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From Turbulence to Sustainability: Green Technology Adoption in the Post-Shock Airline Industry

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Abstract:	This paper presents a theoretical model of product differentiation within an uncovered market, driven by growing consumer awareness of greenhouse gas emissions in the air transport sector. The model specifically evaluates the adoption of green technology, focusing on carbon-free hydrogen technology as an example. By integrating both horizontal and vertical differentiation, the study advances the existing theoretical framework to assess the strategic behavior of duopoly airlines in response to consumer valuation for environmentally friendly products. The findings reveal how these strategies and market coverage evolve as consumer preferences for higher quality, greener options strengthen. The analysis highlights the critical role of regulatory interventions, suggesting policy measures such as targeted subsidies and educational advertising to stimulate the adoption of green technologies. This research contributes to the literature by bridging Industrial Organization (IO) theory with industrial policy implications, offering insights into the design of policies that can enhance sustainable innovation and market resilience. The model demonstrates how IO methodologies can be applied to evaluate strategic responses and regulatory needs in industries facing significant environmental challenges.

Highlights

- Develops a model integrating vertical and horizontal differentiation for green technology.
- Analyzes the adoption of hydrogen technology in air transport under an uncovered market.
- Shows duopoly strategies evolve with increased consumer valuation for green products.
- Highlights the need for regulatory policies like subsidies and educational advertising.
- Provides IO-based policy insights for fostering sustainable innovation in aviation.

From Turbulence to Sustainability: Green Technology Adoption in the Post-Shock Airline Industry

October 31, 2024

Abstract

This paper presents a theoretical model of product differentiation within an uncovered market, driven by growing consumer awareness of greenhouse gas emissions in the air transport sector. The model specifically evaluates the adoption of green technology, focusing on carbon-free hydrogen technology as an example. By integrating both horizontal and vertical differentiation, the study advances the existing theoretical framework to assess the strategic behavior of duopoly airlines in response to consumer valuation for environmentally friendly products. The findings reveal how these strategies and market coverage evolve as consumer preferences for higher quality, greener options strengthen. The analysis highlights the critical role of regulatory interventions, suggesting policy measures such as targeted subsidies and educational advertising to stimulate the adoption of green technologies. This research contributes to the literature by bridging Industrial Organization (IO) theory with industrial policy implications, offering insights into the design of policies that can enhance sustainable innovation and market resilience. The model demonstrates how IO methodologies can be applied to evaluate strategic responses and regulatory needs in industries facing significant environmental challenges.

Keywords—Technology adoption; uncovered market; climate change; horizontal differentiation; Vertical differentiation; Policy implications.

1 Introduction

Climate change has become a critical concern globally, prompting both consumers and policymakers to reevaluate industries with significant greenhouse gas (GHG) emissions. The air transport industry, known for its substantial carbon footprint per flight, faces increasing pressure to reduce emissions. Movements such as "Flight Shame" have led to measurable declines in air travel demand, reflecting a significant shift in consumer behavior due to environmental awareness. For instance, Sweden experienced a 4% drop in air traffic in 2019.[1] This decline not only affects airline revenues but also has broader economic implications, including potential job losses and reduced economic activity associated with air travel.

The urgency of addressing climate change is underscored by international agreements like the Paris Agreement, which emphasize the critical role of sectors like aviation in achieving emission reduction targets. In response to these challenges, the adoption of green technologies—specifically carbon-free hydrogen technology—has emerged as a potential solution in the air transport sector. Hydrogen, the most abundant chemical element on our planet, offers a sustainable energy source that strengthens energy security and provides pathways to decarbonize long-haul transport. When produced using renewable energy sources, hydrogen can be a carbon-free fuel, significantly reducing the environmental impact of aviation.

However, the adoption of such green technology presents significant barriers due to high fixed and variable costs associated with new infrastructure, equipment, and the higher cost of sustainable fuels compared to current technologies.[2] Fuel constitutes a significant portion of airlines' operating costs, accounting for about 40% to 50% of air operating costs and 17.7% of the total operating cost of a single flight.[3] Without regulatory intervention or incentives, airlines may be reluctant to adopt green technology despite consumer demand.

Understanding consumer reactions is crucial, as consumer valuation of green flights becomes a determining factor for adoption. Consumers may derive utility not only from the functional aspects of green technology but also from moral satisfaction associated with making environmentally friendly choices. This introduces the concept of *relative moral sentiment*, where consumers' moral

[1] Statistics from the Swedish Transport Agency, 2019.

[2] In July 2022, the cost of electrolytic hydrogen from renewable energy reached as high as $16.80 per kilogram, while the price of jet fuel in the US was around $1.23 per kilogram ($146.17 per barrel). See `https://www.utilitydive.com/news/green-hydrogen-prices-global-report/627776/`, `https://www.airportwatch.org.uk/iata-jet-fuel-price-monitor-information/`. It is important to note that these figures are illustrative and not directly comparable without considering factors such as combustion efficiency.

[3] See *The Geography of Transport Systems*, "Consumer Airlines Operating Costs, United States, 2019", `https://transportgeography.org/contents/chapter5/air-transport/airline-operating-costs/`.

satisfaction is influenced by their own choices relative to others.

Despite extensive research on consumer behavior and green technology adoption, there is a noticeable gap in the literature concerning the theoretical modeling of green technology introduction in the airline industry using both horizontal and vertical differentiation within an uncovered market. Existing models often consider either horizontal or vertical differentiation in isolation and typically assume fully covered markets. Moreover, the influence of consumer moral sentiments—particularly relative moral sentiments—on firms' strategic decisions has not been thoroughly examined.

This paper fills these gaps by proposing a novel theoretical framework that integrates vertical differentiation into a horizontal differentiation model within an uncovered market setting. By introducing the concept of relative moral sentiment, we capture the nuanced ways in which consumer morality influences purchasing decisions and market outcomes.

Our analysis contributes to the industrial organization (IO) literature in several ways:

1. **Extension of the Model**: We extend traditional differentiation models by integrating vertical differentiation into a horizontal differentiation framework within an uncovered market. This allows us to capture the complex interplay between consumer preferences, firm strategies, and market dynamics when new green technologies are introduced.

2. **Counterintuitive Policy Implications**: We reveal counterintuitive policy implications regarding the adoption of green technology. Specifically, our findings suggest that certain policies that might seem beneficial could have unintended consequences on market outcomes and social welfare.

3. **Concept of Relative Moral Sentiment**: We propose and model the concept of *relative moral sentiment*, reflecting the idea that consumers derive moral satisfaction not only from their own consumption choices but also relative to others. This enriches the understanding of consumer behavior in markets where moral and social considerations influence purchasing decisions.

Our main findings indicate that without appropriate industrial policies, the higher costs of green technology hinder its adoption despite a segment of consumers valuing environmental benefits. Government interventions such as subsidies and educational campaigns are crucial in overcoming these barriers, leading to wider adoption of green technology and improved market outcomes.

The rest of the paper is organized as follows. Section 3 presents the theoretical model. Section 4 discusses the policy implications of our findings, offering recommendations for effective industrial policy design. Finally, Section 5 concludes with insights on the role of industrial policy in promoting sustainable innovation within the airline industry.

2 Literature Review

Understanding consumer behavior and the adoption of green technology is crucial for modeling market dynamics in the airline industry. Environmentally conscious consumers prioritize the service quality of greener airlines, as evidenced by Laroche et al. (2001). There is a growing trend of environmental awareness in the leisure air transport market (Bonini and Oppenheim, 2008). Focus group studies in the Netherlands and the U.K. reveal associations of hydrogen with terms like "clean", "environmentally friendly", "fewer emissions", and "saves fossil fuels" (O'Garra et al., 2005). Surveys using contingent valuation methods in Turkey indicate consumers' willingness to pay more for low-carbon products based on personal preference (Adaman et al., 2011). Chang (2011) show that green product innovation enhances competitive advantage in Taiwan's manufacturing industry due to consumer valuation. Similarly, Chan (2014) find that consumer actions drive airlines to promote green services. Itaoka et al. (2017) observe growing consumer positivity towards hydrogen infrastructure.

Empirical analyses like the consumer questionnaire survey on electric vehicles in Beijing by Huang and Ge (2019) show significant positive effects of consumer attitudes, perceived behavioral control, cognitive status, product perception, and monetary incentives on electric vehicle purchase intentions. Hagmann et al. (2015) find that environmental friendliness influences consumer airline choices during booking, with nearly half of consumers willing to pay more for greener flights. Additionally, Atabekov et al. (2020) find that consumer demand drops by 9.2% with a 50% increase in carbon emissions among environmentally aware consumers.

Despite these findings, there is often a gap between consumers' stated environmental intentions and their actual purchasing behavior. Carrington et al. (2014) address this discrepancy, highlighting challenges in predicting market outcomes based on consumer surveys. This suggests that while environmental concerns are significant, other factors may influence consumer decisions.

Beyond financial incentives, consumer behavior may be morally driven, as suggested by the Norm Activation Model (NAM) (Schwartz and Davis, 1981; Schwartz, 1977). Applications of the NAM to transportation and energy-related behaviors explain pro-environmental intentions and behaviors (Bamberg et al., 2003; Harland et al., 1999; Heath and Gifford, 2002), likening pro-environmental behavior to pro-social behavior in sacrificing self-interest for collective benefits.

Goal-Framing Theory posits that decisions involve multiple goals, where one goal dominates decision-making (Lindenberg and Steg, 2007). Consumer decisions regarding green technology can be financially, personally, morally, and socially motivated. Preferences for green technology vary among consumers, with some willing to pay premiums for lower emissions while others are indifferent. Green preferences extend beyond quality considerations to include moral sentiments, necessitating models that encompass both horizontal and vertical differentiation in technology introduction.

The role of moral sentiments in economic decisions has been explored by Fehr and Schmidt (1999), who introduce concepts of fairness and reciprocity in competition and cooperation. Bénabou and Tirole (2010) discuss how moral considerations influence individual and corporate social responsibility, providing a foundation for incorporating moral sentiments into economic models. This supports the inclusion of *relative moral sentiment* in our model to capture the nuanced ways in which consumer morality influences purchasing decisions and market outcomes.

To model competitive effects, studies have traditionally employed either horizontal or vertical differentiation models. The Hotelling model of horizontal differentiation offers a theoretical framework for analyzing competition along a product characteristic spectrum (Hotelling, 1929; Tirole, 1988). However, d'Aspremont et al. (1979) showed that firms may maximize differentiation to soften competition, a concept further explored under various market conditions (Balvers and Szerb, 1996; Fujita and Thisse, 1986; Neven, 1986; Tabuchi and Thisse, 1995).

Vertical differentiation, focusing on product quality, has been central to product line literature since Mussa and Rosen (1978) and Gabszewicz and Thisse (1979). These models examine how monopolies and competitive markets determine product quality levels, considering consumer heterogeneity in quality preferences (Champsaur and Rochet, 1989; Johnson and Myatt, 2003; Shaked and Sutton, 1983). However, Choi and Shin (1992) relaxed the assumption of a fully covered market, showing that firms might not cover the market if consumer preference for quality is low. Wauthy (1996) refined this threshold, linking market coverage to the ratio of upper and lower bounds of the preference interval. These studies highlight the importance of population characteristics in determining market coverage, which is crucial for evaluating green technology adoption.

Despite these developments, few studies have integrated both horizontal and vertical differentiation within an uncovered market, particularly in the context of green technology adoption in the airline industry. Moreover, the influence of consumer moral sentiments on firms' strategic decisions remains underexplored.

Industrial policy plays a pivotal role in promoting innovation and shaping market competition. Rodrik (2008) discusses the role of industrial policy in economic development and technology adoption, arguing for its normalization in economic planning. Aghion et al. (2015) examine how industrial policy can stimulate competition and innovation, highlighting the importance of policy design in achieving desired outcomes.

In the context of environmental innovation, Jaffe et al. (2002) analyze how different policy instruments impact technological change, emphasizing the effectiveness of regulatory approaches in stimulating green innovation. Acemoglu et al. (2012) explore how policy can direct technological change towards environmentally friendly innovations, suggesting that appropriate incentives are crucial for the adoption of sustainable technologies.

Research on market dynamics and green innovation underscores the importance of policy in influencing firm behavior. Rennings and Rammer (2011) explore how regulation-induced innovation affects firm performance, suggesting that environmental policies can lead to competitive advantages. Horbach (2008) investigate factors influencing firms' adoption of environmental innovations, emphasizing the role of market conditions and policy frameworks.

Understanding consumer behavior is essential for modeling market dynamics in the adoption of green technology. Kahn (2007) examines how environmental ideology influences consumer choice, finding that consumers with strong environmental beliefs are more likely to purchase eco-friendly products. However, behavioral economics suggests that psychological factors can impact decision-making. DellaVigna (2009) provides evidence on how psychological factors influence economic decisions, relevant for modeling consumer responses to green technology. Additionally, Sunstein and Thaler (2003) introduce the idea of nudging consumers towards better choices without restricting freedom, which can be applied to encourage pro-environmental behavior.

In the aviation context, Gössling and Upham (2009) explore environmental challenges and potential technological solutions, emphasizing the need for effective policies to address climate change in aviation. Peeters et al. (2016) analyze the potential and limitations of technological advancements in reducing aviation emissions, questioning whether reliance on future technology may stall current policy actions.

Diffusion of innovation theory, as discussed by Rogers (2003), offers a framework for understanding how new technologies spread in a market. This is particularly relevant for green technologies in aviation, where adoption rates are influenced by factors such as consumer perceptions, costs, and policy incentives.

These studies collectively support the necessity of integrating horizontal and vertical differentiation models within an uncovered market to assess green technology introduction. They also highlight the significant role of industrial policy and consumer moral sentiments in influencing firms' strategic decisions and market outcomes.

Despite the extensive research on consumer behavior and green technology adoption, there is a noticeable gap in the literature concerning the theoretical modeling of green technology introduction in the airline industry using both horizontal and vertical differentiation within an uncovered market. Existing models often consider either horizontal or vertical differentiation in isolation and typically assume fully covered markets.

In the context of the "flight shame" movement that causes some passengers to leave the market and passengers' environmental consciousness, Chen and Malavolti (2023) proposes a model to assess the introduction of hydrogen technology in the air transport sector when the initial market is uncovered, and allowing for some willingness-to-pay for cleaner technologies. However, they propose a constant increase in the willingness to pay for green technology which can be relaxed using a more formal industrial organization model.

Moreover, the influence of consumer moral sentiments. When the technology, particularly "relative moral sentiments" on firms' strategic decisions has not been thoroughly examined. This paper fills these gaps by proposing a novel theoretical framework that integrates vertical differentiation into a horizontal differentiation model in an uncovered market setting. By introducing the concept of relative moral sentiments, we capture the nuanced ways in which consumer morality influences purchasing decisions and market outcomes. Our model provides insights into the strategic interactions between duopoly airlines regarding technology adoption and highlights the conditions under which regulatory interventions become necessary. This contributes to the literature by offering a more comprehensive understanding of green technology adoption in industries facing environmental pressures and by informing effective industrial policy design aimed at promoting sustainable innovation.

3 The Model

We build on the model proposed by Chen and Malavolti (2023), where the adoption of green technology in air transport is analyzed in the context of a market shock, and resulting in a negative shock of the passengers' reserve value. Without the new technology, duopoly airlines both choose the incumbent technology.ch consumer buys one flight ticket, and consumers are uniformly distributed between $[0, 1]$.

3.1 Model setting

Each consumers' utility depends on both the price and the quality of the airline's service. Consumers have a reserve value R, which represents their willingness to pay for a flight ticket. Consumers are heterogeneous in their valuation of quality, which depends on the quality level s_{ij} (with i indexing the airline and j indicating the technology used). Consumers' total utility from purchasing a flight ticket from airline i with technology j is given by:

$$_i(R, p_i) = R + s_{ij}\theta - p_i - \tau(l_i - x)^2, \tag{1}$$

where θ is a quality preference parameter, p_i is the price of the ticket, and $\tau(l_i - x)^2$ represents the disutility from the mismatch between the consumer's ideal flight variety x and the actual product location l_i.

On the supply side, we maintain the assumption that airlines can adopt one of two technologies: the incumbent technology (L) or a green technology (H). The costs for each airline consist of a quadratic cost per seat depending on the quality level and a fixed cost F_{ij}, associated with the choice of technology j. As in Chen and Malavolti (2023), the cost per seat is modeled as a quadratic function $\alpha_j s_j^2$ to reflect the increasing difficulty in achieving higher quality levels.

Airlines choose their flight variety (l_i), quality level (s_{ij}), and price (p_i) to maximize profits, which are given by:

$$\pi_i(p_1, p_2; s_1, s_2; l_1, l_2) = (p_i - \alpha_j s_j^2)D_i - F_j; i \in 1, 2, j \in L, H. \tag{2}$$

where D_i is the demand for airline i's service.

The timing of the game is as follows: Stage 1: Airlines choose their locations (i.e., variety of flight, l_1, l_2) simultaneously; Stage 2: Airlines decide the technology adoption strategies simultaneously by choosing the level of quality (s_1, s_2); Stage 3: Airlines choose the average ticket prices (p_1, p_2) simultaneously; Stage 4: Consumers make their purchase decisions. In subsection 3.2, we establish the status quo scenario where both airlines use the incumbent technology with kerosene. Then, in subsection 3.3, green technology becomes available as a higher quality product. Finally, in subsection 3.4, we model when consumers experience moral relief and when green technology enjoys an efficiency gain.

3.2 Scenario 1: Duopolies airlines with incumbent technology under market shock

The starting point is before the introduction of the new green technology. Both airlines use the incumbent technology, which is treated as more polluting than the new green technology. In this status quo scenario, the market shocks lead to an uncovered market. The economic explanation can be the "Flight Shame" movement resulted in a negative shock to consumers' reserve value ($R < R^0$, where R^0 is the reserve value before the shock). Consumers decide to purchase if and only if their utility is non-negative (see Figure 1). The shock causes some consumers to leave the market because the reserve utility is not high enough. The market then becomes uncovered[4]. The main assumption of this model is the uncovered market due to the demand shock. The model can capture the competition effect of technology adoption by assuming duopoly airlines in the market. Moreover, thanks to the uncovered market setting, one can observe the conditions under which a monopoly would adopt such technology.

We solve the game using backward induction. In stage 4, consumers make their purchase decisions. From Equation 1, we can compute the demand for the two airlines following the participation constraint[5] and incentive constraint[6].

For a given pair of locations, the duopoly airlines will now have three margins: an extensive margin to the left for the old technology, an extensive margin to the right for the new technology, and an intensive margin in between. The extensive margin is obtained by the participation constraint of consumers ($U_i \geq 0$), while the intensive margin is obtained by the incentive constraint of competition between the duopolies ($U_1 = U_2$).

The demand for airline 1 is thus $D_1(p_1, p_2) = 2\sqrt{\frac{R+\theta s_{1L}-p_1}{t}}$, and the demand for airline 2 is $D_2(p_1, p_2) = 2\sqrt{\frac{R+\theta s_{2L}-p_2}{t}}$. Since the two airlines are similar in this setting, intuitively, the price and quality level of the two airlines are the same by symmetry ($p_1 = p_2 = p; s_{1L} = s_{2L} = s_L; F_{1L} = F_{2L} = F_L$). After finding the demand segmentation, we check the reserve value R level that makes the market uncovered ($D_1 + D_2 < 1$). We find that when $R < p + \frac{t}{16} - \theta s_L$, the market is uncovered.

In stage 3, profit-maximizing airlines choose their ticket prices simultaneously. From Equation

[4]Not every consumer purchases a flight ticket in this market. The total demand is less than the unit mass of consumers ($D_1 + D_2 < 1$).

[5]An individual consumer purchases a flight ticket if and only if their utility from consuming the flight ticket is non-negative.

[6]A consumer buys from airline 1 when their utility of buying a flight ticket from firm 1 is higher than the utility of buying a flight ticket from airline 2, and vice versa.

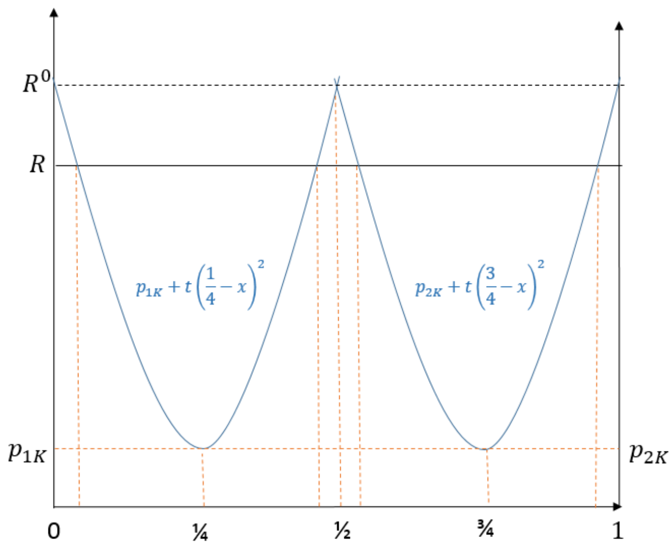

Figure 1: Scenario 1: duopolies airlines with incumbent technology under market shock

2, we can compute the best price response for the two airlines. Since in scenario 1, the green technology is not yet available, both airlines choose the incumbent technology.

In stage 2, profit-maximizing airlines choose their flight quality levels simultaneously. We again use the best price response in Equation 2 to obtain the best quality response. Both airlines have incentives to choose the lowest quality level ($\underline{s_L}$).

Finally, in stage 1, airlines simultaneously choose their product variety (their location on the market line). Duopolies have incentives not to interact to avoid competition in this unfavorable market (due to the market shock). By locating themselves at $(\frac{1}{4}, \frac{3}{4})$, the duopolies can act as 'local monopolies' and retain most of the market (not losing market share on either the left or right side) even when the situation improves. After rearranging all the best responses, we obtain the price strategy and the profit for the duopolies: $\pi_{1L} = \pi_{2L} = \pi_L = \frac{4(R+\theta\underline{s_L}-\alpha_L\underline{s_L}^2)^{\frac{3}{2}}}{3\sqrt{3t}} - F_L$.

Social welfare (S.W.) consists of consumer surplus and total profit:

$$SW^1 = \pi_1 + \pi_2 + \int_{l_1-\sqrt{\frac{R+\theta s_{1j}-p_1}{t}}}^{l_1+\sqrt{\frac{R+\theta s_{1j}-p_1}{t}}} U_1, dx + \int_{l_2-\sqrt{\frac{R+\theta s_{2j}-p_2}{t}}}^{l_2+\sqrt{\frac{R+\theta s_{2j}-p_2}{t}}} U_2, dx \tag{3}$$

In scenario 1, using Equation 3, the social welfare is equal to: $\frac{8(R+\theta\underline{s_L}-\alpha_L\underline{s_L}^2)^{\frac{3}{2}}}{3\sqrt{3t}} - 2F_L + (2R + 2\theta\underline{s_L} - 2\alpha_L\underline{s_L}^2 - \frac{t}{4})\sqrt{\frac{R+\theta\underline{s_L}-\alpha_L\underline{s_L}^2}{3t}} - \frac{16t}{3}(\frac{R+\theta\underline{s_L}-\alpha_L\underline{s_L}^2}{3t})^{\frac{3}{2}}$ Since the market is uncovered, which implies $R < p + \frac{t}{16} - \theta\underline{s_L} = \frac{\alpha_L\underline{s_L}^2+2R}{3} + \frac{t}{16} - \theta\underline{s_L}$, this social welfare level is relatively low. We summarize the results in scenario 1, including the strategy set for the duopolies with the form $S(p_1, p_2; s_{1j}, s_{2j}; l_1, l_2)$ in Lemma 1.

Lemma 1 *The market is uncovered when* $R < p + \frac{t}{16} - \theta \underline{s_L}$ *and both airlines choose the incumbent technology. The strategy set of duopoly airlines is* $S(p_1, p_2; s_{1L}, s_{2L}; l_1, l_2) = (\frac{\alpha_L \underline{s_L}^2 + 2R}{3}, \frac{\alpha_L \underline{s_L}^2 + 2R}{3}; \underline{s_L}, \underline{s_L}; \frac{1}{4}, \frac{3}{4})$, *with a profit equal to* $\frac{4(R + \theta \underline{s_L} - \alpha_L \underline{s_L}^2)^{\frac{3}{2}}}{3\sqrt{3t}} - F_L$. *The welfare is relatively low in this pre-innovation scenario.*

We verify the profitability under the uncovered market condition, which always holds with positive transportation costs t. Under an uncovered market, the two airlines act as "local monopolies" in their market segments. They choose symmetric price and quality strategies. The best quality strategy is the lowest level because profits decrease with the quality level. In this Hotelling game, the socially optimal locations are $\frac{1}{4}$ and

The passengers' environmental consciousness (such as the flight shame movement) makes the market uncovered for the reserve value R lower than a certain level. The two airlines choose symmetric prices and quality strategies, with socially optimal locations $(\frac{1}{4}, \frac{3}{4})$. This location minimizes production, and transportation costs and avoids a negative competition effect, and keeps most demand possible under an uncovered market. The airlines have no incentives to change their location from their "local monopoly" position in the market segment. We treat this equilibrium as the benchmark and propose policy implications based on social welfare improvement from this reference point.

3.3 Scenario 2: The Green Technology Becomes Available

Following scenario 1, green technology becomes available, and airlines can choose their technology by selecting their quality level. We assume the green technology yields a higher quality ($s_{iH} > s_{iL}$) due to its less polluting and quieter properties. Consequently, consumers obtain an extra heterogeneous utility ($s_{iH}\theta$) from buying a green technology flight ticket and are willing to pay more. All consumers prefer higher quality at a given price due to vertical differentiation, allowing the higher quality product to command a higher price. However, green technology is more costly in terms of both variable and fixed costs ($\alpha_H s_{iH}^2 > \alpha_L s_{iL}^2, F_H > F_L$). Intuitively, before solving the game, we can expect the price strategy for the green technology flight to be higher than for the incumbent kerosene flight ($p_H > p_L$). Otherwise, all consumers would choose the green flight, causing firms to lose money by adopting this green technology due to higher costs. Consumers with higher θ are willing to pay more for higher quality. A smaller θ indicates a greater diversity of tastes, leading to two possible scenarios. If θ is large, firms cover the market; if θ is small, tastes are sufficiently diverse so that some consumers do not buy from either firm. We shall focus on this latter case. Starting from horizontally differentiated duopoly airlines with incumbent technology under an uncovered market, the introduction of green technology provides an opportunity for vertical differentiation due to consumers' environmental consciousness.

Table 1: The four possible adoption strategy sets with two players

Airline 1 / Airline 2	Adopt green tech.	Keep incumbent tech.
Adopt green tech.	(H, H)	(H, L)
Keep incumbent tech.	(L, H)	(L, L)

Table 1 presents the four possible adoption strategy sets for the two players, where the status quo scenario is the case (L, L). Since both airlines have the same level of costs and access to the new technology, their strategy sets should be identical for a simultaneous pure strategy game. In other words, both airlines will choose to adopt in a simultaneous game as long as adoption is profitable. Otherwise, neither airline will adopt. The asymmetric cases (H, L) and (L, H) can only occur in a sequential game or in the case of a monopoly owning both airlines. We will study the case (H, H) under a covered market in subsection 3.3.1 and under an uncovered market in subsection 3.3.2. Subsequently, we will generate the dynamics of the adoption strategy as the extra utility increases.

3.3.1 The case of (H, H) leads to a fully covered market

When all airlines in the market adopt the greenest available technology, the market can be fully covered. This occurs when both airlines choose green technology. The consumers' utility function in this scenario is given by:

$$V_i = R + s_{iH}\theta - p_i - \tau(l_i - x)^2 \tag{4}$$

The participation constraint for airline 1 becomes:

$$l_1 - \sqrt{\frac{R + \theta s_{1H} - p_1}{t}} \leq x \leq l_1 + \sqrt{\frac{R + \theta s_{1H} - p_1}{t}} \tag{5}$$

Similarly, the participation constraint for airline 2 is:

$$l_2 - \sqrt{\frac{R + \theta s_{2H} - p_2}{t}} \leq x \leq l_2 + \sqrt{\frac{R + \theta s_{2H} - p_2}{t}} \tag{6}$$

The indifferent consumer, who obtains the same utility from either airline 1 or airline 2, is given by the condition $U_1 = U_2$:

$$x^* = \frac{p_1 - p_2}{2\tau(l_1 - l_2)} + \frac{l_1 + l_2}{2} \tag{7}$$

The market becomes fully covered, meaning all consumers buy a flight ticket, if:

$$2\sqrt{\frac{R + \theta s_{1H} - p_1}{t}} + 2\sqrt{\frac{R + \theta s_{2H} - p_2}{t}} \geq 1 \tag{8}$$

In this fully covered market, the product's quality does not influence the firms' profit. Duopolies offering the same product are in perfect competition, benefiting from the market volume effect but losing profit due to competition.

For this equilibrium to be sustainable, the firm's profit in scenario 2 must be higher than in scenario 1. Denoting the scenarios as upper indices, the requirement for this equilibrium is:

$$\pi_1^2(p_{1H}^2, p_{2H}^2) \geq \pi_1^1(p_{1H}^2, p_{2H}^2) \tag{9}$$

The sustainable condition is symmetric for firm 2. The profitable condition is:

$$\alpha_L s_L^2 < R \leq \alpha_L s_L^2 + \frac{3\tau^{1/3}}{4}\left(\frac{\tau}{2} - 2F\right)^{2/3} \tag{10}$$

where $F = F_H - F_L$ (See computation details in the Appendix).

It is unlikely for (H, H) to be an equilibrium due to the fixed cost difference discouraging firms from adopting new technology. Consumer surplus is:

$$R + \theta s_H - \alpha_H s_H^2 - \frac{31\tau}{48} \tag{11}$$

While consumers are better off, firms in a dynamic game have incentives to reach an implicit agreement on (L, L).

Proposition 1 *If the market recovers in the case of (H, H) and the consumers' preference for quality $\theta > \theta_A$, then the optimal strategy set is:*

$$\mathcal{S}\left(p_1, p_2; s_1, s_2; l_1, l_2\right) = \left(\alpha_H \underline{s_H}^2 + t, \alpha_H \underline{s_H}^2 + t; \underline{s_H}, \underline{s_H}; 0, 1\right) \tag{12}$$

3.3.2 The Case of (H, H) Staying with Market Uncovered

The market can be partially restored and remain uncovered under the strategy set (H, H). When the market stays uncovered, airlines can continue acting as "local monopolies" within their respective segments. The condition for the market to remain uncovered is:

$$R + \theta s_H < \bar{R} \tag{13}$$

$$\begin{cases} \pi_1(p_1, p_2) = (p_1 - \alpha_H s_{1H}^2) 2\sqrt{\frac{R+\theta s_{1H} - p_1 H}{t}} - F_H \\ \pi_2(p_1, p_2) = (p_2 - \alpha_H s_{2H}^2) 2\sqrt{\frac{R+\theta s_{2H} - p_2 H}{t}} - F_H \end{cases} \tag{14}$$

$$\begin{cases} \pi_1(p_1, p_2) = (p_1 - \alpha_H s_{1H}^2) \cdot 2\sqrt{\frac{R+\theta s_{1H} - p_1}{t}} - F_H, \\ \pi_2(p_1, p_2) = (p_2 - \alpha_H s_{2H}^2) \cdot 2\sqrt{\frac{R+\theta s_{2H} - p_2}{t}} - F_H. \end{cases} \tag{15}$$

After determining the best price responses and best quality responses, the strategy set is:

$$\mathcal{S}\left(p_1, p_2; s_1, s_2; l_1, l_2\right) = \left(\frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R, \frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R; \frac{\theta}{2\alpha_H}, \frac{\theta}{2\alpha_H}; \frac{1}{4}, \frac{3}{4}\right) \tag{16}$$

when the consumers' preference for quality θ is between θ_B (the profitability condition: **Condition B**) and θ_A (the market coverage condition: **Condition A**). (See Appendices B.2 for computation details.)

Proposition 2 *If the market remains uncovered in the case of (H, H), and the consumers' preference for quality $\theta_B < \theta < \theta_A$, then the optimal strategy set is:*

$$\mathcal{S}\left(p_1, p_2; s_1, s_2; l_1, l_2\right) = \left(\frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R, \frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R; \frac{\theta}{2\alpha_H}, \frac{\theta}{2\alpha_H}; \frac{1}{4}, \frac{3}{4}\right) \tag{17}$$

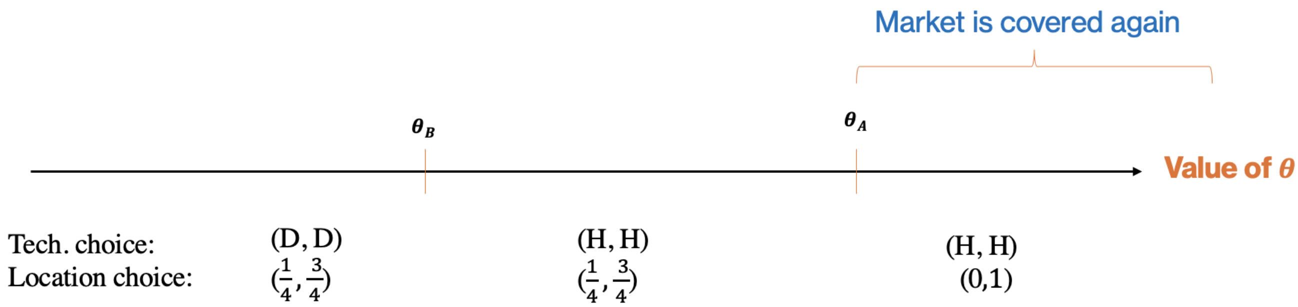

Figure 2: The dynamic of the strategy set with the increase of consumer preference for quality

3.4 Scenario 3: Adding Moral Value or Efficiency Gain

3.4.1 The relative moral sentiments Model

The total price that consumers need to pay is the sum of the ticket price and transportation costs: $p_i + t_i(l_i - x)^2$, where i is the index for the two airlines. Without loss of generality, we assume that $l_1 = l$ and $l_2 = l + \delta$. The transportation costs for the two firms are denoted as t_i. To reflect the ease of consuming flights with green technology compared to incumbent technology, we propose lower transportation costs if consumers choose the airline using the new green technology. This can also represent airlines accessing lower-cost transportation due to efficiency gains or lower future fuel prices, with $0 < \tau = \frac{t_H}{t_L} < 1$.

When the two firms have access to the same transportation technology but are located differently ($\tau = 1, \delta > 0$), this Launhardt model turns into a standard Hotelling model. If the two firms have coincidental locations but differ in transportation costs ($\tau < 1, \delta = 0$), the differentiation is purely vertical. In this case, the firm with lower transportation costs captures the whole market by choosing the same mill price. When $\tau = 1, \delta = 0$, the two firms offer perfectly homogeneous products. Here, δ represents the degree of horizontal differentiation, while τ indicates the degree of vertical differentiation.

Ferreira and Thisse (1996) extend Launhardt's analysis by considering quality strategy prior to price strategy. They treat transportation costs as an inverse measure of quality, $s_H = t_L, s_L = t_H, \tau = \frac{t_H}{t_L} = \frac{s_L}{s_H} < 1$. They find that firms either maximize their differentiation in transport but minimize geographical differences or maximize geographical differences but minimize quality differences. However, linear transportation costs do not adequately cover the quasi-concavity of the profit function, and they assume the market is always covered. This setting can be a good fit for green technology facing the "flight shame" movement, where consumers are morally more comfortable flying with green technology. The model represents this moral comfort by lower transportation costs. The level of this moral relief can be linked to the incumbent level through physiological comparison. Asymmetric transportation costs can also represent efficiency gains. The firm with efficiency gains can be seen as having lower transportation costs for consumers, making transportation costs a function of the own-product quality level.

We will start from maximum horizontal differentiation and assess the firms' interactions, including location strategy. For this one unit mass of continuum consumers, each consumer purchases only one ticket. The utility for quality and environmentally conscious consumers is:

$$V_i(x) = R + s_j\theta - p_i - s_{-j}(l_i - x)^2, \tag{18}$$

where i is the index of the firms and j indicates the technology.

This improvement in product suitability is illustrated by a wider opening of the parabola (lower transportation costs, $t_j = s_{-j}$). Intuitively, if the product better fits the consumer's needs/preferences, the disutility (represented by transportation cost) from consuming this product is lower. It is logical to link the transportation costs to the quality of the other firm because this disutility also depends on the quality of other available products. In other words, this can be understood as better transportation technology for firms to serve a larger market. Again, market coverage depends on the size of the parabola's opening.

3.4.2 The symmetric strategy set

The strategy sets for symmetric cases are similar to those in Scenario 2. When both airlines choose the same technology (either incumbent or green), the transportation costs remain symmetric in Scenario 3. However, the conditions for sustainability and market coverage differ due to the new transportation costs.

Proposition 3 *If the market remains uncovered in the (H, H) case with efficiency gain, and the consumer preference for quality is $\theta_{B.bis} < \theta < \theta_{C.2bis}$, where $\theta_{B.bis}$ is the sustainable condition and $\theta_{C.2bis}$ is the uncovered-market condition, then the optimal strategy set is:*

$$\mathcal{S} = \left(\frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R, \frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R; \frac{\theta}{2\alpha_H}, \frac{\theta}{2\alpha_H}; \frac{1}{4}, \frac{3}{4} \right).$$

Proposition 4 *If the market becomes covered in the (H, H) case with efficiency gain, and the consumer preference for quality is* $\theta_{C.1bis} < \theta < \theta_{A.bis}$*, where* $\theta_{A.bis}$ *is the sustainable condition and* $\theta_{C.1bis}$ *is the uncovered-market condition, then the optimal strategy set is:*

$$\mathcal{S}\left(p_1, p_2; s_1, s_2; l_1, l_2\right) = \left(\alpha_H \underline{s_H}^2 + t, \alpha_H \underline{s_H}^2 + t; \underline{s_H}, \underline{s_H}; 0, 1\right).$$

Comparing with Scenario 2, we find that $\theta_{B.bis} < \theta_B$ and $\theta_{C.2bis} < \theta_C$. Similarly, $\theta_{A.bis} < \theta_A$ and $\theta_{C.1bis} < \theta_C$. Therefore, when consumers also value the product's suitability, the adoption of the new technology becomes easier to achieve. The horizontal preference of consumers favors technology adoption, meaning that the new technology can be adopted with relaxed conditions and fewer subsidies.

The dynamics of market evolution with respect to consumer preference for quality are summarized in Figure 3.

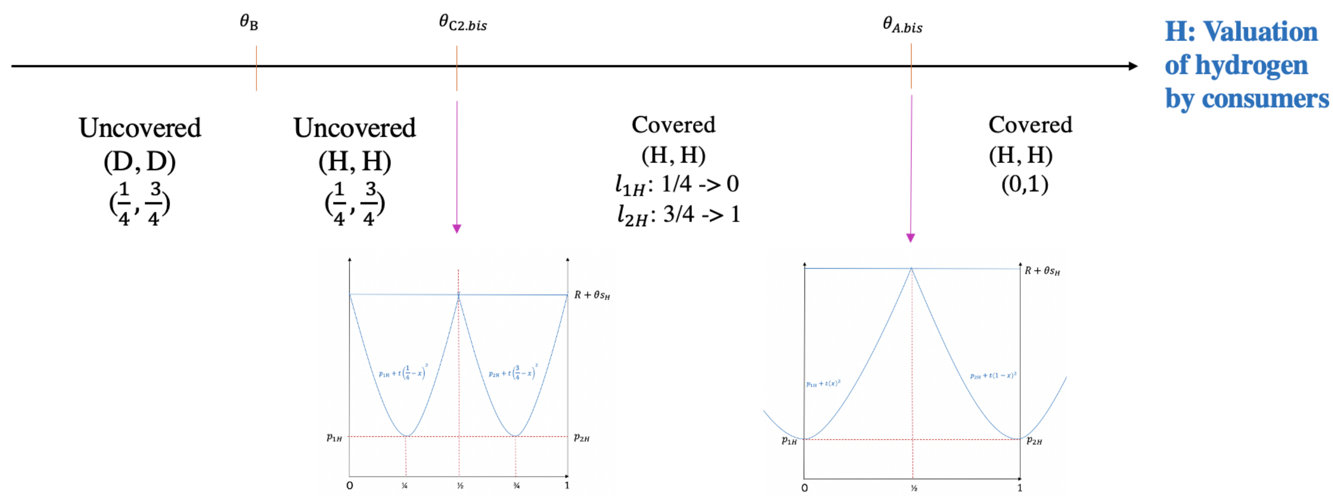

Figure 3: The dynamics of market evolution with respect to consumer preference in the presence of efficiency gain

3.4.3 The Asymmetric Strategy Set

Let us focus on the asymmetric cases (L, H) or (H, L). Without loss of generality, assume that firm 1 chooses the incumbent technology and firm 2 chooses the green technology. We aim to find the optimal strategy set $\mathcal{S}\left(p_L, p_H; s_L, s_H; l_L, l_H\right)$.

The demand equations are given by:

$$\begin{cases} D_L = 2\sqrt{\frac{R-p_L+s_L\theta}{s_H}} \\ D_H = 2\sqrt{\frac{R-p_H+s_H\theta}{s_L}} \end{cases} \tag{19}$$

Proposition 5 *If the market remains uncovered in the asymmetric cases (H, L) or (L, H) with efficiency gain, and the consumer preference for quality is* $\theta_{C.3bis} < \theta < \theta_{C.2bis}$*, where* $\theta_{C.3bis}$ *is the sustainable condition and* $\theta_{C.2bis}$ *is the uncovered-market condition, then the optimal strategy set is:*

$$\mathcal{S} = (p_L, p_H; s_L, s_H) = \left(\frac{2R}{3} + \frac{5\theta^2}{12\alpha_L}, \frac{2R}{3} + \frac{5\theta^2}{12\alpha_H}; \frac{\theta}{2\alpha_L}, \frac{\theta}{2\alpha_H}\right)$$

The locations lie in $l_L \subset \left(\sqrt{\frac{2\alpha_H}{3\theta}\left(R + \frac{\theta^2}{4\alpha_L}\right)}, \frac{1}{4}\right)$ *and* $l_H \subset \left(1 - \sqrt{\frac{2\alpha_L}{3\theta}\left(R + \frac{\theta^2}{4\alpha_H}\right)}, \frac{3}{4}\right)$. *(See proof in Appendix C)*

When $\mathcal{S}(p_L, p_H; s_L, s_H) = \left(\frac{2R}{3} + \frac{5\theta^2}{12\alpha_L}, \frac{2R}{3} + \frac{5\theta^2}{12\alpha_H}; \frac{\theta}{2\alpha_L}, \frac{\theta}{2\alpha_H}\right)$, the profits are:

$$(\pi_L, \pi_H) = \left(\frac{4\sqrt{2\alpha_H}\left(R + \frac{\theta^2}{4\alpha_L}\right)^{3/2}}{3\sqrt{3\theta}} - F_L, \frac{4\sqrt{2\alpha_L}\left(R + \frac{\theta^2}{4\alpha_H}\right)^{3/2}}{3\sqrt{3\theta}} - F_H\right)$$

Firms will maintain this strategy set if it is profitable, i.e. $\frac{4\sqrt{2\alpha_L}\left(R+\frac{\theta^2}{4\alpha_H}\right)^{3/2}}{3\sqrt{3\theta}} - F_H > \frac{4\sqrt{2\alpha_H}\left(R+\frac{\theta^2}{4\alpha_L}\right)^{3/2}}{3\sqrt{3\theta}} - F_L$ and if the market environment remains uncovered. When the market becomes covered again, consumers lie in $\left[0, 2\sqrt{\frac{2\alpha_H}{3\theta}(R + \frac{\theta^2}{4\alpha_L})}\right] \cup \left[1 - 2\sqrt{\frac{2\alpha_L}{3\theta}(R + \frac{\theta^2}{4\alpha_H})}, 1\right]$. The threshold for a covered market can be found by solving:

$$2\sqrt{\frac{2\alpha_H}{3\theta}(R + \frac{\theta^2}{4\alpha_L})} = 1 - 2\sqrt{\frac{2\alpha_L}{3\theta}(R + \frac{\theta^2}{4\alpha_H})}$$

This condition is denoted as Condition C3bis.

In this setting, a firm's profit depends not only on the quality of its own product but also on the quality level of its competitor. The quality strategy depends only on the firm's own cost parameter, as the quality of the competitor is in the denominator of the first-order condition. Both firms choose a higher quality level than in Scenario 1 because higher quality is associated with greater demand and higher transportation costs for the competitor. Firms have more incentive to improve quality when they can influence the consumers' valuation of the competitor. When consumers' horizontal valuation for green technology is linked to the available products in the market through comparison, it can encourage airlines to choose higher-quality products. If there is an efficiency gain for green technology, i.e., $\alpha_H < \alpha_L$, then both firms will choose green technology, increasing their profit. In any case, when the new technology improves the product's suitability, firms are willing to choose higher quality.

In stage 1, firms choose their location (horizontal differentiation strategy):

$$l_L \subset \left(\sqrt{\frac{2\alpha_H}{3\theta}\left(R + \frac{\theta^2}{4\alpha_L}\right)}, \frac{1}{4} \right); \quad l_H \subset \left(1 - \sqrt{\frac{2\alpha_L}{3\theta}\left(R + \frac{\theta^2}{4\alpha_H}\right)}, \frac{3}{4} \right)$$

The dynamics of market evolution with respect to consumer preference for quality, in the presence of efficiency gain of the new technology and asymmetric strategy set, are summarized in Figure 4.

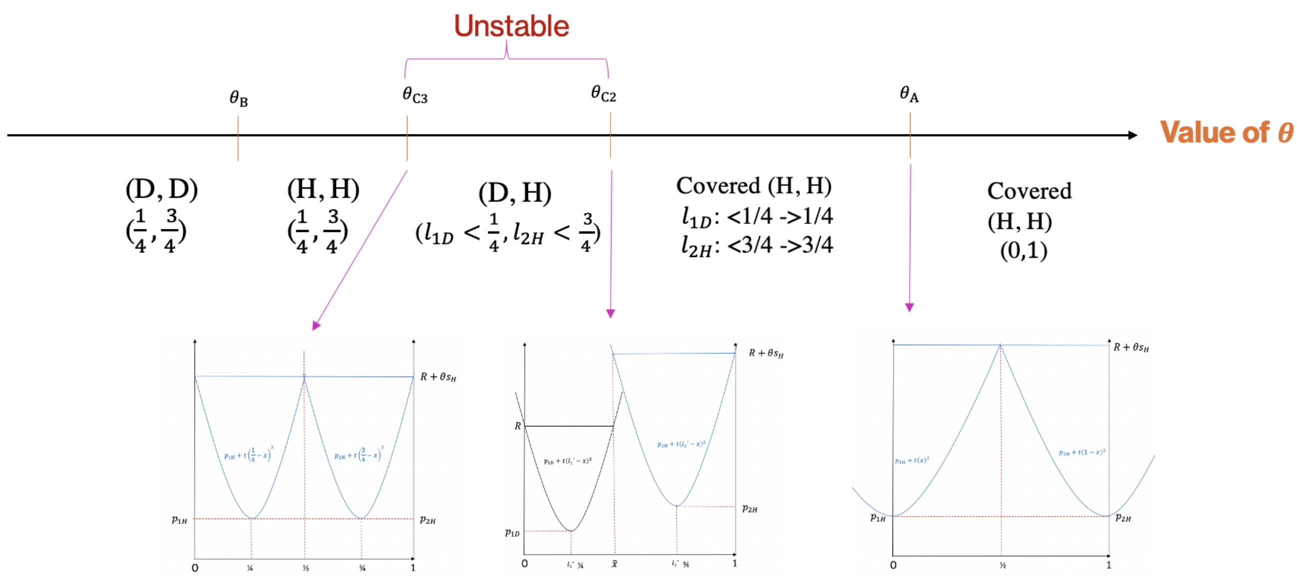

Figure 4: The dynamics of market evolution with respect to consumer preference including an unstable scenario

As long as condition θ_B is satisfied, being a quality leader is profitable. Thus, if both firms choose their quality simultaneously, they will end up with the (H, H) case. In a dynamic game, without intervention or efficiency improvement, firms will reach an implicit agreement to revert to the (L, L) case. However, one firm may deviate to gain dominance. This asymmetric equilibrium can sustain until the market becomes covered (Condition C). The other firm will retaliate by choosing green technology when its marginal consumer reaches the end of the market, followed by location changes to avoid competition. Again, they can reach an agreement to return to the initial (L, L) case. Asymmetric cases can only occur with deviation or under a sequential monopoly game. However, the instability harms the market because this frequent switching generates waste and losses. There is a call for intervention to either subsidize the (H, H) case or allow the game to become sequential. Setting policies to prevent firms from reverting from green technology to incumbent technology can work but may discourage technology adoption.

When comparing Scenario 2 (no efficiency gain) to Scenario 3 (with efficiency gain), welfare is improved, and sustainable conditions are easier to achieve. If the regulator needs to intervene, the subsidy level required is lower than in the scenario without efficiency gain.

4 Policy Implications

4.1 Monetary Policies

The dynamics of market evolution indicate that as consumer valuation for quality increases (as illustrated in Figure 4), more consumers are likely to return to the market, enhancing overall social welfare. However, sustaining these conditions poses challenges due to high fixed costs, necessitating regulatory intervention.

Our model highlights the importance of targeted regulatory measures such as taxes or subsidies. In a covered market, regulators should implement taxes on polluting energy to discourage the use of environmentally harmful technologies. However, in an uncovered market, such taxes can distort consumer and airline behavior. Higher costs result in increased ticket prices, which diminishes utility and may lead some consumers to exit the market. In this context, providing subsidies for green technology becomes essential to foster adoption and facilitate market recovery. Thus, prioritizing green technology subsidies is crucial when the market is uncovered.

Determining an optimal subsidy level is vital for enhancing social welfare within budget constraints. Based on our findings, a fixed cost subsidy to meet Condition B (ensuring H reaches H_B in homogeneous extra utility for hydrogen technology, and θ reaches θ_B in heterogeneous extra utility) emerges as an efficient strategy. This subsidy level is relatively modest compared to the higher amounts needed to achieve H_C and H_A, as well as θ_C and θ_A. This approach promotes higher welfare and greater adoption of green technologies compared to pre-innovation scenarios.

Regulatory objectives should not focus solely on completely covering the market in the aftermath of shocks and budget constraints. Even if the market remains uncovered after achieving Condition B through subsidies, airlines, acting as local monopolies within their segments, can self-finance part of their innovation costs. Allowing firms to temporarily hold market power facilitates profit generation from adopting green technologies. Additionally, with rising consumer environmental awareness or future fuel efficiency gains, the market may eventually become fully covered again. The existence of local monopolies diminishes the incentive to exploit dominant positions due to potential competition. Supporting research and development (R&D) can further enhance efficiency gains, promoting the adoption of hydrogen technology while reducing the necessary subsidy levels.

To set the optimal subsidy amount, regulators could conduct surveys to gauge consumer valuation of quality. Utilizing historical data to predict these valuations is another viable approach. However, shifts in consumer behavior due to movements like “flight shame” necessitate fresh surveys of representative consumers for accurate subsidy level determination.

Given the uncertainties surrounding hydrogen technology in aviation, subsidies may be most effectively administered at the airport level, particularly for publicly owned airports. Such airports aim to maximize local social welfare and enhance consumer experiences, ultimately benefiting both commercial revenue and the local economy. Furthermore, airports are better positioned to monitor the cost evolution of new technologies, allowing for adjustments to subsidy amounts based on efficiency gains and consumer quality valuations. These uncertainties, particularly regarding hydrogen-powered aircraft, may help reduce unit costs and enhance profitability through operational hedging combined with financial derivatives Swidan and Merkert (2019).

In summary, our model indicates that the most effective regulatory intervention involves taxes or subsidies. While taxing polluting energy is advisable in covered markets, it distorts behavior in uncovered markets. Therefore, green technology subsidies should be prioritized in such contexts, as they encourage adoption and contribute to market recovery. Regulators must identify optimal subsidy levels to enhance social welfare while adhering to budget constraints, promoting greater adoption of green technologies.

4.2 Non-Monetary Policies

Despite substantial support for economic incentives to foster pro-social behavior (e.g., Gibbons (1996), Prendergast (1999), Lazear (2000a), Lazear (2000b)), extrinsic incentives can sometimes undermine intrinsic motivation. For example, Titmuss (2018) argued that compensating blood donors could diminish overall supply, and Gneezy and Rustichini (2000) found that performance incentives might lead to reduced funds collected.

Our analysis suggests that social norms and pressures (honor and shame) play significant roles in motivating pro-social behavior Freeman (1997). This includes the influence of social glory or shame imitation (Batson et al., 1998) and self-image concerns (Bandiera and Rasul, 2006). Recognizing these values creates public value perceptions that can encourage pro-environmental behavior.

The literature demonstrates that individuals tend to contribute more when their actions are observable and when others participate (Murnighan et al., 2001). Thus, effective networking and advertising strategies that educate consumers about the environmental benefits of green technology are essential. Marketing strategies should emphasize terms such as "environmentally friendly" and highlight contributions to combating global warming on flight tickets for consumers choosing green technology.

From our review, it is clear that two critical aspects in persuading consumers to adopt green innovations are the reliability and efficiency of these technologies. Advertising should inform consumers that opting for innovative products can significantly benefit future generations and the planet. Consequently, modeling final consumer demand should incorporate Goal-Framing Theory, as articulated by Bénabou and Tirole (2006). Final consumers are influenced by ticket prices and greenhouse gas emissions, shaping stakeholders' strategies.

Moreover, non-monetary policies to enhance consumer environmental awareness are equally vital. For instance, Nyborg et al. (2006) indicate that campaigns emphasizing the environmental benefits of green products can effectively change consumer behavior. Similarly, Kalamas et al. (2014) highlight that public advertising can bridge the gap between consumer intentions and concerns. Thus, promoting carbon footprint information can motivate consumers to select lower-emission options (Motoshita et al., 2015). Informative advertising is critical to prevent free-riding, particularly as many consumers maintain a distinct "green image" for airlines, separate from their general attitudes toward the airline's actual environmental friendliness Hagmann et al. (2015).

In conclusion, our findings suggest that combining monetary and non-monetary policies can significantly enhance the adoption of green technologies in air transport. By implementing targeted subsidies, conducting educational campaigns, and leveraging social norms, regulators can effectively facilitate a transition towards more sustainable practices in the industry.

5 Conclusion

This paper presents a robust model to analyze the adoption of green technology in the airline industry under market shock conditions. We demonstrate how green technology can introduce vertical differentiation based on consumer behavior towards environmental consciousness, transitioning an uncovered market to a covered market, particularly relevant in the post-COVID-19 context.

Our findings underscore the significant role of consumer valuation for green technology quality and ecological consciousness in shaping market dynamics. By constructing various scenarios, we elucidate how green technology adoption can address critical gaps in the literature regarding market coverage during technological transitions.

Moreover, the research offers essential policy implications, highlighting the importance of increasing consumer awareness and efficiency gains from green technology in driving market evolution. These insights are invaluable for policymakers aiming to promote green technology adoption in the airline industry.

Future research should investigate the roles of airports and technology providers, as regulation and competition policies at the airport level could significantly impact adoption strategies.

In summary, this study advances our understanding of green technology adoption under market shocks while laying the groundwork for future research and policy development aimed at promoting sustainable practices in the airline industry.

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Appendices

A Scenario 1: (L, L) under uncovered market

Participation constraint of firm 1 with incumbent technology:
$l_1 - \sqrt{\frac{R+\theta s_L - p_1}{t}} \leq x \leq l_1 + \sqrt{\frac{R+\theta s_L - p_1}{t}}$.

Participation constraint of firm 2 with incumbent technology:
$l_2 - \sqrt{\frac{R+\theta s_L - p2}{t}} \leq x \leq l_2 + \sqrt{\frac{R+\theta s_L - p_2}{t}}$.

Then the market coverage threshold is $\bar{R} = \frac{(4p_1-4p_2)^2+8p_1t+8p_2t-16\theta s_Lt+t^2}{16t}$. If the market is uncovered market, firms can keep acting like a monopoly in their part of market.

The demand for the two firms are: $\begin{cases} D_1(p_1,p_2) = 2\sqrt{\frac{R+\theta s_{1L}-p_1}{t}} \\ D_2(p_1,p_2) = 2\sqrt{\frac{R+\theta s_{1L}-p_2}{t}} \end{cases}$

$$\begin{cases} \pi_1(p_1,p_2) = (p_1 - \alpha_L s_{1L}^2)2\sqrt{\frac{R+\theta s_{1L}-p_1L}{t}} - F_L \\ \pi_2(p_1,p_2) = (p_2 - \alpha_L s_{2L}^2)2\sqrt{\frac{R+\theta s_{2L}-p_2L}{t}} - F_L \end{cases} \Rightarrow \begin{cases} p_{1L} = \frac{\alpha_L s_{1L}^2+2R+2\theta s_{1L}}{3} \\ p_{2L} = \frac{\alpha_L s_{2L}^2+2R+2\theta s_{2L}}{3} \end{cases}$$

$$\Rightarrow \begin{cases} \pi_1(s_{1L},p_{2L}) = (p_1 - \alpha_L s_{1L}^2)2\sqrt{\frac{R+\theta s_{1L}-p_1L}{t}} - F_L \\ \pi_2(s_{1L},p_{2L}) = (p_2 - \alpha_L s_{2L}^2)2\sqrt{\frac{R+\theta s_{2L}-p_2L}{t}} - F_L \end{cases} \Rightarrow \begin{cases} s_{1L} = \frac{\theta}{2\alpha_L} \\ s_{2L} = \frac{\theta}{2\alpha_L} \end{cases} or \begin{cases} s_{1L} = \frac{\sqrt{\alpha_L s_{1L}+\theta^2}+\theta}{2\alpha_L} \\ s_{2L} = \frac{\sqrt{\alpha_L s_{2L}+\theta^2}+\theta}{2\alpha_L} \end{cases}$$

$$\begin{cases} \pi_1(p_1,p_2) = (p_1 - \alpha_L s_{1L}^2)2\sqrt{\frac{R-p_1L}{t}} - F_L \\ \pi_2(p_1,p_2) = (p_2 - \alpha_L s_{2L}^2)2\sqrt{\frac{R-p_2L}{t}} - F_L \end{cases} \Rightarrow \begin{cases} p_1 = \frac{\alpha_L s_{1L}^2+2R}{3} \\ p_2 = \frac{\alpha_L s_{2L}^2+2R}{3} \end{cases}$$

Firms produce if profits are non-negative, implying $\alpha_L s_L^2 < R$. Since duopoly chooses the same technology, the strategy set is symmetric. Firms set the same price as a function of variable costs and residual utility. The second derivative with respect to price is negative $\frac{\partial^2 \pi_L(p_1,p_2)}{\partial {p_L}^2} = \frac{3p_L+\alpha_L s_L^2-4R}{2t^2(\frac{R-p_L}{t})^{\frac{3}{2}}} < 0$, because $R > p_L$ and $R > \alpha_L s_L^2$).

The second-order condition for the price is satisfied. In stage 2, firms choose quality. The increasing quality will decrease firms' profit. Therefore, firms will choose the lowest available quality. There is no incentive to set higher quality.

$$\begin{cases} \pi_1(s_{1H}, p_{2H}) = \frac{4(R-\alpha_L s_L^2)^{\frac{3}{2}}}{3\sqrt{3t}} - F_L \\ \pi_2(s_{1H}, p_{2H}) = \frac{4(R-\alpha_L s_L^2)^{\frac{3}{2}}}{3\sqrt{3t}} - F_L \end{cases} \Rightarrow \begin{cases} \frac{\partial \pi_1(s_1,s_2)}{\partial s_L} < 0 \\ \frac{\partial \pi_2(s_1,s_2)}{\partial s_L} < 0 \end{cases}$$

If $\underline{s_L} = 0$, the consumers surplus equal to $CS^0 = \frac{8R\sqrt{\frac{R}{t}}}{9\sqrt{3}}$. Under this uncovered market ($R < \alpha_L s_L^2 + \frac{3t}{16}$), consumers surplus is low. Social welfare is the sum of consumers' surplus and firms' profits: $\frac{8R^{\frac{3}{2}}}{9\sqrt{3t}} + 2\frac{4R^{\frac{3}{2}}}{3\sqrt{3t}} - 2F_L = \frac{32R^{\frac{3}{2}}}{9\sqrt{3t}} - 2F_L$.

The consumers lie in $[\frac{1}{4} - \sqrt{\frac{R-\alpha_L s_L^2}{3t}}, \frac{1}{4} + \sqrt{\frac{R-\alpha_L s_L^2}{3t}}] \cup [\frac{3}{4} - \sqrt{\frac{R-\alpha_L s_L^2}{3t}}, \frac{3}{4} + \sqrt{\frac{R-\alpha_L s_L^2}{3t}}$. The residual utility $R < \bar{R} = \frac{\alpha_L s_L^2 + 2R}{3} + \frac{t}{16}$, thus $R < \alpha_L s_L^2 + \frac{3t}{16}$. Therefore, $\alpha_L s_L^2 < R < \alpha_L s_L^2 + \frac{3t}{16}$, which is always true because transportation costs is positive.

B Scenario 2: the green technology becomes available

B.1 The case (H, H) under the covered market

The indifferent consumers locates at $\widetilde{x} = \frac{t(l_1)^2 - t(l_2)^2 + p_1 - p_2}{2l_1 t - 2l_2 t}$.

The demand after the introduction of green technology becomes $\begin{cases} D_1 = \widetilde{x} \\ D_2 = 1 - \widetilde{x} \end{cases}$.

$$\begin{cases} \pi_1(p_1, p_2) = (p_1 - \alpha_H s_{1H}^2)\frac{tl_1^2 - tl_2^2 + p1 - p_2}{2l_1 t - 2l_2 t} - F_H \\ \pi_2(p_1, p_2) = (p_2 - \alpha_H s_{2H}^2)(1 - \frac{tl_1^2 - tl_2^2 + p1 - p_2}{2l_1 t - 2l_2 t}) - F_H \end{cases}$$

$$\Rightarrow \begin{cases} p_{1H} = \alpha_H s_{1H}^2 + \frac{t}{3}(l_2^2 - l_1^2 - 2l_1 + 2l_2) \\ p_{2H} = \alpha_H s_{1H}^2 + \frac{t}{3}(l_1^2 - l_2^2 - 4l_1 + 4l_2) \end{cases}$$

The second order conditions for both firms are satisfied, since $\frac{\partial^2 \pi_1(p_1,p_2)}{\partial {p_1}^2} = \frac{2p_1}{2t(l_1-l_2)} < 0$ and $\frac{\partial^2 \pi_2(p_1,p_2)}{\partial {p_2}^2} = \frac{p_2}{2t(l_1-l_2)} < 0$, because $l_1 < l_2$.

In stage 1, firms choose their location. This maximum differentiation result is in line with the standard Hotelling model.

$$\begin{cases} \pi_1(l_1,l_2) = \frac{t}{18}(l_2-l_1)(l_1+l_2+2)^2 - F_H \\ \pi_2(l_1,l_2) = \frac{t}{18}(l_2-l_1)(l_1+l_2-4)^2 - F_H \end{cases}$$

$$\Rightarrow \begin{cases} \frac{\partial \pi_1(l_1,l_2)}{\partial l_1} = -\frac{t}{18}(3l_1^2+2l_1(4+l_2)-l_2^2+4) < 0 \\ \frac{\partial \pi_2(l_1,l_2)}{\partial l_2} = -\frac{t}{18}(l_1+l_2-4)(l_1-3l_2+4) < 0 \end{cases}$$

$$\Rightarrow \begin{cases} l_1^* = 0 \\ l_2^* = 1 \end{cases} \begin{cases} p_1^* = \alpha_H s_{1H}^2 + t \\ p_2^* = \alpha_H s_{1H}^2 + t \end{cases} \begin{cases} \pi_1^* = \frac{t}{2} - F_H \\ \pi_2^* = \frac{t}{2} - F_H \end{cases}$$

Firms will stay on this strategy choice, if they earn at least as the same in case (L, L), then $\frac{t}{2} - F_H \geq \frac{4(R-\alpha_L s_L^2)^{\frac{3}{2}}}{2\sqrt{3t}} - F_L$. Covered market condition: $R + H \leq p_H + \frac{t(l_1-l_2)^2}{16}$, then $H \geq \alpha_H s_H^2 + \frac{17t}{16} - R$.

Therefore, the sustainable condition is $\alpha_H s_H^2 + \frac{17t}{16} - H \leq R \leq (\frac{3\sqrt{3t}}{4}(\frac{t}{2} - F_H + F_L))^{\frac{2}{3}} - \alpha_L \underline{s}^2$. Or $H \leq \alpha_H s_H^2 + \frac{17t}{16} - R$ and $H \leq \frac{3\sqrt{3t}}{4}(\frac{t}{2} - F_H + F_L)]^{\frac{2}{3}} - \alpha_L \underline{s}^2$

$CS = R + H - \alpha_H s_H^2 - \frac{13t}{12}$ Social welfare: $R + H - \alpha_H s_H^2 - t/12 - 2F_H$, where $H \leq \alpha_H s_H^2 + \frac{17t}{16} - R$

B.2 The case (H, H) under uncovered market

Participation constraint of firm 1 in choosing green technology:
$\frac{1}{4} - \sqrt{\frac{R+\theta s_H - p_1}{t}} \leq x \leq \frac{1}{4} + \sqrt{\frac{R+\theta s_H - p_1}{t}}$.

Participation constraint of firm 2 in choosing green technology:
$\frac{3}{4} - \sqrt{\frac{R+\theta s_H - p2}{t}} \leq x \leq \frac{3}{4} + \sqrt{\frac{R+\theta s_H - p_2}{t}}$.

Then the market coverage threshold is $\bar{R} = \frac{(4p_1-4p_2)^2+8p_1t+8p_2t-16\theta s_H t+t^2}{16t}$ If the market is uncovered, firms can keep acting like a monopoly in their part of the market.

$$\begin{cases} \pi_1(p_1,p_2) = (p_1 - \alpha_H s_{1H}^2)2\sqrt{\frac{R+\theta s_{1H} - p_1 H}{t}} - F_H \\ \pi_2(p_1,p_2) = (p_2 - \alpha_H s_{2H}^2)2\sqrt{\frac{R+\theta s_{2H} - p_2 H}{t}} - F_H \end{cases} \Rightarrow \begin{cases} p_{1H} = \frac{\alpha_H s_{1H}^2 + 2R + 2\theta s_{1H}}{3} \\ p_{2H} = \frac{\alpha_H s_{2H}^2 + 2R + 2\theta s_{2H}}{3} \end{cases}$$

$$\Rightarrow \begin{cases} \pi_1(s_{1H}, p_{2H}) = (p_1 - \alpha_H s_{1H}^2) 2\sqrt{\frac{R+\theta s_{1H} - p_1 H}{t}} - F_H \\ \pi_2(s_{1H}, p_{2H}) = (p_2 - \alpha_H s_{2H}^2) 2\sqrt{\frac{R+\theta s_{2H} - p_2 H}{t}} - F_H \end{cases}$$

$$\Rightarrow \begin{cases} s_{1H} = \frac{\theta}{2\alpha_H} \\ s_{2H} = \frac{\theta}{2\alpha_H} \end{cases} \quad or \begin{cases} s_{1H} = \frac{\sqrt{\alpha_H s_{1H} + \theta^2} + \theta}{2\alpha_H} \\ s_{2H} = \frac{\sqrt{\alpha_H s_{2H} + \theta^2} + \theta}{2\alpha_H} \end{cases}$$

$s_{1H} = s_{2H} = s_H$

If $s_H = \frac{\sqrt{\alpha_H s_{1H} + \theta^2} + \theta}{2\alpha_H}$, this means that the variable costs is equal to consumers' willingness to pay. Both firms earn negative profit $\pi_H = -F_H < 0$—this is not the optimal quality strategy.

If $s_{1H} = \frac{\theta}{2\alpha_H}$, $\pi_H = \frac{4\left(R+\theta\frac{\theta}{2\alpha_H} - \frac{\theta^2}{4\alpha_H}\right)^{\frac{3}{2}}}{3\sqrt{3t}} - F_H = \frac{4\left(R+\frac{\theta^2}{4\alpha_H}\right)^{\frac{3}{2}}}{3\sqrt{3t}} - F_H$. Firms have incentive to stay at this case if and only if they make more profit than status quo scenario. $\pi^2\left(p_H^2\right) \geq \pi^0\left(p_L^0\right)$, $\frac{4\left(R+\frac{\theta^2}{4\alpha_H}\right)^{\frac{3}{2}}}{3\sqrt{3t}} - F_H \geq \frac{4(R)^{\frac{3}{2}}}{3\sqrt{3t}} - F_L$. Then, we compute the profitability condition, denote Condition B:
$\theta \geq \theta_B = \sqrt{2^{\frac{2}{3}}\left(\alpha_H{}^3\left(27t(F_H - F_L)^2 + \ 24\sqrt{3}\ R^{\frac{3}{2}}\sqrt{t}(F_H - F_L) + 16R^3\right)\right)^{\frac{1}{3}} - 4\alpha_H R}.$

Uncovered market requires that $U\left(\frac{1}{2}\right) = 0$ with the $(\frac{1}{4}, \frac{3}{4})$ location:
$\theta > \sqrt{4\alpha_H(3t - 16R)}$. Denote this Condition C2. Firms have no incentive to change location for when θ lies in Condition B and Condition A. This is an equilibrium. Then, the strategy set $\mathcal{S}\left(p_1, p_2; s_1, s_2; l_1, l_2\right) = \left(\frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R, \frac{5\theta^2}{12\alpha_H} + \frac{2}{3}R; \frac{\theta}{2\alpha_H}, \frac{\theta}{2\alpha_H}; \frac{1}{4}, \frac{3}{4}\right)$

The consumer surplus:

$$\begin{aligned} &\int_{\frac{1}{4}-\sqrt{\frac{R+\theta s_H - \alpha_H s_H^2}{3t}}}^{\frac{1}{4}+\sqrt{\frac{R+\theta s_H - \alpha_H s_H^2}{3t}}} \left(R + \theta s_H - p_1 - t\left(\frac{1}{4} - x\right)^2\right) dx \\ &+ \int_{\frac{3}{4}-\sqrt{\frac{R+\theta s_H - \alpha_H s_H^2}{3t}}}^{\frac{3}{4}+\sqrt{\frac{R+\theta s_H - \alpha_H s_H^2}{3t}}} \left(R + \theta s_H - p_2 - t\left(\frac{3}{4} - x\right)^2\right) dx \\ &= \left(\frac{8}{9\sqrt{3t}}\right)\left(R + \frac{\theta^2}{4\alpha_H}\right)^{\frac{3}{2}} + \frac{4}{3}(R + \frac{\theta^2}{4\alpha_H}) - \frac{5\sqrt{t}}{4\sqrt{3}}\sqrt{R + \frac{\theta^2}{4\alpha_H}} \end{aligned}$$

C Scenario 3: green technology is also a moral relief

The proof of scenario 3 is similar to scenario 2. We simply need to change the notation of the transportation cost, except the asymmetric case (L, H) or (H, L).

C.1 The asymmetric choose

In stage 4, consumer purchase. The participation constraint of firm 1 in choosing incumbent technology: $l_L - \sqrt{\frac{R-p_L+s_L\theta}{s_H}} \leq x \leq l_L + \sqrt{\frac{R-p_L+s_L\theta}{s_H}}$. Participation constraint of firm 2 in choosing green technology: $l_H - \sqrt{\frac{R+s_H\theta-p_H}{s_L}} \leq x \leq l_H + \sqrt{\frac{R+s_H\theta-p_H}{s_L}}$. The demand are

$$\begin{cases} D_L = 2\sqrt{\frac{R-p_L+s_L\theta}{s_H}} \\ D_H = 2\sqrt{\frac{R-p_L+s_H\theta}{s_L}} \end{cases} \tag{20}$$

In stage 3, firms set their best price strategy in this uncovered market according to their profit function. $\begin{cases} \pi_L = (p_L - \alpha_L s_L^2)2\sqrt{\frac{R-p_L+s_L\theta}{s_H}} - F_L \\ \pi_H = (p_H - \alpha_H s_H^2)2\sqrt{\frac{R-p_L+s_H\theta}{s_L}} - F_H \end{cases} \Rightarrow \begin{cases} p_L = \frac{\alpha_L s_L^2+2R+2s_L\theta}{3} \\ p_H = \frac{\alpha_H s_H^2+2R+2s_H\theta}{3} \end{cases}$

In stage 2, firms choose whether to adopt the new technology and their optimal quality level.

$$\begin{cases} \pi_L = \frac{4(R+\theta s_L-\alpha_L s_L^2}{3\sqrt{3s_H}} - F_L \\ \pi_H = \frac{4(R+\theta s_H-\alpha_H s_H^2}{3\sqrt{3s_L}} - F_H \end{cases} \Rightarrow \begin{cases} p_L = \frac{\alpha_L s_L^2+2R+2s_L\theta}{3} \\ p_H = \frac{\alpha_H s_H^2+2R+2s_H\theta}{3} \end{cases}$$

In this setting, the airline's profit depends not only on the quality of its own product but also on the quality level of the competitor. The quality strategy depends only on the firm's own costs parameter because the competitor's quality is on the denominator of the first-order condition. Both firms choose a positive quality level because higher quality is associated with greater demand and higher competitors' transportation costs. If there is efficiency gain for the green technology, i.e., $\alpha_H < \alpha_L$, both firms will choose green technology, increasing their profit. In any case, when the new technology improves the product's suitability, firms are willing to choose higher quality.

When $\mathcal{S}(p_L, p_H; s_L, s_H) = (\frac{2R}{3} + \frac{5\theta^2}{12\alpha_L}, \frac{2R}{3} + \frac{5\theta^2}{12\alpha_H}; \frac{\theta}{2\alpha_L}, \frac{\theta}{2\alpha_H})$, the profits are $(\pi_L, \pi_H) = (\frac{4\sqrt{2\alpha_H}\left(R+\frac{\theta^2}{4\alpha_L}\right)^{\frac{3}{2}}}{3\sqrt{3\theta}} - F_L, \frac{4\sqrt{2\alpha_L}\left(R+\frac{\theta^2}{4\alpha_H}\right)^{\frac{3}{2}}}{3\sqrt{3\theta}} - F_H)$. Firms will stay with this strategy set if it is profitable, i.e. $\frac{4\sqrt{2\alpha_L}\left(R+\frac{\theta^2}{4\alpha_H}\right)^{\frac{3}{2}}}{3\sqrt{3\theta}} -$

$F_H > \frac{4\sqrt{2\alpha_H}\left(R+\frac{\theta^2}{4\alpha_L}\right)^{\frac{3}{2}}}{3\sqrt{3\theta}} - F_L$ and if the market environment do not change (uncovered market). When market is covered again, consumers lie in $\left[0, 2\sqrt{\frac{2\alpha_H}{3\theta}(R+\frac{\theta^2}{4\alpha_L})}\right] \cup \left[1-2\sqrt{\frac{2\alpha_L}{3\theta}(R+\frac{\theta^2}{4\alpha_H})}, 1\right]$. To found the threshold for covered market can be found by: $2\sqrt{\frac{2\alpha_H}{3\theta}(R+\frac{\theta^2}{4\alpha_L})} = 1-2\sqrt{\frac{2\alpha_L}{3\theta}(R+\frac{\theta^2}{4\alpha_H})}$, denote Condition C3bis.

In stage 1, firms choose their location (horizontal differentiation strategy).

$l_L \left(\sqrt{\frac{2\alpha_H}{3\theta}\left(R+\frac{\theta^2}{4\alpha_L}\right)}, \frac{1}{4}\right)$; l_H $(1-\sqrt{\frac{2\alpha_L}{3\theta}\left(R+\frac{\theta^2}{4\alpha_H}\right)}, \frac{3}{4}))$.

C.2 Profitability and market coverage condition

This appendix will compute the profitability and market coverage conditions for scenario 3. The equilibrium is sustainable if the airlines' profit is higher than the status quo scenario with the incumbent technology, i.e., scenario 1.

The profitability condition for the airline to adopt the green technology when the other airline stays at incumbent technology is as followed: $\theta \geq \theta_{B.bis}$,
where $\theta_{B.bis} = \sqrt{2^{\frac{2}{3}}\left(\alpha_H{}^3\left(27s_L(F_H-F_L)^2 + 24\sqrt{3}\ R^{\frac{3}{2}}\sqrt{s}_L(F_H-F_L)+16R^3\right)\right)^{\frac{1}{3}} - 4\alpha_H R}$.

We remark that theta $\theta_{B.bis}\theta_B$ because the transportation costs is lower in scenario 3.

The market is fully recovered when the total demand equals the market mass, i.e., the unit one mass of consumers.