0$, and $\Delta_3 > 0$;
- **C2:** $\Delta_1 < 0$, $\Delta_2 > 0$, and $\Delta_3 < 0$;
- **C3:** $\Delta_1 > 0$, $\Delta_2 > 0$, and $\Delta_3 < 0$;
- **C4:** $\Delta_1 > 0$, $\Delta_2 < 0$, and $\Delta_3 < 0$.

Proof: It is straightforward to verify that

$$\Delta_2 - \Delta_3 = \frac{(D+s)^2(3D^2+6Ds+3s^2+8r)}{144r^2} \geq 0,$$

which implies that $\Delta_2 \geq \Delta_3$. In other words, it is impossible for $\Delta_2 < 0$ and $\Delta_3 > 0$ to hold simultaneously.

Moreover, we have

$$\Delta_1 + \Delta_2 = \frac{(D+s)^4}{36r^2} \geq 0,$$

which implies that $\Delta_1 < 0$ and $\Delta_2 < 0$ cannot hold simultaneously.

Therefore, only the following four cases are possible:

- $\Delta_1 < 0$, $\Delta_2 > 0$, and $\Delta_3 > 0$;
- $\Delta_1 < 0$, $\Delta_2 > 0$, and $\Delta_3 < 0$;
- $\Delta_1 > 0$, $\Delta_2 > 0$, and $\Delta_3 < 0$;
- $\Delta_1 > 0$, $\Delta_2 < 0$, and $\Delta_3 < 0$.

This completes the proof. $\square$

For case C1, we consider the parameter values $D = 69/128$, $s = 69/64$, $r = 21/16$, and $F = 35/512$ as an illustrative example. It is straightforward to verify that

$$\Delta_1 = -1097/7168 < 0, \quad \Delta_2 = 54120305/205520896 > 0, \quad \Delta_3 = 57474929/822083584 > 0.$$

Under these parameters, the first stage of the game constitutes a deadlock game, in which (A, A) is the unique Nash equilibrium and is Pareto-efficient. In other words, the incentives of self-interest and mutual benefit in choosing abatement are perfectly aligned.

For case C2, we select the parameter values $D = 69/128$, $s = 69/64$, $r = 21/16$, and $F = 23/128$. It can be verified that

$$\Delta_1 = -\frac{299}{7168} < 0, \quad \Delta_2 = \frac{31240049}{205520896} > 0, \quad \Delta_3 = -\frac{34046095}{822083584} < 0.$$

In this scenario, the first stage of the game constitutes a prisoner's dilemma, where (A, A) is the unique Nash equilibrium and is Pareto-inefficient. That is, the incentives of self-interest and mutual benefit in choosing abatement are in conflict.

For case C3, we select the parameter values $D = 69/128$, $s = 69/64$, $r = 21/16$, and $F = 141/512$ as an example. It can be verified that

$$\Delta_1 = \frac{387}{7168} > 0, \quad \Delta_2 = \frac{11571057}{205520896} > 0, \quad \Delta_3 = -\frac{112722063}{822083584} < 0.$$

In this scenario, the first stage of the game has two Nash equilibria: (A, N) and (N, A) . Both (A, N) and (N, A) are Pareto-efficient. This constitutes an asymmetric coordination game.

For case C4, we select the parameter values $D = 69/128$, $s = 69/64$, $r = 21/16$, and $F = 341/512$. It can be verified that

$$\Delta_1 = \frac{3187}{7168} > 0, \quad \Delta_2 = -\frac{68710543}{205520896} < 0, \quad \Delta_3 = -\frac{433848463}{822083584} < 0.$$

In this scenario, the first stage of the game is a deadlock game, in which (N, N) is the unique Nash equilibrium and is Pareto-efficient. That is, self-interest and the mutual benefit of choosing no abatement do not conflict.

The above analysis demonstrates that all four cases presented in Theorem 4.1 can occur within the feasible parameter region. Theorem 4.1 indicates that the outcomes of our model exhibit rich possibilities. As the parameter values vary, any of the four strategy profiles – (A, A) , (N, N) , (N, A) , and (A, N) – may emerge as a Nash equilibrium in the first stage.

The following two propositions consider the possible outcomes of the game under two extreme cases of the green fixed cost F , namely when F is sufficiently large or sufficiently small.

Proposition 4.1. *If F is sufficiently small, then $\Delta_1 < 0$, $\Delta_2 > 0$, and $\Delta_3 > 0$ must hold provided that D and s are not simultaneously zero. In this scenario, the unique Nash equilibrium (A, A) is Pareto-efficient.*

Proof: Suppose that D and s are not simultaneously zero. From (3), it is readily obtained that $\Delta_3 > 0$. Moreover, one can see that $\Delta_1 < 0$ and $\Delta_2 > 0$ if $F = 0$. The proof is completed. $\square$

Proposition 4.2. *Suppose that*

$$\frac{(D+s)^2}{9r} < 1, \quad \frac{(D+s)^2(D^2+2Ds+s^2+4r)}{36r^2} < 1, \quad \frac{(D+s)^2(D^2+2Ds+s^2+8r)}{144r^2} < 1.$$

If F is sufficiently large, then $\Delta_1 > 0$, $\Delta_2 < 0$, and $\Delta_3 < 0$ must hold. In this scenario, the unique Nash equilibrium (N, N) is Pareto-efficient.

Proof: Since $F < 1$ is prerequired, from $\frac{(D+s)^2}{9r} < 1$, we know $\Delta_1 > 0$ must hold for a sufficiently large value of F . Similarly, it can be derived that $\Delta_2 < 0$ and $\Delta_3 < 0$ must hold if F is sufficiently large. The proof is completed. $\square$

From Propositions 4.1 and 4.2, one can see that the fixed green cost F plays a crucial role in the green transformation of transportation firms. If the fixed green cost F is sufficiently large, both firms will choose not to abate. Conversely, if F is sufficiently small, both firms will choose abatement. This result implies that, to promote the green transition of transportation firms, the government can reduce firms' fixed green costs (e.g., by investing in public charging infrastructure or providing one-time subsidies).

Figures 1-3 present two-dimensional cross-sections of the parameter domain

$$\{(D, s, r, F) \mid D \geq 0, s \geq 0, r > 0, F \geq 0\}.$$

The black areas represent the unfeasible parameter regions, where either the firms' green reputation exceeds one (i.e., $\frac{D+s}{2r} > 1$) or the firms' output is negative (i.e., $\frac{D+s}{2\sqrt{r}} > 1$). The colored regions correspond to the feasible parameter regions. The parameter regions associated with the first-stage outcomes C1, C2, C3, and C4 are depicted in green, pink, yellow, and blue, respectively.

Figure 1 presents a cross-section of the parameter space with $D = 1$ and $s = 1$. It confirms the results of Propositions 4.1 and 4.2: if F is too large, the C4 scenario occurs, where both firms choose not to abate; if F is sufficiently small, the C1 scenario arises, where both firms choose to abate. This indicates that reducing the firms' fixed green cost level F has a strong incentive effect on their green transition. Similarly, reducing the firms' variable green cost r also promotes green transition. Moreover, the observations show that during the transition of the two firms from a deadlock game with (N, N) as the Nash equilibrium to one with (A, A) as the Nash equilibrium, the game may first

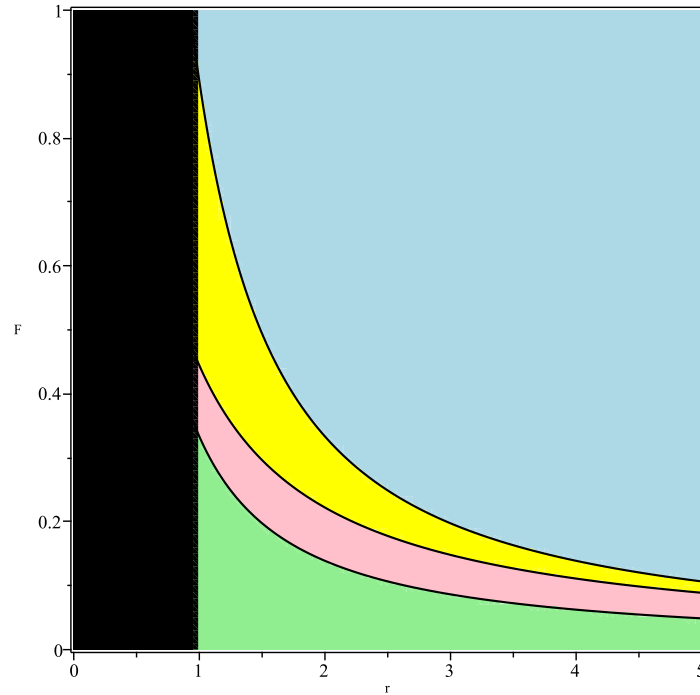


FIGURE 1. (color online) A cross-section of the parameter domain with $D = 1$ and $s = 1$

pass through a coordination game with multiple Nash equilibria (N, A) and (A, N) (i.e., the C3 scenario), and then through a prisoner's dilemma with (A, A) as the unique Nash equilibrium (i.e., the C2 scenario).

In coordination games with multiple equilibria, various criteria can be used to select the equilibrium that is more likely to occur. For instance, risk dominance tends to favor the equilibrium in which players incur smaller expected losses when the strategies of others are uncertain, whereas payoff dominance prefers the equilibrium that maximizes total payoff or social welfare. Additionally, dynamic modeling can be employed to capture evolutionary or learning processes, in which firms continuously adjust their strategies through repeated interactions and eventually converge to a stable equilibrium.

Figure 2 presents a cross-section of the parameter space with $F = 0.2$ and $r = 1$. The figure illustrates the impact of variations in consumer environmental awareness D and the green subsidy rate s on firms' abatement decisions. Overall, increasing D and s promotes the green transition of firms, shifting the competition from a deadlock game with (N, N) as the Nash equilibrium to a deadlock game with (A, A) as the Nash equilibrium. During this transition, the game may also sequentially pass through an asymmetric coordination game with multiple Nash equilibria (N, A) and (A, N) , followed by a prisoner's dilemma with (A, A) as the unique Nash equilibrium.

Figure 3 presents a cross-section of the parameter space with $F = 0.5$ and $r = 2$, where the black region represents the unfeasible parameter area in which the equilibrium output of the non-abating firm is negative in the asymmetric case. The figure illustrates another possible path of the green transition. As consumer environmental awareness D or the green subsidy rate s increases, the game outcome may start from a deadlock game with (N, N) as the unique Nash equilibrium (case C4, both firms choose no abatement), and transition to an asymmetric coordination game with multiple Nash equilibria (N, A) and (A, N) (case C3, one firm abates while the other does not). However, with a further increase in D or s , the equilibrium output of the non-abating firm falls to zero (reaching

the boundary between the yellow and black regions), indicating that the non-abating firm is eliminated from the market. In this scenario, only the abating firm remains in the market, thus achieving a social green transition.

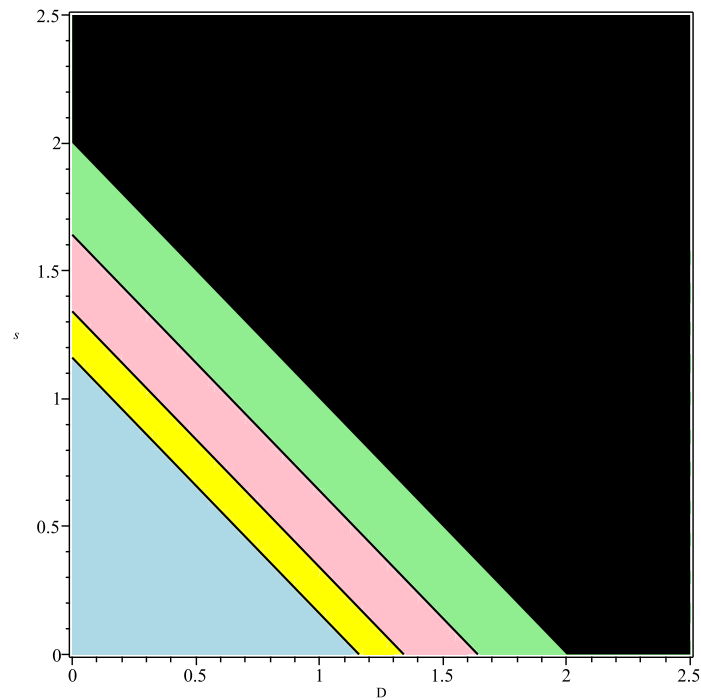


FIGURE 2. (color online) A cross-section of the parameter domain with $F = 0.2$ and $r = 1$

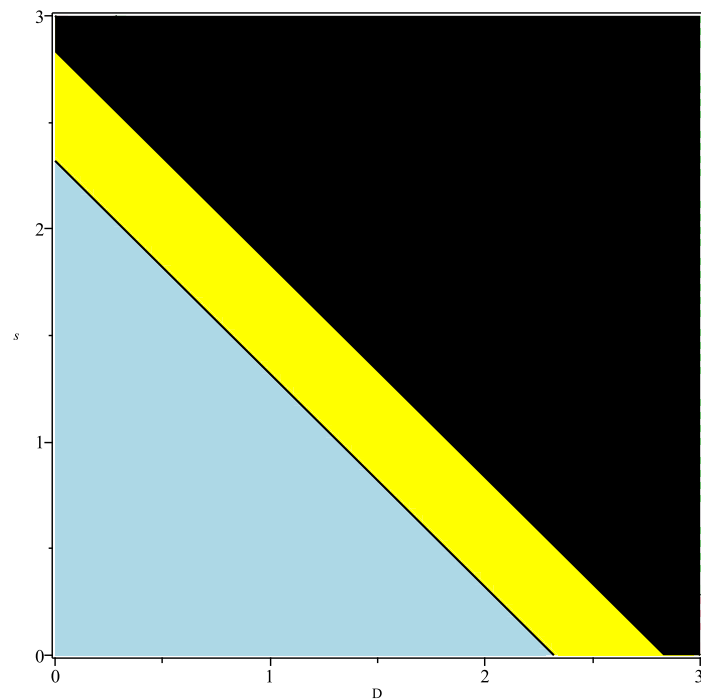


FIGURE 3. (color online) A cross-section of the parameter domain with $F = 0.5$ and $r = 2$

5. Concluding Remarks. This paper investigates the green transition of transportation firms through a two-stage Cournot game, with a primary focus on the impacts of environmental awareness, green subsidies, and technological progress. We consider a duopoly market where the demand function is linear but influenced by the firms' green reputations. The timeline of the game is as follows: in the first stage, the two firms choose whether to abate or not; in the second stage, they compete in quantities while simultaneously selecting both output and green reputation levels. Production costs are ignored, and the cost differences between abating and non-abating firms arise solely from the fixed and variable green costs incurred by abating firms. In addition, abating firms can receive green subsidies proportional to their emission abatement, whereas non-abating firms cannot.

This study employs backward induction to analyze the equilibrium outcomes of the model. In the second stage, we examine three possible subgames and derive the Nash equilibrium for each case. For the first stage, we partition the parameter domain and identify four possible scenarios. We demonstrate that the level of fixed green costs plays a critical role in the green transition of transportation firms, determining whether the transition succeeds or fails. The managerial implication is that the government should help firms with abatement intentions reduce their fixed green costs through public investments or one-time subsidies to promote a societal green transition. Furthermore, we identify two possible pathways for green transition: (i) the first stage evolves from a deadlock game with (N, N) as the unique Nash equilibrium to a deadlock game with (A, A) as the unique Nash equilibrium; (ii) the first stage initially transitions from a deadlock game with (N, N) as the unique Nash equilibrium to a coordination game with (N, A) and (A, N) as Nash equilibria, but ultimately, the non-abating firm is driven out of the market (its output falls to zero) in the broader wave of societal green transition.

In practice, many countries have incorporated carbon tax regulation into their green transition policies. However, this study focuses exclusively on firms' emission abatement decisions under a green subsidy scheme, which constitutes a limitation of the present analysis. Future research will extend the framework to examine firms' abatement choices under carbon tax regulation, with particular emphasis on identifying the optimal carbon tax that maximizes social welfare. Moreover, estimating and calibrating the model parameters using empirical data would be a valuable extension, which would yield a model that better reflects real-world conditions.

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