Competing on Emission Charges

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Short summary

This research presents a game-theoretic model to analyse market equilibria in the presence of environmental policies at national and supranational levels. In a two-stage game, regulators maximise welfare over their jurisdiction by setting emission charges, whilst airlines compete through frequencies, fares, and fleet choice. Consequently, airlines decide whether to absorb the costs of the environmental charges, pass them on to consumers, replace part of their fleet with more efficient aircraft or redistribute the inefficient fleet to less regulated itineraries. The equilibria outcomes suggest the presence of several distorting forces that can undermine the effectiveness of environmental policies. To assess the robustness of our results, we apply the model to North American and Western European markets, under different regulatory setting, finding that a reduction in the emissions produced comes at the expense of the welfare and that the effectiveness of the policy is limited when regulators interact in their own interests.
Keywords: Decarbonization of transport, Transport economics and policy, Operations research applications, Discrete choice modelling.

1 Introduction

Within the transportation domain, the aviation industry currently produces 5% of global anthropogenic carbon dioxide (CO_2) emissions, and this is expected to continue to increase by 2050 (Lee et al., 2021; Kwan & Rutherford, 2015). Decision makers at the local, national, and supranational levels have mandated various environmental policies in an attempt to control aviation emissions (Larsson et al., 2019). However, the strength and environmental efficiency of these measures vary widely. Furthermore, since airlines operate globally, policymakers need information on how airlines respond to different, often overlapping, policies, to ensure that their interventions balance the carbon footprint of aviation with its wider economic and connectivity benefits.

Despite increasing understanding in recent years of the negative impacts derived from emissions, no effective and globally accepted emission control mechanism has yet been implemented. Many governments have developed unilateral emissions reduction schemes to regulate emissions production and to limit climate change. However, the lack of coordination among countries' policymakers likely generates suboptimal outcomes. A clear example is given by the presence of multiple, overlapping policies to address aviation emissions, such as the EU-ETS applied alongside Member States' ticket taxes and CORSIA. Another source of inefficiency that arises from the lack of coordination between countries manifests itself in the form of emissions leakage from heavily regulated countries to those jurisdictions in which the schemes are less strict (Baylis et al., 2013; Nordhaus, 2015; Perino et al., 2019). In addition, other market failures, such as firms' market power, will result in a departure from the standard first-best formulation in which government intervention addresses negative externalities by imposing a Pigouvian tax (Pigou, 1924) equal to the marginal external costs (Pels & Verhoef, 2004).

This calls for a game-theoretic framework to analyse how non-cooperative regulators at different administrative levels will set environmental policies strategically and how firms will subsequently react to such mechanisms. Given the complexity and numerous market distortions in the aviation industry, it is necessary to represent a realistic framework capable of including these industry-specific components. Our focus on the case of airline environmental regulation coincides with rapidly growing concerns about the impact of aviation emissions, and fragmentation in the aviation environmental regulatory setting offers an appropriate context for an applied game-theoretic approach.

The purpose of this paper is to develop a game-theoretic model that assesses the impact of environmental policies in the aviation industry, taking into account both airline and regulatory competition. Specifically, our objective is to investigate how airlines respond to policies instigated by multiple non-cooperative policymakers at different administrative levels that set rules according to their own objectives. Our model allows to analyse and understand the policy implications deriving from the competition of multiple regulators and compare them to the implementation of an optimal global policy. We identify the cases in which a carbon charge may result in effective environmental policy and those in which the implementation of such a policy would fail due to divergence in regulator objectives. This style of game represents a novelty in the (air) transportation literature and may be used to analyse environmental and regulatory issues in other network industries.

2 Methodology

We define our game-theoretic model as a two-stage Nash game with perfect information. The set of players in the first-stage is characterised by the different regulators of the countries in which airlines are based and/or supranational decision-makers. In the first-stage, each regulatory body aims to maximise the social welfare of the area under its control by setting the level of environmental taxation to be applied. The regulator may reduce (global) environmental damages by setting a relatively high environmental tax, but this may come at a cost to both (local) consumer and producer surplus. Consequently, regulators compete on the entire level of emissions produced considering how much they are susceptible to the environmental damage resulting from these emissions. In the second-stage, airlines compete with each other by setting airfares and service frequencies through their best response functions, pursuing profit maximisation. To respond to changes in the climate policies, airlines may replace inefficient aircraft with more environmentally friendly technologies, fly their higher-emission aircraft less, reallocate their higher-emission aircraft to routes with less environmental taxation or reduce frequencies on regulated routes.

We define a hub-and-spoke network, $G(\mathcal{N}, \mathcal{K})$, where the nodes are connected to the spokes through ordered legs within the set $\mathcal{K}$, allowing indirect connections between the spokes passing through the hub airport.
Given the network configuration, airlines are subject to different levels of climate policies imposed by regulators. The sets belonging to the area of influence of a specific regulator are defined as:

$$\mathcal{N}^r = \{i^r, j^r | i^r, j^r \in \mathcal{N}, i^r \text{ and } j^r \text{ are nodes in the area regulated by } r\}$$

$$\mathcal{A}^r = \{a^r | a^r \in \mathcal{A}, a^r \text{ is an airline serving the area regulated by } r\}$$

$$\mathcal{K}^r = \{k^r | k^r \in \mathcal{K}, k^r \text{ is a network leg served by an airline based in the area regulated by } r\}$$

In the first stage, regulators maximise the social welfare of the area under their influence. Welfare is composed of four main components: passenger surplus, producer profits, government income from environmental taxation and environmental damages.

$$\begin{aligned} \underset{\theta_r}{Max}\ SW_r = & \sum_{i^r jt} d_{i^r jt} \frac{1}{-\beta_{2t}} ln \left(e^{V_0 + \sum_a V_{i^r jta}(f^*_{kva}, p^*_{i^r jta})} \right) + \sum_{a^r \in \mathcal{A}^r} \pi_{a^r} \left(f^*_{k^r va^r}, p^*_{ijta^r}, x^*_{hva^r}, \theta_r \right) \\ & + \sum_{k^r va} \varepsilon_{k^r v} f^*_{k^r va} \theta_r - \eta_r \sum_{kva} \varepsilon_{kv} \xi f^*_{kva} \end{aligned} \quad (1)$$

where

$$\varepsilon_{kv} = \gamma_k \phi_{hv} co_2$$

is the ton of CO_2 produced on a flight leg k by a specific version of aircraft v. In 1, the first element represents the consumer surplus, expressed as the log-sum of the utility of passengers departing from the jurisdiction of the regulator (Small & Rosen, 1981). The second element represents the profit generated by airlines certified within the jurisdiction of the regulator. The third element is the income from the carbon charge imposed on CO_2 generated over the regulated arcs and the last element expresses the share η_r of the overall social cost of emissions that the regulator takes into account. The decision variable for the regulatory entity is the charge per ton of carbon (θ_r) originating from a flight departing from its jurisdiction, taking into account the behavior of the other regulatory agencies and the airlines' responses to carbon charges in the second-stage.

Regulators are encouraging the internalization of environmental externalities, which are public goods. The aviation industry belonging to each regulator contributes to the total amount of emissions produced while providing connectivity between regions. However, not all regions are affected in the same way by emissions. Specifically, we allow for different degrees of risk exposure through the parameter η_r. In this way, regulators have the incentive to free-ride on the emissions reduction achieved by the actions of competing regulators. All CO_2 emissions generated by civil aviation bear a social cost common to all regulators, namely the (global) social cost of carbon represented by the parameter ξ. This social cost is homogeneous over the regions given the global impact of carbon emissions on the environment, however the exposure or distribution of this impact varies over regions. In our game, regulators can trade off environmental externalities with the surplus of passengers and carriers (profits) in their region by deciding the level of taxation on CO_2 in their jurisdiction. Consequently, the regulator's decisions are strictly connected to other regulators' actions, creating competition across jurisdictions.

We assume that passengers are utility maximizers when selecting the airline and the itinerary for their trip. According to McFadden (1974), utility can be decomposed into a systematic component, V_{ijsa} and a random element, ϵ_{ijsa}:

$$U_{ijta} = V_{ijta} + \epsilon_{ijta}, \quad \forall i, j \in \mathcal{N},\ t \in \mathcal{T},\ a \in \mathcal{A} \tag{2}$$

The systematic component is defined in the following way:

$$\begin{aligned} V_{ijta} =& \beta_{0t}\delta_{ija} + \beta_{1t} ln\left(1 + \min_{k^* \in \mathcal{K}}(f_{ka})\right) + \beta_{2t} p_{ijta} + \beta_{3t}\tau_{ija}, \\ & \forall i, j \in \mathcal{N},\ t \in \mathcal{T},\ a \in \mathcal{A} \end{aligned} \tag{3}$$

where δ_{ija} is the component of the utility associated with a direct connection and the second term represents the utility of a higher service frequency. When flying indirectly, only the lower frequency of the two legs is taken into account (Hansen (1990)). The third element represents the disutility from paying the ticket fare and the last represents the loss of utility generated by the travel time τ_{ija}. Consequently, demand is shared between airlines through a multinomial-logit model (MNL) that determines market shares:

$$m_{ijta} = \frac{e^{V_{ijta}}}{e^{V_0} + \sum_{a' \in \mathcal{A}} e^{V_{ijta'}}}, \quad \forall i, j \in \mathcal{N},\ t \in \mathcal{T},\ a \in \mathcal{A} \tag{4}$$

where the term V_0 is the utility associated with the outside-option from not flying.

According to Swan & Adler (2006), the direct operating cost of the airline is defined through a cost function that differentiates between long- and short-haul flights.

$$C_{kv} = \begin{cases} (\gamma_k + 722)(s_{kv} + 104)\$0.019 & \text{if } k \in \mathcal{K}^s \\ (\gamma_k + 2200)(s_{kv} + 211)\$0.0115 & \text{if } k \in \mathcal{K}^l \end{cases} \tag{5}$$

where

$$\mathcal{K}^s = \{k^s | k^s \in \mathcal{K} \text{ are the short-haul legs served}\}$$

$$\mathcal{K}^l = \{k^l | k^l \in \mathcal{K} \text{ are the long-haul legs served}\}$$

The monthly cost of owning an aircraft (o_{hv}) is approximated by the equivalent annual capital costs divided by the number of months per year.

In the second stage, airlines maximize their profits, given the environmental charges imposed by regulators in the first stage. Each airline strategically sets the service frequency of each version of aircraft f_{kva} per leg, the fares p_{ijta} on the itineraries between an origin and destination and the optimal number and version of the aircraft x_{hva} to operate given their network.

$$\underset{p_{ijta},f_{kva},x_{hva}}{Max} \pi_a = \sum_{\substack{i,j,t \\ i\neq j}} d_{ijta} m_{ijta} p_{ijta} - \sum_{k,v} C_{kv} f_{kva} - \sum_{k^r,v} \varepsilon_{k^r v} \theta_r f_{k^r va} - \sum_{h,v} o_{hv} x_{hva} \tag{6}$$

where m_{ijsa} is the market share function specified in 4, representing the share of demand served by a specific airline a for each city pair and passenger type, C_{kv} represents the operating costs, defined in 5, incurred by the airline for serving a specific leg, o_{hv} is the monthly ownership cost of the type of aircraft h version v and x_{hva} is the number of aircraft of type h and version v that carrier a operates in its network.

The competition framework for regulators and airlines is structured as an extensive form game with complete and perfect information (Osborne & Rubinstein, 1994). In this model, players make strategic decisions sequentially in two stages. This allows second-stage players to decide their strategy in response to the decisions of first-stage players. The actions of the regulators, in the first-stage, are represented by the environmental charges imposed on airlines, while, in the second-stage, airlines react by choosing service frequency, ticket fares and the number of new and old version aircraft to deploy.
It is possible to solve this two-stage simultaneous game using a Kuhn-Zermelo-type backward induction algorithm (Schwalbe & Walker, 2001), as described in 1. The algorithm starts by initialising the values for the first and second-stages. Successively, the algorithm solves the first-stage problem for each regulator in the set $\mathcal{R}$, moving to estimate the sub-game perfect Nash equilibrium (SPNE) in the second stage for each airline and continuing until no airline changes the values of their decisions variables. The second stage, non-linear mathematical programs are solved using *IPOPT* (Wächter & Biegler (2006)). Following the approach used in Adler et al. (2022), the first-stage algorithm performs a line search around each regulator's incumbent solution starting at + and - 50% and gradually decreasing to the point in which a further reduction would not improve the integer solution. A cycle is completed once all regulators have chosen their current optimal carbon tax. The equilibrium of the game is found when two cycles are completed such that no actor in the game changes the values of their decision variables.
The robustness of the results is tested by selecting different starting points and sequences of players within each specific set of players.

3 Results and discussion

Figure 1: Selected nodes in North America and Western Europe.

Algorithm 1 Solve the two-stage game (pseudo-code)

```
Start
initialise values of competitors' decision variables and their network, for regulators and airlines
while first-stage solution > optimal threshold do:
    while first-stage solution is not a best response for all regulators do:
        for each regulator do:
            create point grid around previous first-stage solution
            for each point in grid do:
                while second-stage solution not a best response for airlines do:
                    for each airline do:
                        solve mathematical program using IPOPT
                    assess whether second-stage solution is a best response for all airlines
                return second-stage solution
            return second-stage solution for each point
            select the point that maximises welfare
        return first-stage solution for each regulator
    shrink grid radius
return first and second-stage solutions
Stop
```

In this section, we analyse a game that describes the aviation markets of North America and Europe. We assume a social cost of carbon of €200, according to the latest IPCC report (Pörtner et al., 2022). Our network covers 9% of the monthly traffic within and between Europe and North America.

The baserun, presented in Table (1) aims to replicate the 2019 transport equilibria outcome taking into account the European carbon charge in order to replicate the EU-ETS scheme. After accounting for free permits, we assume that the cost of carbon in 2019 was approximately €22 per ton of CO_2 produced. The results from the baserun case show that, despite the higher demand in North America, the European market generates a higher surplus than that of North American. This discrepancy between the two regions is due to the disutility faced by North American passengers who paid a higher fare than their European counterparts in 2019 and have a regional network characterized by longer distances. Thus, higher fares are the result of operating costs in North America and the presence of fewer alternative modes of transport, resulting in North American passengers being more dependent on aviation. Given the higher demand in North America, both LCCs and legacy carriers operate more flights in this region compared to Europe. As a result of higher fares and higher demand, North American carriers are more profitable than European airlines, despite the higher operating costs incurred by North American airlines. Regarding CO_2 emissions, we note that European carriers spent around €8 million in the monthly game covering 9% of the European market (equivalent to €1 billion for the entire market in 2019) and emission damages amounted to a total of €29 billion across the two regional markets (EU and NA) and Trans-Atlantic (TA) routes.

Table 1: Baserun scenario

	Baseline	
	EU	NA
θ_r (€)	22	
Government surplus (€ M)	8	
Emissions (€M)	-110	-110
Consumer surplus (€M)	942	683
Producer surplus (€M)	102	139
Welfare (€M)	942	712

Table 2: Validation (real world values in brackets)

	CASK (€c)	RASK (€c)	Demand, two-way (pax. M)		
			EU	NA	TA
EU legacy	7.2 (7.1)	9.1 (7.7)			
NA legacy	6.4 (6.4)	7.9 (8.7)			
EU LCC	4.2 (4.3)	5.3 (4.8)	4.7 (4.7)	5.7 (4.9)	0.5 (0.4)
NA LCC	5.3 (5.9)	6.2 (6.5)			

The second scenario explores the impact of a global regulator who sets a single charge per ton of CO_2 generated in all aviation markets. There is no possibility of free-riding in this scenario because the single regulator fully bears the costs of all generated emissions ($\eta_r = 1$). The results of the model, presented in Table (3), suggest that the optimal charge set by the regulator is much lower than the expected Pigouvian tax, which should compensate for the social costs of the carbon equal to €200 per tonne of CO_2 produced. This is due to the airlines' market power and the Mohring effect, both of which induce the regulator to lower the tax. In the case of market power, the regulator is attempting to counter the output reduction of hubbing carriers that choose to serve fewer passengers with higher fares, thereby increasing their own profits but decreasing social welfare. The Mohring effect captures the idea that each additional passenger contributes towards higher frequency, hence the quality of the air travel services for all other passengers (Mohring, 1972). As these benefits are external to the passengers (i.e. they are positive externalities), too few passengers choose to travel from a societal perspective, which the regulator can address through subsidies. Consistent with the economic literature, these two effects lead to a lower carbon charge compared to the (marginal) social cost of carbon in our game.
It is also important to observe that, in our framework, a regulator is not able to discriminate across routes, and the charge is the same for all operations. Such a limitation may result in a sub-optimal tax, because charges cannot be tailored to local conditions (Benoot et al., 2013). As a result of this global scope policy, we observe a slight departure from the *base-run* scenario. Specifically, as a consequence of this marginal global charge, we do not observe significant changes in airline strategies. With regard to the environment, the imposition of a charge on the North American market too leads to a small reduction in the emissions generated.

Table 3: Single regulator scenario

	Baseline			*1REG*	Δ
	EU	NA	Sum	REG	
θ_r (€)	22	0	22	8	
Government surplus (€M)	8	0	8	10	
Emissions (€M)	-110	-110	-220	-219	1
Consumer surplus (€M)	942	683	1,624	1,623	-2
Producer surplus (€M)	102	139	241	241	0
Welfare (€ M)	942	712	1,654	1,655	-1

We now define scenario, *2REG*, in which two regulators, based in different regions, compete by setting emission charges on all flights departing from their jurisdiction. We assume that one regulator sets charges for all flights departing within and from North America, and similarly, within and from Europe. The environmental risk is distributed equally between the two regions. Given the round-trip assumption of each flight, operations within a region are charged twice by the same regulator. Trans-Atlantic flights are subject to both regulators' charges, one per direction. The results of our model for this scenario are reported in Table (4). We observe that competing regulators decide to free-ride on each other, resulting in charges that are much lower than the social cost of carbon. In this way, regulators protect the surplus of both passengers and carriers under their jurisdiction. Indeed, the results of this competing regulator case closely reflect the charges currently imposed by Europeans (EU-ETS price of €22) and North Americans (€0) in the real world in 2019. In North America, a higher charge would be welfare-damaging given the longer routes flown and the lower surplus of passengers resulting from higher fares. In Europe, where airfares and distances are lower and alternative modes compete with aviation, the regulator has a greater incentive to set a positive charge. As a consequence of the implementation of a small but positive tax on both continents, the airlines respond by slightly increasing airfares and moderately reducing service frequency.

Table 4: Two-regulator scenario

	Baseline		*2REG*		Δ	
	EU	NA	EU	NA	EU	NA
θ_r (€)	22	0	38	4	16	4
Government surplus (€M)	8	0	14	3	6	3
Emissions (€M)	-110	-110	-109	-109	1	1
Consumer surplus (€M)	942	683	936	678	-6	-4
Producer surplus (€M)	102	139	101	139	-1	-0
Welfare (€M)	942	712	943	711	0	-1

Finally, we note that the only path to reducing emissions substantially would appear to be an increase in the social cost of carbon, as demonstrated in Figure (2). Once the cost of carbon is above € 500, the airfares increase by one sixth, the frequencies drop by one third and the social welfare accordingly but so too the emissions.

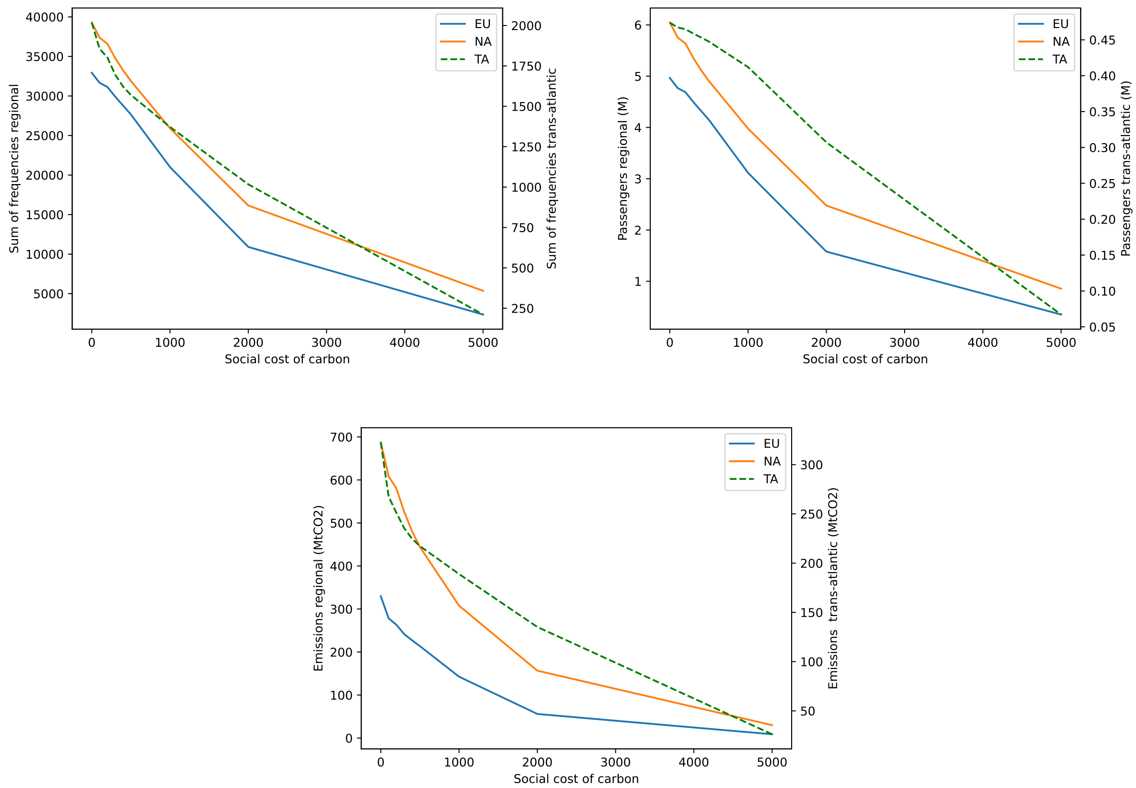

Figure 2: Sensitivity analysis over the social cost of carbon

4 Conclusions

In this paper, we develop a two-stage model capable of representing competition between regulators and airlines under different emission charges. By comparing scenarios with a 2019 baserun case, we assess the impacts of the different regulators' interactions on welfare and the environment. Our analysis suggests that imposing an environmentally optimal carbon charge on the aviation industry can lead to unexpected and welfare-detrimental outcomes. Specifically, we have assessed that the carbon charge imposed by a single regulator results in a level that is well below the social impact of emissions. We further show that when regulators are free to set their charges, they enter into regional surplus protectionism, which undermine the effectiveness of the mechanism. The outcomes we present in our paper are the result of several distorting forces in the aviation industry and offer an explanation behind the reasons for the absence of an international cooperative carbon policy.

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References

Adler, N., Hanany, E., & Proost, S. (2022, 4). Competition in congested service networks with application to air traffic control provision in europe. *Management Science*, *68*, 2751-2784.

Baylis, K., Fullerton, D., & Karney, D. H. (2013, 5). Leakage, welfare, and cost-effectiveness of carbon policy. *American Economic Review*, *103*, 332-337.

Benoot, W., Brueckner, J., & Proost, S. (2013). Intercontinental-airport regulation. *Transportation Research Part B: Methodological*, *52*, 56–72.

Hansen, M. (1990, feb). Airline competition in a hub-dominated environment: An application of noncooperative game theory. *Transportation Research Part B: Methodological*, *24*(1), 27–43.

Kwan, I., & Rutherford, D. (2015). Assessment of U.S. domestic airline fuel efficiency since 2010. *Transportation Research Record*, *2501*, 1–8.

Larsson, J., Elofsson, A., Sterner, T., & Akerman, J. (2019, jul). International and national climate policies for aviation: a review. *Climate Policy*, *19*(6), 787–799.

Lee, D. S., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., ... Fuglestvedt, J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834.

McFadden, D. (1974). The measurement of urban travel demand. *Journal of Public Economics*, *3*(4), 303–328.

Mohring, H. (1972). Optimization and scale economies in urban bus transportation. *The American Economic Review*, *62*(4), 591–604.

Nordhaus, W. (2015, apr). Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review*, *105*(4), 1339–1370.

Osborne, M. J., & Rubinstein, A. (1994). *A course in game theory.* MIT press.

Pels, E., & Verhoef, E. T. (2004). The economics of airport congestion pricing. *Journal of Urban Economics*, *55*(2), 257–277.

Perino, G., Ritz, R. A., & Van Benthem, A. (2019). Understanding overlapping policies: Internal carbon leakage and the punctured waterbed. *National Bureau of Economic Research*.

Pigou, A. C. (1924). *The economics of welfare.* Macmillan.

Pörtner, H.-O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., ... Biesbroek, R. (2022). Climate change 2022: Impacts, adaptation and vulnerability. *IPCC Sixth Assessment Report*.

Schwalbe, U., & Walker, P. (2001). Zermelo and the early history of game theory. *Games and economic behavior*, *34*(1), 123–137.

Small, K. A., & Rosen, H. S. (1981). Applied welfare economics with discrete choice models. *Econometrica: Journal of the Econometric Society*, 105–130.

Swan, W. M., & Adler, N. (2006, mar). Aircraft trip cost parameters: A function of stage length and seat capacity. *Transportation Research Part E: Logistics and Transportation Review*, *42*(2), 105–115.

Wächter, A., & Biegler, L. T. (2006, mar). On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming. *Mathematical Programming*, *106*(1), 25–57.