Essays in Environmental and Political Economics

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This thesis is submitted for the degree of
Doctor of Philosophy

Trinity Hall & Corpus Christi College

January 2020

To my parents, Becca and Johnny

Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the preface and specified in the text. It is not substantially the same as any work that has already been submitted before for any degree or other qualification except as declared in the preface and specified in the text. It does not exceed the prescribed word limit.

Felix Grey
January 2020

Acknowledgements

I am deeply grateful to Toke Aidt, my supervisor, and to Robert Ritz and Hamish Low, my de-facto advisors. I have learned a huge amount from them over the years, as well as enjoyed countless conversations that have shaped how I understand the subjects tackled in this thesis. Working with them has been a privilege as well as a lot of fun. I am also indebted to Donald Robertson, who put up with me asking the most basic econometric questions over and over again.

Working with co-authors has been one of the great pleasures of this PhD. As well as Toke and Robert, I am incredibly grateful to Alex Savu and Romola Davenport (and her encyclopedic knowledge of historical causes of death). I would also like to thank all the research assistants I have worked with, and most especially Andriy Levitskyy, Katie Piner, and Pradeep Venkatesh.

I gratefully acknowledge the financial support of the ESRC for funding my MPhil and PhD, EPRG for research support, and Corpus Christi College for my Fellowship.

I have been supported by a large number of friends in Cambridge during my time here, and I am grateful to them all. To Marco Schneebalg and Juliette Thibaud - I could not have begun studying economics with two better people. To my fellow PhD economists and lunch companions: Athene Laws, Dan Wales, John Spray, River Chen, Samuel Mann, Simon Lloyd, Su-Min Lee, and Zeina Hasna. To non-economist PhDs Freddy Fokks, Hetty van Hensbergen, Tom Pye, and Tom Arnold Forster. To family-and-housemates Guss Grey and Henry Bowyer. To my great friend Lucian Robinson. To friends not physically in Cambridge but present nonetheless, especially the awesome Jono Lain and Sam Kennedy. And to Benny Grey.

Finally, I want to thank Emilija and Ezra. Emilija, for reading my work and for sharing her life with me. And Ezra, for being the best little person imaginable.

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Preface

This thesis explores questions in environmental and political economics. Despite much progress over the last half a century, we still urgently need to better understand the complex interactions between our environmental, political and economic systems. The broader context is that there is widespread consensus among economists, and increasingly the general public, that we need a strong carbon tax or or something equivalent, but there are deep political frictions and failures that keep society stuck in a bad equilibrium. Understanding the political economy of environmental protection, therefore, matters. This thesis aims to offer a small contribution to this effort. The first two chapters concern the intersection of environmental and political economics. The third chapter looks at an example of past improvements in the urban environment, while the final chapter focuses on one particular aspect of our political systems.

In chapter 1, *Corporate Lobbying for Environmental Protection* (published in the *Journal of Environmental Economics and Management* as Grey, 2018), I tackle the question of how and why some polluting firms may politically support environmental protection, and what difference this makes to overall welfare. Political support from firms can be pivotal for governments trying to protect the environment, as we have seen in the cases of ozone and climate change. I suggest that firms behave as they do to gain market share from their rivals, but that society can benefit overall from the greater environmental protection that results.

Chapter 2, *Pass-through, Profits and the Political Economy of Regulation*, is joint work with Robert Ritz.[1] It presents a new theoretical framework for understanding the impact of environmental taxes on firm profits, which are central to the political economy of regulation. We apply the theory in an empirical study of the US aviation market, and estimate there would be major winners and losers if carbon pricing were introduced. This, in turn, would shape the political economy of such a policy.

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[1] We are grateful to Research Assistants Pradeep Venkatesh and Shijian Yang.

Chapter 3, *Sanitation and mortality in urban England 1875-1911*, is joint work with Toke Aidt and Romola Davenport.[2] It assesses the impact of major changes to the urban environment in a historical context, industrialising Victorian England. Using a new dataset constructed from local public accounts and mortality records, we quantify the extent to which sanitation infrastructure explains declines in urban mortality, the subject of ongoing debate among both public economists and economic historians.

Chapter 4, *The Meaningful Votes: Voting on Brexit in the British House of Commons* (published in *Public Choice* as Aidt et al., 2019), is joint work with Toke Aidt and Alex Savu. It aims to increase our understanding of political systems by investigating empirically the reasons for rebellions by legislators against their governing parties. We use novel data from the UK parliament's 'meaningful votes' on Brexit legislation, historic government defeats that allow us to quantify the importance of the different forces acting on rebellious legislators.

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[2] We are grateful to Research Assistants John Black, Huaxiang Huang, David Hutchinson, Andriy Levitskyy, and Katie Piner.

Chapter 1

Corporate lobbying for environmental protection

Abstract

Much of the time, polluting firms lobby against environmental protection, but there are major exceptions to this rule, for example in the regulation of both ozone and greenhouse gases. Political support from firms can be pivotal for governments trying to protect the environment. I offer an explanation for this phenomenon, suggesting firms behave as they do in order to steal market share from their rivals. I develop a model in which a polluting firm makes a clean technology investment and then lobbies successfully for strong environmental protection, since this will shift market share away from its rival who has not made the clean investment. The key result concerns the impact of lobbying on the equilibrium outcome: for a region of the parameter space, it is only because of firms' lobbying that environmental protection is achieved. This is because lobbying increases a firm's returns to going green, by increasing the market share it can steal. The net effect of this distortion is an increase in welfare.

Keywords: lobbying, environmental policy, political economics.

JEL codes: D72, H23, Q58.

1.1 Introduction

This paper aims to answer the question 'when might polluting firms support environmental protection, and what difference does this make to the level of environmental protection a government chooses?' Lack of political support is a major reason why environmental regulations are either delayed or permanently weak.[1] Political support for environmental protection can come from a number of places, but it is arguably most valuable when it comes from business. Many environmental policymakers would go so far as to say that this is almost a necessary condition for feasible environmental regulation - when there appears to be conflict between 'the economy' and the environment, the environment tends to lose (Stern, 2015).

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[1] Oates and Portney (2003) review the literature on the political economy of environmental protection.

Firms spend significant resources on lobbying[2] and there is a general perception that polluting firms inevitably use their lobbying power to slow down, water down, or entirely block measures to protect the environment. This is indeed the case much of the time,[3] but there have been major and important exceptions to this rule. The following two examples motivate much of the paper.

The protection of the ozone layer was arguably the biggest environmental problem of its time. During the 1980s, regulators were attempting to draw up global rules to limit the production of ozone-depleting CFCs and encourage investment in cleaner alternatives. Until 1988, the major ozone-polluting firms had all opposed environmental regulation and successfully used their influence to limit protection of the ozone layer. The largest producer, the US firm DuPont, had lobbied for decades against regulation.[4] However, in March 1988 DuPont abruptly announced that it no longer opposed regulation and in fact now wanted a complete phase-out of global CFC production. DuPont's new political support for regulation is widely seen as the turning point in the story of ozone protection (Barrett, 2003). The European producers continued to lobby against reductions but were unsuccessful: the Montreal Protocol and its successor treaties achieved a total phase out of CFCs. It has been suggested that DuPont's lobbying for regulation may have been in its economic self interest. Since it had already made investments in cleaner production technologies that would give it an advantage over its rivals in the clean substitute market, DuPont potentially stood to gain market share.[5] In the words of DuPont director Joseph Glass, 'when you have $3 billion of CFCs sold worldwide and 70 percent of that is about to be regulated out of existence, there is tremendous market potential.'[6] A key feature of DuPont's lobbying was for controls to be as strong and as international as possible, so that their major European rivals would be affected.

The DuPont example is perhaps particularly straightforward, but similar dynamics are also likely to be operating on various levels in the more complex case of climate

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[2] For example, in the US in the five years prior to 2017, $1.7 billion was spent on lobbying over energy and natural resources, the majority of which was campaign contributions (according to the Center for Responsive Politics, www.opensecrets.org, accessed on 13 Dec 2017). The EU is far less transparent, so financial flows are hard to obtain, but according to Dinan and Wesselius (2010) there are perhaps 30,000 lobbyists in Brussels, the same as the number of EU Commission employees.

[3] Oreskes (2010) details attempts to block environmental protection by polluting firms.

[4] Benedick (1998) gives a definitive and first hand account of the history of ozone protection, as he was the lead US negotiator to the Montreal Protocol.

[5] DuPont probably had several reasons for making this move; all that is argued here is that profit is likely to have been one of them. Smith (1998) gives a detailed discussion of DuPont's potential motives.

[6] Quoted in Gilding (2012).

change. In the run up to the Paris Agreement, a coalition of major oil and gas producers was among those calling for the introduction of a global carbon price. Europe's six largest oil and gas companies (BG, BP, Eni, Shell, Statoil and Total) argued in an open letter to the UN sent on 29 May 2015 for the introduction of an ambitious carbon price. If this were introduced, they argued, they could invest in reducing their emissions by, for example, increasing the proportion of gas they produce (which is relatively clean). The letter also hints at another effect of the carbon price: 'reduced demand for the most carbon intensive fossil fuels' - that is, coal, their biggest competitor product, with a market share of global energy supply around 30%.[7] A moderately strong carbon price would shift market share away from coal and towards gas, creating, to paraphrase the DuPont director, 'tremendous market potential'. It is hard not to see this lobbying, at least in part, as an attempt by the oil and gas companies to steal market share from the coal companies.[8] Although climate regulation is on-going, stronger political support from the private sector is considered by many policy makers to have helped achieve the Paris Agreement in 2015.[9]

Hence there are clear examples of major polluting firms lobbying for environmental regulation of their markets, and this political support can substantially increase the ability of governments to protect the environoment.[10] This paper asks, by modelling these kinds of situations, when and how a firm like DuPont might choose to invest in a costly clean technology, knowing it will be able to influence the political process to get regulations passed that will result in increased market share and so greater profits.

An outline of the model and results presented here is as follows. In the baseline model there are two identical firms, each of which can invest in a new green production technology or keep their old polluting technology. A government then chooses the emissions tax they are subject to, and the firms can influence this choice through

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[7] IEA *Key World Energy Statistics* (2014).

[8] This lobbying probably had multiple aims. For example, by participating actively in the political process of carbon pricing, the oil and gas companies might be able to keep the carbon price from being too much higher than they would like, or by sorting it out sooner rather than later, they might be able to reduce uncertainty around long run demand for their product. All that is argued here is that stealing market share from coal may be one of the reasons for this kind of lobbying.

[9] For example, Nicholas Stern's response to the Paris Agreement included: '... businesses have been strongly represented at the Paris climate change summit and have played an important role in urging governments to achieve a strong agreement.' (New Climate Economy, newclimateeconomy.net, accessed on 29 Jan 2016.)

[10] Barrett (1992) gives other instances of this kind of behaviour. For example, in response to concerns over the environmental impact of phosphates, the German firm Henkel invested in a phosphate-free detergent, lobbied for controls and gained market share in France and Germany in the 1980s. Puller (2006) also details several examples. More generally, this process need not be limited to environmental regulation.

lobbying. The result is that, for a region of the model's parameter space, competition between the firms causes one firm to choose to go green and lobby for strong environmental protection, so that it gains market share in the new regulated market, while the other keeps the old technology and opposes environmental regulation. The lobbying results in the equilibrium emissions tax being distorted above the Pigouvian level, and increasingly so as the government becomes more open to lobbying. The key result concerns the interaction between the political process and firms' green investment choices: there are situations where it is only because a firm can lobby, and therefore secure strong environmental protection, that it will see it as worthwhile to go green. At the same time, it is only because of a firm's political support that the government can take environmental action. Lobbying can therefore induce a switch to a greener economy.

This is the key result of the paper, but I go on to make five further points. First, for other regions of the parameter space (for example, when environmental damage is higher, or green investment costs lower), both firms choose to go green in equilibrium instead of just one. Here, although no lobbying conflict is observed, the threat of loss of market share if a firm doesn't go green, intensified by lobbying, helps to sustain the equilibrium. Second, the welfare implications of these two types of lobbying-induced switches to a greener economy are characterised, and I show that if lobbying induces a switch then it must also be welfare improving. Third, the model can be generalised to the case of n firms and variants of all the key results developed in the two firm case continue to hold, though now with coalitions of green and brown firms. The two firm model is therefore appropriate for examining situations with more than two firms, so the bulk of the paper focuses on this simpler set up. Fourth, the results are robust to various different product market assumptions. However, the extent to which lobbying makes the green investment more attractive to firms falls as demand becomes more elastic, because the market share effect is partially offset by the total market shrinking. Fifth, I discuss three reasons why lobbying-induced switches to a greener economy may not always be observed in practice.

The findings presented here are related to three strands of the economics literature. First, the paper sits within the wide literature on the political economy of environmental regulation. Stigler (1971) argued that regulation is largely the result of profit seeking by firms. Buchanan and Tullock (1975) pointed out that different environmental regulations vary substantially in their distributional consequences, and suggested that firms ensure the regulations chosen are those that most increase their profits. One strand of the contemporary political economy literature builds on these insights by focusing on lobbying as the mechanism by which firms influence policy. Grossman and Helpman (1994) were the first to apply the common agency model of Bernheim and Whinston (1986) to lobbying, which has now become standard.[11] Fredriksson (1997) and Aidt (1998) first applied it to environmental policy making, showing that an environmental lobby group can counter the influence of a polluters' lobby group and thereby bring about environmental protection. This remains an active and productive area of research.[12] However, the standard result is that polluting firms always lobby against environmental protection: for the externality to be adequately controlled, a lobby group with environmental preferences is needed.[13] The model presented here, therefore, offers a novel and complementary explanation of the political processes behind environmental regulation.

Another branch of the environmental political economy literature follows Salop and Scheffman (1983), who argued that firms often attempt to raise their rivals' costs, as this gives them a competitive advantage. Barrett (1991) discusses this in various environmental contexts. Sartzetakis (1997) presents a model in which an exogenously designated 'leader' firm can manipulate the price of emissions permits, which raises rivals' costs. Aside from its focus on lobbying, my model differs from this in that there are no exogenous asymmetries between the rival firms, yet in equilibrium they can behave differently. Puller (2006) analyses the strategic incentives of firms to innovate in order to influence regulatory standards and so raise their rivals' costs. He shows that this effect can counter the well-known incentive to reduce innovation in order to ratchet down regulation. My paper complements this analysis by looking explicitly at the role of lobbying in the formation of regulation that raises rivals' costs.

The second broad area of the literature this paper relates to is the Porter Hypothesis (the idea that firms often gain rather than lose from environmental regulation). My

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[11] Lobbying can alternatively be thought of as a process of information transmission, and therefore an application of Crawford and Sobel's (1982) model of strategic information transmission. Which of the two types of lobbying takes place in reality is context dependent (see Grossman and Helpman (2001) for a discussion). This paper focuses on buying influence.

[12] Damania (2001) shows that polluting firms can use dirty investments as a commitment device to aid their lobbying efforts; Eliste and Fredriksson (2002) look at the relationship between trade and environmental regulation when firms can lobby; Wilson and Damania (2005) explore the environmental impact of corruption at different levels of government; Aidt et al. (2010) shows how recycling revenue from green taxes can be used strategically by firms seeking to lower their tax burden; MacKenzie and Ohndorf (2012) show that lobbying considerations may, counterintuitively, make non-revenue raising environmental regulation the most preferred option for governments; Habla and Winkler (2013) show how national lobbying can play an important role in international environmental agreements.

[13] The only exception to this I am aware of is in Fredriksson and Sterner (2005), who show that when firms can capture the revenue from environmental taxes, some firms support higher taxes. In my model, this channel is shut down, as no firm receives any revenue from environmental taxes (or, equivalently under a cap-and-trade scheme, receives any permits for free).

model gives rise to a version of the Porter Hypothesis without relaxing any of the optimising assumptions of standard economic theory.[14] Hence, it suggests a new mechanism that can give rise to this familiar result.

Third, this model also shares various features with those in the literature on competitive R&D and endogenous technical change. In the competitive R&D literature, firms undertake R&D in an imperfectly competitive market because doing so brings them a competitive advantage, usually lower relative costs, allowing them to gain market share (Reinganum, 1983). The approach taken here can be thought of as an extension of this literature by modelling two sequential investment choices. First, a standard R&D investment (in clean technology) that impacts firms' relative costs; second, a political investment (in a high emissions tax) that is highly complementary to the R&D. Looked at in this way, it is the complementarity of the investments that means that, when offered together they will be undertaken, whereas in isolation they may not. Finally, this paper is relevant to the current literature on endogenous technical change (Acemoglu et al., 2012; Aghion et al., 2016). For example, Acemoglu et al. (2016) present and estimate a dynamic model in which formerly polluting producers choose between investments in clean or dirty production methods. In the absence of significant R&D subsidies, very high carbon taxes are needed for the transition to clean technologies. The present paper can be seen as complementing this literature, by offering one explanation for how such taxes can be politically achieved.

The remainder of this paper is organised as follows. In Section 1.2 the baseline model is presented. Section 1.3 contains the key results: equilibria are characterised and discussed. Section 1.4 examines the welfare consesquences of the results. In Section 1.5 the model is generalised to n firms, and robustness is considered. Section 1.6 concludes with a discussion of the limitations of the theory.

1.2 The baseline model

The baseline model contains two firms and a single government who play a three stage game. First the firms choose whether or not to invest in costly, but emissions-free production technology. Then in the second stage the government sets an emissions tax, which the firms attempt to influence through lobbying. In the third stage firms produce and earn profits.

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[14] Porter and van der Linde (1995) give the original statement of the argument, which holds that '$10 bills are waiting to be picked up', that is, in reality firms are not profit maximising. Other explanations consistent with optimising behaviour are based on market power, asymmetric information and R&D spillovers (see Ambec et al. (2013)).

1.2.1 The economy

There are two firms, 1 and 2. Each firm $i \in \{1, 2\}$ produces a quantity x_i of a single homogenous good. They each face an initial choice over their production technology $f_i \in \{G, B\}$. They can choose the clean, 'green' production technology $f_i = G$, in which case production by the firm results in no emissions. Alternatively they can choose the dirty, 'brown' technology $f_i = B$, in which case production is polluting and each unit of output results in a unit of emissions. Choosing $f_i = G$ costs $s > 0$. This could represent the building of a new factory or power station, some kind of R&D, or any other step to reduce emissions. Choosing $f_i = B$ is free, reflecting the idea that the current technology is polluting and can continue to be used with no new investment required. Note that the cost structure of the firms is otherwise unaffected by this investment choice; the only purpose of investing in clean technology is to reduce emissions to zero.[15] Each firm has emissions per unit of output e_i given by:

$$e_i(f_i) = \begin{cases} 0 & \text{if } f_i = G \\ 1 & \text{if } f_i = B \end{cases} \tag{1.1}$$

The firms face an emissions tax τ, resulting in a tax bill of $\tau e_i x_i$. From the firm's point of view, the green investment can be thought of simply as a way to switch off the emissions tax τ.

The firms have identical and strictly convex production costs. For tractability, I take costs to be given by $\frac{1}{2}kx_i^2$, and normalise k to $\frac{1}{2}$.[16] Denote by π_i profits from production (as distinct from total firm payoffs which include investment and lobbying costs). Given any pair of technology choices by the two firms $f \in \{G, B\}^2$ and emissions tax τ, firm i chooses output x_i to maximise profits from production:

$$\pi_i(x_i \mid \tau, f) = px_i - \frac{1}{4}x_i^2 - \tau e_i x_i \tag{1.2}$$

The market structure is as follows. First, demand is linear and given by:

$$x = 1 - bp \tag{1.3}$$

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[15] In reality investment in new green technology does often have an impact on marginal cost, and this can be a major investment incentive or disincentive. Abstracting away from this allows the paper to isolate a separate reason for green investments.

[16] The only assumption important for the results is that costs must be strictly convex, of which a quadratic cost function is the simplest, and $\sum k_i = 1$ gives the simplest analytical solutions. Convex costs ensure the government faces an interesting tradeoff following $f = (G, B)$; i.e., so that it would not always simply set the tax to push the brown firm entirely out of the market.

where $x = x_1 + x_2$, and $b \geq 0$. Many of the proofs and examples will begin with the case where $b = 0$, that is where demand is inelastic and equal to 1. Fixing the total size of the market in this way generates simple analytical solutions that are useful for understanding how competition for market share drives the key results. This low elasticity benchmark is then contrasted with a high elasticity case and the results are shown to be robust.

The second product market assumption is that firms are price takers. This ensures there is no strategic behaviour at the production stage, and so allows the model to focus cleanly on the strategic interactions between the firms at the investment and lobbying stages.[17] The results are robust to this assumption: in Appendix 1.D the model is re-solved for Cournot competition, giving qualitatively equivalent but analytically less tractable results. The price taking assumption also fits naturally with the n firm generalisation of the model presented in Section 1.5.1.

1.2.2 The political process

After the investment choices have been made, the emissions tax τ is set by a government with two aims: to maximise social welfare and to collect political donations from lobbyists. Social welfare W is the utility of a representative citizen plus the impact of environmental damage. Demand curve (1.3) implies that the representative citizen has quasilinear utility of the form $u(x, y) = \frac{1}{b}(x - \frac{1}{2}x^2) + y$, where y is wealth (or consumption of a numeraire good).[18] Wealth y is equal to total profits $(\pi_1 + \pi_2)$, minus expenditure on x (px), plus emissions tax revenue $(\tau \sum e_i x_i)$. Environmental damage is given by $\eta \sum e_i x_i$, where $\eta \geq 0$ gives marginal environmental damage.[19] Combining

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[17] Any assumption other than price taking will lead to production market failures, and the government will therefore use the emissions tax partly as an instrument of competition policy, which would not be an interesting or helpful feature of the model.

[18] The above utility function is not defined for $b = 0$. A complete specification of the utility function for all $b \geq 0$ implied by demand equation (1.3) is: $u(x, y) = \begin{cases} \frac{1}{b}(x - \frac{1}{2}x^2) + y & \text{if } b > 0 \\ v(x) + y & \text{if } b = 0 \end{cases}$, where $v(x) = \begin{cases} 0 & \text{if } x = 1 \\ -\infty & \text{if } x \neq 1 \end{cases}$. This discontinuity in the utility function does not affect any real quantities in the economy, even for $b = 0$, because demand is continuous at $b = 0$. It matters only when calculating welfares in Section 1.4. A final assumption needed to infer this quasilinear utility function from linear demand is that it is everywhere the result of an interior solution to the consumer's utility maximisation problem.

[19] Linear environmental damage is likely to be a realistic assumption only for emissions within a limited range: most environmental damage functions are ultimately convex (see Ackerman et al. (2009) for a discussion). However the qualitative nature of the results would be the same in either case, so the simplest specification is used here.

the above gives welfare:

$$W(x,\tau|f) = \frac{1}{b}(x - \frac{1}{2}x^2) + \sum \pi_i - px + \tau \sum e_i x_i - \eta \sum e_i x_i \tag{1.4}$$

The government also cares about political contributions c_1 and c_2 from the two firms, who lobby the government over the level of τ. Bernheim and Whinston (1986) give an analysis of games of common agency, which Grossman and Helpman (1994) apply to lobbying, and I follow this now standard approach here. The problem is one of two firms (the principals) attempting to influence the actions of the government (the common agent). They do this through lobbying, which is represented by a contribution function $C_i(\tau)$ specifying how much firm i will pay as a political donation to the government for each level of τ. The government therefore seeks to maximise $W(\tau) + \lambda(C_1(\tau) + C_2(\tau))$, where $\lambda \geq 0$ determines the relative weight the government gives to political contributions compared to social welfare. λ is the openness to lobbying of the government: $\lambda = 0$ represents an incorruptible government only interested in social welfare; as λ rises the government and its policies become increasingly 'for sale'. Determining the effect of λ on the equilibrium outcome is the main aim of this paper.

1.2.3 The overall game

Combining the above components, the model can be summarised as a three stage game:

Stage 1: Investment

- Firms $i \in \{1,2\}$ simultaneously choose production technologies $f_i \in \{G, B\}$.

Stage 2: Lobbying

- Firms $i \in \{1,2\}$ simultaneously choose contribution functions $C_i(\tau)$,
- The government then chooses emissions tax $\tau \in \mathbb{R}$.

Stage 3: Production

- Firms $i \in \{1,2\}$ simultaneously choose outputs $x_i \in \mathbb{R}_{\geq 0}$.
- Prices are taken as given and the market clears.

Payoffs at the end of the game for government and firms are

$$U_{gov} = W + \lambda(C_1 + C_2) \tag{1.5}$$

$$U_i = \pi_i - C_i - s(1 - e_i) \qquad \text{for } i \in \{1,2\} \tag{1.6}$$

1.3 Equilibria

The relevant solution concept for a sequential game of this kind is the subgame perfect Nash equilibrium.[20] It is found by backward induction, starting at stage 3.

Stage 3: Production

Taking as given the investment choice f and emissions tax τ chosen earlier in the game, each firm maximises profits (1.2) and prices adjust so that supply equals demand (1.3). This gives equilibrium outputs $x_i^*(\tau, f)$, price $p^*(\tau, f)$ and profits $\pi_i^*(\tau, f)$ as a function of choices made earlier in the game. Appendix 1.A contains a complete summary of the analytical solutions to this and subsequent stages of the game.

Given the symmetry of the two firms, there are three different technology choices to consider: $f \in \{(G,G),(G,B),(B,B)\}$.[21] The production subgame following $f = (G,G)$ is the simplest. Both firms have made the clean technology investment, so produce no emissions: $e_i = 0$. The emissions tax therefore has no effect, and output is high and split evenly between the two firms.

Next, consider the subgame following $f = (G,B)$, where one firm goes green by investing in the clean technology and the other stays brown by keeping the old technology. Denote, with an abuse of notation, outcomes for the firm that chose $f_i = G$ with a subscript G, and outcomes for the firm that chose $f_i = B$ with a subscript B. The green firm causes no emissions, $e_G = 0$, but the brown firm continues to pollute, $e_B = 1$, and so must pay emissions tax τ for every unit of production. This gives interior[22] equilibrium output, price and profits, which depend on the emissions tax τ as follows:

$$\frac{d}{d\tau}x_G^*(\tau,(G,B)) > 0, \qquad \frac{d}{d\tau}x_B^*(\tau,(G,B)) < 0, \qquad \frac{d}{d\tau}p^*(\tau,(G,B)) > 0, \tag{1.7}$$

$$\frac{d}{d\tau}\pi_G^*(\tau,(G,B)) > 0, \qquad \frac{d}{d\tau}\pi_B^*(\tau,(G,B)) < 0, \qquad \frac{d}{d\tau}\sum \pi_i^*(\tau,(G,B)) > 0 \tag{1.8}$$

Increasing the emissions tax τ has two effects on the goods market: shifting market share from the brown firm to the green firm, and increasing the price. The green firm would like a high emissions tax τ since it will gain both market share and environmental rents resulting from the price rise. These gains to the green firm can, loosely, be thought

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[20] Throughout the paper, I restrict my attention to pure strategies only.

[21] Because the two firms are ex ante identical, the (G,B) and (B,G) outcomes are equivalent.

[22] The solution to the game will be an interior equilibrium if, given the tax rate, each firm chooses non-negative production. We will see a corner solution following (G,B) if the tax is pushed up to the point where the brown firm ceases production. Throughout the main text I focus on the interior solution, with the corner solution given in Appendix 1.E.

of as a kind of first mover advantage if this simple static game were interpreted in a richer dynamic context. The brown firm would like a low τ since this lowers its loss of market share, and limits the fall in its net of tax price. The sum of profits is increasing in τ since production is shifted to the firm receiving a higher net of tax price. This means that the green firm benefits more from an emissions tax increase than the brown firm loses. This result is an important feature of the production subgame, and one that will underpin many of the final results, so is summarised in the following lemma:

Lemma 1. *Following investment $f = (G, B)$, total profits are increasing in the emissions tax τ, $\frac{d}{d\tau}\sum \pi_i^*(\tau, (G, B)) > 0$. That is, the green firm gains more from increasing τ than the brown firm loses.*

Finally, consider the subgame following $f = (B, B)$. Both firms keep the old technology, so both pay emissions tax τ. The firms produce equal output $x_B^*(\tau, (B, B))$ and earn profits $\pi_B^*(\tau, (B, B))$. For any $b > 0$, both output and profits decrease as the government increases the emissions tax, which shrinks total output in the usual way. For $b = 0$, demand is inelastic, so total output is fixed, and the tax has no effect on each firm's output or profits.

Stage 2: Lobbying

In this stage, each firm seeks to influence the emissions tax, while the government balances its two objectives of maximising social welfare and collecting political contributions from each firm. Following the common agency approach of Bernheim and Whinston (1986), this situation is characterised by the decision of a single agent (the government) affecting two principals (the firms). Each firm announces a contribution function $C_i(\tau)$ which specifies how much it will donate to the government for any level of τ that might be chosen.[23] Each firm designs its contribution function $C_i(\tau)$ to encourage the government to distort the tax in the direction that increases its own profits. The government observes the contribution functions and chooses τ to maximise $W(\tau) + \lambda \sum C_i(\tau)$.

An outcome of this lobbying subgame will be an equilibrium if the government cannot choose a better tax rate given the contribution functions it faces, and if each firm cannot offer a contribution function that gives it a better payoff, given the function offered by the other firm. More formally, given any f, a subgame perfect equilibrium of

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[23] The contribution function is formally equivalent to the kind of standard incentive contract offered in the context of performance related pay. In reality lobbyists do not normally offer explicit contracts in such a transparent way, but an implicit contract of this type underpins their use of political contributions to secure favourable policies (see Grossman and Helpman (2001) for further discussion).

this lobbying game is a tax rate τ^*, and pair of contribution functions $(C_1^*(\tau), C_2^*(\tau))$ such that:

1. For the government τ^* is a best response to $(C_1^*(\tau), C_2^*(\tau))$. That is, $\tau^* \in \arg\max_{\tau \in \mathbb{R}} W(\tau) + \lambda(C_1^*(\tau) + C_2^*(\tau))$.
2. For each firm $i \in \{1, 2\}$, $C_i^*(\tau)$ is a best response to $C_j^*(\tau)$. That is, there is no other τ' and $C_i'(\tau)$ such that τ' is a best response to $(C_i'(\tau), C_j^*(\tau))$ and $\pi_i(\tau', f) - C_i'(\tau') > \pi_i(\tau^*, f) - C_i^*(\tau^*)$.

With no restrictions on $C_i(\cdot)$ this game has many equilibria. Following the now standard approach in Grossman and Helpman (1994), equilibria are limited to those where firms offer contribution functions of the form $C_i(\tau) = \pi_i(\tau) + a_i$, where a_i is a constant. Bernheim and Whinston (1986) term such strategies 'truthful strategies' and show that the resulting equilibria are focal among the set of all possible equilibria, since only they are stable to non-binding communication.

I can now find the equilibria of the lobbying subgame following each choice of $f \in \{(G, G), (G, B), (B, B)\}$. First, consider the subgame following $f = (G, G)$. As mentioned above, the production outcomes in equation (1.13) are independent of the emissions tax in this case, so no firm will spend resources lobbying and the government can choose any tax, which has no impact on welfare. The equilibrium outcomes are therefore $\tau \in \mathbb{R}$, $c_G^*(G, G) = 0$.

Now, consider the lobbying subgame that follows $f = (G, B)$. Substituting profit functions (1.13) into the truthful contribution functions $C_i(\tau) = \pi_i^*(\tau, (G, B)) + a_i$, equilibrium condition (1) gives the equilibrium emissions tax $\tau^*(G, B)$. Condition (2) gives the level of contribution $c_i^* = C_i^*(\tau^*)$ from each firm needed to maintain this as an equilibrium. The equilibrium tax rate and two of its properties are:

$$\tau^*(G,B) = \frac{8\eta + b(6\eta + b\eta - \lambda)}{8(1-\lambda) + b(6 - 4\lambda - b\lambda + b)}, \quad \tau^*(G,B)|_{\lambda=0} = \eta, \quad \frac{d}{d\lambda}\tau^*(G,B) > 0 \tag{1.9}$$

The contributions $c_i^*(G, B)$ are given by equation (1.14) in Appendix 1.A. To understand this result, consider the case where the government is not open to lobbying, $\lambda = 0$. The government maximises social welfare and ignores potential lobbying, giving outcome $\tau^* = \eta$ and $c_i^* = 0$ for each i; we observe Pigouvian taxation and no political contributions.[24] As λ increases, i.e. as the government becomes more open to lobbying,

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[24] We would expect the Pigouvian tax because, given f, there is one market failure (environmental damage) and an instrument (the emissions tax) which can implement the first best solution.

τ^* rises and so the tax rate increasingly exceeds the Pigouvian level. This result is a consequence of Lemma 1 (that $\sum \pi_i$ is increasing in τ following $f = (G, B)$). The green firm would like a higher τ and so chooses a contribution function that rewards the government for increasing τ, and the brown firm will likewise reward the government for reducing τ. But by Lemma 1, the green firm gains more than the brown firm loses from an increase in τ, so the green firm lobbies harder than the brown. That is, the sum of the contributions will be increasing in τ and so in equilibrium the lobbying distorts it upwards: the more the government is open to lobbying the more the green firm gets its way. This result can be generalised in the following Lemma:

Lemma 2. *For any technology f, in equilibrium lobbying distorts the emissions tax τ above the Pigouvian level if and only if total industry profits are increasing in the emissions tax; i.e. when $\lambda > 0$, $\tau^*(f) > \eta \iff \frac{d}{d\tau} \sum \pi_i^*(\tau, f) > 0$.*

This result is very general since it holds for any f, any number of firms and any market structure. A proof of Lemma 2 follows almost immediately from contribution functions being truthful, so that $\sum C_i^*(\tau) = \sum \pi_i^*(\tau) + a$, where a is a constant. If the sum of profits is increasing in τ then the sum of contributions will be too, so including it in the government's objective function (condition (i) above) will therefore increase the equilibrium tax above the level optimal for social welfare alone ($\tau = \eta$). Lemma 2 also identifies when lobbying would distort the emissions tax below the Pigouvian level: in any situation where the market structure is such that $\sum \pi_i^*(\tau)$ is decreasing in τ.

Equilibrium contributions c_G^* and c_B^* are strictly positive for $\lambda > 0$, but their derivatives with respect to λ are ambiguous. As λ rises the firms have more influence and therefore are willing to spend more to get more, but the government also needs less compensation from firms for losses in social welfare resulting from distortions in τ. In other words distorting the tax becomes cheaper. These two effects tend to respectively increase and decrease c_i^* as λ rises.

Now consider the lobbying subgame following $f = (B, B)$. Following the same procedure as above, equilibrium condition (1) gives the equilibrium emissions tax $\tau^*(B, B)$ and condition (2) gives the level of contributions. The tax rate is:

$$\tau^*(B,B) = \frac{4\eta + b\eta - \lambda}{4 + b - b\lambda}, \quad \tau^*(G,B)|_{\lambda=0} = \eta, \quad \frac{d}{d\lambda}\tau^*(G,B) \leq 0 \tag{1.10}$$

and the contributions $c_B^*(B, B)$ are given in equation (1.14). As in the previous case, in the absence of lobbying, the government implements a Pigouvian tax. However, now the firms gain from a lower tax, so as the government becomes more open to lobbying, the firms push the tax below the Pigouvian level: $\frac{d}{d\lambda}\tau^*(G, B) \leq 0$.

Stage 1: Investment

Now consider the initial subgame, where each firm decides whether to invest in the new green technology or keep the old brown technology, given their knowledge of how the game will be played following each decision.

Substituting profits (1.13) at tax rate and political contributions (1.14) into firm payoffs (1.6), gives the reduced form payoffs for each firm following each investment outcome. The payoffs are summarised in Table 1.1, and a full analytical description given in Appendix 1.A.

Table 1.1 Payoff matrix for the investment subgame.

		Firm 2	
		G	B
Firm 1	G	$\pi^*_G(G, G) - s$ $\pi^*_G(G, G) - s$	$\pi^*_G(G, B) - c^*_G(G, B) - s$ $\pi^*_B(G, B) - c^*_B(G, B)$
	B	$\pi^*_B(G, B) - c^*_B(G, B)$ $\pi^*_G(G, B) - c^*_G(G, B) - s$	$\pi^*_B(B, B) - c^*_B(B, B)$ $\pi^*_B(B, B) - c^*_B(B, B)$

Notes: See Appendix 1.A for the full analytical results.

The Nash equilibria of this reduced form game, along with τ^* and $\{C^*_i(\tau), x^*_i\}_{i \in \{G,B\}}$ from the next two stages, are the subgame perfect Nash equilibria of the whole game. I will henceforth refer to an equilibrium of the whole game by its investment choices f, omitting for brevity the corresponding $\tau^*(f)$, $C^*_i(f)$ and $x^*_i(f)$. An intuitive summary of the possible equilibria is as follows. If firms choose (G, G), then production profits are high and symmetric, no political contributions are made, and both firms pay green investment cost s. If firms choose (B, B) then production profits are low and symmetric, both firms lobby the emissions tax below the Pigouvian level and both firms avoid the investment cost s. If firms choose (G, B), then the green firm gains profits from increased market share and higher prices ($\pi^*_G(G, B) > \pi^*_B(B, B)$), it must pay a political contribution ($c^*_G(G, B)$) to push the tax up and stop its opponent firm from pushing it down, and it must pay green investment cost s. The brown firm loses profits from loss of market share and lower net of tax prices ($\pi^*_B(G, B) < \pi^*_G(G, G)$), it must pay a political contribution ($c^*_B(G, B)$) to keep the emissions tax from being even higher, but it avoids investment cost s.

The equilibria of the reduced form investment subgame can now be found. I focus on two equilibria: (G, B) and then (G, G).

1.3.1 The (G, B) equilibrium

The asymmetric equilibrium (G, B) is of particular interest, since this features political conflict between the firms. Using the payoff matrix in Table 1.1, the no-deviation conditions for the two firms are:

$$s \leq \pi^*_G(G, B) - \pi^*_B(B, B) - c^*_G(G, B) + c^*_B(B, B) \tag{1.11}$$

$$s \geq \pi^*_G(G, G) - \pi^*_B(G, B) + c^*_B(G, B) \tag{1.12}$$

The (η, λ, b, s) parameter space that gives rise to the (G, B) equilibrium can now be characterised. For any (η, λ, b), let S be the set of values of investment cost s that satisfy no-deviation conditions (1.11) and (1.12). That is, let $S = \{s \in \mathbb{R}$: inequalities (1.11) and (1.12) hold$\}$. Denote by $|S|$ the absolute size of S, so that it is the range of investment costs that leads to (G, B) in equilibrium, and is a function of the remaining parameters, (λ, η, b).

To make progress in deriving tractable results, it is useful to consider the case where b, and therefore the elasticity of demand, is small. In the extreme case, with demand inelastic and so $b = 0$, the size of the market is fixed and the model can concentrate purely on market share effects, which are the focus of this paper. The analytical results in the following propositions are derived for small $b \geq 0$; Section 1.3.3 demonstrates the robustness of these results to high demand elasticities.

Proposition 1 (Existence of (G, B) equilibrium). *For η sufficiently large, and b small:*

(i) The (G, B) equilibrium exists, that is S is non-empty.

(ii) (G, B) is the equilibrium for a greater region of the parameter space as the government becomes more open to lobbying, that is $\frac{d}{d\lambda}|S| > 0$.

Proposition 1(i) confirms the intuition outlined in the Introduction that market share considerations can indeed lead to one firm going green and the other staying brown. It is the gain in market share that makes it profitable for one firm to go green; the second firm would not find it profitable also to go green because they would not see this gain in market share, and therefore stays brown. That such an asymmetric equilibrium exists is not a foregone conclusion in a model where the firms are ex-ante identical, and is therefore of interest. A firm needs no initial technological advantage (or head start of any other kind) over their rival to find it profitable to go green and lobby for increased market share.

Proposition 1(ii) shows that as λ rises, a greater range of parameters give rise to the (G, B) equilibrium. Interpreting this result more broadly and loosely, the (G, B) outcome can be thought of as becoming in some sense more likely. The intuition for this result is that the ability of firms to lobby - understood as the equilibrium response to the government's interest in political contributions - makes green investment more attractive.[25] The green firm is willing to lobby harder than the brown firm for the emissions tax to rise, so τ is increasing in λ (Lemma 2). This extra lobbying results in an increase in profits that outweighs the increased lobbying bill, so the green investment becomes more attractive. Hence, the firm will be willing to make the green investment at higher costs s, tending to increase $|S|$. The brown firm's behaviour will be impacted by rising λ too, since staying brown involves an ever larger loss of market share, tending to decrease $|S|$. However, this loss is smaller than the green firm's gain, so the overall effect is an increase in $|S|$.

These same results can be understood graphically, as shown in Figure 1.1. The Figure shows the regions of the (λ, s) parameter space that give rise to different investment choices in equilibrium (holding η and b fixed). The solid line is the indifference curve of a firm whose competitor has stayed brown (condition (1.11)). At points below the line, green investment costs are low enough that it is profitable to go green, above the line it is better to stay brown. The thick dashed line is the indifference curve of a firm whose competitor has gone green (condition (1.12)), with optimal technology choices likewise above and below the line. As expected, when green investment cost s is low, both firms prefer to go green since this requires only a small investment and avoids market share being stolen by their competitor. As s rises one firm will at some point find it profitable to stay brown, and eventually s will be so prohibitively high that both firms will prefer to stay brown.

Proposition 1(i) is demonstrated by the fact that the indifference curves lie one above the other in the order they do: $|S|$ is the vertical distance between the two lines. Proposition 1(ii) is demonstrated by the fact that the vertical space between the lines grows with λ.

These results indicate that there are situations where is it only because of lobbying, i.e. $\lambda > 0$ rather than $\lambda = 0$, that the economy ends up in equilibrium at (G, B) and

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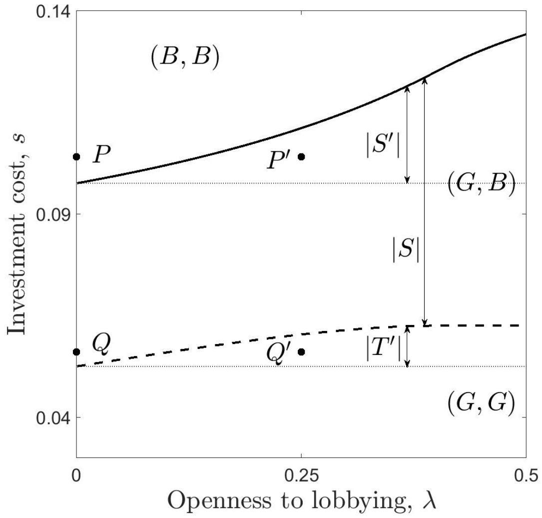
[25] My use of the phrase 'ability of firms to lobby' here and subsequently refers only to the size of λ; it is not a restriction on the contribution functions C_i they can offer.

Figure 1.1 Equilibrium investment outcomes.



Notes: Equilibrium investment outcomes are shown as a function of the parameter space (λ, s), plotted for (b=0, η=0.3). The thick solid line shows the indifference curve of a firm whose competitor has played B, the thick dashed line likewise if the competitor has played G.

not (B, B). I will describe such economies as featuring a 'lobbying-induced switch' from (B, B) to (G, B). (This description refers only to a comparative statics-type switch, not to a transition in the dynamic sense.) To formalise this idea, it is helpful to define a new set: for any (η, λ, b), let $S'(\lambda) = S(\lambda) \setminus S(0)$. That is, $S'(\lambda)$ is the set of investment costs s that result in (G, B) when openness to lobbying is λ, but would have given (B, B) if λ were 0. Proposition 2 gives two key properties of S'.

Proposition 2 (Lobbying-induced switches to (G, B))**.** *For η sufficiently large and b small:*

(i) Parameter constellations exist such that (G, B), and not (B, B), is the equilibrium outcome, that is S' is non-empty.

(ii) The parameter space giving rise to a lobbying-induced switch to (G, B) from (B, B) expands as the government becomes more open to lobbying, that is $\frac{d}{d\lambda}|S'| > 0$.

Figure 1.1 illustrates this result graphically. Proposition 2(i) is demonstrated by the existence of a wedge between the solid line and the thin dotted line labelled $|S'|$, and Proposition 2(ii) is demonstrated by the size of this wedge increasing with λ.

In order to summarise these results (which are the main contribution of the paper) and illustrate the importance of lobbying, consider the following comparative statics.

Suppose an economy has a government not at all open to lobbying ($\lambda = 0$) and green investment costs s, such that the economy is at point P in Figure 1.1. A firm thinking of going green knows that if it were to do so it would gain market share and increase its profits due to the introduction of an emissions tax. But it also knows this emissions tax ($\tau^* = \eta$) will not be high enough to compensate it for the large green investment cost s, hence the equilibrium is for all firms to stay brown and no environmental protection is achieved. If, however, the government were to be somewhat open to lobbying, say $\lambda = \frac{1}{4}$, with the same green investment cost the economy would be at point P'. Now the firm considering going green would reason that, if it were to invest in the green technology, it could use the political process to push up the emissions tax (to $\tau^* = \frac{4}{3}\eta$ for the parameter values used in Figure 1.1), and this would be sufficient to cover the investment cost plus the political contribution needed to push up the tax. The other firm will lobby to reduce τ, which keeps it from being even higher, but it would prefer to lose some market share rather than pay the green investment cost itself and so will stay brown. Hence, it is only the ability of a firm to influence the political process and secure a high emissions tax that gives it an incentive to invest in the green technology, and it is only because of the firm's political support that the government takes strong action on the environment. The welfare implications of this are given in Proposition 4 below.

1.3.2 The (G, G) equilibrium

So far I have focused on the asymmetric (G, B) equilibrium, since it involves firm conflict in the lobbying subgame. However, the model may also help describe situations where all firms make the green investment together and no market share ends up being fought over, that is (G, G) is the equilibrium outcome. In this case, it is the *threat* of having its market share stolen that will make each firm more likely to go green. Using an analogous approach to that in Section 1.3.1, the properties of this equilibrium can be characterised as follows. Let T be the set of investment costs that lead to (G, G) in equilibrium. That is, for any (η, λ, b), let $T = \{s \in \mathbb{R} : \text{inequality (1.12) holds}\}$. Unlike in the previous case, the existence of the (G, G) equilibrium should not itself be a surprising result: given small enough green investment costs, each firm will prefer to make the small green investment in order to avoid emissions tax τ. I therefore move straight to the question of whether lobbying makes the (G, G) outcome more likely, in the sense that it expands the parameter space that supports this equilibrium.

For any (η, λ, b), let $T'(\lambda) = T(\lambda) \setminus T(0)$. That is, let $T'(\lambda)$ be the set of investment costs that result in (G, G) when openness to lobbying is λ, but would not have given

(G, G) if λ were 0. T' captures those situations where (G, G) is the outcome only because a government is open to lobbying, i.e. we have a lobbying-induced switch. The following results can now be given.

Proposition 3 (Lobbying-induced switches to (G, G))**.** *For any η, and b small:*

(i) Parameter constellations exist such that (G, G), and not (G, B), is the equilibrium, that is T' is non-empty.

(ii) The parameter space giving rise to a lobbying-induced switch to (G, G) from (G, B) expands as the government becomes more open to lobbying, that is $\frac{d}{d\lambda}|T'| > 0$.

The intuition for this result is as follows. The more open a government is to lobbying, the further the tax will be distorted above the Pigouvian level following (G, B), and hence the more market share a firm will lose if it stays brown while its rival goes green. This threat of an increasingly damaging emissions tax means firms become increasingly willing to go green as λ rises. This point is made graphically in Figure 1.1. An economy with no lobbying is shown at point Q, and is in equilibrium at (G, B). An otherwise identical economy, except that the government is more open to lobbying, is shown at point Q', and is in equilibrium at (G, G). This result formalises the idea that, even when all firms in an industry go green together in a seemingly 'cooperative' way, it may well be that it is only the threat of losing substantial market share that keeps each individual firm from deviating. The welfare consequences of this are given in Proposition 5 below.

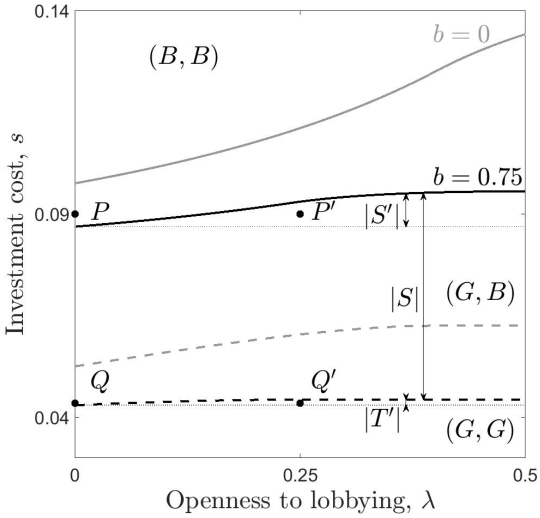
1.3.3 The high elasticity case

The elasticity of demand is determined by the parameter b, from demand equation (1.3). The above results were derived analytically for small b (starting with $b = 0$ and then exploiting the continuity of the relevant expressions in b) and are shown in Figure 1.1 for $b = 0$. The complexity of the final analytical expressions when $b > 0$ (see Appendix 1.A) makes closed form versions of the above and subsequent propositions difficult to obtain when b is large. In this section, I show that the qualitative results continue to hold for large b, though for increasingly narrow (η, λ, s) parameter spaces.

First, note that the production and political stages still have tractable analytical solutions when b is large. In particular, Lemmas 1 and 2 hold for all b, and it can also be shown that $\frac{d}{db}\frac{d}{d\tau}\sum \pi_i^*(\tau, (G, B)) < 0$. That is, when b is large, increasing the emissions tax still increases total profits, but by a smaller amount than when b is small.

Intuitively, when the total size of the market is very price sensitive, the green firm has less to gain from a tax rise because the corresponding fall in total quantity is large: the market stealing effect is somewhat offset by a market size effect. This means the equilibrium tax $\tau^*(G,B))$ falls in b, and approaches the Pigouvian level from above. Hence, the impact of lobbying, qualitatively the same as in the previous sections, falls as b rises.

Figure 1.2 Equilibrium investment outcomes with elastic demand.



Notes: Equilibrium investment outcomes are shown as a function of the parameter space (λ, s). The black lines show indifference curves when $b = 0.75$; for comparison the light grey lines show the $b = 0$ case (and are the same as those in Figure 1.1). As before, $\eta = 0.3$ in both cases.

Figure 1.2 demonstrates numerically for large b what Propositions 1-3 proved analytically for small b.[26] A region of the parameter space gives rise to (G,B) in equilibrium, and this region expands as λ rises (Proposition 1), though the total size of the region is smaller than in the $b = 0$ case. Likewise, regions of the parameter space give rise to lobbying-induced switches to (G,B) and to (G,G), and the sizes of the regions rise with λ (Propositions 2 and 3); once again in each case, however, the region is smaller for $b > 0$ than when $b = 0$.

These results demonstrate that lobbying that supports environmental regulation might be more prevalent in industries where the demand elasticity is low. If it is too high, strong environmental protection shrinks the total market too much, offsetting

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[26] The Figure is plotted for $b = \frac{3}{4}$, chosen as it balances the need to for b to be large with the desire to retain interior solutions for much of the parameter space (larger b give rise to corner solutions at smaller values of λ).

any firm's potential gain in market share and therefore making green investments less attractive.

1.4 Welfare

Section 1.3 showed that the ability of firms to lobby can cause the economy to end up in a greener equilibrium than in the absence of lobbying. In this section I ask whether these lobbying-induced switches are welfare improving. In each case there are trade-offs between increased environmental protection on the one hand, and investment costs and distortions to the production profile of the economy as a result of lobbying on the other.

Using equilibrium outcomes from stages 2 and 3 in welfare equation (1.4), define an indirect welfare function $W(f)$ that depends only on technology profile f; this includes all political and production outcomes, but not investment cost s. Then define social preference $\succ$ over all technology profiles such that for any two technology profiles $f, f' \in \{G, B\}^2$, $f \succ f'$ if and only if $W(\cdot)$ minus any green investment costs is higher for f than f'.

1.4.1 The (G, B) equilibrium

It can now be asked when being in equilibrium at (G, B) rather than (B, B), for example P' rather than P in Figure 1.1, is socially preferable.[27] Using the above definitions, $(G, B) \succ (B, B)$ if and only if $W(G, B) - s > W(B, B)$. For any (η, λ, b), let $Y = \{s \in \mathbb{R} : (G, B) \succ (B, B)\}$. Y is the set of investment costs for which the greener (G, B) is socially preferred to the dirtier alternative (B, B). Recall that S' is the set of investment costs for which the economy is in equilibrium at (G, B) rather than (B, B). Hence, all such lobbying-induced switches will be socially preferable if any economy in S' is also in Y, that is if $S' \subset Y$.

Proposition 4 (Welfare of lobbying-induced switches to (G, B))**.** *For b small, any lobbying-induced switch from (B, B) to (G, B) is socially preferable, that is $S' \subset Y$.*

To understand this result, consider the social costs of being in equilibrium at (G, B) rather than (B, B). In the (B, B) equilibrium, firms produce an equal share of output but they lobby the tax below the Pigouvian level, resulting in too much environmental damage. In the (G, B) equilibrium, lobbying distorts the tax above the Pigouvian level,

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[27] Note that λ does not have a direct effect on welfare in this set up. Its only effect is to introduce distortions into the economy through τ^*.

which reduces environmental damage. But it also distorts the production profile of the economy, both by giving the green firm more than its efficient market share (convex cost functions making this socially undesirable) and also by shrinking total output below the optimal level (for $b > 0$).

Proposition 4 shows that if the green investment cost s is large enough to induce a switch from (B, B) to (G, B), then the net gain in welfare, from reduced environmental damage plus increased product market distortion, more than compensates for s. All such switches are therefore socially preferable.

1.4.2 The (G, G) equilibrium

The same welfare analysis can be used to compare the (G, B) and (G, G) equilibria. $(G, G) \succ (G, B)$ if and only if $W(G, G) - s > W(G, B)$. For any (η, λ, b), let $Z = \{s \in \mathbb{R} : (G, G) \succ (G, B)\}$. Recall T' is the set of investment costs for which lobbying induces the economy to be in (G, G) rather than (G, B). Hence any lobbying-induced switch will be socially preferable if all economies in T' are also in Z, that is if $T' \subset Z$.

Proposition 5 (Welfare of lobbying-induced switches to (G, G))**.** *For b small, any lobbying-induced switch from (G, B) to (G, G) is socially preferable, that is $T' \subset Z$.*

This result is perhaps less surprising than the previous proposition. As outlined above, the (G, B) outcome features product market distortions, both in the firms' shares of production and total output. In contrast, there is no product market distortion in the (G, G) case, since both firms have clean production technologies and so output is shared evenly and at the socially optimal level. Moving from (G, B) to (G, G), therefore, reduces both environmental damage and product market distortions. Hence, if the investment cost is such that a lobbying-induced switch occurs, it will be more than compensated for by the above two welfare gains.

1.5 Extensions and robustness

1.5.1 Generalisation to n firms

In this section I generalise the model by allowing the number of firms to be any $n \in \mathbb{N}$. The results for the special case of $n = 2$ characterised in the previous sections are shown to qualitatively hold in the more general case. Let n_G be the number of firms that chose $f_i = G$ in stage 1. Solving the model in an analogous way to the $n = 2$

case in Section 1.3 gives equilibrium outcomes as a function of n_G at each stage. The details are given in Appendix 1.C.[28]

Proposition 6 (n-firm equilibrium existence)**.** *For any η, $b = 0$, λ sufficiently close to 0, and any $n \in \mathbb{N}$:*

(i) Any number of green firms can be supported as the unique equilibrium. That is, for all $n_G \in \{0, ..., n\}$ there exist regions of (η, λ, s) space such that $S(n_G)$ is non-empty.

(ii) The equilibrium number of green firms n_G^* decreases with the green investment cost s.

The results in the above proposition are demonstrated numerically in Figure 1.3, plotted with $n = 5$. Like Figure 1.1, this shows which regions of the (λ, s) parameter space give rise to different n_G^* equilibria. Proposition 6(i) is demonstrated by each number of green firms $n_G \in \{1, ..., n\}$ being supported by some different green investment s for small λ. Proposition 6(ii) is demonstrated by the number of firms going green in equilibrium falling as the green investment becomes more expensive, for intuitively straightforward reasons.

The n-firm case more closely describes the real world examples discussed in the Introduction. In the case of the ozone layer and DuPont, $n_G^* = 1$ and $n \approx 5$, with just DuPont lobbying for environmental protection and a handful of others opposing. In Figure 1.3, points P and P' illustrate the importance of lobbying for the equilibrium outcome. In the case of climate change and the European oil and gas companies, $n_G^* = 6$ and n is large. However, the key insights gained from the two-firm model remain largely in tact in the n-firm case.

1.5.2 Cournot and other models of competition

The baseline model assumes firms take prices as given. As discussed, by abstracting away from strategic product market behaviour, this allows the model to focus cleanly on the political and investment stages of the game. In this section I demonsrate the robustness of these results, by outlining the solution to the model with Cournot competition in the production stage. Appendix 1.D contains further details.

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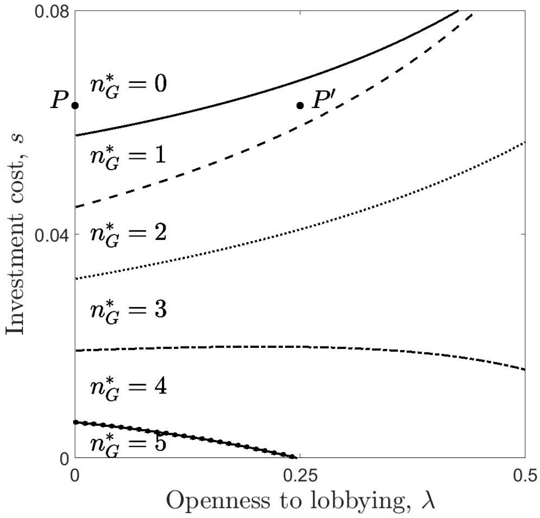
[28] I focus on the case where λ is close to 0, which (hopefully) represents many modern economies. Goldberg and Maggi (1999), among others, estimate Grossman and Helpman's (1994) trade protection model. They estimate, for the US, openness to lobbying λ to be positive but small, around $\lambda = 0.02$.

Figure 1.3 Equilibrium outcomes for multiple firms.



Equilibrium outcomes are shown as a function of the parameter space (λ, s), plotted for $n = 5$ and with (b=0, η=0.2).

Consider the setup in Section 1.2, but now suppose firms know that prices depend on quantity according to demand equation (1.3). Substituting this into their profit equations and maximising gives equilibrium outputs such that Lemma 1 continues to hold. In the lobbying stage, compared to the previous case, the equilibrium taxes are distorted downwards, as the government addresses the market failure resulting from Cournot competition. This use of an environmental tax as an instrument of competition policy complicates the solutions, but they retain the key properties needed for the final results: $\tau^*(G,G) \in \mathbb{R}$, $\frac{d}{d\lambda}\tau^*(G,B) > 0$, and $\frac{d}{d\lambda}\tau^*(B,B) < 0$. Solving the investment stage establishes that the (G,B) equilibrium exists and becomes more likely as λ increases. Appendix 1.D gives further details.[29]

A final point to make about market structure is a more general one. Abstracting away from specific assumptions, the results found here will qualitatively hold so long as total profits are increasing in the government's environmental protection instrument. Instead of a tax, this instrument could most obviously be a reduction in permits under a cap and trade scheme. Hepburn et al. (2013) characterise quite general conditions under which the equivalent of $\frac{d}{d\tau}\sum \pi_i^* > 0$ holds. That it does often hold should not be

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[29] The model can be re-solved for other competitive environments. Hotelling competition gives particularly concise analytical solutions. Again, the results continue to hold, though they are inevitably made more complex by the government using the emissions tax as an instrument of competition policy as well as environmental policy.

too surprising a result: environmental protection frequently involves putting a price on externalities where previously there was none, generating environmental rents which can at least partially accrue to firms. Reinforcing this effect, governments often give away large quantities of permits to firms, especially as a scheme is introduced. Hence, though environmental regulation can sometimes shrink markets, getting a share of the new rents often ensures the winners gain more than the losers lose. Therefore Lemma 1 or its equivalent is arguably a more general property of economies than might initially be supposed.

1.6 Conclusion

This paper presented a model of environmental protection in a situation where firms can lobby the government over the level of an emissions tax and use it as a means to potentially steal market share from their competitors. The paper focused on the equilibrium where one firm goes green, lobbies for a high emissions tax and gains market share from its rival, who stays brown and lobbies to try to lower the tax. The equilibrium tax is increasingly distorted above the Pigouvian level as the government becomes more open to lobbying. I show there are situations where it is only because of lobbying that the economy ends up with one green firm instead of none. The equilibrium where both firms go green is also characterised, and here the threat of loss of market share helps to sustain the equilibrium. In both cases, lobbying-induced switches to a greener economy are welfare improving.

The findings in this paper illustrate a broader point, that we ought to think carefully about why there might be conflict between corporate interests and environmental protection, and whether it is inevitable. Certainly profit maximising behaviour, particularly when it comes to minimising costs,[30] can mean these two forces pull in opposite directions. But the creation of environmental rents and the opportunity to use regulation to gain a competitive advantage over a rival are both powerful reasons for profit maximising firms to support environmental protection. Such political support can have a major impact on the extent to which the environment is protected.

I have argued this model explains some otherwise puzzling examples of environmental lobbying by polluting firms. However, the model is also a bad predictor of the political economy of environmental protection much of the time - since polluting industries are

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[30] The 1984 Union Carbide chemical leak in Bhopal was a particularly deadly and long lasting environmental disaster (see Dhara and Dhara (2002)). Aggressive cost cutting is often said to be its cause, as it was with the 2010 BP oil spill in the Gulf of Mexico.

often united in opposing regulation - a fact which is itself interesting since it suggests that there may be other important effects at work. Three potentially plausible frictions that would generate this result are as follows.

The first, and perhaps most interesting, explanation could be collusion. Firm collusion in the product market has been extensively studied, but it is not the only arena in which firms may be more or less competitive. The model presented here features a highly competitive political stage (in the sense that lobbying is non-cooperative), but perhaps in reality the firms collude, at least to some extent. If the determinants of political collusion are similar to the those of product market collusion, concentrated, established industries that cooperate on other matters might be expected to collude politically and stay brown rather than maximise their individual profits and go green. Both industry and environmental lobbyists often emphasise the practical importance of Trade Associations, the industry-wide lobby groups through which much of each firm's lobbying in reality takes place. In order to function, these institutions foster consensus and cooperation among their members, or, in other words, collusion. Firms' lobbyists are often not keen to deviate from a collusive outcome, either for rational repeated game-type reasons, or perhaps for ingrained social and institutional ones.[31]

A second plausible explanation could be due to uncertainty over government policy. The green firm needs the tax to stay in place and not be changed by future governments, which is the case by construction in the simple model presented here. In reality, however, governments behave less predictably and newly elected governments, for example, often cancel taxes or subsidies introduced by their predecessors. Going green is therefore a risky investment, and companies may decide they don't want the uncertainty in their revenues and may rationally choose to stay brown.

Third, it may be that (due to asymmetries not modelled above) the firms that stand to lose are large incumbents, and those that stand to gain are either small incumbents or entrants. Such firms are likely to be liquidity constrained in their lobbying activities, and may face other barriers to lobbying such as less developed networks with policymakers. In such circumstances, lobbying may not in equilibrium result in a large enough environmental tax for a firm to choose to go green. Whatever the exact mechanism, some additional friction or imperfection is needed before it can be shown that corporate lobbying inevitably harms the environment. Given this may often have large consequences, further, perhaps empirical, work in this area may be fruitful.

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[31] Wider social and cultural factors may also play a role in determining the extent of collusion, for example in explaining why European oil and gas producers lobbied for a carbon price in 2015 when their US counterparts did not.

Appendix 1.A Full analytical solutions to the subgames

	x_1	x_2	p	π_1	π_2
(G,G)	$\frac{2}{b+4}$	$\frac{2}{b+4}$	$\frac{1}{b+4}$	$\frac{1}{(b+4)^2}$	$\frac{1}{(b+4)^2}$
(G,B)	$\frac{4\tau+2}{b+4}$	$\frac{2-(2+b)2\tau}{b+4}$	$\frac{2\tau+1}{b+4}$	$\frac{(2\tau+1)^2}{(b+4)^2}$	$\frac{(1-(2+b)\tau)^2}{(b+4)^2}$
(B,B)	$\frac{2(1-b\tau)}{b+4}$	$\frac{2(1-b\tau)}{b+4}$	$\frac{4\tau+1}{b+4}$	$\frac{(1-b\tau)^2}{(b+4)^2}$	$\frac{(1-b\tau)^2}{(b+4)^2}$

Production subgame equilibrium outcomes (1.13)

	τ^*	c_1^*	c_2^*
(G,G)	$\in \mathbb{R}$	0	0
(G,B)	$\frac{8\eta+b(6\eta+b\eta-\lambda)}{8(1-\lambda)+b(6-4\lambda-b\lambda+b)}$	$\frac{4\lambda(b+2)(2\eta-\lambda+1)^2}{(b-2\lambda-b\lambda+4)(8\lambda-6b+4b\lambda+b^2\lambda-b^2-8)^2}$	$\frac{\lambda(b+2)^2\left(2\lambda-b+4\eta+4b\eta+b^2\eta-2\right)^2}{(b^2+6b-4\lambda+8)(8\lambda-6b+4b\lambda+b^2\lambda-b^2-8)^2}$
(B,B)	$\frac{4\eta+b\eta-\lambda}{4+(1-\lambda)b}$	$\frac{b\lambda(b\eta-1)^2}{(2b-b\lambda+8)(b-b\lambda+4)^2}$	$\frac{b\lambda(b\eta-1)^2}{(2b-b\lambda+8)(b-b\lambda+4)^2}$

Lobbying subgame equilibrium outcomes (1.14)

	G	B
G	$\frac{1}{(b+4)^2} - s$ $\frac{1}{(b+4)^2} - s$	$\frac{(b+2)(2\eta-\lambda+1)^2}{-(b-2\lambda-b\lambda+4)(8\lambda-6b+4b\lambda+b^2\lambda-b^2-8)} - s$ $\frac{\left(2\lambda-b+4\eta+4b\eta+b^2\eta-2\right)^2}{(-6b+8\lambda+4b\lambda+b^2\lambda-b^2-8)(-6b+4\lambda-b^2-8)}$
B	$\frac{\left(2\lambda-b+4\eta+4b\eta+b^2\eta-2\right)^2}{(-6b+8\lambda+4b\lambda+b^2\lambda-b^2-8)(-6b+4\lambda-b^2-8)}$ $\frac{(b+2)(2\eta-\lambda+1)^2}{-(b-2\lambda-b\lambda+4)(8\lambda-6b+4b\lambda+b^2\lambda-b^2-8)} - s$	$\frac{2(b\eta-1)^2(b+4)}{(2b-b\lambda+8)(b-b\lambda+4)^2}$ $\frac{2(b\eta-1)^2(b+4)}{(2b-b\lambda+8)(b-b\lambda+4)^2}$

Investment subgame payoff matrix (1.15)

Appendix 1.B Proofs

Lemma 1

Proof. Using production equilibrium outcomes (1.13), we find $\frac{d}{d\tau}\sum \pi_i(\tau,(G,B)) = \frac{2(8\tau-b+4b\tau+b^2\tau)}{(b+4)^2}$, which is positive if $\tau > \frac{b}{4b+b^2+8} \in [0, \frac{\sqrt{2}-1}{4}]$ for all $b \in \mathbb{R}_{\geq 0}$. The results from the next stage verify that, in the equilibria of interest, τ always satisfies the above inequality. $\square$

Proposition 1

Proof. (i) There are parameters for which S is non-empty if $|S|> 0$. Let $\overline{s}_s = \max S$, obtained by substituting values from payoff matrix (1.15) into no-deviation condition (1.11). Likewise let $\underline{s}_s = \min S$, obtained by substituting values from payoff matrix (1.15) into no-deviation condition (1.12). $|S|= \overline{s}_s - \underline{s}_s$, but the full analytical expression for $|S|$ and subsequent quantities is long, so I proceed in this and the next two proofs as follows. First, I demonstrate the relevant result at $b = 0$, i.e. when demand is inelastic. Second, if the relevant expression is continuous in b at $b = 0$, then any result true at $b = 0$ must also be true for $b > 0$ but close to 0. (The large b case is considered graphically in Section 1.3.3.) Proceeding in this way, $|S|_{b=0}= \frac{\lambda^2-\lambda+8\eta^2}{8(1-\lambda)(2-\lambda)}$, which is positive if $\eta > (\frac{\lambda(1-\lambda)}{8})^{\frac{1}{2}}$. $\eta > \frac{\sqrt{2}}{8} \approx 0.18$ guarantees $|S|> 0$ for all $\lambda \in \mathbb{R}_{\geq 0}$ that give an interior solution. Finally, $\lim_{b\to 0}(|S|) = |S|_{b=0}$, so $|S|$ is continuous in b at $b = 0$.
(ii) Differentiating gives $\frac{d}{d\lambda}|S|\Big|_{b=0} = \frac{(12-8\lambda)\eta^2-(1-\lambda)^2}{4(1-\lambda)^2(2-\lambda)^2}$ which is positive for $\eta > \frac{1-\lambda}{2(3-2\lambda)^{1/2}}$. $\eta > \frac{\sqrt{3}}{6} \approx 0.29$ guarantees $\frac{d}{d\lambda}|S|> 0$ for all $\lambda \in \mathbb{R}_{\geq 0}$ that give an interior solution. Finally, $\lim_{b\to 0}(\frac{d}{d\lambda}|S|) = |S|_{b=0}$, so $\frac{d}{d\lambda}|S|$ is continuous in b at $b = 0$. □

Proposition 2

Proof. (i) S' is non-empty if $|S'|> 0$, where $|S'(\lambda)|= \overline{s}_s(\lambda) - \overline{s}_s(0)$. Using maximum investment cost $\overline{s}_s(\lambda)$ from the above proof, $|S'|_{b=0}= \frac{8\eta+\lambda^2-\lambda+8\eta^2-8\lambda\eta}{16(1-\lambda)(2-\lambda)}$. Hence $|S'|> 0$ if $\eta > \frac{\lambda-1+\sqrt{2}\sqrt{-3\lambda+\lambda^2+2}}{2(3-\lambda)}$; $\eta > \frac{1}{6}$ ensures this holds for all $\lambda \in \mathbb{R}_{\geq 0}$ that gives an interior solution. Finally, $\lim_{b\to 0}(|S'|) = |S|_{b=0}$, so $|S'|$ is continuous in b at $b = 0$.
(ii) Differentiating and then setting $b = 0$ gives $\frac{d}{d\lambda}|S'|\Big|_{b=0} = \frac{(2\eta+1-\lambda)(\lambda+6\eta-4\lambda\eta-1)}{8(1-\lambda)^2(2-\lambda)^2}$. This is positive if $\eta > \frac{1-\lambda}{2(3-2\lambda)}$; $\eta > \frac{1}{6}$ ensures this holds for all $\lambda \in \mathbb{R}_{\geq 0}$ that gives an interior solution. Finally, $\lim_{b\to 0}(\frac{d}{d\lambda}|S'|) = \frac{d}{d\lambda}|S'|\Big|_{b=0}$, so $\frac{d}{d\lambda}|S'|$ is continuous in b at $b = 0$. □

Proposition 3

Proof. The form of the proof is the same as for Proposition 2. (i) T' is non-empty if $|T'|> 0$, where $|T'(\lambda)|= \overline{s}_T(\lambda) - \overline{s}_T(0)$ and $\overline{s}_T = \max T'$. Substituting payoff matrix (1.15) into no-deviation condition (1.11) gives $\overline{s}_T$, which then gives $|T'|_{b=0}= \frac{\lambda(4\eta-\lambda-12\eta^2-4\lambda\eta+4\lambda\eta^2+1)}{16(1-\lambda)(2-\lambda)}$. Hence $|T'|> 0$ if $\eta > \frac{1-\lambda+\sqrt{2}\sqrt{(1-\lambda)(2-\lambda)}}{2(3-\lambda)}$, which holds for all $(\lambda, \eta) \in \mathbb{R}^2_{\geq 0}$ that give an interior solution. Finally, $\lim_{b\to 0}(|T'|) = |T|_{b=0}$, so $|T'|$ is continuous in b at $b = 0$.
(ii) Differentiating and then setting $b = 0$ gives $\frac{d}{d\lambda}|T'|= \frac{(1-\lambda+6\eta-4\lambda\eta)(1-\lambda-2\eta)}{8(1-\lambda)^2(2-\lambda)^2}$. Again this is positive if $\eta < \frac{1-\lambda}{2}$, which holds for all $(\lambda, \eta) \in \mathbb{R}^2_{\geq 0}$ that give an interior solution. Finally, $\lim_{b\to 0}(\frac{d}{d\lambda}|T'|) = \frac{d}{d\lambda}|T'|\Big|_{b=0}$, so $\frac{d}{d\lambda}|T'|$ is continuous in b at $b = 0$. □

Proposition 4

Proof. Let $\overline{s}_Y = \max Y$, that is $\overline{s}_Y$ is the largest investment cost for which $(G, B) \succ (B, B)$. $S' \subset Y$ when $\overline{s}_Y > \overline{s}_S$. Using indirect welfare function $W(f)$, we can calculate $\overline{s}_Y = W(G, B) - W(B, B)$. The limits as $b \to 0$ are $\lim_{b \to 0}(\overline{s}_Y) = \frac{\eta(-2\lambda+\eta+\lambda^2-2\lambda\eta+1)}{2(\lambda-1)^2}$ and $\lim_{b \to 0}(\overline{s}_S) = \frac{\left(\lambda^2-\lambda+8\eta^2\right)}{8(\lambda^2-3\lambda+2)}$. Using these results, in the $b \to 0$ limit, $\overline{s}_Y(\lambda) > \overline{s}_S$ holds if $(16\lambda^2 - 32\lambda + 8)\eta^2 + (24\lambda^2 - 8\lambda^3 - 24\lambda + 8)\eta + (\lambda^3 - 2\lambda^2 + \lambda) > 0$. Solving for η, it can be shown that this holds for any $(\lambda, \eta) \in \mathbb{R}^2_{\geq 0}$ that give an interior solution. Note that at $b = 0$, for welfare analysis we must use the part of the utility function specified in footnote 18. This then ensures continuity in all the relevant expressions at $b = 0$. □

Proposition 5

Proof. Let $\overline{s}_Z = \max Z$, that is $\overline{s}_Z$ is the largest investment cost for which $(G, G) \succ (G, B)$. $T' \subset Z$ when $\overline{s}_Z > \overline{s}_T$. Using indirect welfare function $W(f)$, we can calculate $\overline{s}_Z = W(G, G) - W(G, B)$. The limits as $b \to 0$ are $\lim_{b \to 0}(\overline{s}_Z) = \frac{\eta(-2\lambda-\eta+\lambda^2+2\lambda\eta+1)}{2(1-\lambda)^2}$ and $\lim_{b \to 0}(\overline{s}_T) = \frac{\lambda-\lambda^2-8\lambda\eta-8\eta^2+8\eta}{16(1-\lambda)(2-\lambda)}$. Using these results, in the $b \to 0$ limit, $\overline{s}_Z > \overline{s}_T$ holds if $\eta \in [\frac{(1-\lambda)(-4\lambda+2\lambda^2+1-\sqrt{2}L(\lambda))}{4(2\lambda^2-4\lambda+1)}, \frac{(1-\lambda)(-4\lambda+2\lambda^2+1+\sqrt{2}L(\lambda))}{4(2\lambda^2-4\lambda+1)}]$ where $L(\lambda) = \sqrt{-9\lambda + 16\lambda^2 - 10\lambda^3 + 2\lambda^4 + 2}$. Any η giving an interior solution lies in the above interval. Note that at $b = 0$, for welfare analysis we must use the part of the utility function specified in footnote 18. This then ensures continuity in all the relevant expressions at $b = 0$.

□

Appendix 1.C Generalisation to n-firms

Stage 3: Production

Let n_G be the number of firms that chose $f_i = G$ in stage 1. The investment profile $f \in \{G, B\}^n$ is therefore summarised by n_G. Given n_G and tax τ chosen in stages 1 and 2, firms choose their level of output x_i to maximise their profits. Assuming all firms that made the same investment choice behave in the same way, and denoting as before variables for a firm that chose $f_i = G$ with a G subscript and those that chose $f_i = B$ with a B subscript, the stage 3 equilibrium is given by outputs $x^*_G(\tau, n_G), x^*_B(\tau, n_G)$, with corresponding prices and profits $p^*(\tau, n_G), \pi^*_G(\tau, n_G), \pi^*_B(\tau, n_G)$. As before, any firm that has gone green gains from a higher tax and those that stayed brown gain from a lower tax. Lemma 1 continues to hold since the sum of all firms profits is increasing in τ.

Stage 2: Lobbying

Knowing how a tax will impact their profits and taking n_G as given, the firms non-cooperatively choose their lobbying contribution functions $C_i(\tau)$.[32] The government maximises a weighted sum of social welfare and political contributions as before. The equilibrium is an emissions tax τ^* and pair of contribution functions $(C_G^*(\tau), C_B^*(\tau))$ that satisfy the two equilibrium conditions set out in Section 1.3. When $b = 0$, solving gives $\tau^*(n_G) = \frac{\eta}{1-\lambda}$, and values of $c_i^*(n_G)$ that are generalisations of the $n = 2$ case. As in the two firm case, lobbying results in the emissions tax being increasingly distorted above the Pigouvian level. This is a consequence of Lemma 2, which it was previously noted holds for any n and therefore applies in this setting.

Stage 1: Investment

Having shown that green firms will successfully lobby to distort the emissions tax above the Pigouvian level, it only remains to show that some firms will in equilibrium choose to go green in the investment stage. An equilibrium of the investment subgame is a profile of choices $f \in \{G, B\}^n$, or equivalently a value of $n_G \in \{0, ..., n\}$, such that no firm gains from unilaterally deviating. That is, given the choices of the other firms, no firm choosing G could gain from deviating to B and no firm choosing B could gain from deviating to G, as given respectively by

$$\pi_G^*(n_G) - c_G^*(n_G) - s \geq \pi_B^*(n_G - 1) - c_B^*(n_G - 1) \tag{1.16}$$

$$\pi_B^*(n_G) - c_B^*(n_G) \geq \pi_G^*(n_G + 1) - c_G^*(n_G + 1) - s \tag{1.17}$$

An equilibrium is a value of n_G that satisfies both equations. In principle all the results in the propositions in Section 1.3 can be replicated using the equations derived in this section, but most of the analytical solutions are not tractable. I therefore present, in the main body of the article, the small λ case analytically, and then give a graphical example of the more general case to demonstrate the comparative statics. Following Section 1.3, define set $S(n_G) = \{s \in \mathbb{R}_{\geq 0} : n_G \text{ satisfies (1.16) and (1.17)}\}$. That is, $S(n_G)$ is the set of investment costs that supports n_G firms going green in equilibrium. Proposition 6

Proof. Part (i): Consider the case where $\lambda = 0$, giving $|S(n_G)| = \frac{2\eta^2}{n^2}(n-1)$, which is independent of n_G. $|S(n_G)| > 0$ therefore holds for all n_G and any $n \geq 2$. $\lim_{\lambda \to 0}(|S(n_G)|) = |S(n_G)|_{\lambda=0}$, so $|S(n_G)|$ is continuous in λ at $\lambda = 0$, hence the above results continue to

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[32] For example, all the green firms don't form a special interest group and coordinate their lobbying. This implicitly assumes the firms have not solved the collective action problem that prevents them from colluding at the lobbying stage. This issue is briefly discussed in Section 1.6.

hold for small λ. Part (ii): follows from $|S(n_G)|= \frac{2\eta^2}{n^2}(n-1)$ when $\lambda = 0$, and $|S(n_G)|$ being continuous in λ at $\lambda = 0$. $\square$

Appendix 1.D Cournot competition

Consider a set up identical to that in Section 1.2, except that each firm maximises its profits believing that its own and the other firm's output affects prices according to demand equation (1.3). For analytical simplicity, consider the $b = 1$ case. Solving in exactly the same way as in Section 1.3, we get:

$$\overline{s}_s = \frac{\begin{gathered}11\,005\lambda + 13\,836\eta + 14\,375\lambda^2 - 53\,125\lambda^3 + 15\,625\lambda^4 + 582\eta^2 - \\ 33\,750\lambda^2\eta^2 - 83\,260\lambda\eta + 17\,880\lambda\eta^2 + 112\,500\lambda^2\eta - 12\,500\lambda^3\eta - 3168\end{gathered}}{5(\lambda-1)(\lambda-2)(145\lambda-47)(125\lambda-47)}, \tag{1.18}$$

$$\underline{s}_s = \frac{25(-400\lambda^2 - 4900\lambda\eta + 605\lambda - 6125\eta^2 + 5390\eta - 744)}{49(47-145\lambda)(47-20\lambda)} \tag{1.19}$$

Using these and subsequent expressions, it is possible to obtain the results in the Propositions in the main text. Given the complexity of these expressions, numerical examples (not included in this thesis) are the easiest way to establish many of the results.

Appendix 1.E Corner solutions

A corner solution in the production subgame is a possibility following $f = (G, B)$. If the emissions tax τ is high enough then the brown firm will want to choose negative output by (1.13) when $\tau > \frac{1}{b+2}$. Given equilibrium tax rates (1.14) from the lobbying stage, we have a corner solution if $\eta > \frac{b-2\lambda+2}{4b+b^2+4}$. Intuitively, if the environmental problem is too severe, the government will want to set a tax that entirely prohibits polluting production. The corner solution to the production and lobbying subgames is given by:

$$\begin{gathered} x_G^*(G,B) = \frac{2}{b+' 2}, \quad x_B^*(G,B) = 0, \quad \pi_G^*(G,B) = \frac{1}{(b+2)^2}, \quad \pi_B^*(G,B) = 0 \\ \tau^*(G,B) = \frac{1}{b+2}, \quad c_G^*(G,B) = \frac{(2\eta + b\eta - 1)^2}{\lambda(b+2)(b-2\lambda-b\lambda+4)}, \quad c_B^*(G,B) = 0 \end{gathered} \tag{1.20}$$

These results can then be substituted into production outcomes (1.13) and welfare equation (1.4) to give investment subgame reduced form payoffs. The corner solutions do not feature in the analytical results, but they are shown in the graphical results.

Chapter 2

Pass-through, profits and the political economy of regulation

Abstract

Government regulation, such as the pricing of externalities, often raises firms' unit costs and its impact on their profits is important to its political economy. We introduce "generalized linear competition" (GLC), a new reduced-form model that nests existing models of imperfect competition. We show how firm-level cost pass-through is a sufficient statistic for the profit impact of regulation. In an empirical application on US airline markets, we find considerable intra-industry heterogeneity in pass-through and profit impacts. GLC sidesteps estimation of a consumer demand system, firm mark-ups and conduct parameters. We derive a political-equilibrium emissions tax that incorporates firms lobbying a government "for sale".

Keywords: Cost pass-through, regulation, carbon pricing, airlines, political economy.

JEL codes: D43, H23, L51, L92, Q54.

2.1 Introduction

We present a new approach to estimating the impact of regulation on firms' profits. It is based on a new reduced-form model of imperfect competition that unifies existing models using weaker assumptions. We apply the theory to understand the political economy of carbon pricing for the US airline industry, and quantify its winners and losers.

Government regulation often raises the production cost of regulated firms. In some cases, this is an explicit objective of regulation, for example, when it puts a price on an externality such as carbon emissions or uses an import tariff to protect domestic producers. In other cases, it is an inevitable consequence of a broader policy objective; examples are minimum wage legislation and capital requirements for banks. In addition to their effects on social welfare, such regulations have an important impact on the profits of the firms being regulated.[1]

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[1] See Draca, Machin & Van Reenen (2011) for a recent empirical study of the profit impacts of minimum wage legislation using UK data. In a distortion-free Modigliani-Miller world, the profit

This profit impact is critical to understanding the political economy of regulation. On the extensive margin, regulation that substantially lowers an industry's profitability is often unlikely to be introduced. On the intensive margin, firms may lobby the government to influence the equilibrium level of the regulation enacted. The profit impact is also important, for obvious reasons, to the shareholders of any regulated firm. For instance, major central banks are now among those warning institutional investors about the risks to asset values arising from climate-change policy (Carney, 2015).

Estimating this firm-level profit impact is, however, not straightforward. Regulation raises the costs of a regulated firm and may also affect, to different degrees, the costs of its competitors. In general, its profit impact will depend on the firm's own production technology, the structure of demand, and its rivals' responses. The last factor is particularly problematic because modeling it may require information on the identities of all firms, each of their production technologies, the nature of product differentiation, what variables the firms compete on, how competitive or collusive the market is, and so forth. Our aim here is to present an approach that radically simplifies this problem.

The main part of this paper introduces "generalized linear competition" (GLC) in the spirit of an "aim to build the theory in such a way as to focus attention on those predictions which are robust across a range of model specifications which are deemed reasonable" (Sutton, 2007, pp. 2305-2306). GLC makes weaker assumptions than typical models of imperfect competition. It assumes that firm i, but not necessarily any other firm, is a cost-minimizer that takes input prices as given and operates a technology with linear production costs. The core assumption is that firm i follows a linear product-market strategy; in standard models, this corresponds to a linear supply schedule as implied by its first-order condition. GLC also allows firm i to reduce its exposure to the regulated factor: under environmental regulation, this is switching to cleaner inputs; faced with minimum-wage legislation, it is using less labour-intensive processes.

GLC makes no assumptions on the consumer demand system, no assumptions on the technologies and strategies of firm i's rivals, and imposes no particular concept of "equilibrium". In this sense, our approach is consistent with notions of bounded rationality on the part of both firms and consumers (Ellison, 2006). A further implication is that we can leave open (i) how many firms and products there are in the market; (ii) the extent to which firms' products are substitutes or complements in demand; (iii)

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impact of bank capital regulation is zero; in practice, banking is characterized by imperfect competition alongside other market failures such as asymmetric information (see, e.g., Vives 2016).

the extent to which firms' products are strategic substitutes or strategic complements (Bulow et al., 1985).

We use GLC to characterize the impact of regulation that raises firm i's unit cost and affects those of its rivals in an arbitrary way. In doing so, we allow for "complete" regulation that covers an entire industry as well as "incomplete" regulation that exempts a subset of firms. We show how *firm-level* cost pass-through, i.e., the fraction of i's cost increase that is passed onto i's price, is a sufficient statistic for the profit impact of regulation.[2] That is, all relevant information on i's demand and supply conditions is contained in this single metric. We show that higher pass-through implies a more favourable profit impact; a firm's profit falls with tighter regulation if and only if its pass-through is below 100%. Up to this point, we treat pass-through as a parameter; it can be endogenized by assuming a particular mode of competition or estimated empirically.

To see the idea underlying GLC, consider firm i which competes à la Cournot in a differentiated-products market, with marginal cost $MC_i = c_i + \tau$ and a demand curve $p_i = \alpha - \beta x_i - \delta \sum_{j \neq i} x_j$ (with $\delta \leq \beta$). Make no assumptions on its rivals' technologies or strategies. Firm i's first-order condition for profit-maximization implies a linear supply schedule $x_i = \frac{1}{\beta}(p_i - c_i - \tau)$. Now suppose that regulation τ raises i's own marginal cost by $d\tau$ and those of its rivals in an arbitrary way. How does this affect i's profits? By construction, i's pass-through rate $\rho_i \equiv (dp_i/d\tau)/(dMC_i/d\tau)$ captures the impact on its profit margin $(p_i - MC_i)$. Moreover, due to the linear supply schedule, the change in its sales x_i is proportional to this pass-through rate. Rivals' cost shocks and competitive responses matter only insofar as they affect i's price—but this is precisely what is captured in i's pass-through rate. We show how to derive i's profit impact in a way that does not require knowledge of the demand parameters (α, β, δ) or of i's other costs c_i.

This basic logic extends to a rich class of oligopoly models. GLC's structure nests, among others: Cournot-Nash, Stackelberg and conjectural-variation models (with linear demand); Bertrand and Cournot models with linear differentiated products; two-stage models such as Allaz and Vila (1993)'s model with forward contracting; a linear-symmetric version of the supply function equilibrium (Klemperer and Meyer, 1989); behavioural theories of competition such as Al-Najjar et al. (2008)'s model with sunk cost bias; and models with common ownership of firms (O'Brien and Salop,

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[2] We differ from the "firm-specific" rate of pass-through used in merger analysis (Ashenfelter et al., 1998); this asks how much of the cost saving achieved (only) by the merging firms is passed onto consumers. We also differ from a firm-specific pass-through rate based on a cost shock always incurred only by that single firm. Our setting allows for arbitrary cost changes across firms.

2000) which feature prominently in the current debate on the competitive impacts of cross-industry shareholdings of large institutional investors (Azar et al., 2018).

While it is intuitive, the critical role played by pass-through is also far from obvious. In influential work, Weyl and Fabinger (2013) show, in a general class of symmetric oligopoly models, that a *market-wide* rate of cost pass-through is a useful tool to understand market performance; in light of this, it can also serve as a bridge between structural and reduced-form models (Weyl and Fabinger, 2013; Atkin and Donaldson, 2015; Bergquist, 2017; Miller et al., 2017). As Miller et al. (2017) write: “the effect on producer surplus [of a market-wide cost shock] depends on pass-through and a conduct parameter that equals the multiplicative product of firm margins and the elasticity of market demand”. By contrast, within GLC, the firm-level profit impact depends *solely* on pass-through—no additional information about conduct parameter(s) is needed. This simplification of incidence analysis is the primary attraction of GLC. On one hand, GLC makes heavy use of the assumption that firm i employs a linear product-market strategy; on the other hand, it allows for near-arbitrary heterogeneity across firms.

We present several extensions and robustness checks. First, we endogenize the extent of emissions regulation in a welfare-maximizing setting that combines (i) a second-best distortion due to market power (Buchanan, 1969) and (ii) corporate lobbying a government “for sale”(Grossman and Helpman, 1994). Second, we show that GLC’s central pass-through result extends to settings with: (i) network competition, (ii) price discrimination, and (iii) multiproduct oligopoly using the upgrades approach (Johnson and Myatt, 2003, 2006). Third, we use Monte Carlo analysis to argue that GLC’s results can offer a reasonable approximation in the presence of model misspecification due to non-linearities in demands and/or costs.

The second part of the paper illustrates the utility of the theory in an empirical setting. We estimate the profit impacts of (future) carbon pricing in the US aviation industry. This setting is important in its own right: emissions from airline travel are projected grow well into the 21st century and economic regulation is likely as more countries seek to implement climate targets in a cost-effective manner. At our baseline price of \$30 per ton of carbon dioxide, the annual “value” of domestic US airline emissions is almost US\$4 billion.[3]

Like many other industries, aviation is characterized by important heterogeneities between firms in terms of demand, costs and conduct. First, airlines’ products are differentiated and consumers may also have complex preferences: a passenger might

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[3] Our baseline \$30/tCO_2 carbon price is illustrative but reasonably close to (a) recent prices in the European carbon market, and (b) estimates of the social cost of carbon (Nordhaus, 2017; IAWG, 2016). Our estimated profit impacts generally scale linearly with the carbon price.

regard a Delta flight from B to C as a complement to an American flight from A to B even if American and Delta are substitutes on the A-to-B route. Second, an airline's operating costs depend, among other things, on the fuel efficiency of its aircraft fleet—which varies widely across carriers. Carbon pricing can therefore lead to a heterogeneous cost shock on the same route. Third, airlines operate different route portfolios and conduct may be heterogeneous at the airline- and route-level (i.e., the same carrier competes differently on different routes). Hence it is difficult to know with confidence which specific model of competition is best suited to individual airlines and their routes.

We begin with an econometric estimation of pass-through for individual carriers. Our data are quarterly ticket prices for 1,334 domestic US carrier-routes over 2004 to 2013, yielding 36,650 observations. We have detailed information on fuel costs at the carrier-route level; we use variation in fuel prices to estimate fuel cost pass-through, from which we predict carbon cost pass-through.[4] Our baseline specification is an unbalanced panel with fixed effects for each carrier-route and each year-quarter. We control for variation in demand conditions, non-fuel costs, and in the number of competing firms.

Our results show considerable intra-industry heterogeneity in cost pass-through. The four large legacy carriers (American, Delta, United and US Airways) have pass-through of 62%, on average, across their routes. By contrast, the major low-cost carrier Southwest has a much higher pass-through rate of 141%.[5] We confirm the robustness of this heterogeneity finding in the corresponding balanced panel (in which each carrier-route is operated continuously over the period), and using an alternative econometric approach that estimates a separate regression for each carrier-route.[6]

Leveraging GLC, we use these pass-through estimates to derive the profit impacts of carbon pricing. We provide a detailed discussion of the considerations that arise in moving from GLC theory to empirical application—while remaining agnostic about the mode of competition and structure of consumer demand across routes. At a \$30/tCO$_2$

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[4] Other recent work, like us, relies on variation in fuel costs as a proxy for future US carbon pricing (e.g., Bushnell and Humber, 2017; Miller et al., 2017). For airlines, the conversion is simple, as 1 gallon of jet fuel produces 0.00957 tons of CO$_2$ when burned.

[5] Pass-through above 100% is more readily interpretable in our setting than in other literature. First, we estimate pass-through *rates* (i.e., the \$-price response to a \$1 unit cost increase) rather than pass-through *elasticities* (i.e., the %-price response to a 1% unit cost increase) which are always lower. Second, our firm-level pass-through reflects asymmetries in the cost shocks experienced by different firms; all else equal, a firm that experiences half the cost increase of a rival has pass-through twice as high.

[6] We also provide a simple three-factor decomposition of this pass-through heterogeneity into differences in (i) airlines' route portfolios, (ii) the fuel efficiency of aircraft, and (iii) consumer demand.

carbon price, reflecting its pass-through above 100%, we find a profit *gain* due to regulation for Southwest of 1.4% of revenue. Overall, however, the industry's profits decline modestly as losses incurred by legacy carriers offset Southwest's gain. These findings suggest that airlines will have very different incentives to influence regulation.

Plan for the paper. Section 2.2 explains how this paper contributes to the literature. Section 2.3 sets out GLC, relates it to existing models, and derives our main result on firm-level pass-through as a sufficient statistic. Section 2.4 presents further theory results, and section 2.5 assesses the robustness of the theoretical results. Section 2.6 presents our empirical analysis of pass-through for US airlines, and section 2.7 applies theory to give profit impacts. Section 2.8 concludes. Appendix 2.A gives proofs, Appendix 2.B contains additional information on our data, and Appendix 2.C gives further details on our empirical results and robustness tests.

2.2 Related literature

This paper contributes to several strands of literature. First, we introduce a different approach to the kind of structural modelling typically employed in industrial organization (Bresnahan, 1989; Berry et al., 1995; Nevo, 2001; Reiss and Wolak, 2007; Einav and Levin, 2010). By estimating a full set of primitives, structural models can be widely deployed to estimate merger impacts, the consumer value of new products, and so on. As Reiss and Wolak (2007, p. 39) put it: "The inferences that IO researchers draw about competition from price and quantity data rest on what researchers assume about demand, costs, and the nature of firms' unobservable strategic interactions".[7] In this paper, we sidestep estimation of a differentiated-products demand system (and also the well-known challenge of determining an appropriate market definition), make no assumptions about the precise mode of strategic interaction, and show how firm-level pass-through is sufficient information to "close the model".[8] In our setting, pass-through therefore also captures the import of any departures from Nash

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[7] A typical structural IO model has three main ingredients: (i) the consumer demand system, often specified in a logit form; (ii) firms' production technologies, often relying, like us, on linearity of costs; and (iii) the mode of competition, often chosen as Bertrand-Nash. It then estimates own- and cross-price elasticities of demand as well as the competitiveness of the market via firms' first-order conditions.

[8] Put differently, consider a market with n firms. Structural IO modeling, in general, requires specification and estimation of n demand equations as well as n supply equations. With GLC, we specify only i's supply curve and show how i's profit impact is fully captured by i's pass-through rate—which contains all relevant information about the remaining $2n-1$ model equations.

and/or profit-maximizing behaviour. A drawback is that we are not able to perform counterfactual analysis.[9]

Second, we add to a rich empirical literature spanning macro- and microeconomics that has estimated pass-through in response to a variety of cost shocks, including to excise taxes, input prices, and exchange rates. Empirical work typically reports a single rate of cost pass-through at the market-level. Depending on the detailed market context, it finds evidence of "incomplete" pass-through below 100% (e.g., De Loecker et al., 2016), "complete" 100% pass-through (e.g., Fabra and Reguant, 2014) as well as pass-through above 100% (e.g., Miller et al., 2017).[10] In this paper, we show the value of shifting attention to how pass-through behaves at the level of an individual firm. While prior work has emphasized *inter-industry* heterogeneity in pass-through due to differences in competition, demand and technology (Ganapati et al., 2016), our empirical results highlight *intra-industry* pass-through heterogeneity.

Third, our paper adds to a growing environmental-economics literature that studies the impacts of emissions pricing on industry. This literature has so far mostly focused on markets with limited product differentiation: electricity and heavy industry such as cement and steel. A key theme is that, due to pass-through, the profit impacts of carbon pricing at the industry-level are typically modest; this has been found in general equilibrium (Bovenberg et al., 2018), event study (Bushnell et al., 2013), and Cournot-style oligopoly (Hepburn et al., 2013).[11] From a policy perspective, therefore, only a relatively small fraction of emissions permits in a cap-and-trade system needs to be freely allocated so as to preserve industry profits; any higher free allocation leads to "windfall profits". Our GLC-based analysis extends the theory to richer modes of competition with differentiated products. Our empirical findings confirm that the profit decline is modest at the industry-level but also show that this masks substantial variation in the sign and extent of profit impacts across firms. More broadly, our

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[9] Pass-through also plays a central role in the analysis of cartel damages. The "passing on" defense states that a plaintiff is not harmed by an upstream cartel overcharge to the extent that it is able to pass this onto its own downstream customers. Verboven and Van Dijk (2009) highlight the additional output-contraction effect that arises due to pass-through and further reduces a plaintiff's profits. Our work shows that, for the GLC class of oligopoly models, the output-contraction effect is negative for any firm that does not fully pass on the cartel overcharge. Thanks to Natalia Fabra for this pointer.

[10] See Weyl and Fabinger (2013) for a useful discussion of the diverse set of empirical pass-through results. In earlier theoretical work, Bulow and Pfleiderer (1983) explain pass-through for a monopolist while Anderson et al. (2001) generalize this analysis to different oligopolistic environments.

[11] Another strand of work examines the impacts of incomplete regulation in which only a subset of firms is subject to carbon pricing. This tends to worsen the profit impacts experienced by regulated firms and has important consequences for the efficiency and design of environmental regulation (Fowlie et al., 2016). GLC theory developed in this paper allows for such incomplete regulation, while our empirical application to airlines involves a setting in which regulation is complete.

paper suggests that the political economy of carbon pricing for differentiated-products industries may differ substantially from well-studied markets like electricity.

Fourth, we contribute to the industrial-organization literature on competition in the airline industry. This literature has been primarily concerned with estimating the competitiveness of the industry and issues of market structure (Brander and Zhang, 1990; Kim and Singal, 1993; Berry and Jia, 2010) and the role and impact of financial constraints (Busse, 2002; Borenstein, 2011); recent work has also highlighted differences between legacy and low-cost carriers and the special role played by Southwest (Goolsbee and Syverson, 2008; Ciliberto and Tamer, 2009). This paper finds new evidence showing that large heterogeneity across carriers exists in terms of pass-through as well. We also provide a formal economic assessment of future US climate regulation on this industry that highlights how different carriers have different incentives to influence this regulation.[12]

2.3 Generalized linear competition (GLC)

This section introduces a simple reduced-form model which we call the "generalized linear competition" (GLC). We developed GLC to respond to Sutton's (2007) call for economists to derive "predictions which are robust across a range of model specifications which are deemed reasonable." We first set out and discuss GLC's key features and place it in the context of existing models. We then derive our main result on the profit impact of regulation.

As discussed in the introduction, we have in mind a regulation that leads to an increase in regulated firms' unit costs. Examples are the government putting a price on an externality or imposing minimum wage legislation in the labour market. The following exposition applies to a range of different types of regulation; as discussed in the introduction, we place particular emphasis on the case of environmental regulation.

2.3.1 Setup of GLC

Firm i competes in an industry, selling an output quantity x_i of its product at a price p_i. Let e_i be one of the inputs that i uses in production. Regulation imposes a cost τ

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[12] Our empirical analysis uses an average ticket price across passengers for each carrier-route; our data are not rich enough to estimate the impacts of regulation on price dispersion (Borenstein and Rose, 1994; Gerardi and Shapiro, 2009). Our extension of GLC to second-degree price discrimination, where early buyers pay less for their tickets, shows that the profit impact of regulation remains exactly as in our main analysis, with i's pass-through defined in terms of the change in i's *average* price.

on each unit of this input e_i. In the case of environmental regulation, the regulated factor corresponds to firm i's emissions (e.g., of carbon dioxide); it is standard in the literature to view emissions as an input to production (Baumol & Oates 1988). Regulation then corresponds to putting a price τ on the environmental externality.

The regulation may also apply to all ("complete regulation"), some or none of the other firms in the industry ("incomplete regulation"). More specifically, let $\phi_k \in \{0, 1\}$ be an indicator variable which equals 1 if firm k is subject to the regulation and equals 0 otherwise. Our setup has $\phi_i = 1$ for firm i but does not rely on any assumptions about the ϕ_js of its rivals ($j \neq i$).

In general, firm i's profits can be written as $\Pi_i = p_i x_i - C_i(x_i, e_i) - \tau e_i$, where $p_i x_i$ is its sales revenue and its total costs are made up of its operating costs $C_i(x_i, e_i)$ plus its regulatory costs τe_i.

GLC makes four assumptions about the production technology and supply behaviour of firm i. These are taken to hold over some interval $\tau \in [\underline{\tau}, \overline{\tau}]$ of interest over which the extent of regulation varies:

A1. (*Input price-taking*) Firm i takes input prices, including the regulation τ, as given.

A1 is a standard assumption which is appropriate for many forms of regulation, including a tax on emissions. (We endogenize the extent of regulation later on in this section.)

A2. (*Cost-minimizing inputs*) Firm i chooses its inputs, including the regulated factor e_i, optimally so as to minimize its total costs $C_i(x_i, e_i) + \tau e_i$ of producing output x_i.

A2 is a canonical assumption in microeconomic theory. For market-based environmental regulation, it implies the textbook result that, at the optimum, the emissions price equals i's marginal cost of reducing emissions, that is, $-\frac{\partial}{\partial e_i} C_i(x_i, e_i) = \tau$.[13]

A3. (*Constant returns to scale*) Firm i's optimized total costs faced with regulation τ are linear in output $C_i(x_i, e_i) + \tau e_i = k_i(\tau) x_i$, with unit cost $k_i(\tau) = c_i(\tau) + \tau z_i(\tau)$ where $c_i(\tau)$ is its per-unit operating cost and $z_i \equiv e_i / x_i$ is its "regulatory intensity" (use of the regulated factor per unit of output).

A3 is a more substantive assumption but is also common in the literature, including in pass-through analysis (Bulow and Pfleiderer, 1983; Anderson et al., 2001; Weyl and

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[13] If regulation applies to multiple firms ($\phi_j = 1$ for at least one firm $j \neq i$) their marginal costs of emissions reductions are equalized, yielding the well-known efficiency property of market-based regulation.

Fabinger, 2013), in environmental regulation under imperfect competition (Requate, 2006; Fowlie et al., 2016; Miller et al., 2017) and in the analysis of the profit impacts of a minimum wage (Draca et al., 2011). It rules out, at least over the range $\tau \in [\underline{\tau}, \overline{\tau}]$, the presence of (binding) capacity constraints.

Combining A1–A3, standard production theory shows that, in response to tighter regulation $\tau'' > \tau'$, $z_i(\tau'') \leq z_i(\tau')$ and $c_i(\tau'') \geq c_i(\tau')$. In other words, the firm reduces its use of the regulated input and instead uses more of other inputs; this saves on direct regulation-related costs (lower z_i) but incurs higher unit costs on other inputs (higher c_i).[14] For environmental regulation, this represents emissions abatement: a lower emissions intensity $z_i(\tau'') \leq z_i(\tau')$ comes at a per-unit abatement cost $[c_i(\tau'') - c_i(\tau')]$.[15] If such factor substitution is infeasible or unprofitable then $z_i(\tau'') = z_i(\tau')$.

A key implication is that, by the envelope theorem, $dk_i(\tau)/d\tau = z_i(\tau)$, that is, firm i's unit cost increase arising from a *small* tightening in regulation is given by its optimized regulatory intensity at that level of regulation. At the optimum, the increased costs due to input substitution are of second order. Therefore, if the extent of regulation rises from an initial level $\underline{\tau}$ to a higher $\overline{\tau}$, the corresponding increase in i's optimal unit cost equals $\Delta k_i(\overline{\tau}, \underline{\tau}) = \int_{s=\underline{\tau}}^{\overline{\tau}} z_i(s)ds$.

Remark 1. *While our exposition focuses on regulation that is effectively an* input *tax, GLC nests an* output *tax as a special case where firm i's regulatory intensity per unit of output satisfies* $z_i(\tau) \equiv 1$ *for all* $\tau \in [\underline{\tau}, \overline{\tau}]$.

Remark 2. *GLC can also apply to command-and-control regulation for which the government mandates a particular usage of inputs. An example is the mandatory blending of biofuels into petrol. In such cases, i's unit cost increase* $dk_i(\tau)/d\tau = z_i(\tau)$ *arises from a regulation* τ *that is not an input price (and* $z_i(\tau) = z_i$ *if no factor substitution is feasible).*

Remark 3. *In an earlier version of this paper (Grey and Ritz, 2018), we showed that our key results also holds under an alternative specification of A3, namely an "end-of-pipe" abatement technology under which firm i can make an investment that cleans up production* ex post*.*

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[14] We do not require any specific functional-form assumptions on the relationship between z_i and c_i.

[15] GLC abatement technology is consistent with standard properties from the environmental-economics literature. Write i's operating costs as $C_i(x_i, e_i) = c_i(\tau)x_i$, where emissions e_i are optimally chosen given output x_i; equivalently, the emissions intensity $z_i \equiv e_i/x_i$ is optimally chosen given output x_i. It follows that emissions and output are *complements*: $\frac{\partial}{\partial x_i} C_i(x_i, e_i) = c_i(\tau)$ and so, given x_i, higher e_i implies higher z_i and hence lower c_i, that is, $\frac{\partial^2}{\partial x_i \partial e_i} C_i(x_i, e_i) < 0$.

Remark 4. *To see another application, consider minimum wage regulation (following Ashenfelter and Smith, 1979; Draca et al., 2011). Firm i's regulated factor is labour, denoted by* e_i*. Firm i takes the minimum wage, denoted by* τ*, as given (A1) and chooses the quantity of labour employed optimally to minimize its costs (A2). It operates a production technology for which the unit cost of output* $k_i(\tau) = c_i(\tau) + \tau z_i(\tau)$ *is constant (A3), where* $z_i \equiv e_i/x_i$ *is the labour intensity of its output. In response to a higher minimum wage* τ*, firm i may respond by using more capital-intensive processes, reducing its labour intensity* $z_i(\tau)$ *but raising other costs* $c_i(\tau)$*.*

The final assumption is the defining feature of GLC:

A4. (*Linear product market behaviour*) Firm i's product market behaviour satisfies $x_i(\tau) = \psi_i [p_i(\tau) - k_i(\tau)]$, where $\psi_i > 0$ is a constant and $[p_i(\tau) - k_i(\tau)] > 0$ is its profit margin.

A4 says that firm i behaves such that its output is in (fixed) proportion to the profit margin it achieves. Intuitively, it sells more or prices higher into a more attractive market: its supply curve is (linearly) upward-sloping. The substantive restriction here is that the proportionality factor ψ_i does not vary with the regulation τ. While regulation can shift firm i's supply schedule it does not alter the slope of that schedule.

GLC makes no assumptions on the technology, behaviour or rationality of firm i's rivals. These firms need not be input price-takers (A1), need not choose inputs optimally (A2), have constant-returns technologies (A3) or employ a linear product-market strategy (A4). Regulation may also affect the *set* of i's rivals, that is, induce new entry and/or exit.

GLC also makes no assumptions on the demand system in the industry or on the nature of consumer behaviour. An implication is that we can leave open (i) how many competing firms/products there are in the market; (ii) the extent to which other firms' products are substitutes or complements to i's; (iii) the extent to which firms' products are strategic substitutes or strategic complements to i's. We therefore also do not have to restrict attention to a particular market definition.

Hence GLC has no equilibrium concept; it does not necessarily restrict attention to a Nash equilibrium (or some variation thereof). In this sense, it is much more general than standard models in which all firms are assumed to be Nash profit-maximizers. Moreover, A4 is consistent with "rule-of-thumb" behaviour by firm i that may itself not be profit-maximizing (though we do require cost-minimization as per A2).

2.3.2 Special cases of GLC

To illustrate its scope, we set out examples of well-known oligopoly models for which A4 is satisfied. In these models, given A1–A3 and a linear demand structure, *each* firm's first-order condition for profit-maximization yields a linear supply schedule that takes the form of A4.[16]

- *Cournot competition with a linear market demand curve* $p = \alpha - \beta \sum_i x_i$. It is easy to check that Nash behaviour implies $\psi_i = \beta^{-1}$ $(\forall i)$. Including a *firm-specific* conjectural variation $v_i \equiv \left(\sum_{j \neq i} dx_j\right)/dx_i$ (Bresnahan, 1989) leads to $\psi_i = [\beta(1 + v_i)]^{-1}$, still consistent with GLC. This also nests as a special case the linear Stackelberg model with multiple leaders and multiple followers (Daughety, 1990).

- *Bertrand or Cournot competition with horizontal and/or vertical product differentiation.* Let firm i's demand $p_i = \alpha_i - x_i - \delta \sum_{j \neq i} x_j$, where $\delta \in (0, 1)$ is an inverse measure of horizontal differentiation and $\alpha_i \neq \alpha_j$ reflects vertical differentiation; this leads to $\psi_i = 1$ $(\forall i)$ for Cournot and correspondingly to $\psi_i = [1 + \delta(n - 2)]/[(1 - \delta)[1 + \delta(n - 1)]]$ $(\forall i)$ for Bertrand (Häckner, 2000). The latter is independent of τ as long as the set of active firms and degree of product heterogeneity are unaffected.[17] A richer "semi-linear" demand system $p_i = \alpha_i - \beta_i x_i - f_i(x_1, ..., x_{j \neq i}, ..., x_n)$ remains part of GLC, for *any* cross-price effects implied by the function $f_i(\cdot)$.

- *Linear competition with common ownership between firms (O'Brien and Salop, 2000).* If the shareholders of firm i also own a fraction ω_i of its rival firm j, then the incentives of i's managers will be to maximize $\Pi_i + \omega_i \Pi_j$. The implications of such shareholder diversification have recently received attention for US airlines (Azar et al., 2018) and several other industries. With Cournot competition, linear demand, and assuming symmetry, this yields $\psi_i = [\beta(1 + \omega)]^{-1}$ $(\forall i)$.

- *A linear version of supply function equilibrium (Klemperer and Meyer, 1989).* Demand is linear $p = 1 - \sum_i x_i$ and firm i has a linear supply schedule of the form $x_i = \sigma_i + \mu(p - k)$, where it chooses σ_i and firms' marginal costs are identical $k_i = k$ $(\forall i)$ (Menezes and Quiggin, 2012). Even though the strategy

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[16] It will be clear that the following listing is not exhaustive; other models with similar linear structures are also members of GLC.

[17] Similarly, it is not difficult to check that spatial models of competition, such as Hotelling and Salop, can also be consistent with GLC as long as the distribution of consumer valuations is uniform (which generates linear demand, and, given A1–A3, hence also A4).

space has an affine supply function, the symmetric equilibrium features A4 with $\psi_i = [1 + (n-1)\mu]$ $(\forall i)$.[18]

GLC is more flexible than standard models along important dimensions. First, firms within GLC may think they are playing a different game. Second, they may be using different choice variables (e.g. one firm chooses price and another firm chooses quantity). Third, by allowing ψ_i to vary across firms, GLC does not impose that a firm with a higher market share necessarily has a higher profit margin. This feature is "baked in" to many standard oligopoly models via the restriction $\psi_i = \psi$ $(\forall i)$.

Remark 5. *GLC can represent the outcome of tacit collusion but not necessarily the strategies supporting it. On one hand, appropriate choice of firm-level conjectural variation parameters makes it is possible to generate collusive quantities and prices. On the other hand, it is not possible to use A4 to explicitly feature the underlying trigger strategies that might support a collusive outcome.*

In a similar way, GLC applies to multi-stage models in which product-market competition occurs at the final stage. The key point is that, given A1–A3 and the choices of prior stages, the final stage still yields supply schedules consistent with A4. Examples of well-known models include:

- *Forward contracting and vertical integration (Allaz and Vila, 1993; Bushnell et al., 2008).* In the first stage, firms sell forward contracts on their production; in the second stage, firms compete à la Cournot given their forward positions (Allaz and Vila, 1993).[19] This model is widely used in the study of liberalized electricity markets. A variant has a first stage in which vertically-integrated producers sign long-term contracts with retail customers (Bushnell et al., 2008). In both setups, with linear demand $p = \alpha - \beta \sum_i x_i$, the subgame-perfect equilibrium features $\psi_i = (\beta/n)^{-1}$ $(\forall i)$ (Ritz 2014); this is again independent of τ as long as n is fixed.
- *Competition with behavioural biases: misallocation of sunk costs (Al-Najjar et al., 2008).* Firm i maximizes accounting profits which "erroneously" include some of its fixed costs, at a rate of $s_i > 0$ per unit of output. In the first stage, firms learn about the impacts of costing in a distortion game before product-market

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[18] We have modified the setup of Menezes and Quiggin (2012) slightly, by dropping their normalization in terms of production costs, without affecting any of the conclusions. The equilibrium price in our specification is $p^* = (1 + nk\,[1 + (n-1)\mu])\,/(1 + n\,[1 + (n-1)\mu])$, which tends to the Cournot solution as $\mu \to 0$ and to the Bertrand paradox as $\mu \to \infty$.

[19] To be more precise, this involves a three-stage game: (1) the extent of regulation is determined; (2) firms engage in forward contracting; and (3) firms compete in the product market.

competition in the second stage. With differentiated Bertrand competition with linear demand $D_i = a - bp_i + g\sum_{j \neq i} p_j$, the first-order conditions feature a constant $\psi_i = \psi$ $(\forall i)$ and $s_i = s^* > 0$ in symmetric equilibrium: to soften competition, firms partially set prices based on costs that are sunk.[20]

Remark 6. *GLC is conceptually distinct from classes of oligopoly models that are aggregative games (Corchón, 1994; Acemoglu and Jensen, 2013) or potential games (Monderer and Shapley, 1996). To see this, note that Cournot-Nash competition with linear market demand* $p = \alpha - \beta \sum_i x_i$ *is an aggregative game, a potential game and also a member of GLC. However, with differentiated-products demand for firm* i *of* $p_i = \alpha - \beta_i x_i - \sum_{j \neq i} \delta_{ij} x_j$*, it is no longer aggregative nor a potential game (unless* $\delta_{ij} = \delta_{ji}$ *for all* $i \neq j$*) but still yields A4.*

2.3.3 Profit-neutrality technique

We wish to quantify the impact of regulation τ on firm i's profits Π_i, and now use a simple modelling device to pin this down. Suppose that the extent of regulation rises from initial level $\underline{\tau}$ to a higher $\overline{\tau}$. Of particular interest are the special cases in which (i) a new regulation is introduced, that is, $\underline{\tau} \equiv 0$, and (ii) regulation is tightened by a small amount, that is, $(\overline{\tau} - \underline{\tau}) \to 0$.

Let $\Pi_i(\tau)$ denote firm i's profits as a function of regulation, and similarly $e_i(\tau)$ is the quantity of the regulated factor. Observe that $(\overline{\tau} - \underline{\tau})e_i(\underline{\tau})$ is the "static" cost of regulation associated with firm i's *initial* quantity of the regulated factor.

Now define a profit-neutrality factor γ_i for firm i such that:

$$\Pi_i(\overline{\tau}) + \gamma_i \left[(\overline{\tau} - \underline{\tau})e_i(\underline{\tau})\right] \equiv \Pi_i(\underline{\tau}). \tag{2.1}$$

In other words, γ_i is *constructed* such that firm i's profits under tighter regulation plus "compensation" of $\gamma_i \left[(\overline{\tau} - \underline{\tau})e_i(\underline{\tau})\right]$ are equal to its initial profits under weaker regulation. Hence the change in firm i's profits equals $\Delta\Pi_i(\overline{\tau}, \underline{\tau}) \equiv \Pi_i(\overline{\tau}) - \Pi_i(\underline{\tau}) = -\gamma_i \left[(\overline{\tau} - \underline{\tau})e_i(\underline{\tau})\right]$, so $\text{sign}\{-\Delta\Pi_i(\overline{\tau}, \underline{\tau})\} = \text{sign}\{\gamma_i(\overline{\tau}, \underline{\tau})\}$. If firm i does not respond to the tightening of regulation in any way, and its rivals do not respond either, then its profits simply fall as implied by its initial exposure, $\Delta\Pi_i(\overline{\tau}, \underline{\tau}) = -(\overline{\tau} - \underline{\tau})e_i(\underline{\tau})$ or, equivalently, $\gamma_i(\overline{\tau}, \underline{\tau}) = 1$.

The profit impact is therefore determined by three components: the extent of regulatory tightening $(\overline{\tau} - \underline{\tau})$, firm i's initial exposure $e_i(\underline{\tau})$, and the profit-neutrality

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[20] Specifically, using the results in Section 5 of Al-Najjar et al. (2008), $\psi_i = [b/(2b + g)] \big[b\left(1 + g/[2b - (n-1)g]\right) - (n-1)g^2/[2b - (n-1)g]\big]$.

factor $\gamma_i(\overline{\tau}, \underline{\tau})$. As is standard, we take the first component as given for now. The second component is typically available to policymakers and analysts dealing with regulation; for example, information on firms' historical emissions is collected in the run-up to environmental initiatives. The remainder of this section determines the final component: firm i's profit-neutrality factor $\gamma_i(\overline{\tau}, \underline{\tau})$.

2.3.4 Main result on the profit impact of regulation

We next present our main result on the magnitude of $\gamma_i(\overline{\tau}, \underline{\tau})$ within GLC. We will see that cost pass-through plays a central role for the profit impact of regulation. Define firm i's *marginal* rate of cost pass-through as:

$$\rho_i(\tau) \equiv \frac{dp_i(\tau)/d\tau}{dk_i(\tau)/d\tau}. \tag{2.2}$$

The denominator captures by how much i's optimal unit cost $k_i(\tau)$ responds to a small tightening in regulation; as explained above, given A1–A3, the envelope theorem implies $dk_i(\tau)/d\tau = z_i(\tau)$. The numerator captures by how much i's product price changes. This will, in general be driven by a combination of i's own cost increase and the cost increases and product-market behaviour of i's rivals (also depending on the extent to which they are regulated, i.e., the ϕ_js $(j \neq i)$).

In standard oligopoly models, if all n firms are regulated, i's equilibrium price is a function of the marginal costs of all of its rivals, $p_i(k_1(\tau), ..., k_i(\tau), ...k_n(\tau))$. Therefore the price-response $dp_i(\tau)/d\tau$ also captures any relevant changes in these costs. Our firm-level pass-through rate thus reflects the impact of regulation on *all* players, including any cost heterogeneity across firms. It is distinct from the market-wide pass-through rate considered in much of the literature (for which firms' costs rise uniformly).[21]

Remark 7. *Despite the linearity of A4, GLC does* not *imply that the pricing function* $p_i(k_1(\tau), ..., k_i(\tau), ...k_n(\tau))$ *is necessarily linear in its arguments. For example, with standard Nash differentiated-products competition with linear demand* $p_i = \alpha_i - x_i - \delta \sum_{j \neq i} x_j$ *the pricing function is indeed linear but for semi-linear demand* $p_i = \alpha_i - \beta_i x_i - f_i(x_1, ..., x_{j \neq i}, ..., x_n)$ *it is not.*

Let $\overline{\rho}_i(\overline{\tau}, \underline{\tau}) \equiv \frac{1}{(\overline{\tau} - \underline{\tau})} \int_{s=\underline{\tau}}^{\overline{\tau}} [\rho_i(s)]\, ds$ denote i's *average* rate of cost pass-through over the interval $\tau \in [\underline{\tau}, \overline{\tau}]$. We thus obtain our main result:

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[21] If both demand and costs are symmetric across firms, and A1–A4 apply to all firms, then our measure of pass-through typically coincides with market-wide pass-through.

Proposition 1. *In GLC defined by A1–A4, the profit impact on firm i of regulation τ tightening from $\underline{\tau}$ to $\overline{\tau}$ satisfies $\Delta\Pi_i(\overline{\tau},\underline{\tau}) \equiv -\gamma_i(\overline{\tau},\underline{\tau})(\overline{\tau}-\underline{\tau})e_i(\underline{\tau})$ where:*

(a) if $(\overline{\tau}-\underline{\tau})$ is small, then $\gamma_i(\overline{\tau},\underline{\tau}) \simeq 2[1-\overline{\rho}_i(\overline{\tau},\underline{\tau})]$, where $\overline{\rho}_i(\overline{\tau},\underline{\tau}) \simeq \rho_i(\underline{\tau})$;

(b) in general, $\gamma_i(\overline{\tau},\underline{\tau}) \leq \max\{2[1-\overline{\rho}_i(\overline{\tau},\underline{\tau})],0\}$.

Proposition 1 gives a very simple expression that makes precise how firm i's rate of cost pass-through *alone* is a sufficient statistic for the profit impact of regulation. It holds across all models that are part of the GLC. Conditional on the extent of regulation and firm i's "historical" use of the regulated factor, firm-level pass-through is the only thing that matters: $\Delta\Pi_i(\overline{\tau},\underline{\tau}) \simeq 2[1-\overline{\rho}_i(\overline{\tau},\underline{\tau})](\overline{\tau}-\underline{\tau})e_i(\underline{\tau})$.

Firm i's pass-through rate captures *all* relevant information on the production technologies of i's rivals, the degree of product differentiation, what variables the firms compete on, how competitive or collusive the market is, any entry or exit by rivals, and so on. Whatever their other differences, if any two theories within GLC imply identical pass-through for firm i, then they also imply an identical profit impact. For a "small" regulatory tightening in part (a), this argument holds exactly; for a "large" regulation in part (b), the profit impact is bounded above by the same expression.

What is the intuition for the result? The profit impact is made up of two effects: that on i's profit margin and that on its sales. The first role of i's pass-through rate is that, by construction, it captures the impact of regulation on its own profit margin. Its second role is that, due to the linear supply schedule given by A4, the change in its sales is proportional to its pass-through rate. Rivals' cost shocks and competitive responses matter only insofar as they affect i's price—but this is precisely what is captured in i's pass-through rate. These two roles are what drives $\gamma_i(\overline{\tau},\underline{\tau}) \simeq 2[1-\overline{\rho}_i(\overline{\tau},\underline{\tau})]$.

Two corollaries are immediate. First, pass-through *signs* the profit impact: i's profits fall whenever pass-through is incomplete, $\mathrm{sign}(\Delta\Pi_i) = \mathrm{sign}(\overline{\rho}_i - 1)$. In such cases, the firm's profit margin shrinks and, by A4, it also experiences weaker sales. Conversely, with pass-through above 100%, the firm benefits from tighter regulation: both its profit margin and sales volume rise. Second, all else equal, a lower rate of pass-through implies that regulation has a worse profit impact.

From an empirical perspective, the crucial feature of the result is that the profit impact $\Delta\Pi_i(\tau)$ is *independent* of the proportionality term ψ_i from A4. As we have seen, different theories of imperfect competition within GLC differ in terms of the their implied ψ_i. Yet Proposition 1 tells us that this does not matter for the profit impact. The reason is scaling: by A4, the level of $x_i(\tau) = \psi_i\,[p_i(\tau) - k_i(\tau)]$ and the change

$\Delta x_i(\tau) = \psi_i [\Delta p_i(\tau) - \Delta k_i(\tau)]$ are both proportional to ψ_i. But the corresponding use of the regulatory factor $e_i(\tau) = \psi_i z_i(\tau) [p_i(\tau) - k_i(\tau)]$ is also proportional to ψ_i. This means that the profit impact per unit of the regulatory factor $e_i(\underline{\tau})$, as incorporated into $\gamma_i(\overline{\tau}, \underline{\tau})$, does not depend on ψ_i. This is also one reason for why Proposition 1 applies without requiring information about own-price and cross-price elasticities of demand.

Of course, industry characteristics such as the degree of product differentiation are likely to affect the pass-through rate ρ_i—so they can certainly matter *indirectly* for $\Delta\Pi_i$. The point of Proposition 1, is that, even if they also affect i's supply behaviour, via A4's proportionality term ψ_i, this aspect is irrelevant for the profit impact (conditional on ρ_i).

While it is intuitive, this critical role played by pass-through is also far from obvious. Weyl and Fabinger (2013) present, for a general class of symmetric oligopoly models, a simple formula for the impact of a *market-wide* cost change on aggregate producer surplus (see also Atkin and Donaldson, 2015; Miller et al., 2017). The profit impact depends on a market-wide rate of pass-through as well as on a "conduct parameter" that incorporates the level of firms' profit margins and the price elasticity of market demand. By contrast, within the GLC, the firm-level profit impact depends *solely* on pass-through—no additional information about conduct parameter(s) is needed. This further simplification of incidence analysis is the primary attraction of GLC. Compared to the existing literature, GLC allows for near-arbitrary heterogeneity across firms but makes heavy use of the linear structure implied by A4. In our setting, pass-through therefore also captures the import of departures from Nash and/or profit-maximizing behaviour—including any player "irrationality".

Remark 8. *One interpretation is that GLC is a semi-parametric model in which information on pass-through is, in effect, sufficient to "close the model". Consider a market with n firms selling differentiated products. Standard industrial-organization models specify n demand equations and, based on Nash profit-maximization, then derive n supply equations. With GLC, we specify only i's supply curve and show how i's profit impact is fully captured by i's pass-through rate—which contains* all *relevant information about the remaining* $2n - 1$ *model equations.*

Up to this point, we have treated i's pass-through rate as a parameter. In general, it can depend on a wide range of factors, including the number of firms in the market, their strategies and the intensity of competition, the degree of product differentiation, and on how strongly i's cost rises relative to other firms. To progress further, there are three basic approaches. The first is to select a specific model of competition and derive the theoretical rate of pass-through. The second is to try to utilize existing estimates of cost pass-through from the empirical literature; given that these are typically market-level pass-through estimates, they would have to be converted into firm-level pass-through, perhaps again relying on guidance from a specific theory model. The third is to combine the structural result from Proposition 1 with estimates of firm-level pass-through; we pursue this approach in our empirical analysis of the US airline industry.

2.3.5 Political economy, lobbying and endogenous regulation

So far we have focused on a regulation τ that is exogenous. We now show how, for the case of an emissions tax, regulation can be endogenized using the GLC's structure. This brings together two strands of prior research: (1) an influential literature following Grossman and Helpman (1994) in which firms lobby a government "for sale"; (2) a classic literature following Buchanan (1969) on emissions taxes under imperfect competition.[22]

As in Grossman and Helpman (1994), the government cares about social welfare W and political contributions by regulated firms. Let $K_i(\tau)$ denote firm i's political contribution as a function of the emissions price τ. The government's payoff is $U_{\text{gov}}(\tau) = W(\tau) + \lambda\sum_{i=1}^{n} K_i(\tau)$, where the parameter $\lambda \geq 0$ measures its openness to lobbying, and larger values of λ mean policy is increasingly for sale. Following Bernheim and Whinston (1986) and Grossman and Helpman (1994), the equilibrium of the lobbying game is for each firm i to offer a contribution function $K_i(\tau) = \Pi_i(\tau) + u_i$, where u_i is a constant. Substituting into the government's payoff function, the first-order condition for the "political equilibrium" emissions tax $\tau^*(\lambda)$ is given by:

$$\frac{dU_{\text{gov}}(\tau)}{d\tau} = \frac{dW(\tau)}{d\tau} + \lambda\sum_{i=1}^{n} \frac{d\Pi_i(\tau)}{d\tau} = 0. \qquad (2.3)$$

We assume that this problem is well-behaved, and focus on the interesting case of an interior solution with $\tau^*(\lambda) > 0$. As will become clear, this includes the standard property that an emissions tax reduces aggregate emissions, $dE(\tau)/d\tau < 0$.

To make further progress, some additional assumptions are needed. First, we assume that GLC's A1–A4 now hold for each of $n \geq 2$ firms. Second, we assume that consumers are utility-maximizers, with aggregate consumer surplus $S = V(x_1, ..., x_n) - \sum_{i=1}^{n} p_i x_i$,

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[22] By assumption, the government does not have access to another policy instrument (such as a price control) to directly address market power. See Requate (2006) for a useful survey of emissions pricing under perfect competition.

where $V(\cdot)$ is gross consumer utility; unlike much literature on second-best emissions pricing, this allows firms' products to be differentiated. Third, environmental damages $D(E)$ depend on aggregate emissions $E = \sum_{i=1}^{n} e_i$ and obey the standard properties $D'(\cdot), D''(\cdot) > 0$.

The timing of the game is as follows. First, firms choose their contributions K_i. Second, the government sets the emissions price τ. Third, firms compete according to GLC—now taking τ as given, as per A1.

Social welfare can therefore be written as in terms of the emissions price as follows:

$$W(\tau) = V(x_1(\tau), ..., x_i(\tau), ..., x_n(\tau)) - \sum_{i=1}^{n} C_i(x_i(\tau)) - D(E(\tau)),$$

as firms' revenues $\sum_{i=1}^{n} p_i x_i$ are a transfer from consumers and firms' emissions costs τE are a transfer to government. As a benchmark, recall the standard Pigouvian tax τ^* under perfect competition (i.e., marginal utility equals price, and price equals marginal cost) is to set the emissions price at the social marginal damage, $\tau^* = D'(E(\tau^*))$.

Define the emissions-weighted average rate of pass-through across firms as $\widetilde{\rho}(\tau) \equiv \sum_{i=1}^{n} \frac{e_i(\tau)}{E(\tau)} \rho_i(\tau)$, and let $\eta(\tau) \equiv \frac{d \ln E(\tau)}{d \ln \tau} < 0$ be the tax elasticity of industry emissions.

Proposition 2. *At an interior solution, the third-best political-equilibrium emissions tax that maximizes government utility* U_{gov} *satisfies:*

$$\tau^*(\lambda) = \left[\frac{D'(E(\tau))}{1 - \dfrac{(1+2\lambda)}{\eta(\tau)} [1 - \widetilde{\rho}(\tau)]} \right]_{\tau = \tau^*(\lambda)} .$$

For all models consistent with GLC, the distortion of the equilibrium tax τ^* away from the Pigouvian rule is driven by the industry pass-through rate $\widetilde{\rho}$. To understand the result, observe that in the Buchanan problem, industry profits reflect the extent of the market-power distortion while in the Grossman-Helpman problem, profits drive the incentive to make political contributions. By Proposition 1, firm-level pass-through pins down firm-level profit impacts—and so the industry-level analog is driven by a weighted average of pass-through across firms.[23]

Proposition 2 generalizes existing literature to richer modes of competition and provides a unifying result in terms of pass-through. Intuitively, lower firm-level pass-through ρ_i means that firm i contracts output more strongly, creating greater deadweight

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[23] Under perfect competition, each firm's pass-through is 100% so the Pigouvian rule $\tau = D'$ applies—and there is no political lobbying (even if $\lambda > 0$) since no firm is making any profit.

losses and suffering larger profit losses, thus pushing τ^* downwards—more strongly for large, high-emissions firms (i.e., larger $\frac{e_i(\tau)}{E(\tau)}$). Relatedly, where the government is more open to lobbying (higher λ), and the industry is opposed to the regulation ($\widetilde{\rho} < 1$), this pushes the political equilibrium tax downwards.

We can therefore apply Proposition 1 to calculate the profit impacts of an endogenous regulation, by letting $\underline{\tau} = 0$ and $\overline{\tau} = \tau^*(\lambda)$. Indeed, Proposition 2 shows how it is possible to derive an expression for $\tau^*(\lambda)$ that does not directly hinge on knowledge of consumers' utility function $V(\cdot)$ (which, of course, may indirectly matter both for pass-through $\widetilde{\rho}$ and for the emissions elasticity η.)

2.4 Extensions: Multiple markets, products, and prices

In the baseline GLC, firm i sells a single product into a single market at a single price. Our extensions in this section show how GLC's basic insight—firm-level pass-through as a sufficient statistic for the profit impact of regulation—applies in richer settings with multiple products, markets and prices. While GLC, of course, cannot be a fully general model of competition—given its reliance on supply-side linearity—these further results considerably extend its scope.

2.4.1 Network competition

Firms often compete by selling their products across multiple markets (Bulow et al., 1985). For example, airlines decide how to deploy their aircraft fleet across different routes. Recent work in the networks literature has sought to understand how strategic interaction and network structure affect market outcomes (Bramoullé et al., 2014). We here outline a simple linear model of network competition to illustrate (i) how our main results from GLC apply in this context, and (ii) how GLC compares to approaches taken in the networks literature.

Consider a setting in which $n \geq 2$ firms sell into $m \geq 2$ markets.[24] Firm i has production capacity K_i and sells $x_{il} = \sigma_{il} K_i$ units into market l, where $\sum_{l=1}^{m} \sigma_{il} = 1$, so $\sigma_{il} \in [0, 1]$ reflects i's presence in market l. Given firms' overall capacities $\mathbf{K}$, the price in market l is given by a linear demand curve $p_l(\mathbf{K}) = \alpha_l - \beta X_l$, where $X_l = \sum_{i=1}^{n} \sigma_{il} K_i$ and the demand parameter α_l may vary across markets. Firm i's overall sales to all m markets are $x_i = \sum_{l=1}^{m} x_{il} = K_i$.

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[24] Our exposition here builds on part of Elliott & Galeotti (2019).

We assume that firm i's unit cost satisfies GLC's A1-A3, given regulation τ, with an optimized unit cost $k_i(\tau)$ and emissions intensity $z_i(\tau) \equiv e_i(\tau)/x_i(\tau)$. Firm i chooses its capacity K_i to maximize its overall profits $\Pi_i(\mathbf{K};\tau) = \sum_{l=1}^{m}[p_l(\mathbf{K}) - k_i(\tau)]\sigma_{il}K_i$, which yields the first-order condition:

$$\sum\nolimits_{l=1}^{m}[p_l(\mathbf{K}) - k_i(\tau)]\sigma_{il} - \beta\sum\nolimits_{l=1}^{m}\sigma_{il}^2 K_i = 0$$

that defines i's optimal capacity as a function of the network structure as well as demand and cost conditions.

The networks literature now proceeds by characterizing the Nash equilibrium. It would typically define $g_{ij} \equiv (\sum_{l=1}^{m}\sigma_{il}\sigma_{jl})/\sum_{l=1}^{m}\sigma_{il}^2$ as a key measure of the closeness of competition between firms i and j across the m markets so that the $n \times n$ matrix $\mathbf{g}$ represents the network of interaction.[25] The central results in the literature then use different network measures—such as Bonacich centrality—to characterize Nash equilibrium (Ballester et al., 2006; Bramoullé et al., 2014).

The idea behind GLC leads down a different route based on pass-through. Let $\overline{p}_i \equiv \sum_{l=1}^{m}\sigma_{il}p_l$ be i's weighted-average price across its markets, and use this to rewrite i's first-order condition as:

$$\overline{p}_i(\tau) - k_i(\tau) = \left(\beta\sum\nolimits_{l=1}^{m}\sigma_{il}^2\right)K_i(\tau),$$

now also making explicit dependencies on regulation τ. The key observation is that this supply schedule has exactly the same form as the GLC's A4, with a constant slope parameter, $\beta\sum_{l=1}^{m}\sigma_{il}^2$, that reflects the production network and demand conditions.

Now let $\overline{\rho}_i \equiv [d\overline{p}_i(\tau)/d\tau]/[dk_i(\tau)/d\tau]$ denote i's corresponding weighted-average rate of cost pass-through across markets. For notational convenience, we focus on the "small τ" case (that is, $\underline{\tau} = 0$ and $\overline{\tau} = \tau \to 0$) and thus define i's profit-neutrality factor in the familiar way as $\gamma_i(0) \equiv \left(-\left[d\Pi_i(\tau)/d\tau\right]_{\tau=0}\right)/e_i(0)$.

Proposition 3. *Under linear multimarket network compeitition, regulation τ affects firm i's profits according to:*

$$\gamma_i(0) = 2[1 - \overline{\rho}_i(0)].$$

This shows how our basic result on firm-level pass-through generalizes to a multimarket setting. In this linear setup, GLC's A1–A4 hold and a weighted-average rate of pass-through is a sufficient statistic for i's network-wide profit impact.

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[25] If i and j serve distinct subsets of markets, then $\sigma_{il}\sigma_{jl} = 0$ for all l and so also $g_{ij} = 0$; if they serve identical markets, then $\sigma_{il} = \sigma_{jl}$ for all l and so $g_{ij} = 1$.

At a conceptual level, the main difference compared to the networks literature is that Proposition 3 is derived by making assumptions only about firm i itself. There are no assumptions as such on the technology or behaviour of i's rivals; insofar as these are relevant, they are captured in i's pass-through rate $\overline{\rho}_i$. Therefore, pass-through also captures the salient characteristics of the production network—for example, in our empirical application to airlines. In other words, firm-level pass-through $\overline{\rho}_i$ is a sufficient statistic for information contained in the production network $\mathbf{g}$, in the $m+1$ demand-side parameters, and in all n firms' cost functions and product-market strategies—including any "irrationality on the network". By contrast, the networks literature (i) fully specifies the game, and (ii) derives Nash equilibrium results.

A substantive restriction, also employed in the linear-quadratic games that are widely studied in the networks literature, is that the network structure $\mathbf{g}$ is effectively fixed; in our case, it does not vary with regulation τ.

2.4.2 Multiproduct competition

We next use a simplified version of the upgrades approach (Johnson and Myatt, 2003, 2006) to extend our main GLC result to a multiproduct setting. Each of $n \geq 2$ firms offers two product qualities: low-quality q_1 and high-quality q_2, where $q_U \equiv (q_2 - q_1) > 0$.[26]

We consider a special case that yields linear demand structures for both products. A consumer of type θ has willingness-to-pay $v(\theta, q) = \theta q$ for a single unit with quality $q \in \{q_1, q_2\}$. There is a unit mass of potential buyers with uniformly distributed types $\theta \sim U[0,1]$. Let Y_1^i denote the *combined* number of low- and high-quality units produced by firm i, let Y_2^i be the number of high-quality units, so that $(Y_1^i - Y_2^i)$ is the number of low-quality units. Let $Y_1 = \sum_{i=1}^{n} Y_1^i$ be the industry supply of both qualities and $Y_2 = \sum_{i=1}^{n} Y_2^i$ that of high-quality; the former can be interpreted as the number of "baseline" units while the latter is the number of "upgrades". The marginal buyer of the low-quality product is indifferent to instead buying nothing and has type $\theta(Y_1)$ so the price of the low-quality product satisfies $p_1(Y_1; q_1) = v(\theta(Y_1), q_1) = (1 - Y_1)q_1$. The marginal buyer of an upgrade is indifferent between buying low or high quality and has type $\theta(Y_2)$ so the price of upgrading to the high-quality product satisfies $p_2(Y_2; q_U) = v(\theta(Y_2), q_2) - v(\theta(Y_2), q_1) = (1 - Y_2)q_U$. Observe that both demand curves

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[26] Our exposition here mainly follows recent work by Johnson and Rhodes (2018). Similar to the preceding extension, a substantive restriction is that regulation τ does not alter the quality levels q_1, q_2 offered by firms (or the number of firms n).

$p_1(Y_1)$ and $p_2(Y_2)$ are linear. The total price of the high-quality product is the baseline price plus the upgrade price, $p_1 + p_2$.

We assume that GLC's A1–A3 are satisfied for each of firm i's products. A1 (regulation τ taken as given) and A2 (cost-minimization) apply straightforwardly while A3 (constant marginal cost) can be reformulated for a multiproduct setting. Slightly adjusting notation, firm i's unit cost for the low-quality product is $k_1^i(\tau) = c_1^i(\tau) + \tau z_1^i(\tau)$ while it is $k_U^i(\tau) \equiv [k_2^i(\tau) - k_1^i(\tau)] = c_U^i(\tau) + \tau z_U^i(\tau)$ for the upgrade, where both of the regulatory intensities, $z_1^i \equiv e_1^i/Y_1^i$ and $z_U^i \equiv e_2^i/Y_2^i$, are optimally chosen given τ. Hence, by the envelope theorem, $dk_1^i(\tau)/d\tau = z_1^i(\tau)$ and $dk_U^i(\tau)/d\tau = z_U^i(\tau)$.

Firm i's overall profit is given by:

$$\begin{aligned} \Pi^i(\tau) &= [p_1(Y_1) - k_1^i(\tau)](Y_1^i - Y_2^i) + [p_1(Y_1) + p_2(Y_2) - k_2^i(\tau)]Y_2^i \\ &= \underbrace{[p_1(Y_1) - k_1^i(\tau)]Y_1^i}_{=\Pi_1^i} + \underbrace{[p_2(Y_2) - k_U^i(\tau)]Y_2^i}_{=\Pi_2^i}, \end{aligned}$$

where it separately chooses Y_1^i and Y_2^i (subject to $Y_1^i \geq Y_2^i$). Given the linear demand structure, firm i's first-order conditions will mean that GLC's A4 is met for each of its products.

Two questions can be addressed. The first is how regulation τ affects profits only on a single product, $\Pi_k^i(\tau)$, for which we show that Proposition 1 applies ($k = 1, 2$). The second is how τ affects overall profit, $\Pi^i(\tau) \equiv \Pi_1^i(\tau) + \Pi_2^i(\tau)$, for which we derive a straightforward generalization. We define profit-neutrality factors ("small τ") for both questions in the familiar way:

$$\gamma_k^i(0) = \frac{-\left.\dfrac{d\Pi_k^i(\tau)}{d\tau}\right|_{\tau=0}}{e_k^i(0)} \text{ and } \gamma^i(0) = \frac{-\left(\left.\dfrac{d\Pi_1^i(\tau)}{d\tau}\right|_{\tau=0} + \left.\dfrac{d\Pi_2^i(\tau)}{d\tau}\right|_{\tau=0}\right)}{[e_1^i(0) + e_2^i(0)]}.$$

Let firm i's rates of cost pass-through for the baseline and upgrade products, respectively, as $\rho_1^i \equiv [dp_1(\tau)/d\tau]/[dk_1^i(\tau)/d\tau]$ and $\rho_2^i \equiv [dp_2(\tau)/d\tau]/[dk_U^i(\tau)/d\tau]$.

Proposition 4. *Under multiproduct competition in a linear version of the upgrades approach, regulation τ affects firm i's profits according to:*

$$\begin{aligned} &\gamma_k^i(0) = 2[1 - \rho_k^i(0)] && \textit{for product } k = 1, 2 \\ &\gamma^i(0) = \omega_1^i(0)\gamma_1^i(0) + \omega_2^i(0)\gamma_2^i(0) && \textit{for both products,} \end{aligned}$$

where $\omega_k^i \equiv e_k^i/(e_1^i + e_2^i) \in (0, 1)$ is the share of product k in firm i's overall emissions.

As GLC's A1–A4 hold for each of firm i's products, a firm-product rate of pass-through ρ_k^i is a sufficient statistic for the firm-product profit impact $d\Pi_k^i$. The upgrades approach has the key feature that the baseline units and upgrades are neither substitutes nor complements; in our empirical application to airlines, this will provide a microfoundation for abstracting from "upgrades" to business-class tickets. The multiproduct profit impact is then determined by a weighted-average of product-level pass-through rates.

As in the previous extension, it is worth stressing that Proposition 4 is derived by making assumptions only about firm i itself—there are no restrictions on its rivals' products, technologies or behaviour.

2.4.3 Price discrimination

In practice, consumers often pay different prices for the same good; for example, airlines sell tickets at different prices depending on when a customer buys. Building on Hazledine (2006), we here show how Proposition 1(a) extends to a Cournot oligopoly with price discrimination.

Consumers have unit demand for a homogeneous product (e.g., an economy flight from A to B), with a distribution of $v(X) = 1 - X$ (so the X^{th} keenest consumer has value $1-X$). There are $H \geq 2$ price buckets with class h priced at $p_h = 1 - X_1 - \ldots - X_h$, where X_h is the number of units sold in class h. Each firm i chooses how much of each bucket to supply $\{x_{ih}\}_{h=1}^{H}$. We assume that A1–A3 are met for each firm and, for simplicity, that marginal cost $k(\tau) = c(\tau) + \tau z(\tau)$ is symmetric across firms. Given the linear demand structure, A4 will be met for each firm and each price bucket.

Firm i's profits $\Pi_i = \sum_{h=1}^{H} \Pi_{ih} = \sum_{h=1}^{H} [p_h - k(\tau)] x_{ih}$ so defining the ("small τ") profit-neutrality factor in the familiar way:

$$\gamma_i(0; H) = \frac{1}{e_i(0)} \left(- \sum\nolimits_{h=1}^{H} \frac{d\Pi_{ih}(\tau)}{d\tau} \bigg|_{\tau=0} \right),$$

where $x_i \equiv \sum_{h=1}^{H} x_{ih}$ is firm i's total production across price buckets. Let $\rho_h \equiv dp_h(\tau)/d\tau)/(dk(\tau)/d\tau)$ denote the (symmetric) pass-through rate of bucket h.

Proposition 5. *Under price discrimination with H price buckets, at symmetric Nash equilibrium, regulation τ affects firm i's profits according to:*

$$\gamma_i(0; H) = 2[1 - \rho_{ave}(H)] = 2[1 - \rho_{ave}(1)] = \gamma_i(0; 1) \text{ for any } H \geq 2,$$

where $\rho_{ave}(H) \equiv \sum_{h=1}^{H} \frac{x_{ih}(0)}{x_i(0)} \rho_h$ *is the average rate of cost pass-through across price buckets.*

The firm-level profit impact is driven by a simple average pass-through rate across buckets. Price discrimination (higher H) raises (lowers) the prices paid by high-value (low-value) consumers but, due to the linear model structure, leaves the average price unchanged.[27] Similarly, cost pass-through to high-value (low-value) consumers declines (rises) but average pass-through $\rho_{\text{ave}}(H)$ does not change with H. Hence the uniform pass-through rate $\rho_{\text{ave}}(1)$ pins down the firm-level profit impact.

This extension provides a microfoundation, within the context of GLC, for working with pass-through based on an average of dispersed market prices. In our empirical application to airlines, this will provide support to an analysis that, due to data availability, is based on an average ticket price. A familar substantive restriction is that regulation τ does not alter the number of price buckets H (or the number of firms n).

It is also worth noting that this extension is subtly different from those with multiple markets/products. In the previous extensions, given A1–A3 and a linear demand structure, firm i's first-order condition directly implied the GLC's A4 in each market/product—without requiring any assumptions about its rivals. By contrast, this model of price discrimination has a more complex demand structure in which the price for one bucket depends on prices for other buckets. Nonetheless, at the Nash equilibrium, GLC's A4 is met for each individual price bucket—and hence our pass-through result obtains.[28]

2.5 Robustness to model misspecification

We now explore GLC's robustness to model misspecification. First, we discuss its properties in comparison with logit demand structures (for which A4 is violated). Second, we analyze the quantitative implications of non-linear costs (A3 fails) and/or non-linear demand (A4 fails) in an augmented Cournot model.

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[27] Price discrimination still benefits firms because sales expand to otherwise excluded low-value consumers.

[28] Proposition 5 can be be further generalized to allow cost asymmetries between firms and to more general conduct parameters (building in part on the results of Kutlu 2017).

2.5.1 Comparison with logit demand structures

In a differentiated-products context, the empirical industrial-organization literature (Bresnahan, 1989; Berry et al., 1995; Nevo, 2001; Reiss and Wolak, 2007; Einav and Levin, 2010) employs structural models with discrete choice and a logit demand structure. This literature typically makes assumptions, for each firm, that are equivalent to GLC's A1–A3; firms are cost-minimizers which take input prices as given and operate production technologies with constant marginal cost. However, the logit demand structure implies a particular form of demand non-linearity that results in a firm's first-order condition for profit-maximization departing from GLC's A4.

The implications of functional-form assumptions on demand have been explored in the literature on merger analysis which seeks to predict, with reasonable accuracy, the price and welfare impacts of horizontal mergers. Using simulations, a number of papers have found that logit demand systems give quantitatively similar results to linear demand. In early work, Crooke et al. (1999) calibrate pre-merger equilibria under different demand systems to "known" values of own- and cross-price demand elasticities. More recently, Miller et al. (2016) explore the theoretical finding of Jaffe and Weyl (2013) that pass-through estimates combined with information on demand elasticities can provide a good approximation of the price impact of a merger. Their Monte Carlo simulations assume that the true demand system is logit and calibrate demand parameters to randomly generated market structures. Both papers find that the price changes resulting from a merger are roughly equal under linear and logit demand.

To understand these simulation findings, write $s_i(\mathbf{p}) \in (0, 1)$ as the probability that a consumer will choose firm i's product where $\mathbf{p}$ is the vector of firms' prices, generated by a standard discrete choice model with M consumers and random utility shocks that are *iid* across products according to a Generalized Extreme Value distribution; firm i's demand $D_i(\mathbf{p}) = Ms_i(\mathbf{p})$ and its market share satisfies $\partial s_i/\partial p_i = -s_i(1 - s_i)/\mu < 0$ with $\partial^2 s_i/\partial p_i^2 = s_i(1 - s_i)(1 - 2s_i)/\mu^2 \gtreqless 0$, where $\mu > 0$ is a measure of product differentiation (see, e.g., Anderson et al., 1992). The key observation is that, for a range of different market shares, the non-linearity of this logit market-share function is not too pronounced; this helps explain why merger simulation often finds similar results for logit demand and linear demand (for which $\partial^2 D_i/\partial p_i^2 \equiv 0$).[29]

Two important points follow if logit demand is indeed the true model. First, GLC's qualitative prediction that firm-level pass-through signs the profit impact remains

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[29] Unfortunately, closed-form solutions for pass-through and profits are not available for the logit model.

correct. To see this, write firm i's profits as $\Pi_i(\mathbf{p}) = (p_i - k_i)Ms_i(\mathbf{p})$ where its first-order condition is:

$$\frac{\partial \Pi_i(\mathbf{p})}{\partial p_i} = M\left[s_i(\mathbf{p}) + \frac{\partial s_i}{\partial p_i}p_i\right] = 0 \Rightarrow (p_i - k_i) = \frac{\mu}{(1-s_i)} \Rightarrow (\rho_i - 1)\frac{dk_i}{d\tau} = \frac{\mu}{(1-s_i)^2}\frac{ds_i}{d\tau},$$

recalling our definition $\rho_i \equiv (dp_i/d\tau)/(dk_i/d\tau)$. It follows that $\text{sign}(ds_i/d\tau) = \text{sign}(\rho_i - 1) = \text{sign}(d\Pi_i/d\tau)$. This is exactly as in GLC: a firm's sales and margin shrink if and only if its pass-through is below 100%. Hence the winners and losers from regulation are still correctly identified. Second, GLC entails no systematic bias in that $\text{sign}(\partial^2 D_i/\partial p_i^2) = \text{sign}(\frac{1}{2} - s_i)$ always varies across firms of different sizes.

In general, of course, any parametric model can be sensitive to functional-form misspecification. Crooke et al. (1999) and Miller et al. (2016) both find that demand systems with more extreme curvature (such as constant-elasticity demand) can lead to significantly different predictions than both logit and linear demand. In this respect, a potential advantage of GLC is its semi-parametric nature: Proposition 1 requires such functional-form assumptions to be made only for firm i.

2.5.2 Non-linearities: Monte Carlo results

We now further explore the quantitative implications of GLC being misspecified. Following Hepburn et al. (2013), suppose it is known that the true model is an augmented version of homogenous-product Cournot competition. The setting features two departures from GLC: each firm has non-constant marginal cost (A3 fails) and the demand system may be non-linear (A4 fails).

The salient additional model parameters are as follows. The inverse demand curve is $p(X)$ where X is total industry output; let $\xi \equiv -Xp''(X)/p'(X)$ be an index of demand curvature, so demand is convex (concave) if $\xi \geq 0$ ($\xi < 0$), and firm i's market share is given by $s_i \equiv x_i/X \in (0,1)$. There is a competitiveness parameter $\theta > 0$ which nests Cournot-Nash behaviour when $\theta = 1$ and lower values of θ correspond to more intense competition. Finally, the slope of the marginal cost function is given by m and is identical across firms, and $\overline{m} \equiv -m/p'$ is a measure of cost convexity.

Translating Hepburn et al.'s (2013) results into our context yields firm i's true profit-neutrality parameter $\widetilde{\gamma}_i$ faced with a small tightening of regulation:

$$\widetilde{\gamma}_i(\overline{\tau}, \underline{\tau})|_{\overline{\tau}\to\underline{\tau}} = 2(1-\rho_i) + \frac{\theta}{(\theta+\overline{m})}\theta s_i \xi \rho_i - \frac{\overline{m}}{(\theta+\overline{m})}(1-\rho_i),$$

where $(\theta + \overline{m}) > 0$ (by stability of equilibrium). The underlying equilibrium firm-level rate of cost pass-through is given by:

$$\rho_i = \frac{n}{[n + \theta(1-\xi) + \overline{m}]} \frac{1}{\overline{z}_i},$$

and is driven by market structure (n), demand curvature (ξ), cost convexity ($\overline{m}$), and firm i's cost shock (z_i) relative to the industry-average cost shock ($\frac{1}{n}\sum_{j=1}^{n} z_j$), namely $\overline{z}_i \equiv z_i / \left(\frac{1}{n}\sum_{j=1}^{n} z_j\right)$.

With linear demand and constant marginal costs ($\xi = m = 0$), A3 is met and each firm's first-order condition satisfies A4 so Proposition 1 holds: $\widetilde{\gamma}_i = 2(1-\rho_i) = \gamma_i$. The first additional effect stems from demand: if true demand is convex with $\xi > 0$ then this pushes $\widetilde{\gamma}_i$ up so GLC's γ_i underestimates the adverse profit shock. This effect is quantitatively modest if either the market is very competitive (low θ) or firm i's market share s_i is small or the pass-through rate ρ_i itself is small. The second additional effect arises from costs: if these are convex with $\overline{m} > 0$ this pushes down $\widetilde{\gamma}_i$ (as long as $\rho_i \leq 1$) so GLC then yields an overestimate.

Two conclusions follow. First, GLC again exhibits no systematic bias: depending on the precise way in which A3 and/or A4 are violated, it may over- or under-estimate the true firm-level profit impact of regulation. Second, the impacts of plausible departures from A3 may partially offset those of A4. It is probably true that convex demand is more likely than concave demand—and indeed this applies for most demand curves commonly used by economists. In addition, it is probably true that the case of convex costs, at equilibrium, is more likely than concave costs (especially for emissions-intensive industries). These two departures from GLC tend to work in opposite directions such that $\widetilde{\gamma}_i \approx 2(1-\rho_i) = \gamma_i$ may still be a reasonable approximation.

We now explore quantitatively the impacts of model misspecification using Monte Carlo analysis. In the following design, we create 10,000 hypothetical industries for which, on average, A3 is violated for each firm and so A4 is also violated for each firm. The design is such that there is significant heterogeneity in firms' marginal costs and emissions intensities.[30]

For each industry, we draw the following six sets of parameters to reflect model uncertainty underlying GLC:

1. The number of firms is drawn uniformly as $n \in [2, 8]$, with an integer constraint, to create a relatively concentrated market structure;

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[30] Firms' second-order conditions and stability conditions are always satisfied given our parameter assumptions below.

2. The market competitiveness parameter is drawn uniformly as $\theta \in [0, 1]$ so that competition, on average, lies mid-way between Bertrand and Cournot-Nash;

3. For each of the $n \in [2, 8]$ firms in the industry, firm i's market share is drawn uniformly as $s_i \in (0, 1)$; then firms' market shares are re-normalized so that they sum to 100%;

4. The cost convexity metric is drawn uniformly according $\overline{m} \equiv m/[-p'(X)] \in [0, 1]$ leading to modestly convex costs (thus violating A3);

5. Demand curvature ξ is drawn uniformly from five discrete values $\{-1, -\frac{1}{2}, 0, \frac{1}{2}, 1\}$, in line with the common assumption from economic theory that demand is log-concave $\xi \leq 1$. This range (i) includes three convex demand systems used in an influential paper by Genesove and Mullin (1998): linear ($\xi = 0$), quadratic ($\xi = \frac{1}{2}$), exponential ($\xi = 1$). While linear demand ($\xi = 0$) remains focal, A4 is nonetheless violated as A3 is already violated;

6. For each of the $n \in [2, 8]$ firms in the industry, firm i's relative emissions intensity $\overline{z}_i$ is drawn uniformly as $\overline{z}_i \in [\frac{1}{2}, \frac{3}{2}]$ so that each firm is somewhere between 50% cleaner or 50% dirtier than the industry average.

We then drawn one firm from each industry, such that we have 10,000 firms, and complete the analysis of the true model and the misspecified GLC in four steps. For each firm, we calculate: (1) the true firm-level rate of cost pass-through $\rho_i(n, \theta, \xi, \overline{z}_i)$ ("true CPT"), (2) the true profit-neutrality factor $\widetilde{\gamma}_i(\rho_i, \theta, s_i, \xi, \overline{m})$ ("true PNF"), (3) GLC's estimated profit-neutrality factor $\gamma_i(\rho_i) = 2(1 - \rho_i)$ ("GLC PNF"), and (4) GLC's error $\varepsilon_i \equiv \gamma_i - \widetilde{\gamma}_i$. An important point is that GLC's PNF picks up the variation in the true CPT even if some or all of these assumptions A1–A4 are violated.[31]

Table 2.1 summarises paramter draws and results. Firm-level cost pass-through rates ρ_i vary widely between around 30% up to almost 200%, partly driven by variation in emissions intensities, that is, in the size of firms' cost shocks relative to their rivals. Similarly, there is large variation in true profit-neutrality factors, with some firms being hit hard ($\widetilde{\gamma}_i > 1$) and others benefitting from regulation ($\widetilde{\gamma}_i < 0$). Overall, the average GLC PNF of $\gamma_i = 0.205$ lies close to the average true PNF of $\widetilde{\gamma}_i = .0156$. Figure 2.1 is a kernel density plot of the true PNF and GLC PNF over all draws. The means (shown in grey) are strikingly close. The true PNF has a a slightly larger spread, but their overall distributions are similar in shape.

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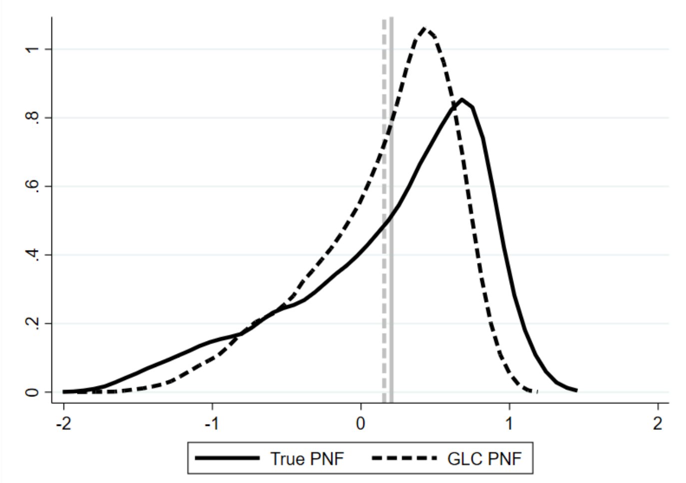
[31] See Miller et al. (2017) for an analysis of noisy or biased pass-through estimation.

Table 2.1 Monte Carlo parameter draws and results.

	Mean	Min	Max
Parameters drawn			
Number of firms n	4.998	2.000	8.000
Demand curvature ξ	0.004	-1.000	1.000
Cost convexity $\overline{m}$	0.500	0.000	1.000
Market share s	0.247	0.000	0.998
Competitiveness θ	0.502	0.000	1.000
Relative emissions intensity $\overline{z}$	1.001	0.500	1.500
Results			
True pass-through ρ	0.897	0.316	1.959
GLC profit neutrality factor γ	0.205	-1.918	1.367
True profit neutrality factor $\tilde{\gamma}$	0.156	-1.843	1.123
GLC error ϵ	0.049	-0.860	0.523
Number of firm draws	10,000		
Herfindahl Index H	0.317	0.128	0.998

Figure 2.1 Density plots of the true PNF and GLC PNF.



Notes: Vertical lines in grey indicate the means of the distributions. Kernel densities plotted over all 10,000 draws.

In sum, this analysis suggests that if a researcher knows the true pass-through rate then GLC can perform reasonably well even in situations with significant model misspecification on the demand and/or cost side.

2.6 Empirical analysis of cost pass-through for US airlines

In this section we estimate cost pass-through rates for US airlines. In Section 2.7 we use these estimates in the theoretical results for GLC, to obtain predicted profit impacts for carbon pricing.

2.6.1 Background on aviation and climate change policy

Airlines currently produce around 2.5% of global CO_2 emissions (McCollum et al., 2009); as these emissions occur high up in the atmosphere, an effect known as climatic forcing means that the proportion of "effective" emissions is around twice as high. Airline emissions are projected to grow well into the 21^{st} century due to rising global demand for air travel and limited scope for large-scale substitution away from jet engines to low-carbon technologies. As other sectors of the economy, such as electricity generation, decarbonize more quickly the role of aviation in future climate policy is set to grow. Economic regulation appears increasingly likely as countries seek to implement internationally-agreed climate targets in a cost-effective manner.[32]

In this paper, we study the domestic US airline market. This is the world's largest aviation market, producing around 28% of global aviation emissions, but has so far not been subject to carbon pricing. We study the domestic market because international aviation is regulated under a separate organization and set of agreements. At a baseline carbon price of $30/$tCO_2$, the level proposed by the US Government's IAWG (2016), aviation's 2013 emissions of 120 million tCO_2 would have had a value of $3.6 billion.

There is a rich literature that explores many important features of US aviation markets, principally the presence of market power and firm heterogeneity. The number

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[32] Aviation is already subject to carbon pricing in some international jurisdictions. Intra-EU flights have since 2012 been included in the EU ETS. However the impact on airlines has been limited by a low carbon prices. Aviation has recently also been included in some regional trading schemes in China, though again with very low carbon prices. In 2018 Sweden introduced an additional carbon tax, on all flights departing from Sweden, that operates alongside the EU ETS. The first global aviation emissions reduction agreement was negotiated by the UN's International Civil Aviation Organization (ICAO) and signed by its 191 member nations in October 2016; it amounts to a carbon-offset scheme for emissions growth after 2020.

of firms competing on a given route is typically small, and it is widely acknowledged that despite deregulation airlines continue to exercise market power (Brander and Zhang, 1990; Borenstein and Rose, 2007; Ciliberto and Tamer, 2009). Over the period we study, US aviation was dominated by four large legacy carriers (American, Delta, United and US Airways) and a single large low-cost carrier, Southwest Airlines. Legacy airlines were established on interstate routes before deregulation in 1978; they tend to operate hub-and-spoke networks with relatively high costs and high levels of service while low-cost airlines tend to offer direct flights at lower prices (Borenstein, 1992). A recurring theme in the literature is the importance of this heterogeneity and the central role played by Southwest, sometimes labelled the "Southwest is special" effect. From the 1980s onwards, Southwest's low costs, innovative business model and generally astute management have made it an especially disruptive and profitable competitor, with large impacts on incumbent prices and profits (Borenstein, 1989; Morrison, 2001; Borenstein and Rose, 2007; Goolsbee and Syverson, 2008; Ciliberto and Tamer, 2009).[33] We follow this literature by ensuring potential heterogeneity between Southwest and the legacy carriers is captured in our analysis.

2.6.2 Description of the data

Our unit of analysis is at the individual-product level. As is standard in the airline literature, we take a product to be a seat on a flight by airline i on route j at time t. Our dataset is a panel of price and cost data for airlines over the period 2004Q1–2013Q4.[34] For each carrier i, route j and quarter t, we have the average ticket price p_{ijt}, the average per-person fuel cost k_{ijt}, and a vector of covariates. All monetary quantities are in real 2013Q4 USD. We restrict our attention to the four large legacy carriers (American, Delta, United and US Airways) and one large low-cost carrier (Southwest) operating throughout the period.[35] The resulting dataset is an unbalanced panel, with $N = 1,334$ carrier-routes and $T = 40$ quarters, a total of 36,650 observations. The routes in our sample make up 27% by revenue of all domestic US aviation activity over the period.

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[33] The "Southwest is special" effect is widely recognised beyond the economics literature. See, for example, Heskett and Sasser (2010) and Tully (2015).

[34] The start year was chosen to exclude the effects of 11 September 2001 from our dataset. The end date avoids the 2015 "mega merger" between American Airlines and US Airways.

[35] A third type of carrier in the US market, the regional airline, is not included in our analysis. There are now many more low-cost carriers than only Southwest, but these were either very small or non-existent at the start of our period, so we do not include them.

We construct our data by combining elements of three datasets from the US Bureau of Transportation Statistics. Price data come from the DB1A Origin and Destination Survey, a 10% sample of all airline tickets sold.[36] Prices are for a one-way trip; all round-trip tickets are split equally into two one-way observations. A route is defined by its origin and destination airports, regardless of direction. Following much of the airlines literature, we exclude indirect flights.[37] Finally, we exclude carrier-routes that carried fewer than 1,000 passengers per quarter (i.e. 83 per week). For the resulting observations we calculate p_{ijt}, an average of all fares purchased on carrier-route ij in quarter t.

The remaining datasets (T-100 and Form 41) are used to construct k_{ijt}, the average per-passenger fuel cost for flying with carrier i on route j in time t.[38] This is the total fuel cost for a given flight divided by the number of passengers on that flight. (Appendix 2.B describes this procedure in more detail.) Our ultimate objective is to obtain estimates of carbon cost pass-through – the dollar increase in prices following a $1 increase in carbon costs. Given there is currently no variation in carbon prices for US airlines away from zero, our empirical approach is to estimate fuel cost pass-throug – the dollar increase in prices following a dollar increase in fuel costs. For a cost-minimising airline, fuel and carbon costs are equivalent and pass-through rates should therefore be the same.[39]

The value of fuel cost k_{ijt} is determined by three factors: (i) the market price of jet fuel, which tracks the crude oil price; (ii) the fuel efficiency of the passenger's journey, driven by the type and age of aircraft used, the configuration the seating and the proportion of seats filled (any other variation in the airline's physical operating

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[36] We use a cleaned version of the DB1A provided by Severin Borenstein. The following ticket types are excluded: international, first class, frequent flier (those with a price less than $20), entry errors (price higher than $9,998 or five times the industry standard for that route-time), and open or circular itineraries. Observations are aggregated up to the carrier-route-time level. (In section 2.4.2, we provide a microfoundation for the widespread approach in the literature of analyzing economy-class tickets in a separable way from business or first-class tickets.)

[37] Indirect flights—involving a change of aircraft at another airport en route, using the airline's hub-and-spoke network—are well-known to have different economic characteristics to direct flights. Excluding indirect flights is, therefore, commonplace in the airlines literature (e.g. Borenstein and Rose, 1994; Goolsbee and Syverson, 2008; Gerardi and Shapiro, 2009).

[38] The overlap between the DB1A and T-100 is good but not perfect (see Goolsbee and Syverson, 2008, for a fuller discussion). Merging with data from T-100 results in around 10% of DB1A revenue being dropped.

[39] A similar approach of using variation in other input costs to estimate the impact of future environmental costs is also taken by Miller et al. (2017). In related work, Ganapati, Shapiro & Walker (2016) estimate the pass-through of energy input prices across six US manufacturing industries while Bushnell and Humber (2017) focus on the pass-through of natural gas prices in the fertilizer industry and its implications for the allocation of carbon emissions permits.

Table 2.2 Descriptive statistics.

	Southwest				Legacy			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Quarterly av. statistics								
Price (\$)	154.73	40.76	63.07	298.91	227.75	70.89	72.80	599.11
Fuel cost (\$)	32.95	17.86	5.61	129.81	52.98	28.74	2.05	366.63
Distance (miles)	717	466	133	2,298	1,044	629	130	2,724
Emissions (tCO_2)	0.13	0.06	0.03	0.41	0.20	0.10	0.01	0.71
Emissions cost ($\$/tCO_2$)	4.00	1.84	1.03	12.44	6.02	2.89	0.18	21.22
Passengers (000s)	42	39	1	289	30	29	1	245
Competitors (#)	2.24	2.40	0.00	16.00	2.82	2.29	0.00	16.00
LCC competitors (#)	0.40	0.73	0.00	4.00	0.67	0.97	0.00	5.00
Revenue (\$million)	5.46	4.37	0.12	32.12	5.85	5.84	0.11	53.87
Whole sample statistics								
Revenue in sample (%)	56				43			
Observations (#)	13,199				22,451			
Carrier-routes (#)	416				918			

Notes: Data are quarterly, over the period 2004Q1-2013Q4. Price, fuel cost, emissions and emissions cost are per passenger. Emissions cost are calculated at a carbon price of $\$30/tCO_2$. Whole sample statistics are aggregated over all N and T. Revenue in sample is the proportion of all US aviation revenue (ie all flights on all airlines) in the sample over this period. The legacy carriers are American, Delta, United and US Airways. All averages are unweighted.

procedures can also influence this factor); and (iii) the carrier's use of hedging or other financial instruments when buying fuel. This varies significantly between carriers and over time for a given carrier. For example, in our sample period, Southwest was known for its extensive use of hedging, while US Airways never hedged. Carriers therefore ended up paying very different prices: in 2008 (when oil prices were rising) US Airways paid 30% more for each gallon of fuel than Southwest, whereas in 2009 (when oil prices fell) it paid 18% less.[40]

Table 2.2 presents descriptive statistics on airlines' prices, costs and other variables related to competition and environmental performance. The four legacy carriers are grouped together (Table 2.6 in Appendix 2.C.2 gives descriptive statistics by carrier and confirms the similarity of the legacy carriers compared to Southwest). Southwest tends to fly larger numbers of passengers on shorter routes than the legacy carriers; it

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[40] We do not have detailed data on the precise extent of hedging by each carrier at each point in time. Turner and Lim (2015) document and analyse the different hedging strategies of US airlines, and the different effective fuel prices that result.

charges lower prices and has lower fuel costs and emissions. Revenue and numbers of competitors are broadly similar.

Figure 2.2 shows trends over the period for each carrier type. Figure 2.2(a) compares Southwest's average per-passenger fuel cost with the spot price of jet fuel. They track each other reasonably closely, with a lag indicating the presence of hedging, which also smooths out the peak and trough from the 2008 price spike. Note also the substantial variation in fuel costs over the period. Figure 2.2(b) plots average ticket prices (left axis) against per-passenger fuel costs (right axis) for Southwest. As expected, there is a positive correlation. Figure 2.2(c) shows per-passenger fuel costs for the legacy carriers and how they compare to the spot price of jet fuel. Fuel costs follow spot prices more closely than for Southwest, consistent with a more limited use of hedging. Figure 2.2(d) shows ticket prices and fuel costs for the legacy carriers; as for Southwest, these appear to be closely related.

2.6.3 Baseline econometric specification

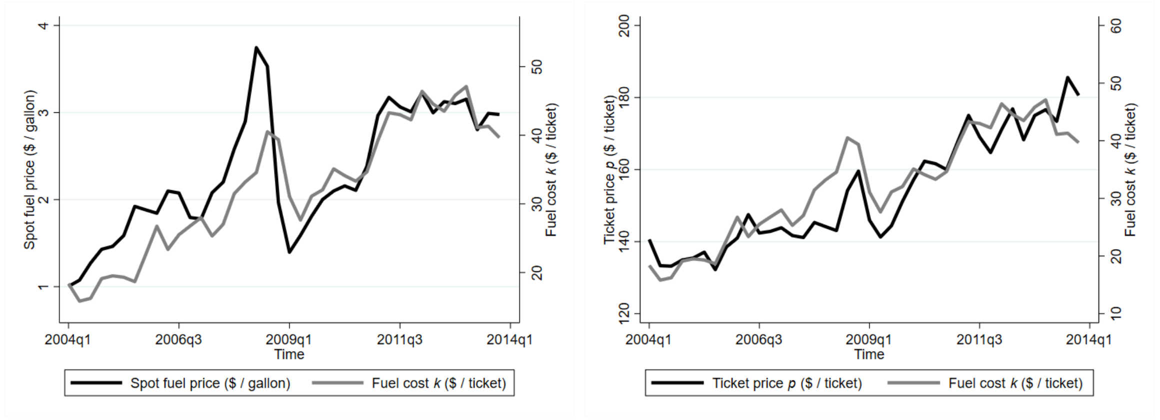
Following a standard approach in the pass-through literature (e.g., Fabra and Reguant, 2014; Atkin and Donaldson, 2015; Stolper, 2016; Miller et al., 2017), our baseline specification is a regression of quarterly average prices p_{ijt} on quarterly average per-passenger fuel costs k_{ijt}. Given the dimensions of our panel ($N = 1,334$, $T = 40$) we can estimate a standard fixed effects specification. We are interested pass-through heterogeneity so interact costs with carrier identity – either Southwest or a legacy carrier – and estimate the following equation:

$$p_{ijt} = \rho_S k_{ijt} \cdot S_i + \rho_L k_{ijt} \cdot L_i + X'_{ijt}\beta + \lambda_t + \eta_{ij} + \epsilon_{ijt}. \tag{2.4}$$

The parameter of interest is ρ, the rate of cost pass-through. By interacting fuel cost k_{ijt} with dummies S_i and L_i that are equal to 1 for Southwest and legacy carriers, respectively, we obtain pass-through rates ρ_S and ρ_L for the two carrier types, respectively. Controls (X_{ijt}), time effects (λ_t), fixed effects (η_{ij}), and residuals (ϵ_{ijt}) are further explained below.

Equation (2.4) cannot be estimated using OLS because the per-passenger fuel cost k_{ijt} is potentially endogenous. It depends in its denominator on the number of passengers flying in quarter t, which in turn will generally be an outcome of the price p_{ijt}. Hence this regressor depends on an outcome variable, introducing the possibility of simultaneity bias. To address this, we use the spot price of jet fuel as an instrument

Figure 2.2 Aggregate trends in prices and costs.

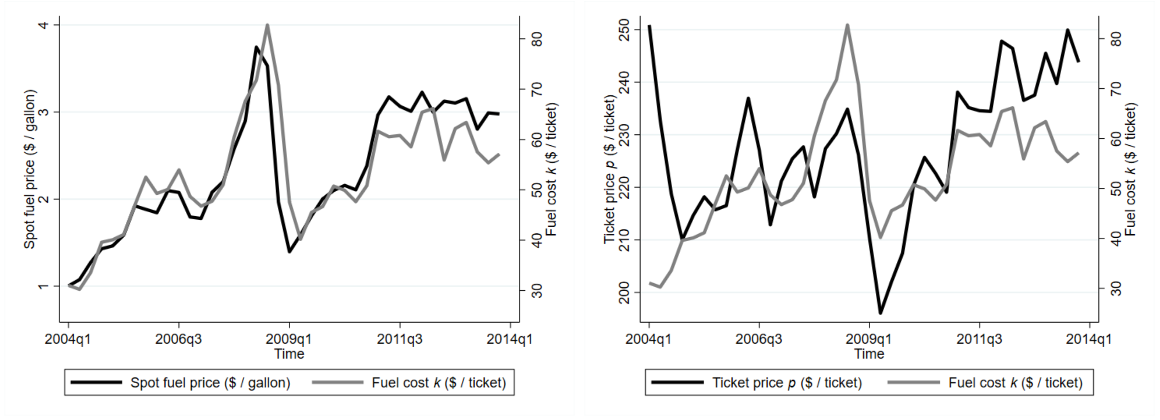


(a) Southwest

(b) Southwest

(c) Legacy

(d) Legacy



Notes: Panels (a) and (c) show jet fuel spot prices and per-passenger fuel costs; panels (b) and (d) show ticket prices and per-passenger fuel costs. Variables are quarterly averages (unweighted) over all carrier-routes in our sample.

for fuel cost k_{ijt}.[41] Since the price of jet fuel is determined by the global oil price, it is exogenous to passenger numbers on a particular route, satisfying the exclusion principle. In order to accommodate potential hedging, we include three lags of spot prices. We also include a term interacting distance with fuel costs, in order to capture the differential impact of spot fuel prices on the dollar fuel cost of flights of different

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[41] We use jet fuel price data from Bloomberg (JETINYPR index, New York Harbor 54-Grade Jet Fuel).

lengths. The first stage regressions are given by:

$$k_{ijt} \cdot a_i = \sum_{q=0}^{3} \gamma_q f_{t-q} \cdot a_i + \sum_{q=0}^{3} \delta_q f_{t-q} \cdot a_i \cdot d_{ij} + X'_{ijt}\beta + \mu_t + \theta_{ij} + \omega_{ijt} \quad \text{for each } a_i \in \{S_i, L_i\} \tag{2.5}$$

where f_t is the spot fuel price, d_{ij} is the route distance, and the remaining controls are the same as in Equation (2.4).

Equations (2.4) and (2.5) include a vector of controls X_{ijt} which capture changes in supply and demand that could otherwise bias the regression results. In addition to a constant, X_{ijt} is constructed as follows. (i) We include GDP growth to proxy for demand because jet fuel prices closely track the oil price, which may be systematically related to demand for air travel. We use the average GDP of the two states at either end of the route. (ii) We construct an index of the main non-fuel costs, at the carrier level, principally made up of labour and aircraft maintenance costs. (iii) We include the number of competitor firms on route j. If this quantity remained stable over time, there would be no need to include it when estimating Equation (2.4); however we do see entry and exit in the data, which could potentially be systematically related to fuel costs. (iv) We also include the number of low-cost competitors, as these may have a different impact to other competitors. (v) We include carrier size, the total number of passengers travelling on all of airline j's routes in a given quarter, as a measure of overall demand for airline j's product. As robustness tests in Appendix 2.C.3, we explore several other controls to capture changes in supply and demand. Time effects are controlled for using dummies for each year-quarter t, and fixed effects are at the carrier-route level ij. Standard errors are clustered at the carrier-route level. Finally, we weight observations by carrier-route emissions, so smaller routes do not disproportionately affect the resulting carrier-level pass-through estimates (see Section 2.7.2 for further details).

It is worth noting an implicit assumption in our estimation of cost pass-through. Our specification does not directly include competitors' costs. A firm's equilibrium price, however, is usually a function of its own as well as its rivals' costs. The literature on pass-through estimation takes a variety of approaches to this. Miller et al. (2017) include in their overall pass-through rate the coefficient on a measure of firm-specific competitive pressure to capture the rival-cost component of pass-through. Stolper (2016) argues for the theoretical importance of including rivals' costs but then, for reasons of identification, estimates an overall industry cost pass-through. Our approach is to allow firm i on route j to have costs k_{ijt} that may be correlated in any arbitrary way with any other rival's costs. The substantive assumption is that the relationship between own and rivals' costs is unchanging over the period we study. If this holds, then our pass-through rates capture both own-cost and rival-cost effects. In this respect our approach is similar to both Atkin and Donaldson (2015) and Stolper (2016).[42]

2.6.4 Estimation results

Table 2.3 shows the results of estimating Equation (2.4) using the 2SLS approach described above, with the first stage given by Equation (2.5). Column (1) shows the baseline result, using the full unbalanced panel. We see substantial heterogeneity: Southwest's pass-through rate is 1.41, whereas the legacy carriers' pass-through is 0.62. They are significantly greater and smaller than 1, respectively. This means that when Southwest's costs rise, their rise in equilibrium price more than offsets this. The opposite is true for the legacy carriers. To the best of our knowledge, our finding of pass-through heteroegeneity in the airline industry is novel. We document, therefore, a new dimension in which the "Southwest is special" result operates.

The coefficients on the controls generally have the signs we would expect. We see that greater competition lowers prices, and that competition from low-cost carriers has a large additional effect. Non-fuel costs raise prices as expected. Less expected is that GDP growth and carrier size have a negative relationship with price. The first stage results are also as we would expect: the spot price of jet fuel has a positive relationship with per-passenger fuel costs, and the Sanderson-Windmeijer F-statistics provide strong evidence that the instruments are relevant in all cases.

Column (1) gives our baseline results, which we will use in conjunction with GLC to produce predicted profit impacts below. Column (2) shows the results of estimating the same equations but on the subsample of the full dataset that gives a balanced panel. We report these results because they are for the 'stable' routes only - those that were operated continuously throughout the period. The near-identical results for the balanced and unbalanced panel suggest that both newly opened routes and routes shortly to be discontinued appear to have the same rate of pass-through as the stable routes. This is encouraging for the external validity of our estimates.

In column (4), we show the results of estimating Equation (1) by OLS. The results differ quantitatively from the baseline, suggesting the instruments are not redundant. The qualitative result, however, that pass-through is significantly higher for Southwest

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[42] Fabra and Reguant (2014) take another approach, given their focus on electricity: they analyze pass-through for a homogeneous good (electricity) with a single market price, and their resulting pass-through rate gives the dollar increase in the electricity price when the carbon costs of the marginal supplier increase by $1.

Table 2.3 Pass-through estimates.

	(1) Baseline	(2) Balanced Panel	(3) Common routes	(4) OLS
Panel A: 2SLS	Dependent variable: Price			
Fuel cost · Southwest	1.41***	1.47***	1.08***	1.17***
	(0.12)	(0.13)	(0.16)	(0.12)
Fuel cost · Legacy	0.62***	0.64***	0.58***	0.55***
	(0.11)	(0.11)	(0.14)	(0.08)
Competitors	-2.79***	-2.86***	-0.09	-2.94***
	(0.69)	(0.76)	(1.00)	(0.68)
LCC competitors	-5.06***	-5.35***	-6.78***	-5.11***
	(0.90)	(0.98)	(1.73)	(0.93)
Non-fuel cost index	6.49**	6.90**	7.86**	6.85**
	(2.60)	(2.84)	(3.41)	(2.69)
GDP growth	-1.30***	-1.52***	0.40	-1.33***
	(0.39)	(0.44)	(0.33)	(0.40)
Carrier size	-15.24***	-16.15***	-1.40	-14.95***
	(5.15)	(5.75)	(4.56)	(4.44)
R squared	0.212	0.216	0.436	0.213
Time- and fixed-effects	✓	✓	✓	✓
Unbalanced panel	✓		✓	✓
Observations	35,650	24,600	6,138	35,650
Carrier-routes	1,334	615	183	1,334
Panel B: First stage regressions				
	Dependent variable: Fuel cost · Southwest			
Spot · Southwest	17.24***	17.31***	22.35***	
	(1.06)	(1.19)	(2.79)	
Spot · Distance · Southwest	10.20***	10.48***	9.95***	
	(0.18)	(0.21)	(0.24)	
F-statistic excluded instruments	734	681	197	
p-value	0.000	0.000	0.000	
	Dependent variable: Fuel cost · Legacy			
Spot · Legacy	26.71***	25.83***	8.54***	
	(3.24)	(3.49)	(3.08)	
Spot · Distance · Legacy	12.13***	12.24***	11.46***	
	(0.88)	(0.87)	(1.36)	
F-statistic excluded instruments	288	256	104	
p-value	0.000	0.000	0.000	

Notes: All regressions have a full set of carrier-route fixed effects, and year-and-quarter time dummies. Standard errors are shown in parentheses and clustered at the carrier-route level. All regressions except (3) are weighted by total emissions of the carrier-route over the period. Columns (1), (2), and (3) are estimated by 2SLS. Column (2) is estimated on an balanced panel. Column (3) is estimated on the subsample of common routes (see text). Column (4) is estimated by OLS on the full sample. In Panel B, all first stage regressions include the full set of controls, fixed effects, and time effects as in Panel A. Significance levels and p-values are denoted by: * significant at 10%, ** significant at 5%, and *** significant at 1%.

than the legacy carriers, and these are on either side of 100%, continues to hold. This is reassuring, because it shows that our key finding is not being driven by the instruments in our baseline results.

What explains the heterogeneity in pass-through rates? To answer this we can decompose the difference in baseline pass-through rates into three factors: route portfolio, production costs, and product differentiation. Firstly, from the descriptive statistics in Table 2.2 it is clear that Southwest operates different kinds of routes to the legacy carriers since they are considerably shorter. Short haul flights are likely to have systematically different characteristics: on the demand side, there are more close substitutes (such as car, bus or rail travel); on the supply side, entry may be more or less difficult so there may be differences in market power (e.g., Brander and Zhang, 1990; Berry and Jia, 2010). To quantify the importance route portfolios, we present in Column (3) of Table 2.3 the results of re-estimating our baseline using only routes common to both Southwest and the legacy carriers. To achieve a fully like-for-like comparison of pass-through rates we run an unweighted regression (rather than weighting by emissions as in the baseline). We find that Southwest's pass-through rate falls significantly, to 1.08, while the legacy carriers' pass-through remains statistically unchanged, at 0.58. By comparing the difference in pass-through rates for the common routes to that in the baseline results, we can attribute 32% of the original difference in baseline pass-through to differences in route portfolio.

Secondly, we can quantify the importance of production cost heterogeneity. Southwest has lower average fuel costs on common routes: \$30.37 per passenger compared to \$40.59 for the legacy carriers. This is principally due to the use of newer aircraft and more efficient seating configurations. In the absence of any demand asymmetries between firms there is a single market price; in such cases, any two firms' (i and j) pass-through rates are related only by their relative cost shocks, $\rho_j/\rho_i = z_i(\tau)/z_j(\tau)$. Using the fuel cost figures for the common routes, Southwest's superior fuel efficiency can explain 36% of the original difference in baseline pass-through rates.[43]

Thirdly, 32% of the pass-through differential remains. This residual difference now shows hetergeneity in pass-through rates for a uniform cost shock on common routes (that hits all carriers equally). We therefore attribute this residual to demand-side asymmetries between carriers, based on their differentiated-product offering. Such demand asymmetries now imply departures from a single market price on common routes so also mean that differences in competitive conduct may be driving pass-

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[43] All else equal, we would expect the legacy carriers to have a pass-through rate 25% lower than Southwest using $\rho_j/\rho_i = z_i(\tau)/z_j(\tau)$. Using Southwest as the baseline, this explains 36% of the original difference in Table 2.3.

through asymmetry.[44] In sum, this decompostion suggests that around one third of the pass-through difference is due to different route portfolios; around one third is driven by Southwest's superior fuel efficiency and the final third stems from differences in demand patterns (and competitive conduct).[45]

2.6.5 Further results and robustness

We have explored a large number of robustness tests and alternative specifications, and find that our central result of pass through greater than 100% for Southwest and less than 100% for the legacy carriers is robust. We summarize the results here; Appendix 2.C contains further details. First, we present the results of estimating Equation (2.4) in a way closely related to the Mean Group estimator in Pesaran and Smith (1995) and the estimation strategy used in Atkin and Donaldson (2015). The principal advantage of this approach is that it allows for greater heterogeneity across routes within an airline, at the cost of less comprehensive time controls.[46] The results, however, are similar to our baseline. Second, we re-estimate our baseline results but allowing for heterogeneity at the individual airline level, rather than grouping the legacy carriers together. Southwest remains the only carrier to have a pass-through rate significantly greater than 1. Third, we explore a larger set of control variables that address additional demand- and supply-side factors that could be relevant to airlines' pricing choices. The pass-through rates are statistically unchanged in all cases. Further robustness tests (such as varying the time period, adding interaction terms between fuel cost and covariates of interest) are discussed in Appendix 2.C.

2.7 Estimating the profit impacts of carbon pricing using GLC

In this section, we combine our pass-through estimates with our theoretical results for GLC to estimate the predicted profit impact of a carbon price on US airlines.

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[44] For example, Southwest has a higher market share on the common routes in our sample; this is one factor than can lead to asymmetry in pass-through in the context of differentiated-products competition.

[45] To add together the above elements of this back-of-the-envelope decomposition, we implicitly require the ratio of fuel efficiencies $z_i(\tau)/z_j(\tau)$ between Southwest and the lagacy carriers to be the same for the whole sample as it was in the common routes.

[46] An earlier version of this paper, Grey and Ritz (2018), uses this estimation technique as the empirical baseline.

2.7.1 From theory to empirics

GLC requires no assumptions to be made about demand functions, the number and nature of competitors, competitors' technologies and strategies, competitive conduct, rationality or equilibrium. Many of these factors are unknown for airlines, and there will be considerable intra-industry heterogeneity. For our profit impact estimates to be valid, we need only the four assumptions of GLC to hold for the five airlines in our data. We therefore discuss these assumptions in turn:

Input price-taking (A1) is an appropriate assumption in that an airline cannot influence the global oil price, which is the primary determinant of its jet fuel price. Likewise, the price-taking assumption is appropriate in the context of an emissions tax and also approximately correct in the context of a cap-and-trade scheme in which firm i is one among many as in the EU ETS and other current systems.

Cost-minimizing inputs (A2) also appears reasonable for airlines. Fuel costs are often an airline's largest cost, amounting to 20–50% of its total cost base Zhanga and Zhang (2017) so it clearly has strong incentives to minimize fuel costs. Future carbon costs are likely to be managed in conjunction with an airline's overall commodity-market exposure, so we expect these to be similarly optimized. Examples of fuel/emissions reductions by airlines include adjusting flight time, cabin weight, and leasing newer aircraft. These kinds of reversible, continuous and often operational changes are consistent with our framework; anything that airlines did in the past in response to fuel prices, they are likely to do again in response to a carbon price.[47]

Constant returns to scale (A3) is a more substantive assumption, though it is standard in much of the airlines literature.[48] The evidence on whether it holds empirically is inconclusive: while some studies estimate modest scale economies others find no such evidence (Zhanga and Zhang, 2017) so our analysis is consistent with the notion that these are relatively weak in comparison with the marginal price-cost shifts studied here.[49] Note also that the presence of fixed costs is not an issue for the application of GLC.

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[47] Other abatement activities that fit less well with our approach are one-off, predominantly capital changes, such as purchasing new aircraft or installing wing tips. If these kinds of abatement dominate over the period we study, our historic average pass-through results may give less good predictions of the impact of future carbon pricing.

[48] Brander and Zhang (1990) discuss how to conceptualise constant marginal costs in the case of airlines; Berry and Jia (2010) estimate marginal costs which are constant for a given vector of route characteristics.

[49] There is stronger evidence for economies of *scope*: a higher network density of its route portfolio confers a competitive advantage on an airline—but this is not inconsistent with GLC theory. As is common in the airlines literature, our empirical analysis considers each route separately, without accounting for potentially complex network effects with other routes (see, e.g., Ciliberto and Tamer,

Linear product market behaviour (A4) is the core assumption underlying GLC. We allow the proportionality factor ψ to vary arbitrarily over routes and across carriers. So, in contrast to standard oligopoly models, a higher market share does not necessarily mean a higher profit margin. An empirical test of whether A4 holds in a given setting would require full information on marginal costs. While we have fuel cost and some other cost data, we do not have a good measure of full marginal costs at the carrier-route level, and so cannot perform an adequate test of A4.[50] It is, therefore, a maintained assumption.

2.7.2 Profit impacts of an exogenous carbon price

If assumptions A1-A4 hold then we can apply GLC and use Proposition 1 to estimate the profit impact of a carbon price. We begin by examining the impact of an exogenous carbon price of \$30/tCO$_2$, which is roughly the Social Cost of Carbon reported by Nordhaus (2017) and calculated by the US government.[51] Importantly for the external validity of our results, the wide variation of jet fuel prices over our period (the maximum is 540% larger than the minimum) exceeds by a considerable margin the variation in costs that a \$30/tCO$_2$ carbon price would induce.[52] Hence our simulated carbon-price shock lies within the range of fuel cost shocks that airlines responded to over the sample period. Proposition 1 gives us the profit impact at the product level; to obtain profit impact at the firm level we sum over all products for a given firm: $\Delta\Pi_i \simeq \tau \sum_j 2e_{ij}(0)(1-\rho_{ij}) = 2(1-\rho_i)\tau e_i(0)$, where ρ_i is firm i's emissions-weighted average pass-through rate.

Using our baseline pass-through estimates and Proposition 1, the impact of a \$30/tCO$_2$ carbon price is summarised in Table 2.4 columns (1)-(3). The legacy carriers' profits fall by 1.24 percentage points, whereas Southwest's profits *rise* by 1.41 percentage points. The intuition for this result is as follows. The legacy carriers' pass-through rate is less than 1, so as their costs rise their margin falls. By A4, their sales also fall. Hence, their profits fall. For Southwest, however, with a pass-through rate greater than

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2009). A strength of our estimation procedure is that it allows for arbitrarily complex networks, so long as these are stable over the period we study.

[50] While we have information on fuel, labour and maintenance costs, we do not have data on aeroplane purchase/lease costs, airport costs, sales and marketing costs, etc. Given this, we cannot be confident we have a good measure of marginal cost. An advantage of the theory applied here is that it only requires information on marginal cost shocks, which we do have via fuel cost shocks.

[51] The US Interagency Working Group on Social Cost of Greenhouse Gases has compared and averaged the results of the major models that are used to estimate the SCC. The results for the end of our period of study are around \$30/tCO$_2$. See IAWG (2016) for the most recent estimates.

[52] 1 gallon of jet fuel produces 0.00957 tons of CO$_2$ when burned.

Table 2.4 Profit impacts, from by applying GLC to our pass-through estimates.

	Exogenous τ = \$30.00			Endogenous τ = \$18.68		
	Southwest	Legacy	All	Southwest	Legacy	All
Pass through, ρ	1.41	0.62	0.87	1.41	0.62	0.87
	(0.12)	(0.11)	(0.16)	(0.12)	(0.11)	(0.16)
Profit neutrality factor, γ	-0.82	0.76	0.26	-0.82	0.76	0.26
	(0.24)	(0.22)	(0.33)	(0.24)	(0.22)	(0.33)
Profit impact, $\Delta\Pi$	1.41	-1.24	-0.43	0.88	-0.77	-0.27
	(0.41)	(0.36)	(0.54)	(0.26)	(0.22)	(0.34)

Notes: The first three columns show the profit neutrality factor and profit impact (as a proportion of revenue, given in percentage points) resulting from an exogenous carbon price of \$30/tCO$_2$, as implied by the pass-through estimates and Proposition 1. The next three columns give the endogenous carbon price and other outcomes using our pass-through estimates and Proposition 2, assuming a SCC of \$30/tCO$_2$. The 'All' pass-through rates are an emissions-weighted average of Southwest and legacy results.

1, when their costs rise their margins rise. This may be because their higher priced or less efficient rivals have increased prices even more, allowing Southwest to raise prices in this way, or because other substitutes such as travel by car have also risen steeply in price. By A4 their output rises, and hence their profits rise. The overall effect on the airline industry (as represented by these five firms) is a modest 0.43 percentage point decline in profits.

While our finding of pass-through heteroegeneity in the airline industry is novel, when applied via GLC to calculating profit impacts it consistent with several findings in the literature. Goolsbee and Syverson (2008), Ciliberto and Tamer (2009), and Berry and Jia (2010) variously point to Southwest being more efficient, better able to cope with shocks, or especially threatening to its rivals (the "Southwest is special" effect discussed above). Gaudenzi and Bucciol (2016) report jet fuel price rises are associated with significantly more negative stock-market returns for legacy carriers than for Southwest. While these authors stress differences in hedging strategies, our findings offer a new explanation for their results.

2.7.3 Political economy and an endogenous carbon price

We can also use our pass-through results along with Proposition 2 to calculate an endogenous carbon price and its impacts. Recall that this the equilibrium carbon price implemented by a government that cares about carbon emissions, but also seeks to alleviate distortions from imperfect competition (Buchanan, 1969) and is lobbied by an industry lobby group (Grossman and Helpman, 1994). We use the following parameter values in the expression for the endogenous carbon price. For the marginal damage from emissions we use an SCC of \$30/tCO$_2$ as above. For the lobbying parameter λ, we turn to the literature. Goldberg and Maggi (1999) were the first to empirically estimate this parameter, finding $\lambda = 0.02$ for the US. McCalman (2004) and Mitra et al. (2002) obtain similar results for Australia and Turkey respectively while Gawande and Bandyopadhyay (2000) find a much higher estimate of $\lambda = 0.5$. Based on these findings, we take $\lambda = 0.1$ as our baseline. For the elasticity of industry emissions, we take the midpoint of the range of estimates in Fukui & Miyoshi (2017), which is $\eta = -0.256$.

The resulting endogenous carbon price is \$18.68, 37% lower than the exogenous carbon price equal to the SCC. We can decompose this shortfall into two underlying distortions. The Buchanan market-power effect is logically prior in that it can exist without any political lobbying (i.e., where $\lambda = 0$) but the reverse is not true.[53] Of the two effects driving the result, the Buchanan effect is empirically much stronger than the Grossman-Helpman effect: if we re-run the calculation with $\lambda = 0$ (i.e. with the lobbying channel switched off), we find an endogenous carbon price of \$19.93. Hence, the Grossman-Helpman effect explains only around 10% of the disparity between the endogenous and exogenous carbon prices. The profit impacts, shown in columns (4)-(6) of Table 2.4, are smaller for the endogenous carbon price: a loss of only 0.77 percentage points for the legacy carriers and a gain of only 0.88 percentage points for Southwest.

2.8 Conclusion

We have developed GLC – a new, simple, flexible reduced-form model of imperfect competition that nests many existing oligopoly models as special cases. We showed that, within GLC, firm-level cost pass-through *alone* is a sufficient statistic for the profit impact of regulation on individual firms. Compared with the existing pass-through literature, GLC relies heavily on supply linearity but allows near-arbitrary firm heterogeneity and does not require additional information on conduct parameters or mark-ups.

We have presented *ex ante* empirical estimates of the impacts of future carbon pricing for US airlines. We found considerable *intra-industry* heterogeneity in pass-through between legacy and low-cost carriers, driven by differences in product portfolios,

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[53] In our setting, without any market power, there are no profits and hence nothing to lobby over and so the Grossman-Helpman effect is zero.

cost structures and consumer demand. Pass-through is heterogeneous even for a cost shock that hits all firms equally. From a policy perspective, we therefore expect these carrier types to have very different incentives to embrace climate regulation.

We hope that GLC will prove useful in other contexts in industrial organization, public economics, international trade, and networks. In this paper, we have shown its value in radically simplifying incidence analysis. More broadly, GLC lends itself to large-scale estimation both in a *single-industry* context characterized by complex firm heterogeneity demand, costs and conduct and for *cross-industry* analysis that seeks to apply a consistent structure across many different markets. Relative to widely-used structural empirical modeling, its comparative advantage lies in lower complexity and greater transparency in addressing a narrower range of questions.

Appendix 2.A Proofs of the propositions

Proof of Proposition 1. The proof begins by deriving a general expression for the profit impact, and then shows parts (a) and (b) of the result. In general, using A1, firm i's optimum profit as a function of regulation τ is $\Pi_i(\tau) = p_i(\tau)x_i(\tau) - C_i(x_i(\tau), e_i(\tau)) - \tau e_i(\tau)$. Using A2 and A3, $[C_i(x_i(\tau), e_i(\tau)) + \tau e_i(\tau)] = k_i(\tau)x_i(\tau)$ so this simplifies to $\Pi_i(\tau) = [p_i(\tau) - k_i(\tau)]x_i(\tau)$. Using A4, this becomes $\Pi_i(\tau) = \psi_i[p_i(\tau) - k_i(\tau)]^2$.

For part (a), note that the profit-neutrality factor from (2.1) can be written as:

$$\gamma_i(\overline{\tau}, \underline{\tau}) = \frac{1}{e_i(\underline{\tau})}\left[-\frac{\Pi_i(\overline{\tau}) - \Pi_i(\overline{\tau})}{(\overline{\tau} - \underline{\tau})}\right] = \frac{1}{e_i(\underline{\tau})}\left[-\frac{\Delta\Pi_i(\overline{\tau}, \underline{\tau})}{(\overline{\tau} - \underline{\tau})}\right].$$

Therefore, for small values of $(\overline{\tau} - \underline{\tau})$:

$$\gamma_i(\overline{\tau}, \underline{\tau})|_{\overline{\tau}\to\underline{\tau}} = \frac{1}{e_i(\underline{\tau})}\left(-\left.\frac{d\Pi_i(\tau)}{d\tau}\right|_{\tau=\underline{\tau}}\right).$$

Differentiation of the profit function $\Pi_i(\tau) = \psi_i[p_i(\tau) - k_i(\tau)]^2$ yields:

$$\left.\frac{d\Pi_i(\tau)}{d\tau}\right|_{\tau=\underline{\tau}} = 2\psi_i[p_i(\underline{\tau}) - k_i(\underline{\tau})]\left(\left.\frac{dp_i(\tau)}{d\tau}\right|_{\tau=\underline{\tau}} - \left.\frac{dk_i(\tau)}{d\tau}\right|_{\tau=\underline{\tau}}\right).$$

By the definition of (2.2), marginal pass-through $\rho_i(\underline{\tau}) = [dp_i(\tau)/d\tau]_{\tau=\underline{\tau}} / [dk_i(\tau)/d\tau]_{\tau=\underline{\tau}}$, and also by definition i's quantity of the regulated factor equals its output times its regulatory intensity, $e_i(\underline{\tau}) = z_i(\underline{\tau})x_i(\underline{\tau})$. By A1–A3 and the envelope theorem, $[dk_i(\tau)/d\tau]_{\tau=\underline{\tau}} = z_i(\underline{\tau})$ and, by A4, $x_i(\underline{\tau}) = \psi_i[p_i(\underline{\tau}) - k_i(\underline{\tau})]$. So $[d\Pi_i/d\tau]_{\tau=\underline{\tau}} = 2e_i(\underline{\tau})\,[\rho_i(\underline{\tau}) - 1]$. Combining results, it follows that, for small values of $(\overline{\tau} - \underline{\tau})$:

$$\gamma_i(\overline{\tau}, \underline{\tau}) \simeq \gamma_i(\overline{\tau}, \underline{\tau})|_{\overline{\tau}\to\underline{\tau}} = 2\,[1 - \rho_i(\underline{\tau})]\,, \tag{2.6}$$

where, locally, marginal pass-through approximately equals average pass-through, $\rho_i(\underline{\tau}) \simeq \overline{\rho}_i(\overline{\tau}, \underline{\tau})$.

For part (b), the change in profits $\Delta\Pi_i(\overline{\tau}, \underline{\tau}) = \psi_i\left\{[p_i(\overline{\tau}) - k_i(\overline{\tau})]^2 - [p_i(\underline{\tau}) - k_i(\underline{\tau})]^2\right\}$. Defining $\Delta p_i(\overline{\tau}, \underline{\tau}) \equiv [p_i(\overline{\tau}) - p_i(\underline{\tau})]$ and $\Delta k_i(\overline{\tau}, \underline{\tau}) \equiv [k_i(\overline{\tau}) - k_i(\underline{\tau})]$ and expanding and simplifying yields:

$$\Delta\Pi_i(\overline{\tau}, \underline{\tau}) = \psi_i\left\{2\,[p_i(\underline{\tau}) - k_i(\underline{\tau})]\,[\Delta p_i(\overline{\tau}, \underline{\tau}) - \Delta k_i(\overline{\tau}, \underline{\tau})] + [\Delta p_i(\overline{\tau}, \underline{\tau}) - \Delta k_i(\overline{\tau}, \underline{\tau})]^2\right\}. \tag{2.7}$$

Recalling that $dk_i(\tau)/d\tau = z_i(\tau)$, it follows that $\Delta k_i(\overline{\tau}, \underline{\tau}) = \int_{s=\underline{\tau}}^{\overline{\tau}} z_i(s)ds$. This in conjunction with (2.2) gives $\Delta p_i(\overline{\tau}, \underline{\tau}) = \int_{s=\underline{\tau}}^{\overline{\tau}} \rho_i(s) z_i(s)ds$ and so $[\Delta p_i(\overline{\tau}, \underline{\tau}) - \Delta k_i(\overline{\tau}, \underline{\tau})] = \int_{s=\underline{\tau}}^{\overline{\tau}} z_i(s)[\rho_i(s) - 1]ds$. Using these expressions and $e_i(\underline{\tau}) = z_i(\underline{\tau})x_i(\underline{\tau})$ in the profit-neutrality factor from (2.1) gives:

$$\gamma_i(\overline{\tau}, \underline{\tau}) = \frac{\psi_i \left\{ 2\left[p_i(\underline{\tau}) - k_i(\underline{\tau})\right] \left[\int_{s=\underline{\tau}}^{\overline{\tau}} [1-\rho_i(s)] z_i(s)ds\right] - \left[\int_{s=\underline{\tau}}^{\overline{\tau}} [1-\rho_i(s)] z_i(s)ds\right]^2 \right\}}{(\overline{\tau} - \underline{\tau}) z_i(\underline{\tau}) x_i(\underline{\tau})}.$$

From A4, $x_i(\underline{\tau}) = \psi_i \left[p_i(\underline{\tau}) - k_i(\underline{\tau})\right]$ and some rearranging gives a general expression for the profit impact:

$$\gamma_i(\overline{\tau}, \underline{\tau}) = 2\left[\frac{1}{(\overline{\tau} - \underline{\tau})}\int_{s=\underline{\tau}}^{\overline{\tau}} \frac{z_i(s)}{z_i(\underline{\tau})}[1-\rho_i(s)]ds\right] - \frac{(\overline{\tau} - \underline{\tau}) z_i(\underline{\tau})}{[p_i(\underline{\tau}) - k_i(\underline{\tau})]}\left[\frac{1}{(\overline{\tau} - \underline{\tau})}\int_{s=\underline{\tau}}^{\overline{\tau}} \frac{z_i(s)}{z_i(\underline{\tau})}[1-\rho_i(s)]ds\right]^2 \tag{2.8}$$

Observe that the profit-neutrality factor is bounded above according to:

$$\gamma_i(\overline{\tau}, \underline{\tau}) \leq 2\left[\frac{1}{(\overline{\tau} - \underline{\tau})}\int_{s=\underline{\tau}}^{\overline{\tau}} \frac{z_i(s)}{z_i(\underline{\tau})}[1-\rho_i(s)]ds\right], \tag{2.9}$$

where $z_i(s) \leq z_i(\underline{\tau})$ for all $s \in [\underline{\tau}, \overline{\tau}]$ given A1–A3. There are two cases. If $\rho_i(s) > 1$, then $[z_i(s)/z_i(\underline{\tau})]\,[1-\rho_i(s)] < 0$. If $\rho_i(s) \leq 1$, then $0 < [z_i(s)/z_i(\underline{\tau})]\,[1-\rho_i(s)] \leq [1-\rho_i(s)]$. Therefore, whatever the value of $\rho_i(s)$, $[z_i(\underline{\tau})/z_i(0)]\,[1-\rho_i(s)] \leq \max\{0, [1-\rho_i(s)]\}$. It follows that $\gamma_i(\overline{\tau}, \underline{\tau}) \leq \max\{0, 2[1-\overline{\rho}_i(\overline{\tau}, \underline{\tau})]\}$, where average pass-through $\overline{\rho}_i(\overline{\tau}, \underline{\tau}) \equiv \frac{1}{(\overline{\tau} - \underline{\tau})}\int_{s=\underline{\tau}}^{\overline{\tau}} [\rho_i(s)]\, ds$, as claimed.

Proof of Proposition 2. We first derive the marginal impact of a tax on welfare, and then use this to pin down the equilibrium tax rate. By consumer optimization, marginal utility equals price, $\partial V/\partial x_i = p_i$, and, by GLC's A3, $\partial C_i/\partial x_i = k_i$. Using this, differentiation of the welfare function yields:

$$\frac{dW(\tau)}{d\tau} = \sum\nolimits_{i=1}^{n} \left[p_i(\tau) - k_i(\tau)\right] \frac{dx_i(\tau)}{d\tau} + (\tau - D'(E(\tau))\frac{dE(\tau)}{d\tau}.$$

A4 $x_i(\tau) = \psi_i[p_i(\tau) - k_i(\tau)]$ implies that $dx_i(\tau)/d\tau = \psi_i[\rho_i(\tau) - 1]z_i(\tau)$ since $dk_i(\tau)/d\tau = z_i(\tau)$. As $e_i(\tau) = z_i(\tau)x_i(\tau)$, this leads to:

$$\frac{dW(\tau)}{d\tau} = \sum\nolimits_{i=1}^{n} e_i(\tau)[\rho_i(\tau) - 1] + (\tau - D'(E(\tau))\frac{dE(\tau)}{d\tau}.$$

The profit impact follows directly from the proof of Proposition 1(a):

$$\textstyle\sum_{i=1}^{n} \dfrac{d\Pi_i(\tau)}{d\tau} = 2\textstyle\sum_{i=1}^{n} e_i(\tau)[\rho_i(\tau) - 1],$$

Putting these parts together in the first-order condition from (2.3) shows that $\tau^{\bigstar}(\lambda) > 0$ is determined by:

$$\left.\frac{dU_{\text{gov}}(\tau)}{d\tau}\right|_{\tau=\tau^*(\lambda)} = \left[(1+2\lambda)\textstyle\sum_{i=1}^{n} e_i(\tau)[\rho_i(\tau) - 1] + (\tau - D'(E(\tau))\dfrac{dE(\tau)}{d\tau}\right]_{\tau=\tau^*(\lambda)} = 0.$$

Using the definitions $\widetilde{\rho}_i(\tau) \equiv \sum_{i=1}^{n} \frac{e_i(\tau)}{E(\tau)} \rho_i(\tau)$, and $\eta(\tau) \equiv \frac{d\ln E(\tau)}{d\ln\tau} < 0$ gives the expression for $\tau^*(\lambda)$ in the proposition as claimed.

Proof of Proposition 3. Rewriting firm i's profit function $\Pi_i(\mathbf{K}) = \sum_{l=1}^{m} \sigma_{il} K_i(p_l - k_i)$, given profit-maximization and regulation τ, yields:

$$\Pi_i(\tau) = [\overline{p}_i(\tau) - k_i(\tau)]\, K_i(\tau) \ (\text{as } \textstyle\sum_{l=1}^{m} \sigma_{il} = 1)$$

Differentiating and making use of the first-order condition $\overline{p}_i(\tau) - k_i(\tau) = (\beta \sum_{l=1}^{m} \sigma_{il}^2)\, K_i(\tau)$ then gives:

$$\begin{aligned}
\frac{d\Pi_i(\tau)}{d\tau} &= 2K_i(\tau)\left(\frac{d\overline{p}_i(\tau)}{d\tau} - \frac{dk_i(\tau)}{d\tau}\right) \\
&= 2K_i(\tau)\,(\overline{\rho}_i - 1)\,\frac{dk_i(\tau)}{d\tau} \ \ (\text{as } \overline{\rho}_i \equiv [d\overline{p}_i(\tau)/d\tau]/[dk_i(\tau)/d\tau]) \\
&= 2e_i(\tau)\,(\overline{\rho}_i - 1) \ \ (\text{as } dk_i(\tau)/d\tau = z_i(\tau) \text{ by A1–A3 and } z_i \equiv e_i/K_i).
\end{aligned}$$

Using the definition of the profit-neutrality factor it follows that:

$$\gamma_i(0) \equiv \frac{1}{e_i(0)}\left(-\left.\frac{d\Pi_i(\tau)}{d\tau}\right|_{\tau=0}\right) = 2[1 - \overline{\rho}_i(0)],$$

as claimed.

Proof of Proposition 4. Using results from Hazledine (2006, *eq* 11 & 13) for symmetric Nash equilibrium, it is easy to check that A4 is met for each price bucket with $[p_h - k(\tau)] = \varphi_h x_{ih}$ where $\varphi_h = (n^H + ... + n + 1)/n^h$ is a constant for each h as required (for any given $n \geq 2$ and $H \geq 2$). So firm i's profit impact satisfies:

$$\begin{aligned}
\sum\nolimits_{h=1}^{H} \left.\frac{d\Pi_{ih}(\tau)}{d\tau}\right|_{\tau=0} &= 2\sum\nolimits_{h=1}^{H} \frac{1}{\varphi_h}[p_h(0) - k(0)] \left[\frac{dp_h(\tau)}{d\tau} - \frac{dk(\tau)}{d\tau}\right]_{\tau=0} \\
&= 2z(0)x_i(0)\sum\nolimits_{h=1}^{H} \frac{x_{ih}(0)}{x_i(0)} (\rho_h - 1),
\end{aligned}$$

where $[dk(\tau)/d\tau]_{\tau=0} = z(0)$ again follows from A1–A3, and $\rho_h \equiv (dp_h/d\tau)/(dk/d\tau)$ is the (symmetric) pass-through rate for price bucket h.

So the profit-neutrality factor $\gamma_i(0; H)$ at $\tau \to 0$ can be written as:

$$\gamma_i(0; H) \equiv \frac{1}{z(0)x_i(0)} \left(-\sum\nolimits_{h=1}^{H} \left.\frac{d\Pi_{ih}(\tau)}{d\tau}\right|_{\tau=0}\right) = 2\sum\nolimits_{h=1}^{H} \frac{x_{ih}(0)}{x_i(0)} (1 - \rho_h) = 2[1-\rho_{\text{ave}}(H)],$$

where $\rho_{\text{ave}}(H) \equiv \sum_{h=1}^{H} \frac{x_{ih}(0)}{x_i(0)} \rho_h$ is i's average pass-through rate across the H price buckets.

Hazledine (2006, Proposition 2) shows that price discrimination does not affect the average price paid by consumers, that is, $p_{\text{ave}}(H) \equiv \sum_{h=1}^{H} \frac{X_h}{X} p_h = p_{\text{ave}}(1)$ for all H, where $p_{\text{ave}}(1)$ is the uniform price. This implies that the change in price due to cost-raising regulation satisfies $\frac{d}{d\tau} p_{\text{ave}}(H) = \frac{d}{d\tau}\sum_{h=1}^{H} \frac{X_h}{X} p_h = \frac{d}{d\tau} p_{\text{ave}}(1)$ for all $H \geq 2$. Note also that firm symmetry implies that $x_{ih}/x_i = X_h/X$ (for all i).

The linear model structure implies that $\frac{d}{d\tau}\left(\frac{X_h(\tau)}{X(\tau)}\right) = 0$, that is, higher cost due to tighter regulation decreases in equal proportion the output of each price bucket, so the ratio between output of bucket h and total output across all H buckets remains unchanged.

Therefore the change in the average price and the average pass-through rate are related according to:

$$\begin{aligned}
\frac{d}{d\tau} p_{\text{ave}}(H) &\equiv \frac{d}{d\tau}\sum\nolimits_{h=1}^{H} \frac{X_h(\tau)}{X(\tau)} p_h(\tau) \\
&= \sum\nolimits_{h=1}^{H} \frac{X_h}{X} \frac{dp_h(\tau)}{d\tau} \text{ (as } \tfrac{d}{d\tau}\left(\tfrac{X_h(\tau)}{X(\tau)}\right) = 0 \text{ by linearity)} \\
&= z(\tau)\sum\nolimits_{h=1}^{H} \frac{X_h}{X} \rho_h \text{ (as } \rho_h \equiv \frac{dp_h(\tau)/d\tau}{dk(\tau)/d\tau} \text{ and } dk(\tau)/d\tau = z(\tau)) \\
&= z(\tau)\sum\nolimits_{h=1}^{H} \frac{x_{ih}}{x_i} \rho_h \text{ (as } x_{ih}/x_i = X_h/X \text{ by firm symmetry)} \\
&= z(\tau)\rho_{\text{ave}}(H) \text{ (by the definition of } \rho_{\text{ave}}(H)).
\end{aligned}$$

As $\frac{d}{d\tau}p_{\text{ave}}(H) = \frac{d}{d\tau}p_{\text{ave}}(1)$ for all $H \geq 2$ it thus follows that also $\rho_{\text{ave}}(H) = \rho_{\text{ave}}(1)$ for all $H \geq 2$. Finally, therefore:

$$\gamma_i(0; H) = 2[1 - \rho_{\text{ave}}(H)] = 2[1 - \rho_{\text{ave}}(1)] = \gamma_i(0; 1) \text{ for all } H \geq 2,$$

as claimed.

Proof of Proposition 5. As firm i sells both product qualities, using the linear demand curves $p_1(Y_1) = (1 - Y_1)q_1$ and $p_2(Y_2) = (1 - Y_2)q_U$ from the main text, its two first-order conditions for Z_1^i and Z_2^i (taking as given rivals' outputs) are given by:

$$\begin{aligned}
\frac{\partial \Pi^i}{\partial Y_1^i} &= \frac{\partial \Pi_1^i}{\partial Y_1^i} = p_1 - k_1^i(\tau) - Y_1^i q_1 = 0; \\
\frac{\partial \Pi^i}{\partial Y_2^i} &= \frac{\partial \Pi_2^i}{\partial Y_2^i} = p_2 - k_U^i(\tau) - Y_2^i q_U = 0.
\end{aligned}$$

It is easy to see that each first-order condition yields the linear structure of GLC's A4. We begin by deriving the profit-neutrality factor for the baseline product, and then characterize the overall profit impact. First, recalling firm i's baseline profit $\Pi_1^i(\tau) = [p_1(\tau) - k_1^i(\tau)]\, Y_1^i(\tau)$ and using its first-order condition for Y_1^i yields:

$$\begin{aligned}
\frac{d\Pi_1^i(\tau)}{d\tau} &= 2Y_1^i(\tau)\left(\frac{dp_1(\tau)}{d\tau} - \frac{dk_1^i(\tau)}{d\tau}\right) \\
&= 2Y_1^i(\tau)\left(\rho_1^i - 1\right)\frac{dk_1^i(\tau)}{d\tau} \quad (\text{as } \rho_1^i \equiv [dp_1(\tau)/d\tau]/[dk_1^i(\tau)/d\tau]) \\
&= 2e_1^i(\tau)\left(\rho_1^i - 1\right) \quad (\text{as } dk_1^i(\tau)/d\tau = z_1^i(\tau) \text{ by A1–A3 and } z_1^i \equiv e_1^i/Y_1^i).
\end{aligned}$$

Using the definition of the profit-neutrality factor $\gamma_1^i(0)$ from the main text it follows that:

$$\gamma_1^i(0) = \frac{1}{e_1^i(0)}\left(-\left.\frac{d\Pi_1^i(\tau)}{d\tau}\right|_{\tau=0}\right) = 2[1 - \rho_1^i(0)],$$

as claimed. In exactly the same way, $\gamma_2^i(0) = 2[1 - \rho_2^i(0)]$ for the upgrade. Second, for the overall profit impact, note that the profit-neutrality factor $\gamma^i(0)$ from the main text can be written as:

$$\begin{aligned}
\gamma^i(0) &= \frac{-\left(\left.\dfrac{d\Pi_1^i(\tau)}{d\tau}\right|_{\tau=0} + \left.\dfrac{d\Pi_2^i(\tau)}{d\tau}\right|_{\tau=0}\right)}{[e_1^i(0)+e_2^i(0)]} \\
&= \frac{e_1^i(0)\gamma_1^i(0)+e_2^i(0)\gamma_2^i(0)}{[e_1^i(0)+e_2^i(0)]} \text{ (using the results for } \gamma_1^i(0) \text{ and } \gamma_2^i(0)) \\
&= \omega_1^i(0)\gamma_1^i(0)+\omega_2^i(0)\gamma_2^i(0) \text{ (as } \omega_k^i \equiv e_k^i/(e_1^i+e_2^i) \text{ for } k=1,2),
\end{aligned}$$

as claimed.

Appendix 2.B Construction of airline data

Ticket price p_{ijt} we obtain from the cleaned DB1A data provided by Severin Borenstein (the raw DB1A data, along with all the data below, are from the Bureau of Transportation Statistics). We drop any non-direct tickets for ijt, and then convert the nominal prices to real 2013Q4 USD using St. Louis Fed CPI data (as we do with all monetary variables).

Per-passenger fuel cost k_{ijt} is constructed as follows, with the raw variable names given parentheses. First we use the Form 41 (Schedule P-5.2) dataset, which contains carrier-aircraft-time specific fuel costs (fuel_fly_ops), which we denote k_{ilt}. Following O'Kelly (2012), we assume the fuel used to fly route j is a linear function of distance d_j with a non-zero intercept: $k_{ilj} = b^0_{ilt} + b^1_{ilt}d_{ilj}$. The fixed cost comes from the fuel used in take-off and landing, and any airport related activities; the variable cost is the 'miles per gallon' fuel consumption at cruising altitude. The fuel use data we have do not allow us to identify both the slope and the intercept, so we use an average value for their ratio taken from EEA (2016): we set the ratio $\frac{b^0_{ilt}}{b^1_{ilt}} = 131$ for all ilt, meaning take off and landing uses the same fuel as cruising 131 miles. Next we use the T-100 Domestic Segment to assign aircraft to routes. We construct the share $\alpha_{ijt}(l)$ of carrier i's passengers on route j at time t that travelled on aircraft type l (aircraft_type). We use total 'effective distance' flown by each aircraft type l on each route j, $\tilde{d}_{iljt} = (\frac{b^0}{b^1} + \text{distance}_j) \times \text{dep\_performed}_{ijlt}$, so that $\alpha_{ijt}(l) = \frac{\tilde{d}_{ijlt}}{\sum_l \tilde{d}_{ijlt}}$. Using these shares we construct the weighted average fuel cost $k_{ijt} = \sum_l \alpha_{ijt}(l)k_{ilt}$.

Non-fuel cost index is constructed from Form 41 (Schedule P-5.2). We take, for each ilt, total flying operating costs (tot_fly_ops) plus total maintenance costs (tot_dir_maint) minus fuel costs (fuel_fly_ops). We then construct a weighted average value for each ijt using the weights $\alpha_{ijt}(l)$ described above. Finally, we transform the carrier-route-time specific costs (which could be subject to endogeneity via their denominator), into a carrier-time index of costs. This is done by dividing total costs by total passengers, for each carrier-time. We normalise to the 2004Q1 value for American Airlines.

GDP growth is constructed with data from the Federal Reserve Bank of St. Louis. Using state-level GDP data, for each route j we take the average of the states in which each of the origin and destination airports are located. For 2004 we interpolated the annual data as quarterly data are not availble.

Competitors and **LCC competitors** we construct from the full DB1A data (i.e. not just the routes in our panel). We define competitors to include all routes that serve the same city-city market as route j. For example LAX-SLC is a competitor product to SNA-SLC because LAX and SNA both serve the city of Los Angeles. Using the Bureau of Transportation Statistics' definition of a market (origin_city_market_id and dest_city_market_id), we count all carriers serving that market with at least 1,000 passengers in a quarter. LLC competitors is the number of competitors from the set of low-cost carriers, as defined by ICAO.

Carrier size is constructed from the full DB1A (i.e. not just the routes in our panel). It is the sum of all passengers on all routes in a given quarter for a give airline.

Appendix 2.C Further empirical results and robustness

2.C.1 Mean Group regressions

As explained in Grey and Ritz (2018), if we allow for full heterogeneity across routes within a given carrier's portfolio, then our relationship of interest is a variant of Equation (2.4) given by:

$$p_{ijt} = \rho_{ij} k_{ijt} + X'_{ijt}\beta_{ij} + \lambda_{ijt} + \eta_{ij} + \epsilon_{ijt}. \tag{2.10}$$

Carrier-specific pass-through rates ρ_i are obtained from Equation (2.10) by running a separate regression for each carrier-route, and then taking a weighted average of the carrier-route specific ρ_{ij} to obtain a pass-through rate at the carrier level, ρ_i. The weights are emissions on the carrier-route. This approach imposes no homogeneity restrictions on the parameters across carrier-routes within an airline, which could be important given heterogeneities across routes in the airline industry (see Grey and Ritz, 2018, for further discussion). In running a separate regression for each product, we take a similar approach to Atkin and Donaldson (2015). The procedure could also be considered a special (non-dynamic) case of the "Mean Group" estimator in Pesaran and Smith (1995).[54] Note that allowing pass-through rates and other parameters to vary across carrier-routes does not mean the routes are independent in an economic sense, rather that their interdependencies are one of the many characteristics captured by the pass-through rate that we seek to estimate.

A draw back of using this approach is that, unlike in the standard fixed-effects baseline, year-and-quarter time effects are not identified. Equation (2.10) is therefore estimated only with quarterly time effects. We use the analogue of Equation (2.5) to estimate Equation (2.10) by 2SLS. The results are given in Table 2.5. Southwest's pass-through rate is 1.24, significantly above 1, and the legacy carriers' pass-through rate is 0.75, significantly below 1. The results are, therefore, qualitatively the same as the baseline, and quantitatively similar too.[55]

2.C.2 Results for individual legacy carriers

Table 2.6 gives descriptive statistics for the individual carriers in our sample. These confirm that the legacy carriers form a group distinct from Southwest, for example on the basis of price, fuel cost or distance.

Table 2.7 contains the results of estimating a variant of Equation (2.4) with an interaction term for each individual legacy carrier, rather than a single dummy for all legacy carriers. It therefore gives a pass-through rate for each airline. Column (1) is the baseline result in the main text, and column (2) gives the pass-through results by airline. Southwest's pass-through remains unchanged. The average of the individual legacy carriers' pass-through rates is in line with the overall legacy carrier result in the baseline. There is, however, considerable heterogeneity among the legacy carriers. Delta has a particularly large pass-through rate. Despite this range, the results do support our prior (following the airlines literature) to consider Southwest as distinct

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[54] Estimating our relationship of interest as a system of N seemingly unrelated regression equations would not change the point estimates but would give efficiency gains. SURE estimation is, however, not feasible here because the number of equations in our system is so much larger than the degrees of freedom of each individual regression.

[55] The small differences between these results and those in Grey and Ritz (2018) reflect a slightly different time period and slightly different set of airlines in the legacy group (the small, non-mainland US carriers Hawaiian and Alaska were included in that paper).

Table 2.5 Pass-through estimates from a route-by-route estimation procedure.

	Dependent variable: Price	
	(1) Southwest	(2) Legacy
Fuel cost	1.24^{***}	0.75^{***}
	(0.04)	(0.04)
Competitors	-1.04^{***}	-4.43^{***}
	(0.25)	(0.64)
LCC competitors	-1.12^{***}	-3.86^{***}
	(0.26)	(0.64)
Non-fuel cost index	41.08^{***}	15.01^{***}
	(2.53)	(2.25)
GDP growth	1.40^{***}	2.16^{***}
	(0.11)	(0.29)
Carrier size	0.70	-35.67^{***}
	(1.02)	(3.62)
R squared	0.87	0.46
Observations	9,920	14,680
Carrier-routes	248	367

Notes: All regressions include quarterly time dummies. Newey-West standard errors are shown in parentheses and are heteroskedasticity and autocorrelation consistent. The estimates shown are an emissions-weighted average of the estimates from each separate regression. Significance levels and p-values are calculated on the assumption that errors are independent across carrier-routes, and are denoted by: * significant at 10%, ** significant at 5%, and *** significant at 1%.

Table 2.6 Descriptive statistics for individual carriers.

	Southwest	American	Delta	United	US
Quarterly av. statistics					
Price ($)	154.73	212.54	236.54	231.41	230.85
Fuel cost ($)	32.95	57.12	50.73	56.31	45.14
Distance (miles)	717	1,102	992	1,128	915
Emissions (tCO_2)	0.13	0.23	0.18	0.21	0.18
Emissions cost ($\$/tCO_2$)	4.00	6.91	5.44	6.23	5.30
Passengers (000s)	42	36	30	28	25
Competitors (#)	2.24	2.84	2.40	3.70	2.20
LCC competitors (#)	0.40	0.40	0.73	0.94	0.60
Revenue ($ million)	5.46	6.76	5.76	5.76	4.66
Whole sample statistics					
Revenue in sample (%)	0.56	0.47	0.40	0.52	0.35
Observations (#)	13,199	6,110	6,879	5,759	3,703
Carrier-routes (#)	416	198	323	239	158

Notes: Data are quarterly, over the period 2004Q1-2013Q4. Price, fuel cost, emissions and emissions cost are per passenger. Emissions cost are calculated at a carbon price of $\$30/tCO_2$. Whole sample statistics are aggregated over all N and T. Revenue in sample is the proportion of all US aviation revenue (ie all flights on all airlines) in the sample over this period. All averages are unweighted.

Table 2.7 Pass-through estimates for individual carriers.

	Dependent variable: Price	
	(1) Baseline	(2) Individual airlines
Fuel cost · Southwest	1.41*** (0.12)	1.40*** (0.14)
Fuel cost · Legacy	0.62*** (0.11)	
Fuel cost · American		0.67*** (0.13)
Fuel cost · Delta		1.13*** (0.15)
Fuel cost · United		0.30*** (0.08)
Fuel cost · US		0.72*** (0.10)
Competitors	-2.79*** (0.69)	-2.37*** (0.67)
LCC competitors	-5.06*** (0.90)	-4.50*** (0.89)
Non-fuel cost index	6.49** (2.60)	12.38*** (2.67)
GDP growth	-1.30*** (0.39)	-1.21*** (0.40)
Carrier size	-15.24*** (5.15)	-18.60*** (5.22)
R squared	0.212	0.208
Observations	35,650	39,753
Carrier-routes	1,334	1,396

Notes: All regressions have a full set of carrier-route fixed effects, and year-and-quarter time dummies. Standard errors are shown in parentheses and clustered at the carrier-route level. Regressions are weighted by total emissions of the carrier-route over the period. Significance levels and p-values are denoted by: * significant at 10%, ** significant at 5%, and *** significant at 1%.

from the legacy carriers: it is the only airline with a pass-through rate statistically significantly greater than 1.

2.C.3 Robustness of empirical results

Table 2.8 contains the results of adding additional control variables that plausibly could impact airlines' pricing decisions. Columns (1)-(5) show the impact of using alternative measures of demand. All but two of the demand controls are self-explanatory. Gravity demand (analogous to the concept as used in the trade literature) is a measure of demand on a route constructed as the product of (per capita GDP times population) in origin and destination cities, divided by distance. Network density is the number of actual connections (ie routes) between airports in a carrier's network, divided by the total number of possible connections (the standard definition in the networks literature). Column (1) is the same baseline as in the main text, and contains the only measure of demand that is statistically significant (this motivated its inclusion in the baseline specification). In which ever measure is used, the pass-through rates are very stable around the baseline result.

Column (6) includes a dummy for potential entry by Southwest, using the definition in Goolsbee and Syverson (2008). We don't find a significant effect, and the pass-through rates are unchanged from the baseline. Column (7) reports the effect of bankruptcy (all carriers except for Southwest were bankrupt at some point in this period). This is significant, but does not statistically effect pass-through.

In addition to investigating the effect of controls on prices, we also interacted these variables with fuel costs, to see if they had an effect directly on pass-through rates. We found almost no results of statistical significance. We also experimented with varying the start and end dates of our time period, which again had little impact on our estimates. These results are omitted in the interests of space, but available on request.

Table 2.8 Robustness checks.

	Dependent variable: Price						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Fuel cost · Southwest	1.42***	1.45***	1.43***	1.47***	1.36***	1.41***	1.37***
	(0.12)	(0.12)	(0.13)	(0.12)	(0.12)	(0.12)	(0.12)
Fuel cost · Legacy	0.66***	0.67***	0.67***	0.68***	0.67***	0.66***	0.67***
	(0.10)	(0.11)	(0.11)	(0.11)	(0.10)	(0.10)	(0.10)
Competitors	-2.17***	-2.20***	-2.17***	-2.27***	-2.10***	-2.17***	-2.31***
	(0.72)	(0.70)	(0.72)	(0.68)	(0.72)	(0.72)	(0.70)
LCC competitors	-7.81***	-7.82***	-7.80***	-7.72***	-7.77***	-7.69***	-7.56***
	(1.36)	(1.36)	(1.38)	(1.35)	(1.35)	(1.38)	(1.34)
Non-fuel cost index	6.89***	6.77***	6.81***	6.86***	7.30***	6.99***	8.08***
	(2.58)	(2.58)	(2.59)	(2.56)	(2.67)	(2.58)	(2.45)
Carrier size	-15.12***	-14.88***	-14.98***	-14.86***	-9.27*	-15.12***	-12.70**
	(5.22)	(5.24)	(5.19)	(5.22)	(4.98)	(5.21)	(5.43)
GDP growth	-1.34***					-1.34***	-1.31***
	(0.39)					(0.39)	(0.39)
GDP per capita		1.81					
		(2.48)					
Population (million)			-0.12				
			(4.48)				
Gravity demand				12.44			
				(9.97)			
Network density					-8.40*		
					(5.06)		
Southwest potential entry						1.86	
						(1.52)	
Bankrupt							6.41***
							(1.91)
R squared	0.219	0.218	0.218	0.218	0.220	0.219	0.223
Observations	35,650	35,650	35,584	35,584	35,650	35,650	35,650
Carrier-routes	1,334	1,334	1,326	1,326	1,334	1,334	1,334

Notes: All regressions have a full set of carrier-route fixed effects, and year-and-quarter time dummies. Standard errors are shown in parentheses and clustered at the carrier-route level. Regressions are weighted by total emissions of the carrier-route over the period. Significance levels and p-values are denoted by: * significant at 10%, ** significant at 5%, and *** significant at 1%.

Chapter 3

Sanitation and mortality in urban England, 1875-1911

Abstract

What is the impact of investing in the urban environment? Both economic historians and public economists continue to disagree, especially on the role of sanitation infrastructure in reducing mortality. We present new evidence using a detailed panel of the 16 largest towns in England over the period 1875-1911. We construct a novel dataset by digitising public accounts and public health records at the same geographical unit. We find sanitation infrastructure is not associated with a reduction in any of our mortality outcomes. We explain our null result compared to other results in the literature by quantifying the importance of consistency in geographical units, which previous studies reporting large effects have lacked.

Keywords: infrastructure, health, sanitation, water, local government, urban history.

JEL codes: N93, R53, I18, H51, H54.

3.1 Introduction

One of the most protracted debates in British economic and demographic history concerns the relative contributions of economic growth and public health interventions to the early stages of the British mortality decline. McKeown and Record (1962) famously argued that improvements in living standards, particularly diet, substantially outweighed medical, public health and other contributions, before the twentieth century. While critics of McKeown and Record have often argued that he under-estimated the benefits of public health interventions, there remains no consensus on whether public investments in improving water quality and sewage disposal in the late nineteenth and early twentieth centuries had a major impact on mortality trends. Three recent papers have used broadly the same evidence for public investments and mortality rates to arrive at very different conclusions. Chapman (2019) argued that that investments by urban sanitary authorities in public health initiatives, as measured by the value of loans, accounted for as much as 60% of the total improvement in urban mortality rates between 1861 and 1900. Conversely, Harris and Hinde (2019) and Hinde and Harris

(2019) used evidence of loans and mortality for both ‘high-performing’ towns and for all Registration Districts over the longer period 1851–1910 to argue that mortality fell almost everywhere and with similar patterns in rural and urban populations, regardless of wide variations in public investment in water supplies and sewerage.

The historical study of public health and urban mortality patterns in England and Wales has been seriously hampered by the types of data available. The two largest problems are difficulties in quantifying public health investment, and the lack of mortality data for specifically urban populations. In this paper we use two novel sources of evidence that partially overcome these problems. These are annual expenditures by urban authorities, and weekly counts of deaths in the largest English towns. We use these to improve upon the existing evidence base in three ways: (1) by creating measures of municipal investment, by type of investment, based on expenditure, rather than loans; (2) by using annual rather than decadal mortality data, (3) by using mortality and expenditure data that relate to the same administrative units (Urban Districts). These sources avoid some of the shortcomings of previous studies, however they come at the price of sample size. Our final sample comprises only the sixteen largest cities (excluding London) for the period 1875-1911. Although this is a relatively small number of cities, it is roughly one quarter of the total urban population over the period. Using these data we find no negative relationship between expenditure on sanitation (water and sewerage) and infant, diarrhoeal or all-cause mortality. In order to test whether our results were a consequence of our sample size or composition, we replicated Chapman’s (2019) method with our sample, and were able to reproduce approximately his results. We think therefore that the discrepancy between our main results and previous work reflects the enhanced precision of our measures, rather than shortcomings of our sample. We suggest that investment may provide a poor measure of water quality or sanitary conditions in British cities in this period.

Section 3.2 reviews previous work on public health investments and mortality improvements in urban populations in the nineteenth and early twentieth centuries. We describe the construction of our measures of public expenditure in Section 3.3, and mortality outcomes in Section refsec:ch3:mortality. Regression analyses are presented in Section 3.5, and Section 3.6 concludes.

3.2 Literature review

One of the most striking apparent demonstrations of the impact of improvements in water quality is Cutler and Miller’s (2005) study of the introduction of filtration and chlorination of public water supplies in American cities in the early twentieth century. In a panel study of thirteen major cities between 1900 and 1936, they found that water filtration and chlorination was associated with a near halving of infant mortality, a halving of child mortality, and a 13% reduction in total mortality. These very large effects of water treatment were similar to results reported by Ferrie and Troesken (2008) for Chicago, where progressive steps to improve water quality were associated with large falls in both typhoid and all-cause mortality rates (see also Beach et al., 2016). However, these large and apparently ubiquitous effects contrasted with some earlier studies which found effects of water treatment on typhoid mortality but not on other causes of death. For example, in Philadelphia, one of the cities in Cutler and Miller's panel, Condran (1987) studied the effects of the staggered introduction of filtration on a ward by ward basis within the city. She also found marked declines in typhoid mortality upon the introduction of filtration. However, in contrast to Cutler and Miller's findings, all-cause, infant and diarrhoeal mortality were relatively unaffected.

More recently, a reanalysis of Cutler and Miller's results has revealed that their data included transcription errors that invalidated some of their results. Using an expanded panel of 25 cities over the period 1900-1940, and examining the effects of measures to improve water supply, sewage disposal, and milk quality, Anderson et al. (2019) demonstrated that water filtration was associated with significant reductions in typhoid death rates, and small but significant reductions in infant mortality. However, none of the interventions studied showed a statistical association with improvements in infant diarrhoeal mortality, nor all-cause mortality.[1]

Other authors have argued that interventions to prevent the faecal contamination of water (such as cleaner sources, filtration and chlorination) are much more effective when combined with modern sewerage to remove faecal waste. Alsan and Goldin (2019) exploited temporal delays in the roll-out of a combined water and sewerage scheme to municipalities in the Boston area of Massachusetts (1880–1920) to compare the effects of introduction of either clean water or sewerage alone with water and sewerage combined. They found that clean water and more especially sewerage contributed to reductions in child (under five) mortality, but the effect was much larger when both interventions were present (accounting for a third of the decline in under 5 mortality, and nearly half of the decline in infant mortality, over the period). The importance of faecal disposal, as well as uncontaminated water, hints at the multiple pathways

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[1] An analysis of estimated typhoid transmission rates in relation to per capita expenditures on water and sewerage in 16 major U.S. cities also suggested significant but also very variable effects of expenditures on typhoid rates in the period 1889-1931 (Phillips et al., 2019; Vanderslott et al., 2019).

by which faecal-oral diseases may be transmitted, that include fly-borne transmission from exposed faeces to food and surfaces as well as faecal contamination of water.

In contrast to the findings for U.S. cities, studies of water and sanitary improvements in nineteenth century cities elsewhere have generally reported relatively modest effects of water and sanitary interventions on mortality. For example, fairly small or negligible beneficial effects of piped water supply and sewerage on infant mortality were reported for Munich and other urban districts in Bavaria, 1825-1909, for larger Finnish cities before c.1900, Swedish urban centres 1875-1930, and Swiss towns 1876-1901, and in Dutch cities (Brown and Guinnane, 2018; Floris and Staub, 2019; Helgertz and Önnerfors, 2019; Peltola and Saaritsa, 2019; van Poppel and van der Heijden, 1997). However, larger reductions in infant mortality were observed in response to water and sewerage improvements in Sydney and in smaller Finnish towns in the early twentieth century, and the extension of modern sewerage was associated with large improvements in life expectancy in Parisian neighbourhoods 1880-1914 (de Looper et al., 2019; Kesztenbaum and Rosenthal, 2017; Peltola and Saaritsa, 2019). However, as in the case of U.S. cities, studies that considered typhoid generally observed much larger reductions in typhoid mortality compared with other causes of death in response to sanitary interventions, especially those that improved water quality (de Looper et al., 2019; Floris and Staub, 2019).

In the British case there is also substantial disagreement in the historical literature about the efficacy of public health interventions to improve water supplies. English cities were some of the first in the world to introduce modern sewerage and clean piped water supplies. Early accounts of the public health movement in Britain attributed considerable success to the efforts of Edwin Chadwick and the Health of Towns movement in the 1840s; however, revisionist accounts now identify the 1870s as decisive (Hassan, 1985; Szreter, 1997; Szreter and Woolcock, 2004; Wohl, 1984). The first half of the nineteenth century was characterised by a major expansion in the provision of piped water in towns, and most of this was supplied by private water companies (Hassan, 1985). After c.1850 there was a very substantial increase in municipal waterworks, as a result both of new waterworks, and of the acquisition of private works by local governments. Hassan (1985) has argued that the short-sighted nature of private investment proved detrimental to both industrial and public interests, and many towns therefore turned to public provision of water after mid-century. Some of the largest towns, including Liverpool and Manchester, undertook very ambitious long-distance supply schemes in the 1850s and 1860s. However, according to Hassan (1983, 1985) the main beneficiaries of early municipalisation of waterworks were urban industries that required clean (and soft) water, and public health benefits were minimal. Only in the 1870s did expenditures by local governments demonstrate a sustained and substantial rise. As Szreter and Woolcock (2004, pp. 659-660) put it, '[engineers and health professionals] technically knew how to construct a sanitary environment… since at least as early as the 1840s, but it took a religiously infused moral movement to motivate the mobilisation of collective will'. Other authors have pointed out that the early stages of sanitary reform were bedevilled not only by the parsimony of municipal councils and ratepayers, but also by ideological conflicts over the causes of high urban death rates, and by uncertainty regarding the efficacy of new technologies (including water filtration, efficient drainage pipes, sewage treatment and water quality testing) and their suitability to local conditions (Wohl, 1984; Hamlin, 1988, 1990; Sheail, 1996; Hamlin, 1998; Thornton and Pearson, 2013). Local councils were reluctant to incur large debts for experimental systems, and there was no legal compulsion to do so before the Public Health Acts of 1866 and 1875, which required towns to provide clean water and sewage disposal for their populations, and provided cheap finance to do so.[2]

The strongest evidence for substantial effects of sanitary investments on public health in Britain has been provided by Chapman (2019). He analysed the relationships between total investments made by towns, as measured by the outstanding value of loans contracted by urban municipalities, and decadal mortality in English and Welsh towns. He restricted his analysis to the period 1867-1900, because data on loans were not reported in the *Local Taxation Returns* before 1867, and because he considered that 'this period marked the very beginning of the public health movement'.[3] He reported a strong negative relationship between total investment and mortality from both 'airborne' and all-cause mortality between 1861 and 1900, and for 'waterborne' mortality (cholera, typhoid and diarrhoea) from 1871-1900.

Harris and Hinde (2019) used the same source of mortality data as Chapman (2019), i.e., the Registrar-General's decennial averages of deaths by age and cause for Registration Districts. However, they used the full available data (1851-1910), for rural as well as urban Registration Districts, and they used the information on age and cause of death to estimate the contribution of particular causes to improvements in

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[2] See Webster (2015) regarding the importance of the reduction in the interest rate for Public Works Loans Board loans specifically for sanitary purposes from 1872 onwards. See Harris and Hinde (2019), and references therein, regarding other motives for increased borrowing, including greater resolution to tackle sanitary problems, and increased income from rates and municipal gas works.

[3] The discrepancy between the start of the analysis in 1861 and the start of loans expenditure data in 1867 is because the mortality data used were decennial averages and included 1861-70. The choice of end date of 1900 is somewhat unclear.

life expectancy.[4] Using a much longer and more comprehensive time series of loans which urban authorities sought approval for or contracted, and a more impressionistic analytical approach, Hinde and Harris (2019) found no obvious associations between loans related to water supplies or sanitary projects and improvements in mortality from 'waterborne' (a category that included typhus, in contrast to Chapman's) or other causes over the period 1851-1910. They noted that mortality fell in rural and urban districts, regardless of expenditure or sanitary interventions, and that typhus/typhoid and tuberculosis declined at similar rates in urban and rural areas.

In a very insightful article, van Poppel and van der Heijden (1997) set out the conceptual and methodological difficulties involved in identifying relationships between water and sanitary interventions on the one hand, and mortality improvements on the other (see also Bell and Millward, 1998). They identified two key conceptual difficulties. First, while gut pathogens are often described as 'water-borne', they can in fact infect humans via multiple routes. These diseases are described as 'faecal-oral' because they result from ingestion of infected faeces, and sources of infection include contaminated drinking water, but also poor personal hygiene, faecal contamination of crops and seafood, unsafe food preparation, transfer of faeces to food and skin by insects (especially flies), and even bathing in unclean water. Ewald (1991, 2004) demonstrated this variability in dependence on water-borne transmission using evidence from historical outbreaks of faecal-oral diseases where the pathogen was identified and also the likely source of the infection. He found that the most lethal faecal-oral diseases, including Asiatic cholera, typhoid and dysentery, are the most dependent on water transmission, while those diarrhoeal pathogens that kill mainly very young children and the elderly are less commonly waterborne and depend largely on human-to-human transmission (Table 3.1).[5] If this thesis is correct, then improvements in water quality could have had significant effects on those diseases that depended most on water-borne transmission (cholera, typhoid and dysentery). However, such improvements may have

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[4] Chapman (2019) used only crude all-cause or cause-specific death rates, that is, deaths divided by the total population, without any adjustment for age structure. It is not clear why he used the decennial mortality reports in this way. The key advantage of the decennial data is that the deaths are cross-tabulated for each Registration District by cause and age, making it possible to estimate life expectancies or to age-standardise mortality rates. If crude death rates sufficed then it would have been preferable to use the Registrar-General's annual reports, because these provided annual deaths by cause, although without any age information. The use of decadal averages meant that the effects of any intervention could only be measured by inter-decadal changes in mortality rates. It also severely restricted the number of data points for each Registration District, to three in the case of typhoid (1871-1900) in Chapman's study.

[5] Pathogens associated with contemporary infant diarrhoea in low-income countries include E. coli and Shigella species, however the causal agents of infant diarrhoea in our period remain unknown (Hardy, 2014).

had little effect on diarrhoeal mortality. Conversely, diarrhoeal mortality may have been more sensitive to the removal of faecal waste from domestic or neighbourhood environments by sewerage systems. In the case of typhoid, by the late nineteenth century typhoid rates had converged in urban and rural populations in Britain, and there appears to have been a shift from predominantly water-borne to food-related epidemics associated especially with milk, ice-cream and shellfish, and possibly with fly-borne contamination (Hardy, 1993, 2014; Luckin, 1986). Variations in infant feeding practices could also lead to very large differences in the efficacy of interventions. Where most infants were breastfed, and rarely fed untreated (unboiled) water, the improvements in water quality might have had negligible effects on infant mortality, but profound effects on typhoid or cholera mortality at older ages, where exposure to untreated water was greater. Conversely, where infants were regularly fed untreated water, the improvements in water supplies could lead to large improvements in infant mortality.

Table 3.1 Pathogens with faecal-oral transmission routes.

Pathogen	Mortality (% of cases)	Waterborne outbreaks (% of all outbreaks)
Vibrio cholerae, classical biotype [Asiatic cholera]	15.7	83.3
Shigella dysenteriae type 1 [dysentery]	7.5	80
Salmonella typhi [typhoid]	5.8	74
Vibrio cholera, el tor biotype	1.44	50
Shigella flexneri	1.32	48.3
Shigella sonnei	0.65	27.8
Enterotoxic E. coli	<0.1	20
Campylobacter jejuni	<0.1	10.7
Non-typhoid salmonella	<0.1	1.6

Source: Ewald (1991).

In addition, van Poppel and van der Heijden (1997) argued that starting conditions and local geography mattered. Jaadla and Puur (2016) provided an elegant demonstration of this in late nineteenth-century Tartu, Estonia. Using household-level data on water supply and infant mortality, they demonstrated that before any introduction of piped water, water from the river was associated with a two-fold higher infant mortality than water from household wells, and four-fold higher mortality compared with public artesian wells (after adjusting for paternal education and occupation, mother's age, household size, and waste disposal method). The quality of locally available water supplies also varied widely in British towns. Birmingham, for example, enjoyed access to unpolluted aquifers, and was the only major British town to escape a significant cholera outbreak in all of the four nineteenth century epidemics. Other towns were forced to seek remote sources of clean water or to purify river water. We develop these points further in the following two Sections, which describe our explanatory and outcome variables.

3.3 Measures of Sanitation Capital

Previous studies of investment by urban authorities in public health services have used evidence from loans to approximate investment expenditure. Chapman (2019) used the value of total loans outstanding between 1867 and 1900. These debts are not disaggregated by purpose, and therefore contain investment in a very wide variety of a town's activities, including roads, hospitals, markets, gasworks, public lighting, and trams. Harris and Hinde (2019) used evidence from a range of archival and parliamentary sources to reconstruct total loans sanctioned by central government, and divided these loans by purpose, separating loans relating to water supplies from loans for other health-related purposes (including bath-houses, hospitals, street improvements, sewerage and drainage) and other functions. Harris and Hinde's painstaking reconstruction supports the longstanding view that public investment in water and sanitation was very limited before the 1870s.

In this paper, we analyse a sample consisting of the 16 largest cities in England (excluding London) over the period we study.[6,7] We obtained annual public accounts data from the *Local Taxation Returns* reported to Parliament, which provide expenditure data by city, over the period 1867-1913.[8] The accounts data is available for a large number of towns and cities (approximately 1,000); our constraint to look at only the largest 16 cities is dictated by mortality data availability (see Section 3.4). In the *Local Taxation Returns*, data are reported at the geographical and administrative unit

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[6] The 16 cities are: Birmingham, Bradford, Bristol, Hull, Leeds, Leicester, Liverpool, Manchester, Newcastle, Norwich, Nottingham, Portsmouth, Salford, Sheffield, Sunderland, and Wolverhampton.

[7] London had a different structure of local government to the rest of England in this period, and so expenditure was not reported in the *Local Taxation Returns*. In any case, its sanitary investments were also structured differently, divided between a number of private waterworks which served different Boroughs, and so it would not fit easily into our analysis.

[8] Local Government Board, *Local Taxation Returns* (Parliamentary Papers 1867-1913). Throughout this paper we use the year in which a town's fiscal year ends to refer to the entire fiscal year. For example the year 1874-75 in the *Local Taxation Returns* is referred to as 1875 in this paper.

of the Urban District.[9] These were the local authorities tasked with managing and improving many aspects of urban life, and they had a very high degree of autonomy from central government.[10] They had the power to raise funds using local property taxes, by running local natural monopolies (e.g., waterworks, gasworks, markets), or taking out loans. The Urban Districts, and not central government, were responsible for spending on water and sewerage provision (as well as roads, hospitals, markets, gasworks, public lighting, and trams). Importantly, Urban Districts had a great deal of freedom in the quantity and quality of public services they provided: they could provide very little, and so minimise the local tax burden, or undertake hugely expensive infrastructure projects if they perceived a benefit in doing so. There was wide variation in expenditure both between Urban Districts and over time for a given Urban District (see Figures 3.1 and 3.2).

The goal of this paper is to investigate the impact of sanitary investments in the 16 Urban Districts in our sample. In order to do this, we construct an annual measure of each Urban District's stock of sanitation capital. This is the stock of sanitation assets in place, which produce sanitation services, which potentially impact health. We construct this variable as follows. From 1872, expenditure on sewerage is disaggregated from general public works expenditure in the *Local Taxation Returns*, and in 1875 expenditure on water is likewise reported separately. These data allow us to construct three measures of interest: water capital, sewerage capital and the total of water and sewerage capital, which we henceforth refer to as sanitation capital. We construct a capital stock for each of these variables according to the standard capital accumulation equation:

$$S_{it} = S_{it-1} + I_{it} - \delta S_{it-1}, \tag{3.1}$$

where S_{it} is the per capita stock of (sanitation, water or sewerage) capital in town i in year t, I_{it} is per capita investment, and δ is the depreciation rate. Investment I_{it} is directly available in the accounts from 1883 onwards, as expenditure was disaggregated into current spending and capital spending (i.e., funded by loans). For the period 1875-1882, when only combined (current and capital) spending is reported in the accounts, we construct a measure of capital spending in the following way (Appendix 3.A describes the procedure in further detail). We estimate the Urban District-specific relationship between capital spending (I_{it}) and combined spending (C_{it}) for a period

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[9] These were Local Boards or Improvement Commissioners up until 1872, Urban Sanitary Districts in the period 1873-1895, and Urban Districts from 1896. We use the term Urban District (UD) to describe these urban units throughout our study.

[10] See Millward and Sheard (1995) and Daunton (2001) for institutional background on local and urban government in this period.

of years in which we have disaggregated data:[11]

$$I_{it} = F_i(C_{it}) + \omega_{it}. \tag{3.2}$$

We tested a large number of possible functions F_i, evaluating the performance of the model based on out-of-sample fit over the 10 year period following the estimation period. The function giving the best out-of-sample fit was cubic in C_{it} and included two leads in C_{it}. As described further in Appendix 3.A, our final results are not sensitive to the choice of F_i. On the assumption that the estimated relationship holds also over the period 1875-1882, we then estimate capital spending for these years according to:

$$\widehat{I}_{it} = \max\{\widehat{F}_i(C_{it}), 0\}. \tag{3.3}$$

This gives us a panel of investment spending for 1875-1913. In order to pin down the initial capital stock, we use the value of loans outstanding in 1884, the first year in which it is disaggregated into spending type (water and sewerage). To address the issue of possible municipalisation of waterworks during this period, if an Urban District's waterworks were initially privately owned but municipalised after 1884, we take the value of water loans outstanding in the first year after municipalisation. For the depreciation rate δ, we assume a value of 0, with the rationale that current spending over this period included maintenance of the capital stock.

Sanitation, water and sewerage capital are shown for our sample as a whole in Figure 3.1, and for each Urban District in Figure 3.2 (together with all-cause mortality rates, discussed in the next Section). There were very wide variations in expenditure over time and between Urban Districts, especially in the provision of water. Some of this variation was caused by reliance on private waterworks. Of the 16 Urban Districts in our sample, nine had private waterworks in 1870, and five water supplies remained in private ownership in 1911 (Bristol, Newcastle, Norwich, Portsmouth and Sunderland).[12] These five Urban Districts were characterised by very low public expenditures on water. Four Urban Districts in our sample municipalised existing private waterworks in the period under study. Municipalisation was associated with a sudden rise in public water investment, in Birmingham (municipalised in 1876), Leicester (1878), Nottingham

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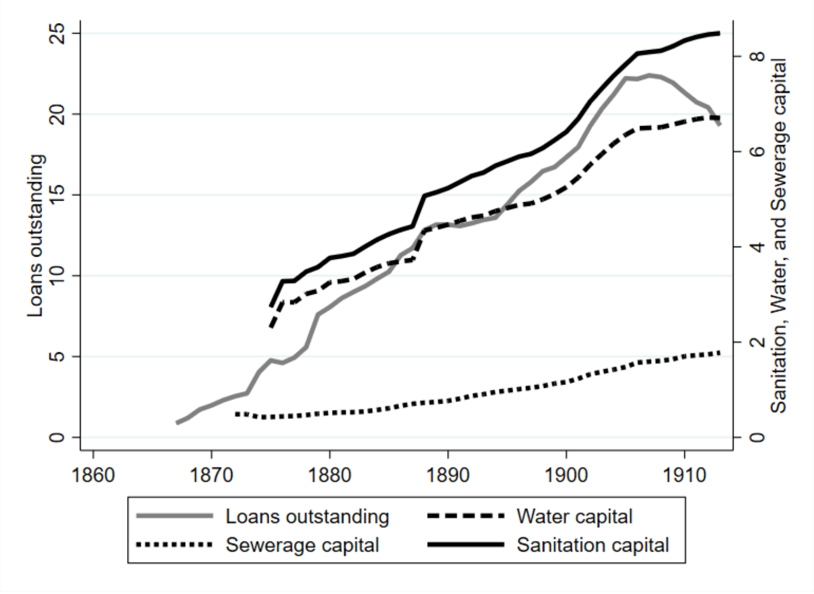
[11] As explained in Appendix 3.A, we test two different estimation periods: the 10 years following 1883 (a short window as close to the period 1875-1882 as possible), and the entire sample other than the final 10 years (as large an estimation period as possible while leaving 10 years of observations for out-of-sample evaluation). The results were not sensitive to this choice.

[12] The towns in our sample were in fact characterised by a later move to municipalisation compared with the larger sample of 81 provincial towns in Hassan (1985) (where 55% of waterworks were in municipal ownership by 1871).

(1880), and Sheffield (1887). Importantly, these very substantial public investments may have had no immediate effect on the nature or extent of the water supply, because the money was used in the first instance to acquire existing waterworks. Moreover, municipalisation was often triggered by the need to expand existing provision, and so further investment was often required simply to maintain per capita supply in the face of urban growth (Hassan and Taylor, 1998; Silverthorne, 1881). Indeed as Hassan (1985) argued, the best performing towns in terms of supply per capita and revenue to capital ratio were those where municipalisation was of relatively long duration, presumably as a result of cumulative investment after the initial acquisition of the waterworks. We cannot estimate investment by private water companies in our sample, however we do compare mortality outcomes by public or private status of water supplies. Other studies have focussed only on public investments, and sometimes ignored the issue of private ownership entirely.

Figure 3.1 Aggregate sanitation capital, water capital, and sewerage capital, and loans outstanding.



Notes: Data are annual averages, weighted by town population. All quantities are in £ per capita. Source: *Local Taxation Returns.*

There were also substantial variations in expenditure amongst Urban Districts with municipal waterworks. Some of this variation reflected the fact that many Urban Districts sold water to neighbouring rural and urban districts.[13] Manchester,

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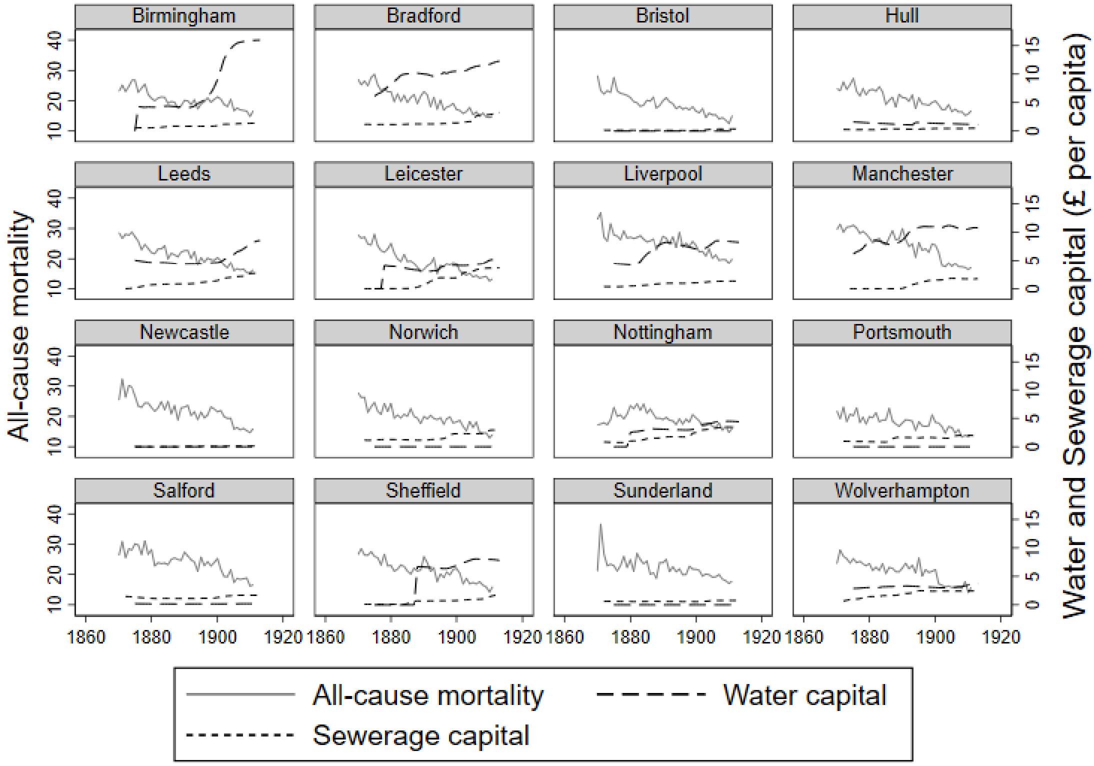
[13] The arguments and in this and the next paragraph are based on Water Undertakings (Parliamentary Papers, 1888).

Figure 3.2 All-cause mortality, water capital and sewerage capital, by town.



Sources: *Weekly Returns of the Registrar-General* and *Local Taxation Returns.*

for example, invested in very expensive long-distance water supplies, constructing reservoirs and transporting clean upland water from Longendale in the Pennines in the 1850s and from Thirlmere, over 90 miles away in the Lake District, in the 1890s. The water was then supplied both to Manchester residents and to surrounding districts, including Salford. Therefore, in our data Salford expended relatively little on water, yet benefitted from the investments made by Manchester. Conversely, the investments made by Manchester overstate the benefit to local residents. In the case of the Urban Districts of Leicester, Sheffield, Nottingham, and Derby, competition for water led to the creation of the Derwent Valley Water Board in 1899. The cost of construction of the new reservoirs and waterworks was apportioned between the four Urban Districts, and expenditures on water by these Urban Districts declined over the next decade despite a very significant augmentation in water supplies.

A third factor that caused major variations in especially water expenditures was the importance of variations in natural endowments. Urban Districts varied in their access to river water and to deep uncontaminated sources of groundwater. Hull, for example, spent relatively little on its public water supply (Figure 3.2). It obtained its water wholly from deep local wells, and did not employ filtration, an arrangement that must have been relatively cheap compared with long-distance sourcing of uplands water, or with the very substantial storage facilities required for sand filtration. Other Urban Districts that partly sourced their water from local bores and wells also spent relatively modestly on water supplies (Nottingham, Leicester, Wolverhampton, and Birmingham before 1903). Birmingham, however, demonstrated an extraordinary rise in investment in the first decade of the twentieth century, when the Urban District finally resorted to a long-distance water supply from Wales. This did not necessarily result in any improvement in water quality (which was already high), but pre-empted a deterioration in supply in the face of continued urban expansion. With respect to filtration, usage varied. Sand filtration was first introduced in the early nineteenth century, however it was generally reserved for river water, which was widely deemed polluted. The adoption of filtration was thus not necessarily an indicator of superior water quality. In 1870 only four of the 16 Urban Districts in our sample used sand filtration to treat part or all of their water. By 1910 all river water was filtered, and most upland sources. However, Manchester (and Salford) and Sheffield still depended on unfiltered upland water, and Urban Districts generally did not filter piped water from wells and boreholes.

Investments in sewerage were more modest, and generally demonstrated smoother rises across our sample period (Figure 3.2). Early attempts to privatise sewerage and faecal collection failed, and all town councils had to deal with their own local wastes and the methods employed varied (Sheail, 1996). Although Chadwick called for combined water carriage (flush toilets and water-flushed sewers) in the 1840s, flush toilets were still not universal even in the largest Urban Districts by 1911. Many Urban Districts focussed in the early part of our period on replacing the most egregious hazards, such as midden privies (where faecal waste was stored in heaps in yards or on the street awaiting collection), with other dry conservancy methods (involving domestic storage of faecal waste and regular house-to-house collection). This type of public health expenditure is not captured by our sewerage variable. Installation of flush toilets was accompanied by the provision of sewers for faecal waste (as distinguished from drainage, the older function of sewers). However most sewers emptied into waterways, and sewage treatment, the chemical and mechanical breakdown of faecal waste to destroy pathogens, was introduced only very slowly. The recognition that faecal contamination of drinking water was dangerous initially resulted only in the separation of contaminated and uncontaminated water, as sewage outfalls were removed further downstream, and water supplies either filtered or sourced from more remote areas. The purification of sewage was costly, and was not necessarily of direct benefit to Urban Districts, because the main advantages often accrued to downstream users. Thus the rapid removal of faecal waste from houses using water-borne disposal was associated, in its early stages, with the progressive pollution of waterways and coastal areas. These practices appear to have led to food-borne typhoid outbreaks associated with contaminated shellfish by the late nineteenth century, but clear guidelines for chemical and mechanical treatment of sewage were only developed in the course of a Royal Commission (1898-1915) on the treatment and disposal of sewage (Hardy, 2014). Unfortunately, our sources (the *Local Taxation Returns*) do not allow us to unpick the components of expenditure on sewage disposal versus treatment.

Ideally, investments in water supply or sanitation should capture changes in both the quantity and quality of provision. However, as detailed above, there are many reasons why this relationship may be complicated. As discussed in Section 3.2, early efforts to provide public water supplies may have been motivated more by industrial demand than by considerations of public health, and much of the water supplied may have been used for non-domestic use. Ideally, we would have annual data on the proportion of the population served by piped water and by in-house supply versus standing pipes in the street. We would also have measures of per capita domestic consumption, and whether water was provided on a constant system, or was available only on certain days or between certain hours (the ‘intermittent’ system). Intermittent water supplies necessitated storage of water in cisterns or other containers, and increased the chances of domestic contamination. Unfortunately, these kinds of data are scanty in chronological and geographical range. All the Urban Districts in our sample provided a constant supply (either in-house or via standpipes in the street) to all or almost all residents of the Urban District by 1911, but we lack consistent evidence for our panel before this date. With respect to pathogenic contamination of the water, despite the development of increasingly sophisticated tests of water content, controversy persisted over the best means of detecting faecal contamination into the twentieth century (Hamlin, 1990). The extension of constant piped water to all inhabitants, the introduction of flush toilets and sewerage occurred progressively in most British towns, and it is not generally possible to pinpoint decisive turning points. In conclusion, while our measures of sanitation, water and sewerage capital provide some measure of the quality of sanitation services experienced by the residents of the Urban Districts in our sample, we also wish to draw attention to reasons why they may be a poor proxy in specific cases. These critiques apply to any analysis using variables derived from the *Local Taxation Returns*, or in many cases from the use of public accounts data in general.

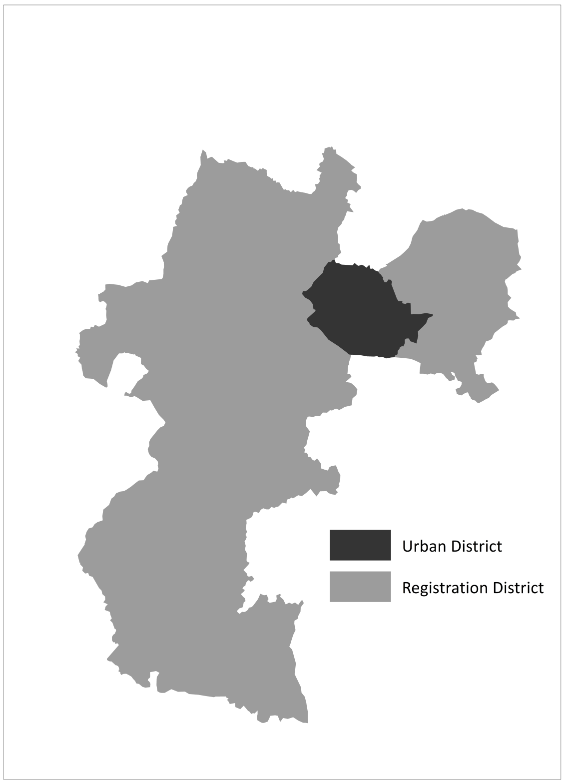
3.4 Measures of Mortality

In this Section, we describe our outcome variables, mortality rates. The study of urban mortality patterns in Victorian England and Wales has been severely hampered by the reporting practices of the Registrar-General's office. The two most serious problems are the geographical units for which most mortality data were reported before 1912, and the ways that deaths by individual causes were aggregated and reported. Our study largely overcame the first problem, but could only partially address the second problem.

The main administrative unit used by the Registrar-General to report deaths before 1912 was the Registration District (RD). Registration Districts were based on poor law unions created from the aggregation of groups of parishes under the Poor Law Amendment Act of 1834. In the case of towns and cities, poor law unions, and therefore Registration Districts, were deliberately designed, where possible, to combine rural with urban populations, in order to spread the costs of supporting the urban poor. Thus except in the case of some districts in the very largest towns, Registration Districts were generally larger than their constituent towns in area and population, and included a mix of rural and urban communities. Figure 3.3 illustrates the point for Wolverhampton. Wolverhampton was one of the 16 largest non-metropolitan towns in England and Wales in the period 1870-1911, but the borough (the Urban District), was nonetheless included within a much larger Registration District and comprised only half of the Registration District population in 1871 (Table 3.2, columns 2-4).

Critically for the study of public health, urban political and administrative functions were not organised on the basis of Registration Districts. As described in Section 3.3, investments in urban public health were undertaken by Urban Districts. These units were often co-terminus with pre-existing municipal boroughs (as in the case of Wolverhampton), and were either contained within a single Registration District, or overlapped several. The reporting of deaths by Registration District, therefore, poses a serious problem for studies of the health effects of urban improvements in water supply and sanitation, because investments made by Urban Districts would be expected to

Figure 3.3 Wolverhampton Urban District and Registration District, 1911.



Source: Max Satchell's Urban District boundary data (described in text).

affect only that fraction of the Registration District populations that lived within the Urban District.[14]

Previous studies have generally confronted this problem of mismatch between urban areas and their related Registration Districts by aggregating mortality data for all the Registration Districts that overlapped Urban Districts.[15] The extent of the mismatch between Urban Districts and their associated Registration Districts produced by this method is documented for our sample of the 16 largest non-metropolitan towns in England and Wales in Table 3.2. The table compares the population of each Urban District and the Registration Districts that overlapped it, in 1871 (columns 2-4). It also documents the extent to which the Registration District populations exceeded

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[14] The Registrar-General also reported a more limited set of mortality statistics for registration sub-districts (Table 3.3). These were sub-divisions of Registration Districts (comprising over. 2,000 in total, compared with c. 630 Registration Districts), but were never designed to distinguish urban from rural districts.

[15] Chapman (2019); Harris and Hinde (2019); Hinde and Harris (2019); but see Woods (1978) for an outstanding, though unfortunately only cross-sectional, small area study of Birmingham c.1885.

the populations of the Urban Districts which they overlapped in successive censuses (columns 5-7). In some cases (Portsmouth, Leicester and Norwich) the fit was perfect, and the Registration District and Urban District were co-terminus. In other cases the Registration District populations substantially exceeded the Urban District, by almost 100% in the case of Wolverhampton. Table 3.2 also indicates the effects of the redrawing of boundaries of both Urban Districts and Registration Districts across the period and particularly in the 1890s. In some cases, as in Bristol and Nottingham, there was a reconciliation of the Registration and Urban District boundaries during our period.

Our study uses a previously unexploited source of mortality data that pertains to Urban Districts, not Registration Districts. This is the *Weekly Returns of the Registrar-General*, which reported deaths from a limited set of causes for the largest Urban Districts, from 1870 to 1911. The *Weekly Returns* reported weekly counts of total births and deaths, deaths aged under one year and 60 years and over, and deaths attributed to a limited number of causes, including diarrhoea, fever (which included deaths from typhus, typhoid and 'simple continued fever'), and several other infectious diseases, and accidental and violent deaths. The series started in 1870 with the 17 towns with populations that approached or surpassed 100,000 in 1861. London was included, but was excluded from our study because data for London were not reported in the *Local Taxation Returns*. While the 16 Urban Districts in our sample constitute a small panel compared with the roughly 1,000 Urban Districts in England and Wales in this period, these were the largest Urban Districts. They accounted for around a quarter of the total population of non-metropolitan Urban Districts, and most or all of the population living in large towns (with populations of 100,000 or more, excluding London) (Table 3.2).

A central issue is which mortality rates provide the best measure of the success of sanitary interventions to reduce faecal exposure. In the English case previous studies have used as outcome measures all-cause, typhoid, infant, or diarrhoeal mortality rates, or an aggregated category of 'water-borne' causes of death (Table 3.3). Chapman's (2019) 'water-borne' category included typhoid, cholera, diarrhoea and dysentery. Since typhoid was not reported separately from typhus until 1869, he included only the three decades 1870-1900 in his analysis of these causes. Hinde and Harris (2019) instead constructed a 'water-borne' category for the whole period 1851-1910, and so were forced to include typhus together with typhoid, although typhus is transmitted by lice, not faeces. In our study, the main outcome measures were all-cause, infant and diarrhoeal mortality. We could not construct a 'water-borne' disease category that

Table 3.2 Populations of the largest 16 non-metropolitan urban districts in England and Wales and their corresponding Registration Districts, 1871-1901.

Town	Municipal-isation of water	UD population 1871	RDs comprising UDs, population 1871	RD population % of UD population			
				1871	1881	1891	1901
Liverpool	1848	493,405	581,336	118	124	146	119
Manchester	1851	351,189	463,340	132	155	121	124
Birmingham	1875 (1876)	343,787	444,636	129	136	132	143
Leeds	1852	259,212	274,753	106	106	105	105
Sheffield	1887 (1888)	239,946	249,703	104	105	106	107
Bristol	-	182,696	244,618	134	141	147	100
Bradford	1854	147,101	257,713	175	160	158	128
Nottingham	1880	138,876	204,971	148	148	155	100
Newcastle	-	128,443	131,198	102	103	106	109
Kingston upon Hull	1843	125,758	136,513	109	107	193	106
Salford	1850	124,801	128,890	103	103	103	104
Portsmouth	-	113,569	113,595	100	100	100	100
Sunderland	-	98,278	112,643	115	120	121	124
Leicester	1878	95,220	95,220	100	100	100	100
Norwich	-	80,386	80,386	100	100	100	100
Wolverhampton	1869	68,291	136,053	199	192	187	183
16 towns		2,990,958	3,655,568	122	126	129	116
Population of all UDs				n/a	13,820,163	17,516,969	20,521,814
16 towns % of all UDs				n/a	25	23	24
Population of UDs with Population 100,000+ (ex. London)				n/a	3,882,692	5,371,455	6,953,654
16 towns as % of UDs with Population 100,000+ (ex. London)				113	90	67	70

Notes: Municipalisation dates in parentheses indicate the date the relevant act came into effect. No summary statistics were reported for urban districts by size for 1871 in the censuses. The proportion of the population in towns with populations of 100,000 or more that was in our sample was 113% because the Registrar-General reported mortality for the largest 17 towns, including towns with populations under 100,000 (see column 2).

was comparable to previous studies, because the *Weekly Returns* distinguished only diarrhoea and cholera deaths, and cholera had virtually disappeared as a cause of death in Britain after 1866. Typhoid deaths were included in the ill-defined category of ‘fevers’, and dysentery was not reported (but was anyway a very minor cause of death by 1870).

Our incapacity to construct a ‘water-borne’ category of deaths was not in itself a shortcoming, because while such categories are usually intended to include all major faecal-oral diseases, it is widely recognised that these diseases vary in the extent to which they depend on faecal contamination of water. Therefore, it is preferable to study these diseases separately where possible. In the English case diarrhoeal deaths accounted for around 80% of all deaths attributed to faecal-oral diseases by 1870, and diarrhoeal mortality was a major component of the ‘urban penalty’ (Davenport, 2007). Our source allowed us to track diarrhoeal mortality in great detail. However, as suggested in Section 3.2 (Table 3.1), there is reason to expect that diarrhoeal mortality was not closely related to water quality, although it may have been sensitive to other aspects of faecal disposal. Typhoid appears to have provided a much more sensitive indicator of water quality in previous studies, and it was unfortunate that it was not reported separately in our source. To provide a partial remedy, we constructed annual rates of typhoid mortality for the Registration Districts corresponding to our 16 Urban Districts (Table 3.3).

To construct our main mortality variables, we aggregated weekly deaths into annual series, because our expenditure and constructed sanitation capital data were available on an annual basis, and converted these to mortality rates using annual population estimates. To do this, we extracted census populations for our 16 Urban Districts from census reports, together with dates on which boundary changes, and therefore changes in population, came into effect, and interpolated between census dates.[16] The resulting death rates were crude rates, that is, they were calculated using the whole population as the denominator. For infant and diarrhoeal deaths, we constructed rates as deaths per 1,000 births, because most or all of the deaths in these categories occurred to infants.

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[16] We used geometric interpolation between census dates in cases where there was no intercensal boundary change. In cases where a boundary change occurred, we used the ratio of the number of (weekly) births in the 52 weeks before the boundary change, to the number in the 52 weeks following the change to estimate the change in population. We then used the intercensal growth rate in the decade closest to the change to either forward-project or back-project the nearest census population to the date of the boundary change to estimate the population at the date of change, and then estimated the population before or after that date from the ratio of births before and after the boundary change.

Table 3.3 The main sources of mortality data reported by the Registrar-General between 1850 and 1911.

Source	Period	Spatial units	Frequency	Ages	Faecal-oral diseases	Previous uses	This study
Decennial returns	1851-1910	Registration districts	Decennial averages	Yes	Yes	Hinde & Harris, Woods, (age-standardised and crude rates 1851-1910) Chapman (crude rates, 1861-1900)	Age-standardised and crude rates 1861-1910
Annual returns	1856-1911	Registration districts	Annual	No	No		Crude typhoid rates
Quarterly returns	1870	Registration sub-districts	3 monthly	No	No	Chapman (third quarter all-cause mortality)	
Weekly returns	1870-1911	Selected urban districts	Weekly	No	No		Crude all-cause and cause-specific rates, infant and diarrhoeal deaths per 1,000 births

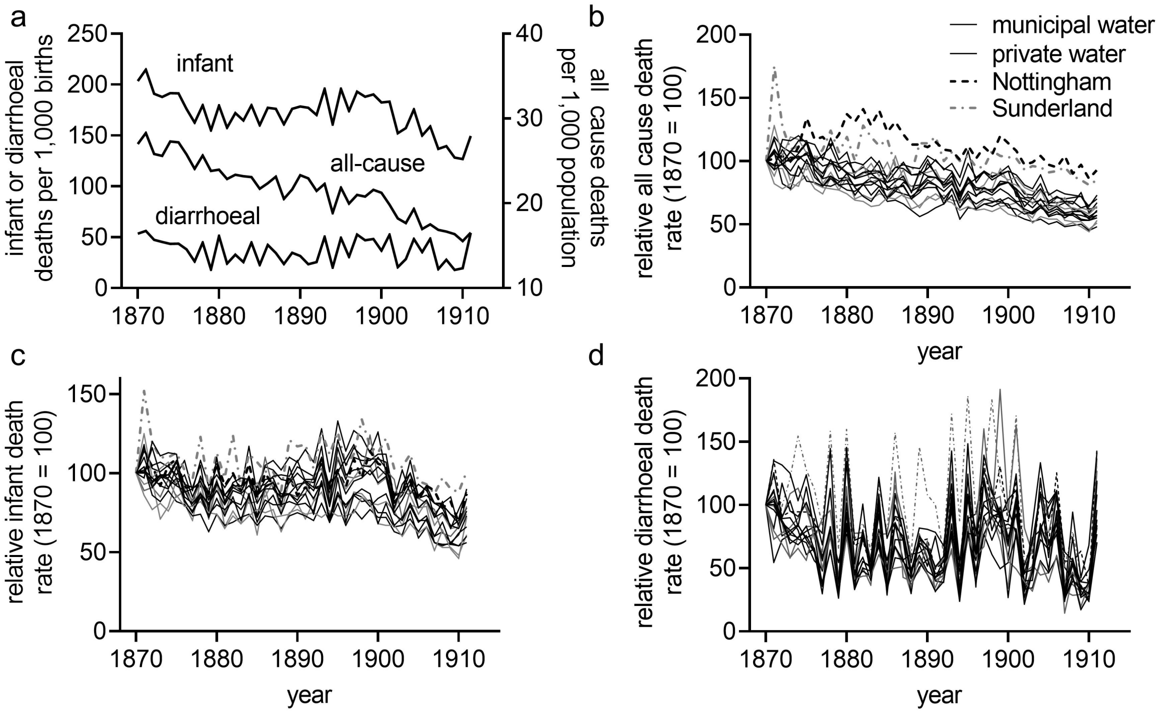
Sources: *Annual*, *Decennial*, *Weekly*, and *Quarterly returns of the Registrar-General*; Chapman (2019); Harris and Hinde (2019); Hinde and Harris (2019).

For comparison with other studies, we also constructed decennial death rates for the Registration Districts associated with the 16 Urban Districts in our sample. We constructed crude decennial death rates (Chapman's (2019) measure) using the decennial deaths and average intercensal population totals for the Registration Districts reported by the Registrar-General in his decennial Supplements. We also created age-standardised decadal rates by first creating age-specific death rates (using the Registrar-General's average population totals for each Registration District by age) and then using these to calculate the number of deaths, and crude death rates, that would have occurred at these rates if the Registration District populations had had the same age structure as the population of England and Wales as whole in 1901. Annual crude death rates for Registration Districts were also constructed for typhoid and typhus.

Trends in our main mortality measures are displayed in Figure 3.4. In the 16 Urban Districts in aggregate, crude all-cause death rates declined fairly continuously between 1870 and 1911 (Figure 3.4a). This was also the case in individual Urban Districts (Figure 3.2). However, as Figure 3.2 demonstrates, mortality levels varied markedly between Urban Districts. In the early 1870s, crude death rates hovered around 30 per 1,000 in Liverpool, Manchester, Salford and Newcastle, but were only around 20 per 1,000 in Portsmouth. In order to compare performance over time, regardless of initial levels, Figures 3.4b-d display annual mortality by cause for each Urban District, standardised to the rate in 1870 (1870 = 100). With the exception of two very poorly performing Urban Districts (Nottingham and Sunderland), crude all-cause mortality trended downwards fairly consistently across Urban Districts, and had halved by 1911 in some cases (Figure 3.4b).

In contrast to all-cause mortality, our two more specific measures of sanitary conditions, diarrhoeal and infant mortality, showed little improvement before c.1901, and actually rose in the 1890s (Figures 3.4a, c-d). This pattern reflected national trends, and was attributed to a string of hot dry summers in the second half of the 1890s that caused major summer diarrhoeal epidemics (Woods et al., 1988, 1989). Diarrhoea was largely a phenomenon of late summer, and the size of epidemics was influenced by summer temperatures. Indeed Figure 3.4d draws attention to the marked synchrony of inter-annual variations in diarrhoeal mortality across all Urban Districts, regardless of the differences in levels of mortality. We could not measure typhoid mortality in our 16 Urban Districts , however death rates from this disease fell markedly in the period 1869-1880 in the Registration Districts associated with our Urban Districts (Figure 3.5a). There was, however, no further improvement in typhoid mortality until c.1900, despite large increases in expenditures on water and sanitation in this period, and there

Figure 3.4 All-cause, infant and diarrhoeal mortality rates, by town.



Notes: Panel a represents aggregated rates for all 16 towns (weighted by population). Panels b-d represent rates standardised to the rate in 1870. Source: *Weekly returns of the Registrar-General.*

was no obvious difference in levels or trends in mortality from these diseases in towns with municipalised water supplies compared to those with private supplies. Trends in typhoid mortality clearly differed from those of diarrhoeal mortality, a fact suggestive of different aetiological pathways, as noted in Section 3.2. Louse-borne typhus displayed different geographical and chronological patterns compared with typhoid, and had virtually disappeared as a cause of death by 1890 in our 16 Urban Districts (Figure 3.5b).

In order to construct demographic and economic control variables for our 16 Urban Districts, we created a Geographical Information Systems (GIS) dataset of boundaries for the 16 Urban Districts in 1911.[17] This was augmented to reflect historical boundary changes to the 16 Urban Districts between 1870 and 1911. These boundaries were then used to identify sets of quasi-parish units that corresponded most closely to each of the Urban Districts for each census year. Individual-level census data were extracted

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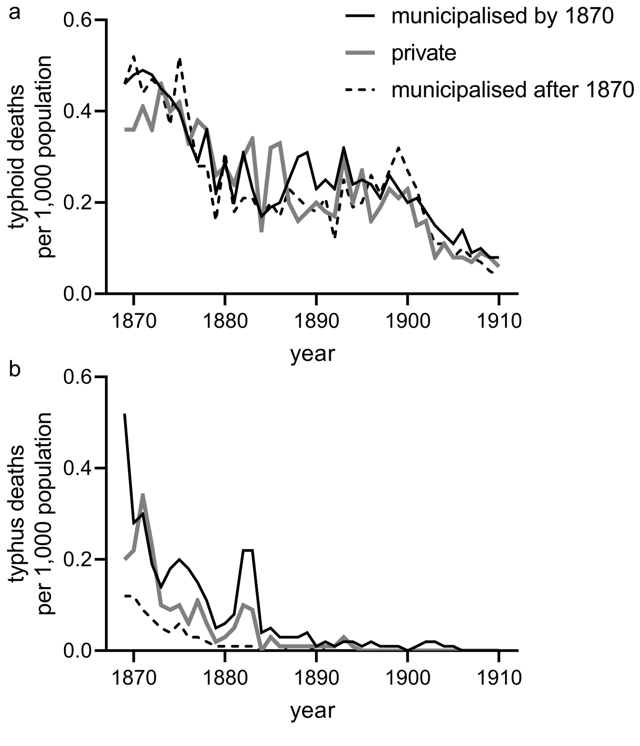
[17] This dataset was created by Max Satchell, Cambridge Group for the History of Population and Social Structure.

Figure 3.5 Typhoid mortality rates in Registration Districts associated with our 16 panel towns, by type of water supply.



Source: *Weekly returns of the Registrar-General.*

from the Integrated MicroCensus (I-CeM) database for each of these quasi-parish units (into which the I-CeM data are already organised), and combining these with the GIS data, we constructed variables for each Urban District, for each decade following the census. These variables were: measures of the age structure, sex ratio, and workers per capita employed in textiles, manufacturing and waterworks. The tax base per capita was extracted from the *Local Taxation Returns*, by dividing the 'assessable value' of all property an Urban District by its population. A dummy equal to one if an Urban District had a municipal waterworks was constructed from parliamentary sources.[18]

3.5 Empirical Results

Table 3.4 provides descriptive statistics for our data. The primary dataset is a balanced panel of dimension N=16, T=37, spanning the years 1875-1911. The length of the panel is constrained by either mortality data availability at the end of the period (1870-1911) or the availability of data on water-related expenditure at the start (1875-1913). Since five Urban Districts had private waterworks throughout the period, and a further four Urban Districts had for some of the period, and we therefore have no data on their expenditures, we also use an unbalanced N=11 panel for robustness checks, containing only Urban District-year observations with municipal supply of water.

In order to quantify the relationship between sanitation infrastructure and mortality, we estimate the following equation:

$$M_{it} = \alpha + \beta S_{it} + \gamma X_{it} + \eta_i + \lambda_t + \epsilon_{it} \tag{3.4}$$

where M_{it} is a mortality rate for UD i in year t, S_{it} is a measure of sanitation infrastructure, X_{it} is a vector of controls, η_i is a UD-level fixed effect, λ_t is a time effect, and ϵ_{it} is the residual. Table 3.5 reports the results of estimating Equation (3.4) using our panel data, with all-cause mortality as the outcome variable and sanitation capital (the sum of water capital and sewerage capital) as the measure of sanitation infrastructure. All coefficients are standardised and standard errors are clustered at the Urban District level. Regressions are weighted by average population over the period, so that larger Urban Districts have a proportionately larger influence on the coefficients. Column (1) shows there is a negative raw correlation between sanitation capital and all-cause mortality. The R^2 is very low, however, suggesting sanitation capital alone has little explanatory power. Column (2) reports the results

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[18] *Means by which drinkable water is supplied to every urban district in England and Wales* (Parliamentary Papers, 1879), *Water undertakings* (Parliamentary Papers, 1888).

Table 3.4 Descriptive statistics.

	Mean	S.D.	Min	Max	N
Weekly Returns of the R.G.					
All-cause mortality rate	21.07	4.07	12.48	36.63	672
Diarrhoea mortality rate	36.20	15.17	5.69	85.18	672
Infant death rate	168.81	26.16	90.66	269.99	672
Accidental mortality rate	0.78	0.23	0.39	3.30	672
Birth rate	33.63	5.06	18.98	46.74	672
Annual Returns of the R.G.					
Typhus mortality rate	0.04	0.11	0.00	1.44	672
Typhoid mortality rate	0.26	0.16	0.00	0.97	672
Local Taxation Returns					
Sanitation capital	4.60	4.19	0.00	17.45	624
Water capital	3.50	3.89	0.00	15.98	624
Sewerage capital	1.07	0.84	0.00	3.65	664
Loans outstanding	10.91	8.93	0.11	34.79	716
Tax base	4.47	1.39	0.10	8.37	690
Census					
Population growth (%)	1.55	0.98	-0.64	4.03	706
Population	255,220	154,395	65,521	759,540	752
Female (%)	51.74	1.33	47.12	55.04	752
Aged 0 to 14 (%)	34.76	2.85	24.81	40.94	752
Aged 15 to 40 (%)	47.47	1.90	42.81	51.55	752
Water works employment (%)	0.04	0.02	0.00	0.08	752
Manufacturing employment (%)	10.02	6.67	3.61	28.81	752
Textiles employment (%)	6.74	9.43	0.15	35.51	752
Other					
Municipalised water (%)	61.30	48.74	0.00	100.00	752

Notes: Data cover the period 1867-1913, though not all variables are available for the full period: Column N gives the number of observations for each variable. Mortality rates are per 1,000 population, other than diarrhoeal and infant mortality which are per 1,000 births. All variables derived from the *Local Taxation Returns* are in £ per person. Census data are exponential interpolations of decadal data. Sex and age variables are normalised by the total population. Employment variables are normalised by the working age population (15-64).

when we include Urban District fixed effects (that capture average differences in levels of mortality between Urban Districts), and we find a much larger and significantly negative effect of sanitation capital. Column (3), however, also includes year effects, and the coefficient on sanitation capital becomes positive but not significantly different from zero. The large increase in R^2 suggests that the majority of the explanatory power in this and subsequent regressions is coming from common time effects. If the common time effect and sanitation are positively related while the common time effect and mortality are negatively related, then the OLS estimate with no common time effects is subject to a negative bias, which could explain the coefficient being negative in columns (1) and (2) and positive in column (3). Column (4) reports the results when including a full set of controls in Equation (3.4): Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. Sanitation capital is not associated with a statistically significant change in all-cause mortality. This is the central result of our paper, and, as we go on to show, it is highly robust. The R^2 does not change much by the addition of controls. Taking columns (1)-(4) together, it appears that mortality is primarily driven by unobserved factors changing over time which are common to all Urban Districts. These include year-to-year variations in weather conditions, but also reflect the ubiquity of mortality declines in this period as shown in Figure 3.4b (and see Hinde and Harris, 2019).

In column (5) of Table 3.5, we disaggregate sanitation capital into its components: water capital and sewerage capital. Water capital has a positive but insignificant effect, whereas sewerage capital has a negative but insignificant effect. To explore whether water and sewerage might have a complementary impact on mortality, column (6) includes an interaction term. The coefficient is negative and significant at the 5% level, providing some evidence that there may be complimentarities between the two forms of investment: water infrastructure lowers mortality only when there is sewerage infrastructure in place, and vice versa. Finally, in column (7) we include only Urban District-year observations for which an Urban District's water supply was publicly owned, and its spending therefore appeared in our public accounts data. This addresses the serious concern that many Urban Districts that appear to have no water infrastructure according to the public accounts in fact have substantial water infrastructure run by private water companies. The result, however, is similar to our baseline result in column (4).

We explore the robustness of our result in three ways: interacting our capital measures with other variables of interest, dividing the sample into different time periods, and exploring alternative measures of sanitation infrastructure. Regression

Table 3.5 Baseline regression results.

	Dependent variable: All-cause mortality rate						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Sanitation capital	-0.100** (0.041)	-0.801*** (0.256)	0.134 (0.107)	-0.012 (0.079)			0.030 (0.112)
Water capital					0.015 (0.053)	0.052 (0.044)	
Sewerage capital					-0.113 (0.092)	-0.026 (0.058)	
Water-sewerage int.						-0.143** (0.066)	
Fixed effects		✓	✓	✓	✓	✓	✓
Time effects			✓	✓	✓	✓	✓
Controls				✓	✓	✓	✓
R^2	0.010	0.308	0.832	0.887	0.888	0.895	0.911
No. observations	592	592	592	592	592	592	385
No. towns	16	16	16	16	16	16	11

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Dependent variable is all-cause mortality rate per 1000 population. Time period is 1875-1911. All coefficients are standardised. Standard errors are clustered at the town level. R^2 calculated for within variation when specification includes fixed effects. Regressions are weighted by average population over the period. All variables are measured at the Urban District (UD) level. Control variables are: Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. Columns (1)-(6) are for the full balanced panel of all towns, whereas column (7) only includes town-year observations where a town's water supply is municipally owned (and its expenditure therefore appears in its public accounts).

results are reported in Appendix 3.B. First, we investigate whether more industrial Urban Districts have a different relationship between infrastructure and mortality to less industrial Urban Districts. We interact our capital measures with the proportion of an Urban District's workforce employed in industry (the sum of employment in manufacturing and textiles divided by the working age population). The results are given in Table 3.8, columns (1) and (2). For both sanitation capital and water capital, we find a negative and statistically significant (at 10% and 5%, respectively) effect for the level of the respective capital stock, and a positive and statistically significant effect (at 1% for each) on the interaction term. These results suggest that in less industrial Urban Districts, investing in sanitation and water capital may have affected mortality negatively, but that the more industrial an Urban District is, the less negative is this effect. This is consistent with the arguments of Hassan and Silverthorne, that the public benefits of municipal investments in water were offset to some extent in industrial Urban Districts by the high proportion of that water that was supplied to industries, including compensation to mill-owners with riparian rights to the water sources (Hassan, 1985; Silverthorne, 1884).

Second, we investigate different measures of water infrastructure other than those derived from the accounts in the *Local Taxation Returns*. From the census we know the proportion of an Urban District's population employed in its waterworks, which we take to be a proxy for the quantity of water infrastructure operated by an Urban District. This has the advantage that it captures the presence of private waterworks, unlike any public accounts derived variables. Another independent measure is a dummy variable equal to one if an Urban District had municipalised its water supply in a given year. This correlates with public water infrastructure for obvious reasons, and it has been argued that it correlates with the quality of an Urban District's water supply more generally in this period. Table 3.8 columns (3) and (4) suggest, however, that neither of these independent measures of water infrastructure are associated significantly with all-cause mortality.

Third, we investigate whether the effect of water capital on mortality might be different in the earlier part of our sample period relative to the later part. Plausibly, infrastructure investments might be subject to diminishing marginal returns, and this could be driving our overall result (Hassan, 1985). Table 3.8 columns (5)-(8) report the results of estimating Equation (3.4) separately for the early and late halves of our sample period. No results are significant, but for all three capital measures the coefficients are more positive in the later period, consistent with the presence of diminishing marginal returns.

Table 3.6 reports the results of estimating Equation (3.4) with other mortality rates: diarrhoeal, infant, accidental, typhus and typhoid. As discussed in Section 3.4, typhus and typhoid data are not available at spatial units consistent with the accounts data, so these two results should be treated with a large degree of caution. We do not find significantly negative effects for any mortality outcome. Sanitation capital is in fact associated positively with diarrhoeal (at 10%) and infant (at 1%) mortality. In the Appendix, we report the results of many of the robustness tests described above applied to diarrhoeal and infant mortality respectively. For diarrhoea, Table 3.9 reports that when disaggregating into water and sewerage capital, it is the water capital that is associated positively (at 10%) with mortality. When adding interaction terms, using alternative measures of water capital, or restricting the sample to Urban District-year observations with municipal waterworks, we find no significant results. Taken together, these findings suggest that sanitation, water and sewerage capital probably had no effect on diarrhoeal mortality in our sample.

For infant mortality, Table 3.10 reports that the significantly positive baseline result is somewhat more robust. When disaggregating into water and sewerage capital, it appears that water is driving the positive association. There is no significant interaction between water and sewerage, though the industry-sanitation capital interaction is significantly positive. Unlike for all-cause mortality, this appears to be driven by the industry-sewerage interaction. Both alternative measures of sanitation infrastructure are positive at 10%. When restricting the sample to Urban District-year observations with municipal water supply, the results are not significant. (The time decompositions, not shown in the interests of space, do not give significant results but are consistent with a more positive effect in the first half of the period.) Taken together, these findings suggest that sanitation infrastructure correlates either positively or not at all with infant mortality.

In conclusion, the one robust finding to emerge from our analysis of the 16 Urban Districts is that water and sewerage infrastructure does not appear to reduce diarrhoeal or infant mortality. This is, perhaps, not so surprising, given the relative stability of these mortality rates in the face of large increases in sanitary expenditures (Figure 3.1 and Figure 3.4).

We have also explored possible dynamic relationships between our variables of interest. In regresions with up to 10 lags of the capital stock measures, no clear patterns emerge. The long run effect (the sum of coefficients on the lags) is at best significantly different from zero only at the 10% level. We have also explored a dynamic panel specification, as well as a Pooled Mean Group (Pesaran and Smith, 1995) specification to allow for heterogeneity between different Urban Districts in the sample. In no cases did we find a significantly negative effect.[19]

The results above differ markedly to those of Chapman (2019), who reported significantly negative relationships between various measures of mortality and infrastructure, as measured by loans outstanding recorded in the *Local Taxation Returns*. Our econometric methods are very similar. Other than the control variables used, the only difference is that we use weighted regressions whereas he uses non-weighted regressions, so that in his results the smallest town has the same impact on estimated coefficients

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[19] These results are omitted in the interests of space, but available upon request.

Table 3.6 Regression results for different mortality measures.

	Dependent variable: Mortality rates					
	(1) All-cause	(2) Diarrhoeal	(3) Infant	(4) Accidental	(5) Typhus	(6) Typhoid
Sanitation capital	-0.012 (0.079)	0.103** (0.047)	0.196*** (0.055)	-0.008 (0.089)	-0.041 (0.161)	0.107 (0.073)
Fixed effects	✓	✓	✓	✓	✓	✓
Time effects	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
R^2	0.887	0.784	0.770	0.467	0.555	0.524
Geographical unit	UD	UD	UD	UD	RD	RD
Time period	1875-1911	1875-1911	1875-1911	1875-1911	1875-1910	1875-1910
No. observations	592	592	592	592	576	576
No. towns	16	16	16	16	16	16

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: For All-cause, Accidental, Typhus and Typhoid mortality the rate is per 1,000 population. For Diarrhoeal and Infant mortality the rate is per 1,000 births. Control variables are: Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. All coefficients are standardised. Standard errors are clustered at the town level. R^2 calculated for within variation. Regressions are weighted by average population over the period. All variables are measured at the Urban District (UD) level, except the mortality rates for Typhus and Typhoid at the Registration District (RD) level.

as the largest town.[20] There are, however, some important differences between the data used in each case. As discussed in Sections 3.3 and 3.4, the two principal differences are that Chapman used data at a decennial frequency, and he used mortality rates measured on a different geographical unit (the Registration District, RD) to that of the accounts data (the Urban District, UD). We explore the quantitative importance of these differences for the towns in our sample below.

Table 3.7 reports the results of estimating Equation (3.4) with data at different frequencies (annual or decennial) and geographical units (UD or RD). We look at the effect of the square root of loans outstanding on all-cause mortality, as this is Chapman's baseline specification.[21] For further comparability to Chapman's (2019) results, we have calculated the 'decline explained', i.e., the proportion of the decline in mortality over the period that could be explained by multiplying the change in loans over the period with the estimate of the effect of loans on mortality.[22] Column (1) is most similar to our baseline results in Table 3.5, with the only differences being: the independent variable is loans outstanding square rooted (the variable used by Chapman), the time period is 1870-1911 (reflecting the earlier availability of the loans data), and the regressions are unweighted (as in Chapman's specification). Importantly, the geographical units for the mortality rate and the infrastructure variable are the same (UD). The result is an insignificant effect of loans on mortality, with a very small 'decline explained'. This result is comparable in magnitude and significance to column (4) of Table 3.5, our baseline result. In column (2) of Table 3.7, we report a specifcation of Equation (3.4) estimated with data at the decennial frequency, with the first decade being 1861-1870, and the final decade being 1901-1910.[23] The results do not change

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[20] We explored whether weighted an unweighted regressions gave different results for our 16 Urban District sample and found that generally the difference was small. This result will not necessarily hold in Chapman's (2019) larger sample, which contained considerably greater heterogeneity.

[21] We take Table 1 Column (3) to be Chapman's (2019) baseline result. He finds the square root of loans outstanding has a standardised coefficient of -0.17, significant at 1%. The '% decline explained' by loans is 29%.

[22] To calculate the 'decline explained' we use the following formula: Decline explained = $\frac{\sum_i P_{it}\hat{\beta}(I_{it}-I_{i,1870})}{\sum_i P_{it}(M_{it}-M_{i,1870})}$, where P_{it} is population in town i in decade t, $\hat{\beta}$ the estimated regression coefficient, I_{it} is the measure of infrastructure investment, and M_{it} is mortality. This is in spirit of the formula Chapman (2019) reports (Equation (2) on p. 244), but different in that he uses final infrastructure over the change in mortality, rather than the change in infrastructure over the change in mortality. We cannot see that dividing a level by a change gives a meaningful measure.

[23] There is an issue with incomplete data when using the first decade of 1861-1870. No accounts data exist before 1867, and hence the decade of '1861-1870' is really an average of 1867-1870 at best. Chapman (2019) does not address this, but it could potentially be seriously problematic. We follow his method for consistency, while noting the potentially issues. When using mortality data at the UD level, this problem takes the form of the decade '1861-1870' being made up solely of the observation for 1970, as this is the first year these data are available for.

Table 3.7 Decennial regression results.

	Baseline controls				Chapman controls			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Loans square root	-0.003	-0.094	-0.304***	-0.330*	0.045	0.115	-0.226	-0.203
	(0.047)	(0.133)	(0.103)	(0.155)	(0.123)	(0.268)	(0.132)	(0.146)
Fixed effects	✓	✓	✓	✓	✓	✓	✓	✓
Time effects	✓	✓	✓	✓	✓	✓	✓	✓
Controls	Baseline	Baseline	Baseline	Baseline	Chapman	Chapman	Chapman	Chapman
R^2	0.861	0.931	0.960	0.927	0.813	0.858	0.941	0.898
Geographical units	UD	UD	RD	RD	UD	UD	RD	RD
Frequency	Annual	Decennial	Decennial	Decennial	Annual	Decennial	Decennial	Decennial
Decline explained	0	9	28	35	-4	-11	21	22
Time period	1870-1911	1861-1910	1861-1910	1861-1900	1870-1911	1861-1910	1861-1910	1861-1900
No. observations	655	77	77	61	657	77	77	61
No. towns	16	16	16	16	16	16	16	16

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Dependent variable is All-cause mortality rate per 1,000 population. UD indicates variables are measured over an Urban District, RD indicates they are measured over a Registration District. For the independent variables, data from the accounts (Loans and Tax base) are only available at the UD level, and these are therefore always for UDs. Data from the census and mortality data are calculated both at the UD and RD level. ‘Baseline controls’ variables are: Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. ‘Chapman controls’ variables are: Tax base square root, Population, Female, Age 0-14, and Age 15-44. All coefficients are standardised. Standard errors are clustered at the town level. R^2 calculated for within variation. ‘decline explained’ is calculated as explained in the text and accompanying footnote.

substantially: the effect of loans on mortality remains insignificant and the decline explained remains small. In column (3), we report a specification with the mortality outcome and all controls (other than any from the *Local Taxation Returns*) measured at the Registration District level. The result is a significantly negative coefficient on the loans variable, and an explained decline of 28%. This is comparable to Chapman's baseline result of 29% (he reports figures as high as 60% for other specifications). In column (4), we restrict the time period to 1861-1900, so that it is the same as in Chapman's analysis. We find a less precisely estimated but larger negative coefficient, and a larger decline explained of 35%.

In columns (5)-(8), we repeat this exercise but using the same control variables as in Chapman.[24] The results show a similar pattern: when using consistent geographical units the effect of loans on mortality is small, positive and insignificant, whereas with inconsistent geographical units we see large negative effects. While the coefficients on the loans variable in columns (7) and (8) are not quite significant (the p-values are 10.8% and 18.5%, respectively), this could be due to our smaller sample, and the decline explained is similar to Chapman's baseline result quoted above. Taken as a whole, the results in Table 3.7 suggest that there are small differences between an annual and a decennial analysis, whereas there are large differences between an analysis with consistent and inconsistent geographical units. This has important consequences for studies such as Chapman's which use data from both the *Local Taxation Returns* (at the Urban District level) and the Registrar-General's *Decennial*, *Annual* or *Quarterly Returns* (at the Registration District level).

Table 3.11 in Appendix 3.B repeats the above analysis but for different mortality measures. For each mortality outcome, we see substantially more negative point estimates for the specification with inconsistent spatial units. This suggests that analyses with inconsistent spatial units are problematic for all outcome variables under consideration.

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[24] There are three differences in the controls used. First, we use information from the census to construct control variables, at the right spatial unit, for manufacturing employment and textiles industry employment. These are plausibly correlated with both water infrastructure and mortality. Second, we include the birth rate as a demographic control. It is an important determinant of all-cause mortality, and birth rates varied substantially over time and space during this period. Third, we use population growth as a control variable, whereas Chapman uses the level of population. In our view, population growth should proxy for unobservable time-varying characteristics of towns that affect mortality considerably better than the level of population. This is particularly the case for our 16 panel towns, where there was relatively little variation in population size compared with Chapman's sample.

3.6 Conclusion

Debates regarding the importance of public investment in urban public health for mortality declines in British cities have been hampered by inadequate data with which to test the strength of these relationships. A particular problem has been the lack of fit between mortality data (available as decadal averages for Registration Districts) and investment data (available annually for Urban Districts). In this paper, we overcame this problem by using annualised mortality data for the 16 largest (non-metropolitan) Urban Districts. We also used refined measures of investment based on actual expenditures in public health-related areas (water and sewerage), in preference to data on loans as deployed in previous studies. While our approach limited us to the study of only 16 towns, these were the largest towns and constituted a major component of the 'urban penalty' nationally in this period. We were able to replicate previous findings of a strong relationship between loans and crude mortality improvements when using data for non-comparable units (loans data for Urban Districts and mortality rates for Registration Districts). However, any relationship between investment in public health and health improvements disappeared when examined for the same geographical units (Urban Districts). Our results therefore contradict those of Chapman (2019), but are consistent with those of Harris and Hinde (2019).

Why did very substantial investments in water and sanitation over the period 1870-1911 apparently have so little effect on public health, as measured by mortality rates? One obvious answer is that the investments made by urban sanitary districts did not reflect accurately the provision of water and sanitary services to their urban populations. We have already detailed in Section 3.3 why this might be the case. Water supply was the largest component of sanitary expenditure in the aggregate, but some towns had private waterworks, and the cost of obtaining water varied significantly between towns. An additional factor may have been the extent to which domestic users benefited from public investments in waterworks. There was some evidence in our study that less industrial towns benefited more from investments in water, although the effect was only evident in the case of crude all-cause mortality, and not diarrhoeal or infant mortality (Table 3.8, column 2). This was consistent with the arguments of Silverthorne (1884) and Hassan (1985) that industrial towns diverted a greater proportion of their water to industrial uses (further distorting the relationship between investment and public health outcomes).

An important limitation of our study was the restricted range of causes of death, and age information, that were reported in the *Weekly Returns*. We have focussed mainly on crude all-cause mortality rates because these provide a close comparison with Chapman's study. However, crude death rates are strongly affected by changes in both population age structure and age-specific death rates, and are therefore difficult to interpret. It is notable that our more specific and robust measures of mortality (diarrhoeal and infant mortality rates) indicated none or positive relationships between sanitary investments and mortality (Tables 3.6, 3.9, and 3.10). This may be, as suggested in Section 3.2, because infant and diarrhoeal mortality was fairly insensitive to water quality. Our study did not include a specific measure of any more clearly water-borne diseases, such as typhoid or cholera, and so we may have missed the impact of sanitary measures on water-borne diseases. We think, however, that this is unlikely. By 1870, when our study started, typhoid was already a minor cause of death, and cholera and dysentery had virtually disappeared (Davenport, 2007; Hassan, 1985). This left diarrhoeal mortality as the main component of 'water-borne' diseases between 1870 and 1911, and diarrhoeal rates remained stubbornly high in the face of large increases in public investment (as indicated in Figure 3.4a,d).

An additional and complementary explanation for our failure to find a strong (negative) relationship between sanitary expenditures and mortality is that mortality outcomes were not linearly related to water quality and sewerage provision. As Hassan (1985) has noted, 'the chronologies of changes in water supplies and the relevant disease-specific mortality rates often fail to exhibit the expected relationships'.[25] It may be the case that early investments by the largest towns in clean water supplies, before 1870, were sufficient to weaken or sever the links between faecal disposal and drinking water, and thus to cause dramatic reductions in mortality from water-borne diseases. However, for diarrhoeal diseases that may have depended more on domestic and fly-borne contamination of foods, much larger efforts to rid local environments of contaminated faeces and flies may have been required. By 1911 all the towns in our sample provided a constant and universal supply of clean water to their inhabitants. However, the adoption of water-based faecal disposal and comprehensive sewage treatment progressed more slowly, and flush toilets were not universal even in the largest towns by 1911. Opportunities for fly-borne transmission also remained abundant. These issues call for greater attention in future studies to the quantification of actual sanitary provision, to the extent that this is possible, and to the multiplicity of potential pathways for disease transmission.

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[25] See also Bell and Millward (1998), Davenport (2007), Luckin (1986).

Appendix 3.A Data construction

In order to obtain a series of capital expenditure data going back to 1875, it was necessary to estimate capital expenditure during the period 1875-1882, for which only combined expenditure was given in the *Local Taxation Returns*. We constructed estimated data as follows. First, we estimated the relationship between capital expenditure I_{it} and combined (current and capital) expenditure C_{it} during a period (defined below) for which it was disaggregated, using Equation (3.3), where the function F_i is specific to Urban District i. We tested a large number of possible functions F_i: linear, quadratic or cubic in C_{it}; including controls for the change in i's tax base or total loans outstanding; and including up to five years of leads in C_{it} (since future current spending may be a good predictor of today's capital spending); and all possible combinations of these. We then calculated the predicted values for capital investment using the estimated function F_i. We assessed out-of-sample fit by calculating the residual sum of squares (RSS):

$$RSS = \sum_i \sum_t (I_{it} - \widehat{I}_{it})^2 \tag{3.5}$$

We tested two possible sets of time periods for the estimation and out-of-sample evaluation. First, motivated by the desire to capture the relationship between capital and total spending as temporally close to the period 1875-82 as possible, we chose the 10 year window 1883-1992 to estimate the model and then considered the out-of-sample performance of the model for the 10 years after that, 1893-1902. Second, motivated by the desire to use the whole sample period, we estimated the model over all but the last 10 years of available data, 1883-1902, and then assessed out-of-sample performance for the final 10 years, 1904-1913.

The results were as follows. When estimating over 1883-1892, for water and sewerage, the function F_i that gave the lowest out-of-sample RSS included a linear, quadratic and cubic in C_{it}, two leads in C_{it}, and no other controls. When estimating over 1883-1902, this remained true, but the RSS (per out-of-sample year) was considerably higher. We therefore chose to use the above function F_i estimated over 1883-1892 when calculating the estimated capital expenditure for the period 1875-1882 to be used in our analysis.

As a robustness check, to see whether our final results were sensitive to our choice of F_i in constructing our data, we re-estimated our baseline regression results using different choices of F_i and different time periods of estimation. We compared our minimum-RSS choice of F_i described above with the simplest possible choice, a linear function (this was one of the worst based on our RSS evaluation). We also compared both time periods described above for each F_i. The final regression results were very stable: no significances in Table 3.5 changed, and the point estimates typically changed a little only at the third decimal place. This gives us confidence that the way we constructed our investment data for the early part of our period is not driving any of the final results we report.

Appendix 3.B Further empirical results

Table 3.8 Further regression results for All-cause mortality.

	Dependent variable: All-cause mortality rate							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Sanitation capital	-0.151*				-0.069	0.061		
	(0.079)				(0.156)	(0.039)		
Sanitation - Industry interaction	0.244**							
	(0.083)							
Water capital		-0.133*					-0.047	0.049
		(0.069)					(0.156)	(0.035)
Water - Industry interaction		0.218**						
		(0.098)						
Sewerage capital		-0.042					-0.077	0.061
		(0.060)					(0.127)	(0.060)
Sewerage - Industry interaction		0.055						
		(0.047)						
Waterworks employment			0.097					
			(0.073)					
Municipalised water				0.296				
				(0.294)				
Fixed effects	✓	✓	✓	✓	✓	✓	✓	✓
Time effects	✓	✓	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓	✓	✓
R^2	0.895	0.895	0.884	0.821	0.720	0.890	0.720	0.890
Time period	1875-1911	1875-1911	1875-1911	1875-1911	1875-1897	1898-1911	1875-1897	1898-1911
No. observations	592	592	656	672	288	304	288	304
No. towns	16	16	16	16	16	16	16	16

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Dependent variable is All-cause mortality rate per 1,000 population. All coefficients are standardised. Control variables are: Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. Standard errors are clustered at the town level. R^2 calculated for within variation. Regressions are weighted by average population over the period. All variables are measured at the Urban District (UD) level.

Table 3.9 Further regression results for Diarrhoeal mortality.

	Dependent variable: Diarrhoeal mortality rate								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Sanitation capital	0.103**			0.050				0.092	
	(0.047)			(0.095)				(0.081)	
Sanitation - Industry interaction				0.093					
				(0.100)					
Water capital		0.114*	0.086		0.075				0.092
		(0.058)	(0.055)		(0.112)				(0.087)
Water - Industry interaction					0.044				
					(0.125)				
Sewerage capital		-0.059	-0.124		-0.043				-0.034
		(0.129)	(0.118)		(0.140)				(0.132)
Sewerage - Industry interaction					0.054				
					(0.069)				
Water - sewerage interaction			0.106						
			(0.065)						
Waterworks employment						0.077			
						(0.076)			
Municipalised water							0.094		
							(0.173)		
Fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time effects	✓	✓	✓	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓	✓	✓	✓
R^2	0.784	0.784	0.788	0.785	0.785	0.778	0.765	0.836	0.836
Time period	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911
No. observations	592	592	592	592	592	656	672	385	385
No. towns	16	16	16	16	16	16	16	11	11

Notes: Dependent variable is Diarrhoea mortality rate per 1,000 births. All coefficients are standardised. Control variables are: Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. Standard errors are clustered at the town level. R^2 calculated for within variation. Regressions are weighted by average population over the period. All variables are measured at the Urban District (UD) level.

Table 3.10 Further regression results for Infant mortality.

	Dependent variable: Infant mortality rate								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Sanitation capital	0.196^{***}			0.093				0.161	
	(0.055)			(0.086)				(0.096)	
Sanitation - Industry interaction				0.181^{**}					
				(0.077)					
Water capital		0.229^{**}	0.228^{**}		0.177				0.176
		(0.083)	(0.082)		(0.107)				(0.105)
Water - Industry interaction					0.024				
					(0.087)				
Sewerage capital		-0.165	-0.167		-0.148				-0.170
		(0.151)	(0.185)		(0.151)				(0.152)
Sewerage - Industry interaction					0.162^{**}				
					(0.071)				
Water - sewerage interaction			0.002						
			(0.081)						
Waterworks employment						0.211^{*}			
						(0.100)			
Municipalised water							0.417^{*}		
							(0.211)		
Fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time effects	✓	✓	✓	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓	✓	✓	✓
R^2	0.770	0.777	0.777	0.775	0.781	0.769	0.747	0.826	0.832
Time period	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911	1875-1911
No. observations	592	592	592	592	592	656	672	385	385
No. towns	16	16	16	16	16	16	16	11	11

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: Dependent variable is Infant mortality rate per 1,000 births. All coefficients are standardised. Control variables are: Tax base, Population growth, Female, Age 0-14, Age 15-44, Birth rate, Manufacturing employment, and Textiles employment. Standard errors are clustered at the town level. R^2 calculated for within variation. Regressions are weighted by average population over the period. All variables are measured at the Urban District (UD) level.

Table 3.11 Regression results showing the impact of variables' spatial consistency and frequency for different mortality rates.

	All-cause		Diarrhoeal		Infant	
	(1)	(2)	(3)	(4)	(5)	(6)
Loans square root	0.045 (0.123)	-0.226 (0.132)	-0.103 (0.145)	-0.355 (0.324)	0.081 (0.127)	-0.124 (0.202)
Fixed effects	✓	✓	✓	✓	✓	✓
Time effects	✓	✓	✓	✓	✓	✓
Controls	Chapman	Chapman	Chapman	Chapman	Chapman	Chapman
R^2	0.813	0.941	0.733	0.797	0.719	0.803
Geographical units	UD	RD	UD	RD	UD	RD
Frequency	Annual	Decennial	Annual	Decennial	Annual	Decennial
Decline explained	-4	21	16	44	-8	17
Time period	1870-1911	1861-1910	1870-1911	1861-1910	1870-1911	1861-1910
No. observations	657	77	657	77	657	77
No. towns	16	16	16	16	16	16

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: All-cause mortality is rate per 1,000 population. Diarrhoeal and Infant mortality rates are per 1,000 births. 'Chapman controls' variables are: Tax base square root, Population, Female, Age 0-14, and Age 15-44. All coefficients are standardised. Standard errors are clustered at the town level. R^2 calculated for within variation. All regressions are unweighted.

Chapter 4

The Meaningful Votes: Voting on Brexit in the British House of Commons

Abstract

Why do politicians rebel and vote against the party line when high stakes bills come to the floor of the legislature? To address that question, we leverage the three so-called Meaningful Votes that took place in the British House of Commons between January and March 2019 on the Withdrawal Agreement that the Conservative government had reached with the European Union. The bill was defeated decisively three times following a major revolt amongst Conservative backbench Members of Parliament (MPs). We find that three factors influenced their rebellion calculus: the MP's own ideological views, constituency preferences and career concerns. Somewhat paradoxically, the rebellion within the Conservative Party came from MPs who had supported Leave in the 2016 Brexit referendum and from MPs elected in Leave-leaning constituencies.

Keywords: Brexit, roll call votes, rebels, party discipline, party coherence, House of Commons

JEL codes: D72

4.1 Introduction

In January 2019 the United Kingdom's Conservative government led by Prime Minister Theresa May suffered the worst defeat ever recorded in the history of the House of Commons. Its flagship policy, leaving the European Union (EU) in a way that compromised between the polarized "Hard Brexit" and "Remain" factions in Parliament, was defeated by 432 to 202 votes, a majority of 230. The principal reason for the defeat was a huge rebellion by 118 Conservative Members of Parliament (MPs). In March the government held two further votes, on the same policy, and again lost by large margins: 149 and 58. Two months later the Prime Minister announced her resignation.

Those three so-called Meaningful Votes on May's Withdrawal Agreement rank among the great votes of British parliamentary history. They echo the vote on the repeal of the Corn Laws, which put an end to trade protection of agricultural products and split the Tory party in 1846 (Schonhardt-Bailey, 2006), and also the Great Reform Act, which altered the system of parliamentary representation in 1832, with Tory MPs who broke the party line playing a pivotal role (Aidt and Franck, 2013; Aidt et al., 2019). It is historically very rare for a UK government to lose with more than 100 votes on a key piece of legislations. The last time was in 1924, when the minority Labour government of Ramsay MacDonald was defeated by margins of 166, 161 and 140.

In this paper, we seek to explain why Conservative MPs rebelled and understand what drove their individual decisions not to toe the party line. We argue that the three Meaningful Votes potentially can provide valuable general insights into why MPs rebel against their leaders and why the organizational structures and mechanisms that normally ensure party discipline and unity occasionally break down, resulting in the government being "rolled" and losing important votes. The sequence of Meaningful Votes has at least four appealing features that allow us to do just that. First, as already noted, it is rare that a high stakes government bill is defeated so decisively. Second, it was not a so-called free vote on which the party leaders allow their co-partisan MPs to vote as they like. On the contrary, both the Conservative Party and the Labour Party "whipped", demanding that MPs toe the respective party lines. It thus was not costless for MPs to rebel. Third, as a consequence of the 2016 Brexit referendum, we, uniquely, observe revealed preferences on the question of leaving the EU for each MP (we know how they voted and campaigned) and for their voters in each of Britain's 650 parliamentary constituencies (we know the shares voting Leave and Remain). Fourth, the MPs effectively voted on the same bill three times, which also is highly unusual. That information enables us to develop an innovative test of career concerns.

The purpose of the paper is, therefore, two-fold. First, we want to document the correlates underlying the mass rebellion against the Withdrawal Agreement (May's deal) inside the Conservative Party. Second, we want to leverage the unique features of the sequence of Meaningful Votes to test the "tripartite model" of party rebellion (Muller and Strom, 1999). The model, which we outline in Section 4.4, postulates that an MP's voting decision is a function of three potentially conflicting factors: the MP's own preferences (his or her ideology), political career concerns, and the preferences of their constituents. The fact that we observe plausible proxies for the revealed preference of the MPs and their constituents enables us to contribute to the extensive literature on party discipline and rebellion (see Kam, 2014; Kirkland and Slapin, 2018).

Our inquiry into the rebellion amongst Conservative backbench MPs yields the following insights. First, we find evidence that MPs were influenced by their own preferences, career concerns and constituency preferences, but that their own preferences were almost twice as important as the other two factors. Specifically, MPs who had voted and campaigned against leaving the EU in the referendum (Remain MPs) were almost 40 percentage points more likely to support May's deal than other (Leave)

MPs, while MPs representing constituencies with (one standard deviation) more Leave voters were 17 percentage points less likely to support the deal. MPs mindful of their career prospects under a May government were about 20 percentage points more likely to support May's deal. We also present (suggestive) evidence that the prospect of promotion to posts in a *future* government motivated the MPs. Somewhat paradoxically, the rebellion within the Conservative Party that defeated May's deal in the House of Commons three times in a row originated from MPs who had supported Leave in the referendum and from MPs elected in Leave leaning constituencies. Second, we find that the effects are heterogeneous across different sub-samples of MPs in theoretically interesting ways. MPs elected to safe seats placed more weight on career concerns than MPs elected in marginal seats who placed more weight on constituency preferences in their rebellion calculus. Leave MPs but not Remain MPs were motivated by constituency preferences. This conclusion is consistent with two types of grandstanding: Leave MPs could signal "ideological purity" to their Leave voters by opposing May's deal; Remain MPs could pander to their Leave voters by "converting" and voting for May's deal. MPs with a history of rebellion did not weight career concerns differently from party loyalists in their voting calculus.

The rest of the paper is organized as follows. Section 4.2 offers a short literature review that places our study in context. Section 4.3 sets out the background to the three Meaningful Votes. Section 4.4 presents the "tripartite" model of partisan rebellion. Section 4.5 presents the data. Section 4.6 explains our estimation strategy. Section 4.7 presents the results. Section 4.8 concludes.

4.2 Literature review

Our analysis of the sequence of Meaningful Votes contributes to two main strands of literature. First, we contribute to the literature on party discipline and roll call rebels (for overviews, see Kirkland and Slapin (2018) or Kam (2014)). The central question in that literature is why individual politicians decide to defy the political party to which they belong and vote against the party's agreed policy in roll call votes or parliamentary divisions (as they are known in the UK). Krehbiel (1993) views rebellions as a competition between politicians' ideological preferences, their concern about re-election, and their loyalty to their party. Loyalty may, in turn, be induced by political career concerns (Muller and Strom, 1999) or through a process of political socialization (Crowe, 1986). We build on that theoretical framework. Empirical work has focused on the United States where roll call rebellion is widespread and it is common for moderate legislators to "cross the aisle" (e.g., Kirkland and Slapin, 2018). However, in spite of greater party discipline in many parliamentarian systems, it is not uncommon for individual "backbench" politicians (i.e., those with no positions in government) to revolt against their party in many other countries too (e.g., Morgenstern, 2003; Hix et al., 2007; Carey, 2008; Kam, 2009; Kauder et al., 2017). Unlike in US politics, however, in the United Kingdom and elsewhere dicipline-breakers tend to be politicians with ideologically extreme views (Kam, 2009), and they belong mainly to the governing party (Kirkland and Slapin, 2018). The available evidence suggests that voters pay some attention to how their representatives vote, at least when the issue is controversial, and that they reward them for rebelling (e.g., Pattie et al., 1994; Longley, 1998; Johnston et al., 2002; Bertelli and Dolan, 2009; Vivyan and Wagner, 2012; Campbell et al., 2019). The evidence also shows that career concerns play a role (e.g., Benedetto and Hix, 2007; Eggers and Spirling, 2018) although the evidence on whether parties actually punish individual politicians for voting against the party line is mixed (Eggers and Spirling, 2016; Kauder et al., 2017). We contribute to that empirical literature by studying how ideology, career concerns and voter preferences shaped the pattern of rebellion within the Conservative Party in the British House of Commons on an especially high stakes bill. In particular, we are able to leverage the fact that we have plausible measures of both MP and voter preferences on the issue to evaluate the relative importance of the three forces that generally influence a politician's decision to rebel.

Second, our analysis contributes to the fast emerging literature on the causes of the Brexit referendum result itself.[1] Becker et al. (2017), Arnorsson and Zoega (2018), Zhang (2018) and Fidrmuc et al. (2019) use aggregate vote share results at the local authority, constituency or ward level to study the socio-economic correlates of the Leave vote share. Four groups of correlates were important. The first group includes indicators of socio-economic deprivation. The Leave vote share was high in areas with low levels of education, low incomes, historical reliance on manufacturing employment, and high unemployment rates (Becker et al., 2017). The second group includes demographic factors. Areas with large proportions of British male adults and with high proportions of elderly voters predominately voted Leave (Zhang, 2018). The third group of correlates relates to immigration, which played an important role for the rhetoric of the referendum campaign. Areas with high net immigration were more likely to vote Leave (Arnorsson and Zoega, 2018). The final group of correlates relates to the direct benefits an area has received over the years from the EU's Cohesion

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[1] See Clarke et al. (2017) for a comprehensive analysis of the Brexit referendum and its background.

Fund.[2] Areas that received more money from the Cohesion Fund were moderately more supportive of Remain, but this effect is dwarfed by the fact that those areas had low turnouts in the referendum (Fidrmuc et al., 2019).

It is, of course, always a danger trying to infer individual vote intentions from aggregate vote share data (the ecological fallacy), so the correlations should be interpreted with caution. A better approach is to examine individual-level survey data and a number of studies have done so previously. They largely confirm what the correlations reported above suggest. Alabrese et al. (2019), for example, find that voting Leave is associated with older age, white ethnicity, low educational attainment, infrequent use of smartphones and the internet, receiving public benefits, adverse health, and low life satisfaction. Others have found that negative attitudes towards immigration increases the probability that an individual voted Leave (Arnorsson and Zoega, 2018) and that the generational divide – younger individuals are less Eurosceptical than older ones – reflects a combination of individuals' experience of the EU during their formative years and differences in access to education for different generations (Fox and Pearce, 2018). Another approach to understanding why many voters supported Leave in the referendum is to study support for the United Kingdom Independence Party (UKIP)– a single-issue party that since the 1990s has campaigned for the United Kingdom to leave the European Union. Using within individual variation in exposure to welfare cuts, Fetzer (2019) shows that individuals were more likely to "feel close" to UKIP after they were affected personally by the government's austerity program. Insofar as UKIP support is a good proxy for how an individual voted in the 2016 referendum, the results suggest that austerity played a major role in bringing about the referendum result. In conclusion, the evidence, both from the analysis of aggregate vote share data and from the analysis of individual vote choices, suggest that socio-economic deprivation, austerity, demographics, and attitudes to immigration contributed to the referendum result favoring Leave. We add to that literature by studying another aspect of the Brexit process – the sequence of Meaningful Votes. This provides new insights into the link between the referendum result in particular constituencies and the ways in which the MPs elected in those constituencies behaved in Parliament.

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[2] The Cohesion Fund redistribute funds from the EU budget to Member States whose Gross National Income (GNI) per inhabitant is less than 90% of the EU average. It aims at reducing economic and social disparities.

4.3 The narrative: what actually happened?

The relationship with Europe has been a major issue for the UK's center-right Conservative Party for the past 50 years. The UK joined the EU in 1973 under a Conservative government, but with a broad base of political support: in a 1975 referendum on EU membership 67% of voters and all major political parties supported joining.[3] However, over the next 40 years, the EU moved from being primarily a trading bloc, to a much closer economic and political union. That process was bitterly, but unsuccessfully, opposed by a minority of Conservative Party MPs, especially in the early 1990s when the Maastricht Treaty (an expansion of EU powers with a corresponding loss of UK sovereignty) came into force (Sowemimo, 1996). In parallel to those events, a minority of generally right-leaning voters favoured leaving the EU. Support for that position grew in response to migration from Eastern European countries that joined the EU from 2004 onwards. The United Kingdom Independence Party (UKIP), a single issue party advocating the UK's departure from the EU, began to gain significant support, principally at the expense of the Conservative Party: in EU Parliamentary elections, UKIP came third in 2004, second in 2009 and first in 2014 (e.g., Clarke et al., 2016).

In an attempt to both neutralize growing voter support for UKIP and deal with internal divisions in the Conservative Party, Conservative Prime Minister David Cameron offered a referendum on EU membership as part of his re-election campaign in 2015, alongside an attempt to renegotiate the UK's relationship with the EU.[4] In the short run, the policy was a successful: somewhat against expectations the Conservatives won the 2015 election and UKIP support collapsed. In order to achieve Cameron's second aim of mending divisions within the Conservative Party, he allowed his MPs to campaign for either side in the 2016 referendum, rather than requiring them to toe the party line and support continued membership in the EU ("Remain"). A significant minority of both backbench and frontbench, i.e., those serving in the government, Conservatives campaigned subsequently for exiting the EU ("Leave"). The referendum was held on 23 June 2016, and resulted in an unexpected victory for Leave, with 52% of the vote (and considerable geographic and demographic heterogeneity; see Becker et al. (2017)). Cameron resigned immediately, and was replaced as Prime Minister

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[3] At the time the bloc was called the EEC (European Economic Community), becoming the EU in 1993. For simplicity this article uses EU throughout.

[4] Bernholz et al. (2004) propose a reform of EU institutions that would protect the subsidiarity principle and create effective checks and balances by breaking the Commission's agenda monopoly. If that proposal had been adopted in the mid-2000s, the critique levied against the EU by many British euro-sceptics regarding the risk of an EU super state and democratic deficits would have been answered.

by Conservative MP Theresa May, who began the process of withdrawing from the EU. Under EU law, a member state can leave the union by triggering Article 50 of the Lisbon Treaty. That provision gives that member state up to two years to negotiate a Withdrawal Agreement with the EU, which sets out the terms under which it leaves (covering everything from future customs arrangements to past pension liabilities). If no agreement is in place at the two-year deadline, the member state can leave without an agreement, or can ask for an extension of the negotiating period, during which the country remains part of the EU.

Over the course of the two-year UK-EU negotiation of the Withdrawal Agreement, divisions within the Conservative Party deepened. On one side, many Leavers became "Hard Brexiteers", such as senior government minister Boris Johnson and members of the European Research Group (ERG), who increasingly favoured a policy of little or no future cooperation with the EU ("no deal"). On the other side, a smaller group of former Remainers favored a "Soft Brexit", a close future relationship with the EU resembling full membership. In November 2018, the final Withdrawal Agreement was struck between May and the EU. Although that did not specify all aspects of the future UK-EU relationship, generally speaking it was a compromise somewhere between Hard and Soft Brexit. Over the course of the negotiations, Johnson and several other high profile Hard Brexiteer government ministers resigned in protest at compromises made by May.

The final step was for Parliament to pass the Withdrawal Agreement. That requirement itself was the result of an earlier parliamentary setback for May, when MPs succeeded - against the wishes the government - in securing a "Meaningful Vote" on whatever terms the UK eventually left the EU on. Five full days of parliamentary debate were set aside, with the vote to be held on 11 December 2018. The Whips, MPs whose jobs it is to ensure internal party discipline, worked hard to persuade potential rebels to back the government. The main tool at their disposal is the prospect of future promotion in government. Over the course of the debate, it became clear that May was not going to win the vote, so she delayed it to 15 January 2019, in an attempt to buy more time in which to persuade potential rebels. That strategy was not successful: the first Meaningful Vote was lost by the government by 432 to 202 votes, a majority of 230, representing the most serious defeat of a UK government in the history of Parliament.

Table 4.1 shows the breakdown of MPs' votes on the three Meaningful Votes by party (panel A) and for the Conservative Party between front- and backbenchers (panel B). From these data, we see that a number of factors contributed to May's

Table 4.1 Breakdown of Meaningful Votes by Party & Govt. Positions

	First Vote			Second Vote			Third Vote		
	For	Against	Abstain	For	Against	Abstain	For	Against	Abstain
Panel A - Vote by Party									
Conservative	196	118	3	235	78	4	277	37	3
Labour	3	248	5	4	247	5	6	243	7
LD	0	11	0	0	11	0	0	11	0
SNP	0	35	0	0	35	0	0	34	1
DUP	0	10	0	0	10	0	0	10	0
Other	3	10	8	3	10	8	3	9	9
Total	*202*	*432*	*16*	*242*	*391*	*17*	*286*	*344*	*20*
Panel B - Conservatives by Govt. Position									
Frontbench	93	0	2	93	0	2	93	0	2
Backbench	103	118	1	142	78	2	184	37	1
Total	*196*	*118*	*3*	*235*	*78*	*4*	*277*	*37*	*3*

Note: Frontbench MPs hold government posts; backbench MPs do not. SNP is the Scottish National Party; DUP is the Democratic Unionist Party; LD is the Liberal Democrats. The four Conservative MPs who abstained were the two Whips, the Deputy Speaker and, in the second vote, MP Douglas Ross (who ended up voting with the government in the third vote); the Whips served as Tellers and, as such, they are not counted in the totals of those voting for or against a motion and we include them amongst those who abstained; the Speaker and the Deputy Speaker traditionally abstain on all votes. We record the MPs as belonging to the party that they belonged to in January 2019 (before the first Meaningful Vote), but note that ten MPs (three Conservative MPs and seven Labour MPs) resigned from their respective parties between the first and the second Meaningful Vote. For the purpose of the statistical analysis, it does not make any difference if we eliminate the three Conservative MPs who resigned from the sample for the second and third vote.

defeat. The Democratic Unionist Party (DUP) - a socially conservative, pro-Brexit, Northern Irish party - which had agreed to support the Conservative government (having its majority in the 2017 general election), but rebelled because in their view the Withdrawal Agreement treated Northern Ireland differently to the rest of the UK (related to the so-called Irish backstop problem). Very few pro-Brexit MPs from the center-Left opposition Labour Party ended up supporting the government.[5] The centrist Liberal Democrats (LD) and center-left Scottish National Party (SNP) opposed the government unanimously, but that opposition had been anticipated. By far the main factor behind May's defeat was the huge scale of the rebellion by her own backbench MPs. The frontbenchers with government posts, on the other hand, toed the line and none of them rebelled (Table 4.1, panel B).

After the vote, the EU refused to renegotiate the Withdrawal Agreement; under Article 50, time was running out before the UK would either have to ask for an extension (politically very costly for the Conservatives) or leave without a deal (economically very costly for the country). May, therefore, held a Second Meaningful Vote on 12 March 2019, essentially a repeat vote on the policy that had been rejected two months before (some minor changes in interpretation of certain aspects of it were introduced). May and her Whips worked hard to persuade rebel Conservative MPs, but again unsuccessfully: the government lost by 391 to 242 votes, a majority of 149. Following that defeat, she asked the EU for an extension, rather than leaving with no deal at end of March.

On the day the UK originally was supposed to leave the EU, May held a Third Meaningful Vote, again on essentially the same Withdrawal Agreement. She and her Whips made a final push to persuade rebels, increasingly with the threat to Hard Brexiteers that Brexit may not happen at all if the Withdrawal Agreement was not passed. Again, the government lost, although it cut its margin of defeat, from 344 to 286 votes, a majority of 58. Boris Johnson was the most prominent rebel to change his mind, and vote with the government for the first time on that final vote.

Immediately after losing the third vote, May had to ask the EU for another extension of Article 50, a further major political humiliation. In local and EU elections in May 2019, the Conservatives did exceptionally badly. With the central policy of the

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[5] Some predictions at the time of the first vote had up to 30 Labour MPs intending to vote with the government. More generally, Brexit has produced serious internal divisions in the Labour Party, although they did not have a major impact on the Meaningful Votes. Hence, this article focuses on the Conservative Party.

government in disarray and her party falling apart, the Prime Minister announced her resignation on 24 May 2019.[6]

Johnson, the frontrunner to replace May among Conservative Party members (who select the party leader), won the ensuing leadership contest and became Prime Minister in July 2019. A proponent of Hard Brexit, he replaced much of May's relatively balanced government with a group of Hard Brexiteers in all of the most senior government posts. Johnson negotiated some changes to the Withdrawal Agreement concerning the Irish backstop, and on 22 October 2019 MPs passed a second reading of the resulting bill by a majority of 30. However, they also voted down Johnson's attempt to rush through the legislation in time for him not to have to extend the UK's membership of the EU past 31 October (politically costly for Johnson after his 'do or die' commitment to leaving before that date). Hence, Johnson pushed for and eventually obtained a general election on 12 December 2019. The parliament that rejected May's deal three times, therefore, never got a chance to have a final say on Johnson's deal: passing a second reading does not indicate that the bill necessarily would have become law. Many MPs who voted for it at the second reading, for example, were said to be planning amendments radically to soften the deal in ways Johnson had categorically ruled out.

4.4 Theoretical framework

In this section, we develop a theoretical framework that explains why politicians (henceforth MPs) may decide to vote against their own party's policy, and which we use to structure our empirical investigation of the Meaningful Votes. For that reason, we formulate the framework with reference to the Westminster system. This system is charaterized by a high level of party unity in general, a clear government-opposition divide, agenda control monopolized by the Cabinet within the governing party, and MPs elected in single-member districts with local party organizations having significant input into who is selected to represent the constituency (e.g., Baughman, 2004).[7]

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[6] Three major aspects of the breakdown the Conservative party's unity were the following. May suffered a large number of resignations of both junior and senior ministers: from 11 June 2017 onwards, 33 ministers resigned over Brexit. Four Conservative MPs also defected from the party over Brexit, either to new parties or to sit as independents. On 11 December 2018, the day the first Meaningful Vote originally was to be held, Theresa May faced an internal Conservative Party vote of No Confidence, brought by Hard Brexit ERG (European Research Group) members, which she defeated.

[7] Broader legislative institutions and party structures help shape the costs and benefits for politicians to deviate from the party line, along with the constraints that party leaders face in creating party coherence (Krehbiel, 1993). The differences, for example, between a Westminster-type system and a US-type system often are emphasised (Gaines and Garrett, 1993). Stratmann (2006) leverages the

MPs are members of political parties and are elected under those party labels and on the party manifesto. The members share policy preferences and have common goals, but only up to a point. Within a party, in general, substantial preference heterogeneity on particular issues exists, with extreme and moderate MPs both belonging to the same party. Such heterogeneity creates a fundamental tension for party members between supporting the party's policy (selected by the party leadership), which will appeal to some but not to all, and pursuing their own preferred policy. Party leaders are, of course, well aware of that tension and will seek to devise incentives and rules to enforce party discipline, create party coherence and avoid mass rebellion on critical bills (Kam, 2014). Party leaders can, in principle, pursue that goal by controlling the selection of candidates to be fielded (select only candidates who will toe the party line), by controlling the policy agenda (make sure that proposals are agreeable to most party members), by fostering socialization (Crowe, 1986), and by sharing and withholding the perks of public office strategically.

Building on Muller and Strom (1999)'s tripartite model, we make a distinction between three factors that affect an MP's decision to rebel against his or her party. The first consideration is *ideology*: MPs care about policy and their position on a particular issue often deviates from the party's official stance. That gap may motivate an MP to rebel. The second consideration is *career concerns*: MPs usually want a legislative career. In the Westminster system, where agenda control is monopolized by the Cabinet, political promotion is about government posts for members of the governing party and about posts in the shadow cabinet for opposition MPs. Such allocation procedures make rebellion costly for backbenchers as well as for frontbenchers (those with government or shadow government posts) because party leaders can withhold promotion for rebellious backbenchers and demote frontbenchers who do not toe the line.[8] The third consideration is *constituency preferences* and re-election. In the Westminster system, MPs are elected to represent the voters in their constituency. As

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mixed plurality and proportional election system in Germany to show that federal politicians who are elected under plurality rule from single member districts are more likely than those elected on a party list under proportional representation to vote against party lines in roll call votes. For a comparative study of the UK and the US, see Kirkland and Slapin (2018) and for a study of the European Parliament see Benedetto and Hix (2007). For a study of the consequences of government ideology, see Aidt et al. (2018).

[8] Bertelli and Dolan (2009) present evidence from intervention in House of Commons's debates related to health care that is consistent with political careerism. The evidence on whether party leaders in actual fact punish rebels by denying them promotion is mixed. Eggers and Spirling (2016) study over 20,000 parliamentary divisions that took place between 1836 and 1910 in the British House of Commons and show that more loyal MPs were more likely to obtain ministerial posts. In contrast, Kauder et al. (2017) study 218 roll call votes in the German federal parliament (Bundestag) and ask if rebels are punished by party leaders by being allocated a less attractive position on the party list in

argued by, for example, Gaines and Garrett (1993), Kirkland and Slapin (2018), Kam (2009) and many others, MPs in that system have an incentive, albeit not necessarily as strong an incentive as US legislators, to develop a persona independent of their party that connects them with their constituents and their local party organization. They can do so publicly by deviating from their party's policy on issues that their voters and selectors in the local party organization care particularly about in parliamentary divisions. Such grandstanding signals their ideological purity, integrity or trustworthiness, gets them media exposure and can potentially insulate them from the electoral unpopularity (in their constituency) of the party's policy.[9]

Within the public choice tradition, MPs are viewed as rational decision makers who need to navigate the foregoing three considerations when they decide if they should rebel on a particular issue. More often than not, the forces pull in different directions and MPs find themselves in the cross fire at the center of a triangle with their voters, their ideological conviction, and their party (Hix et al., 2007; Morgenstern, 2003; Saiegh, 2011). Figure 1 illustrates this tripartite model of roll call voting.

The costs and benefits of rebellion differ systematically between the governing and opposition parties on the one hand, and within the governing party (or coalition) between the frontbenchers with government posts and backbenchers without on the other. First, with regard to the government-opposition split, Kirkland and Slapin (2018) argue that it is MPs with *extreme* preferences (far from the center) within the governing party that stand to benefit the most from rebellion. That is because they can signal to their constituents that they are "ideologically pure" by voting against the party line and expect to be rewarded electorally for it. For opposition MPs, the incentive to break the party line to signal "ideological purity" is weaker. Assuming that the opposition policy will vote against the government's policy, neither extreme nor moderate (who are relatively close to the center) opposition MPs are likely to gain electorally by breaking the party line because most of their voters would, in fact, prefer the opposition party's official policy stance to that of the government. All rebels, of course, face the cost of the disciplinary actions taken by their party leaders in response, but the benefit of rebellion between the party of government and the opposition clearly

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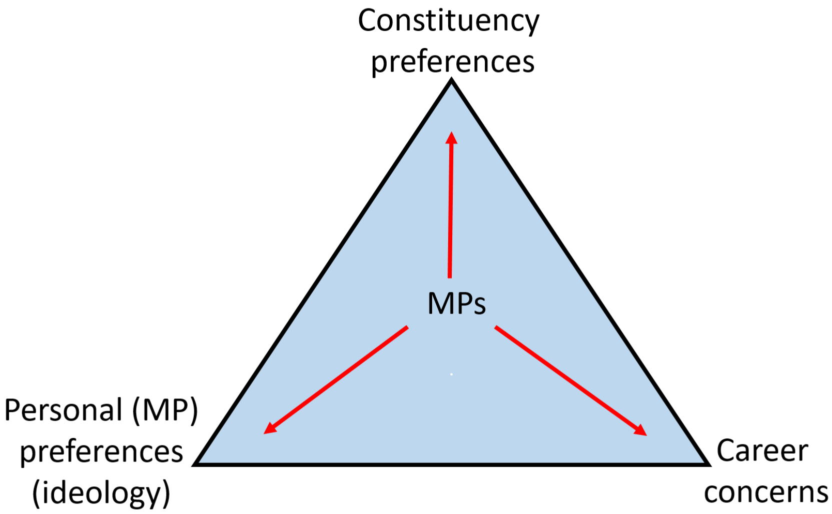
the next election. They find that parties do not punish politicians who have voted against the party line in that way.

[9] Campbell et al. (2019) and Vivyan and Wagner (2012) present evidence from the UK that deviating from the party line can help MPs seeking re-election. Pattie et al. (1994) show that rebellion on high profile issues, such as capital punishment or the poll tax, had affected re-election prospects of the rebels, but otherwise they find no discernible consequences. Ragusa (2016) shows that US legislators take more extreme positions if they won election to the Senate after representing a highly partisan state.

is asymmetric. That logic is consistent with the fact that it is MPs with extreme views that tend to rebel in the House of Commons and that MPs from the governing party are more likely to rebel than MPs from the opposition (e.g., Benedetto and Hix, 2007; Kirkland and Slapin, 2018).

Second, the within-party difference between front- and backbenchers is important and arises from the fact that frontbenchers have much more to lose from rebelling (their perks and posts, the ability to formulate policy and so on). Backbenchers also have to mind their political careers, but those who have been “passed over” for political promotion or those who have been demoted from the frontbench previously have less to lose (Kam, 2009). That logic suggests that it is amongst “old” backbenchers that most rebels can be found. The cause of a backbench revolt by that group of MPs may not just be that they are unhappy with the party’s policy, but also may be because they hope to destabilize the leader under whom their political careers have stalled. Such considerations give rise to two distinct career motives. On the one hand, MPs can promote their careers by pleasing the current leadership of their party *if* the leadership is sufficiently stable to justify the expectation of future rewards for good behaviour. On the other hand, MPs can promote their careers by destabilising the current leader of their party and encouraging a leadership challenge. If successful, the revolting MPs reasonably may expect to be rewarded by the new leader.

Figure 4.1 MPs in the crossfire: The tripartite model



Notes: Own illustration.

4.5 The data and operationalization

Our objective is to study how MPs resolved the tension among their personal ideological views, career concerns and constituency preferences in the context of the three Meaningful Votes on May's deal. The raw numbers (reported in Table 4.1) clearly show that party cohesion was strong among all opposition parties. All but six opposition MPs in the first Meaningful Vote and nine in the third toed their respective party lines.[10] An implication, then, is that the rebellion that defeated May's deal three times in a row took place within the governing Conservative Party.[11] Our focus is, therefore, on the 317 Conservative MPs. We have recorded how each of them voted in the three Meaningful Votes and coded the indicator variable *VOTE* as one if the (Conservative) MP supported the Withdrawal Agreement, voting with the government, and zero if the MP rebelled by voting against.

While, theoretically, the three factors of the tripartite model – ideology, career concerns and constituency preferences – are distinct, in practice they often overlap and it is a challenge to measure them independently. With that caveat in mind, we now explain how we operationalize and measure those factors. First, we operationalize the MPs' ideological positions on the Brexit question by how they voted and campaigned in the 2016 referendum on leaving the European Union. For Conservative MPs, the referendum, arguably, was a "free vote" on which the MPs could vote and campaign as they liked. The official policy of the Cameron government that had called the referendum was to vote Remain, but many leading Tory MPs – most notably Boris Johnson and Michael Gove – campaigned to leave. We code the dummy variable *REMAIN MP* as one if the MP voted and campaigned for remain in the referendum and zero otherwise. We argue that such an *expressed* preference is a good measure of each MP's personal judgment of the merits of leaving the EU.[12] However, we acknowledge that how the MPs voted in the referendum can, in principle, also reflect career concerns and constituency preferences. In our judgment, it is unlikely that many

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[10] Dewan and Spirling (2011) develop a game theoretical argument for why opposition parties are able to act coherently in spite of the temptation of some of their MPs to support the government's policy. The source of such strategic opposition is that if the opposition as a block vote against the government (and no opposition MP deviates from that), it can force the government to propose a more moderate policy than otherwise and that outcome is in the interest of all opposition MPs.

[11] The "rebellion" by the 10 MPs from the Democratic Unionist Party (DUP) upon which May's government relied on for a parliamentary majority also was important but not pivotal.

[12] Moreover, it is plausible to argue that most of them were voting socio-tropically, i.e., were thinking about what, in their view, was best for the country, rather than ego-tropically, i.e., were thinking about the private benefit that they would derive from the result. See Nannestad and Paldam (1994) and Lewis-Beck and Stegmaier (2013) for a discussion of the distinction between ego- and socio-tropic voting.

Conservative MPs viewed their position on the referendum question as a career move. It was widely expected that the Remain side would win and the Cameron government was unlikely to reward or punish the MPs the stance they took, as Cameron had called the referendum, at least partly, to settle the "Europe question" within the Conservative Party once and for all. It is harder to dismiss the possibility that a significant number of MPs (who did not have strong views on the issue of Europe) chose their positions to match the (perceived) preferences of their constituents. If that were the case, we would expect to find a strong correlation between an MP's position and that of his or her constituents. In fact, the correlation between the leave stance of the MPs and the Leave vote share of their constituents is just 0.129. That correlation does, of course, not rule out that the dummy variable *REMAIN MP* captures a mixture of personal and constituency preferences. To bolster our interpretation of the variable, we exploit in a robustness check that Theresa May called a general election in 2017 and that we can make a distinction between (current) MPs who were elected before (in 2015) and after (in 2017) the referendum. It is reasonable to expect that constituency preferences played little role in the stances taken by the "MPs" who did not get elected until after the referendum; for them, the expressed preference in the referendum is a reflection of their personal views. We also stress that we condition on a host of constituency characteristics and on the share of leave voters in the estimations. That strategy helps isolate the variation in *REMAIN MP* that represents the MPs' personal preferences from the variation that may relate to constituency preferences.

Second, to operationalize career concerns, we make a distinction between "junior" and "senior" backbenchers, on the one hand, and between backbenchers and members of the government (frontbenchers) on the other. As discussed above, the group of "senior" backbenchers, i.e., those with long parliamentary tenures, consists of two sub-groups: one group has been "passed over" for government jobs previously and have little prospect of ever getting one under the current Prime Minister; the other consists of MPs who previously have served in government but have resigned or been dismissed. Either group has little to lose from rebellion because what the government and its Whips can do to sanction them for such behavior is limited since they have little chance of promotion under the current leadership. They are, therefore, *ceteris paribus* more likely to rebel than "junior" MPs who are newly elected to their seats and who are particularly concerned with their political career prospects under the current leadership. On top of that, if the power base of the current leadership inside the party is fragile, then MPs may anticipate that if they rebel, the current leadership eventually will fall and a new Prime Minster will be appointed. Likely, the new leader will replace most of the old frontbenchers and promote MPs from the backbench. Consequently, MPs who think they have a fair chance of being part of a new government have an extra incentive to rebel. However, that strategy, arguably, is more appealing to "senior" than to "junior" backbenchers who hope to get back into government. So, "junior" MPs have two reasons to toe the party line: they fear sanctions from the current government and they do not anticipate rewards from a new government should the current government fall because of rebellion. We code two variables to capture those calculations. The first, *FRONTBENCH*, is a dummy variable coded one if the MP holds a position in government and zero otherwise. The second, *JUNIOR MP*, is a dummy variable coded one if the MP was first elected in either in 2015 or 2017, and zero otherwise.[13] The fact that we observe the same MPs voting on the same policy three times and we observe a change in Prime Minister (from Theresa May to Boris Johnson) opens a window of opportunity for a more refined test of career concerns related to destabilizing the current leader. We return to that issue in Section 4.7.2.

Third, the Brexit situation provides a unique opportunity for measuring the constituency preferences since we know, in the aggregate, how voters in each constituency voted in the 2016 referendum.[14] We code the variable *LEAVE VOTE SHARE* as the fraction of voters in each constituency who voted Leave in the referendum.

We also have collected information on many other MP and constituency specific characteristics. The constituency specific control variables include population size, the unemployment rate, the share of foreign-born residents, the share of residents with higher education, the age structure of the constituency, and share of public employment, all measured at the parliamentary constituency level. The MP specific control variables include the MP's age, gender and win margin in the 2017 election. We also enter a rebellion index that proxies for the MP's tendency to rebel against his or her own party in the past. We have standardized these data so that all non-binary variables have a standard deviation of one. Appendix A lists and defines all of the variables we use in the statistical analysis and provides details on their sources. Table 4.2 reports summary statistics.

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[13] The most recent previous election was in 2010, so by the time of the Meaningful Votes in 2018 an MP with *JUNIOR MP*=0 had served as an MP for at least eight years, long enough to be considered for a government position.

[14] Given that actual numbers often are not reported at the parliamentary constituency level, we follow the political science literature (see e.g. Heath and Goodwin, 2017) and use estimates constructed by Hanretty (2017).

Table 4.2 Summary Statistics for sample of Conservative Backbench MPs

Variable	(1) N	(2) Mean	(3) Std. Dev.	(4) Min.	(5) Max.
VOTE (Binary)	662	0.648	0.478	0	1
VOTE CHANGE 1-2* (Binary)	118	0.331	0.472	0	1
VOTE CHANGE 2-3* (Binary)	118	0.356	0.481	0	1
Main Determinants					
REMAIN MP (Binary)	222	0.464	0.500	0	1
JUNIOR MP (Binary)	222	0.365	0.482	0	1
LEAVE VOTE SHARE (%)	222	55.1	8.79	25.7	75.0
JOHNSON GOVERNMENT SENIOR* (Binary)	118	0.068	0.252	0	1
JOHNSON GOVERNMENT JUNIOR* (Binary)	118	0.076	0.267	0	1
Constituency Controls					
FOREIGN (%)	222	8.56	6.51	2.40	46.9
POPULATION (No.)	222	99,558	11,238	58,873	140,264
UNEMPLOYED (%)	222	1.59	0.795	0.503	4.81
PUBLIC (%)	222	18.1	6.75	5.60	47.1
EDUCATED (%)	222	27.2	6.94	12.3	55.2
WORKING AGE (%)	222	60.7	2.86	51.4	70.3
MP Controls					
AGE (Yrs.)	222	52.3	10.8	27.0	78.0
FEMALE (Binary)	222	0.176	0.381	0	1
REBELLION (Index)	222	0.723	1.87	0	21.8
WIN MARGIN (pp)	222	22.6	12.8	0.066	49.7

Note: Appendix A lists the definitions of the variables and provides details regarding the sources. Appendix Table 4.10 provides summary statistics for the sample of all Conservative MPs. * These variables are coded for the sub-sample of Conservative backbench MPs who voted against the Withdrawal Agreement in the first Meaningful Vote. See Section 4.7.2 for more details.

4.6 Estimation strategy

We want to estimate the following statistical model:

$$\text{VOTE}_{i,v} = F[\alpha_v + \beta_1 \text{IDEOLOGY}_i + \beta_2 \text{CAREER}_i + \beta_3 \text{CONSTITUENCY}_i + \beta_4 X_i] \tag{4.1}$$

where i is the index for a Conservative MP (and for his or her constituency since all constituencies are single seat), v is the index for the three Meaningful Votes with $v \in \{1, 2, 3\}$ and X_i is a vector of control variables. We want to understand how the three forces – ideology, career concerns and constituency preferences – influence the decision to rebel by voting against May's deal. We use *REMAIN MP* to proxy for ideology, *LEAVE VOTE SHARE* to proxy for constituency preferences and *JUNIOR MP* and *FRONTBENCH* to proxy for career concerns in the main specifications, but consider a number of refinements aimed at validating those three proxies. We estimate equation (4.1) with a probit estimator and, in specifications when we pool the three votes, we cluster the standard errors at the constituency level to account for the fact that we study a sequence of votes.

We know from Table 4.1 that all Conservative frontbench MPs supported the government's Withdrawal Agreement in the three Meaningful Votes. This implies that we cannot include *FRONTBENCH* in the probit specification (the variable predicts the outcome perfectly and is dropped). For that reason, the main analysis is restricted to the sample of Conservative backbenchers where we observe variation in *VOTE*. To compare the effect of the *FRONTBENCH* variable to the others, we estimate a linear probability model on the sample of all Conservative MPs. We also know from Table 4.1 that 81 Conservative (backbench) MPs changed their votes from opposition to support in the sequence of votes. To study why they did so, we estimate a version of equation (4.1) where we replace *VOTE* with either *VOTE CHANGE 1-2* or *VOTE CHANGE 2-3*. Those variables record whether the MPs changed their votes in the second or third Meaningful Vote relative to the position they took in the previous vote, respectively.

4.7 Results

We present the results in three subsections. In Section 4.7.1, we discuss the main results and a validation test of the proxy for the MPs' personal preferences. In Section 4.7.2, we test for career concerns related to promotion to government posts in a future administration. In Section 4.7.3, we investigate heterogeneity in the effects across three dimensions related to electoral competition, history of rebellion, and the MP's personal preferences.

4.7.1 Main results

Table 4.3 reports the main results. Column (1) shows a parsimonious specification without any control variables other than the dummy variables for the three Meaningful Votes, column (2) adds the constituency specific control variables, and column (3) adds MP-specific control variables. We report marginal effects evaluated at the means of the variables. In column (4), we report the results from a linear probability model estimated with Ordinary Least Squares (OLS) wherein we can include all Conservative MPs, including those serving on the frontbench in the sample.

Looking across Table 4.3, we observe that the four variables capturing personal preferences (*REMAIN MP*), career concerns (*JUNIOR MP* and *FRONTBENCH*), and constituency preferences (*LEAVE VOTE SHARE*) are all strongly correlated with MP support for May's deal. The effects are stable across specifications as we add the control variables, except for *LEAVE VOTE SHARE* which is very imprecisely estimated in the parsimonious specification in column (1). That is, perhaps, not so surprising because the constituency specific controls include many of the variables – such as the unemployment rate and the share of highly educated residents in the constituency – which we know are correlated with the share of Leave voters (see, e.g., Becker et al., 2017). Specifically, we find that *REMAIN MP* and the two career concerns variables *JUNIOR MP* and *FRONTBENCH* are positively correlated with the probability of voting for May's deal and that *LEAVE VOTE SHARE* is negatively correlated. That is, MPs who had voted and campaigned against leaving the EU in the referendum were almost 40 percentage points more likely to support May's deal than other MPs, while MPs representing constituencies with (one standard deviation) more Leave voters were 15 percentage points less likely to support the deal. Junior MPs mindful of their career prospects under a May government were about 22 percentage points more likely to support her deal and so were frontbench MPs serving in the government (column (4)). Relatively speaking, ideology (as captured by the MP's revealed preference for membership of the EU) appears to be about twice as important a factor as career concerns and constituency preferences. In sum, we conclude that the rebellion did *not* come from MPs with strong career concerns. That result is in line with previous findings in the literature on roll call rebels (see, e.g., Benedetto and Hix, 2007). Rather, and somewhat paradoxically, rebellion came from MPs who had supported Leave in the referendum and from MPs elected in Leave leaning constituencies.

Table 4.3 The probability of voting for the Withdrawal Agreement in the three Meaningful Votes combined

	Backbencher sample			Full Sample
Outcome: VOTE	(1) Probit	(2) Probit	(3) Probit	(4) OLS
FRONTBENCH	-	-	-	0.329***
				(0.035)
				[0.000]
REMAIN MP	0.379***	0.369***	0.393***	0.264***
	(0.048)	(0.049)	(0.048)	(0.034)
	[0.000]	[0.000]	[0.000]	[0.000]
JUNIOR MP	0.179***	0.145**	0.223***	0.146***
	(0.053)	(0.058)	(0.069)	(0.047)
	[0.001]	[0.012]	[0.001]	[0.002]
LEAVE VOTE SHARE	-0.002	-0.156**	-0.151**	-0.069*
	(0.029)	(0.066)	(0.073)	(0.036)
	[0.949]	[0.017]	[0.038]	[0.063]
Vote Dummies	YES	YES	YES	YES
Const. Controls	NO	YES	YES	YES
MP Controls	NO	NO	YES	YES
N	662	662	662	941
(Pseudo-)R2	0.22	0.25	0.27	0.33

Note: Columns (1)-(3) report Probit estimates (marginal effects evaluated at the mean of the explanatory variables) for the sample of Conservative backbenchers and column (4) reports OLS estimates for the sample of all Conservative MPs. The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero when the MP rebelled by voting against. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency; and *FRONTBENCH* is a binary variable equal to 1 if the MP holds a position in government. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; $^{*}p<0.10$, $^{**}p<0.05$, $^{***}p<0.01$

Table 4.4 reports the results (corresponding to the specification with the full set of control variables in Table 4.3, column (3) for each of the three Meaningful Votes separately. That evidence is important to consider because a significant shift in the scale of the rebellion materialized from 118 Conservative MPs, dropping in the first Meaningful Vote down to 37 in the third. The results are qualitatively similar across the three votes: the marginal effects have the same signs and are, with one exception, statistically significant. Importantly, the tests for whether the marginal effects are the same in the first and third vote reported in column (4), however, show the quantitative importances of ideology and career concerns, but not constituency preferences, weakened over time, in line with the fact that more and more backbenchers rallied behind May's deal as time went on.[15] To illustrate, relative to the first Meaningful Vote, wherein the MPs who had voted Remain in 2016 were 56 percentage points more likely to support May's deal, the marginal effect dropped down to 16 percentage points by the time of the third Meaningful Vote. We also note that the fraction of the variance explained by the three factors (as measured by the Pseudo-R^2) drops from 31% to 17%.

As discussed above, we cannot fully rule out that the estimated marginal effect of *REMAIN MP*, which records the stance of each MP in the 2016 referendum, captures constituency as well as the MP's personal preferences. The fact that we condition on the *LEAVE VOTE SHARE* and, thus, estimate the effect of *REMAIN MP* holding the preferences of the voters in each constituency for leaving the European Union constant militates against that interpretation. Yet, it is important to consider the issue further.

The MPs who voted on the Withdrawal Agreement in the three Meaningful Votes can be divided between those who also were part of the 2015 Parliament and, therefore, were serving as representatives at the time of the referendum, and those who were not members of the past legislative (i.e., those entering the House of Commons in 2017). If the MPs' stances in the referendum were selected strategically to match constituency preferences, we conjecture that the incentive to do so would be much stronger for those who already were MPs at the time of the referendum. After all the MPs elected in 2017 did not know in 2016 that they would be running in a general election shortly after the referendum vote and, thus, their incentive to match their stances with those of future voters arguably is much weaker. For *them*, it stands to reason that the referendum vote does reflect their personal preference.

Given that consideration, we can isolate the effect of the MPs' personal preferences by restricting the sample to the Conservative backbench MPs who did not serve in parliament at the time of the 2016 referendum and test if those who voted Remain are more likely than those who did not to vote for the Withdrawal Agreement. Table 4.5 reports three specifications with different sets of control variables similar to Table 4.3. We see that *REMAIN MP* is statistically significant in all specifications, and that the

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[15] It is not straight-forward to compare coefficient in a non-linear model. We follow Mood (2010) and use a one-sided z-test to calculate, for each variable, if one marginal effect (rather than the raw probit coefficients) is large (smaller) than the other. We use the same procedure in the heterogeneity analysis in Section 4.7.3.

Table 4.4 The probability of voting for the Withdrawal agreement in each of the three Meaningful Votes separately

Outcome: VOTE	(1) 1st Vote	(2) 2nd Vote	(3) 3rd Vote	(4) Diff. p-value
REMAIN MP	0.556***	0.399***	0.158***	0.000
	(0.061)	(0.059)	(0.044)	
	[0.000]	[0.000]	[0.000]	
JUNIOR MP	0.327***	0.209**	0.112**	0.031
	(0.103)	(0.087)	(0.051)	
	[0.002]	[0.016]	[0.027]	
LEAVE VOTE SHARE	-0.150	-0.165*	-0.120**	0.414
	(0.121)	(0.088)	(0.061)	
	[0.217]	[0.061]	[0.048]	
Controls	YES	YES	YES	-
N	221	220	221	-
Pseudo-R2	0.31	0.22	0.17	-

Note: The table reports Probit estimates (marginal effects evaluated at the mean of the explanatory variables) for the sample of Conservative backbenchers separately for the three Meaningful Votes. The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero if the MP rebelled by voting against. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; and *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. The p-value reported in column (4) is associated with the one-sided null hypothesis that the marginal effect of the respective row variable is numerically smaller in the third vote (column (3)) than in the first vote (column (1)). Robust standard errors (in round brackets); p-values are given in [square brackets]; *p<0.10, **p<0.05, ***p<0.01

marginal effect is about 30 percentage points compared to 40 percentage points in the full sample (see Table 4.3). The result bolsters our interpretation of *REMAIN MP* as a plausible proxy for the MPs' personal preferences.

4.7.2 Career concerns and leader replacement

So far we have assumed that the MPs' career concerns are shaped by the ability of the *current* party leadership to reward loyalty and punish rebellion. However, the prospect of a career under a *new* party leader also can be a strong motivator for rebelling against the current leadership, particularly so if its position is perceived to

Table 4.5 The probability of voting for the Withdrawal Agreement for the Conservative backbench MPs not serving in 2016

Outcome: VOTE	(1) Probit	(2) Probit	(3) Probit
REMAIN MP	0.295***	0.286***	0.295***
	(0.103)	(0.093)	(0.105)
	[0.004]	[0.002]	[0.005]
LEAVE VOTE SHARE	-0.066*	-0.148**	-0.084
	(0.037)	(0.065)	(0.082)
	[0.076]	[0.023]	[0.303]
Vote Dummies	YES	YES	YES
Const. Controls	NO	YES	YES
MP Controls	NO	NO	YES
N	104	104	104
Pseudo-R2	0.27	0.33	0.38

Note: The table reports Probit estimates (marginal effects evaluated at the mean of the explanatory variables) for the sample of Conservative backbenchers who did not serve as representatives at the time of the 2016 EU Membership Referendum. Due to limited variation, the variable *JUNIOR MP* is omitted. The other variables are as in the specifications reported in Table 4.3, columns (1) to (3). Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; *p<0.10, **p<0.05, ***p<0.01

be weak and rebellion is a means to weaken it further. In the context of the three Meaningful Votes, it is clear that the position of the May government was fragile. This, combined with the fact that she eventually was replaced by Boris Johnson as Prime Minster, opens up a unique opportunity to test if the backbenchers' vote choices in the Meaningful Votes were influenced by the prospect of a promotion under a future Johnson-led government. To do that, we note two points. Firstly, since Theresa May had "survived" an internal vote of no confidence before the first meaningful vote, it is reasonable to assume that expectations of a change in leadership were lower at the time of the first vote than at the time of the last. This motivates investigating why some Conservative backbenchers *changed* their positions on the Withdrawal Agreement between the first, second and third votes. Secondly, Johnson widely was tipped as the most likely candidate to replace May if her administration were to fall. He announced just before the third Meaningful Vote that he would support it after having voted against in the previous votes.[16] We can use Johnson's PM expectations to test if those MPs who (ex post) got promoted by his new administration were "loyal" to him and also switched their votes when he did. If so, such vote switching would be consistent with the prospect of promotion under a future government being a motivator.

To implement that test, we code the two variables *JOHNSON GOVERNMENT SENIOR* and *JOHNSON GOVERNMENT JUNIOR* which are set equal to one if an MP got a senior (Cabinet) or a junior (non-cabinet) post, respectively, in the Johnson administration. We, then, test whether those variables can predict if the 118 Conservative backbench MPs who voted against the Withdrawal Agreement in the first Meaningful Vote changed the way they voted in subsequent votes. Table 4.6 reports the results. In column (1), the dependent variable (*VOTE CHANGE 1-2*) is a dummy equal to one for MPs who voted against in the first Meaningful Vote and for in the second (zero otherwise). In column (2), the dependent variable (*VOTE CHANGE 2-3*) is a dummy equal to one for MPs who voted against in the second Meaningful Vote and for in the third (zero otherwise). While our results should be interpreted cautiously because of the small sample size,[17] we see that the MPs who were appointed to senior positions in the Johnson administration were 36 percentage points less likely to change their votes between the first and the second vote, but 36 percentage points more likely to switch between the second and the third vote. Those appointed junior positions were not more likely to change their vote than other MPs. That finding is consistent with a "follow Johnson effect" whereby the rebels who anticipated (correctly) that they might get senior posts in a Johnson administration changed their votes when Johnson did. Although other explanations for that pattern are possible, it suggests that career concerns related to rewards by a future leader were salient.

4.7.3 Heterogeneity

We explore three dimensions of heterogeneity in the main results: constituency competitiveness, history of rebellion, and the MP's personal preferences.[18]

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[16] Since the DUP was sure to vote against for a third time, it would have required a major rebellion in the Labour Party to create a majority for the Withdrawal Agreement, even if most of the rebels on the Conservative backbench switched their votes. So, Johnson's change of mind never was likely to make a material difference in the outcome of the vote.

[17] Only about 7% of the backbenchers who voted initially against the Withdrawal Agreement are now part of the Johnson Cabinet.

[18] Methodologically, we study heterogeneity by splitting the sample along the relevant dimension and then test if the marginal effects of the core variables are different in the two sub-samples. An alternative is to introduce interaction terms. However, since we are interested in heterogeneity across many variables, that approach, despite the efficiency gain associated with a larger sample, is inferior for our purposes.

Table 4.6 Voting with Johnson: The probability that the 118 Conservative backbench MPs who voted against the Withdrawal Agreement in the first Meaningful vote subsequently switched their vote

Outcome: VOTE CHANGE	(1) Switch in 2nd vote	(2) Switch in 3rd vote
JOHNSON GOVERNMENT SENIOR	-0.363***	0.362**
	(0.105)	(0.161)
	[0.001]	[0.027]
JOHNSON GOVERNMENT JUNIOR	0.113	0.070
	(0.188)	(0.187)
	[0.550]	[0.712]
REMAIN MP	0.092	-0.028
	(0.111)	(0.108)
	[0.407]	[0.799]
JUNIOR MP	-0.098	0.110
	(0.153)	(0.150)
	[0.523]	[0.463]
LEAVE VOTE SHARE	-0.010	-0.141
	(0.136)	(0.130)
	[0.944]	[0.283]
Const. Controls	YES	YES
MP Controls	YES	YES
N	118	118
R^2	0.17	0.15

Note: The sample is restricted to Conservative backbencher MPs who voted against the Withdrawal Agreement in the first Meaningful Vote. In column 1, the dependent variable (*VOTE CHANGE 1-2*) is a dummy equal to 1 for MPs who voted against in the first Meaningful Vote and for in the second (zero otherwise). In column (2), the dependent variable (*VOTE CHANGE 2-3*) is a dummy equal to one for MPs who voted against in the second Meaningful Vote and for in the third (zero otherwise). The dummy variable *JOHNSON GOVERNMENT SENIOR* is equal to one if the MP was appointed to a senior (Cabinet) position in the Johnson administration (zero otherwise). The dummy variable *JOHNSON GOVERNMENT JUNIOR* is equal to one if the MP was appointed to a junior (non-cabinet) governmental position in the Johnson administration (zero otherwise). The model is a linear probability model estimated with Ordinary Least Squares (OLS). The probit estimates are similar. However, because no MP who got a senior position in the Johnson administration started supporting Theresa May's deal in the 2nd vote, we cannot estimate the specification in column (1) with that estimator. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. Robust standard errors are reported in (round brackets); p-values are given in [square brackets]; $^*p<0.10$, $^{**}p<0.05$, $^{***}p<0.01$

Constituency competitiveness

The relative importance of ideology, career concerns and constituency preferences in an MP's rebellion calculus is likely to be influenced by the competitiveness the MP's seat. An MP elected to a safe seat by a large majority is likely to put more weight on career concerns and ideology than on constituency preferences than an MP elected to a marginal seat. To investigate that hypothesis, we split the sample of Conservative backbench MPs into sub-samples defined by their win margins in the 2017 general election and re-estimate equation (4.1) on these sub-samples. We define a seat as marginal if it is in the bottom 25% of the distribution with win margins below 11 percentage points and safe if it is in top 50% of the distribution with a win margin above 23 percentage points.

Table 4.7 reports the results. Column (1) repeats the baseline model estimated on the entire sample of backbench Conservative MPs. In columns (2) and (3), we report the results for safe and marginal seats separately. We observe a remarkable difference in the relative importance of career concerns and constituency preferences between MPs elected in safe versus marginal seats. Specifically, the effect of career concerns is significantly weaker in marginal constituencies, while the influence of constituency preferences is significantly stronger. The results align with previous findings by Baughman (2004), who associates the greater attention paid to constituency preferences by MPs under electoral threat by pandering to local party officials whose support is essential for future electoral success. Likewise, Kauder and Potrafke (2019) show that conservative politicians elected in safe rather than in contested districts were less likely to support same-sex marriage in a roll call vote in the national German parliament (Bundestag).

While those results should not necessarily be interpreted causally because win margins may be correlated with unobserved mediating factors, we do believe that they bring credibility to our main findings. If the main results from Table 4.3 were wholly spurious, we would have no reason to expect the particular pattern we observe when the sample is split between safe and marginal seats. Hence, while making a causal claim is not possible with the data at hand, the results in Table 4.7 are in line with what we would expect theoretically, which is reassuring.

History of rebellion

While many MPs are loyal, some MPs are serial rebels and have long histories of voting against their parties. Famous examples include the now leader of the Labour Party Jeremy Corbyn and the shadow Chancellor John McDonnell and, amongst the

Table 4.7 The probability of voting for the Withdrawal Agreement in safe versus marginal seats

Outcome: VOTE	(1) Baseline	(2) Safe	(3) Marginal	(4) Diff. p-value
REMAIN MP	0.393***	0.493***	0.431***	0.278
	(0.048)	(0.076)	(0.085)	
	[0.000]	[0.000]	[0.000]	
JUNIOR MP	0.223***	0.271***	-0.048	0.034
	(0.069)	(0.105)	(0.139)	
	[0.001]	[0.010]	[0.730]	
LEAVE VOTE SHARE	-0.151**	-0.055	-0.314***	0.076
	(0.073)	(0.154)	(0.095)	
	[0.038]	[0.722]	[0.001]	
Vote Dummies	YES	YES	YES	-
Controls	YES	YES	YES	-
N	662	330	164	-
Pseudo-R2	0.27	0.30	0.46	-

Note: The table reports Probit estimates (marginal effects evaluated at the mean of the explanatory variables) for the sample of Conservative backbenchers and for the three votes combined. Column (1) replicates the full baseline results from Table 4.3. Columns (2) and (3) estimate the model separately for safe (top 50 percent of the distribution) and marginal (bottom 25 percent of the distribution). The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero if the MP rebelled by voting against. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; and *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. The p-value reported in column (4) is associated with the one-sided null hypothesis that the marginal effect of the respective row variable is larger (smaller) in one sub-sample than in the other. Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; $^{*}p<0.10$, $^{**}p<0.05$, $^{***}p<0.01$

Conservatives, the MP Philip Hollobone. We conjecture that an MP with a history of rebellion would respond differently to, in particular, career concerns than an MP who always has been loyal. An MP who has rebelled at least once may, from a career point of view, perceive another rebellious vote differently from an MP who has been loyal in the past.

Based on the the "rebellion history index" constructed by the website The Public Whip from divisions in the House of Commons over the period from June 2017 to

November 2018 (i.e., before the first Meaningful Vote), we have divided the sample of Conservative backbench MPs into two groups: those who never rebelled in the past and for whom a vote against the Withdrawal Agreement would be their first rebellious vote (first-time rebels) and those who rebelled at least once prior to the first Meaningful Vote (serial rebels). We re-estimate equation (4.1) on the two sub-samples. Table 4.8 reports the results. From columns (2) and (3), we observe that based on a comparison of the marginal effects (28 versus 19 percentage points), career concerns do appear to matter more for first-time than for serial rebels, but the difference is not statistically significant. An MP's history of rebellion, thus, did not make much of a difference for how they voted on Brexit.

The MPs' personal Brexit preference

We already have established that conservative backbench MPs who supported Remain in the 2016 referendum were more likely to support May's deal in the three Meaningful Votes than Leave MPs. We split the sample into Leave and Remain MP sub-samples in order to investigate if the two groups of MPs reacted differently to career concerns and to constituency preferences. Table 4.9 reports the results. We observe that Remain MPs reacted to career concerns and not to constituency preferences, while for Leave MPs, career concerns appear to play no role, but they were more likely to vote against the deal if elected in constituencies with large fractions of Leave voters. However, despite the fact that the marginal effect on *JUNIOR MP* is insignificant for Leave MPs and significant for Remain MPs, the difference between the two marginal effects is not statistically significant. For *LEAVE VOTE SHARE* the difference is significant. One interpretation of that evidence is that Leave MPs, many of whom belong to the European Research Group (ERG) led by Jacob Rees-Mogg, signalled "ideological purity" to the Leave voters and local party officials in their constituencies by voting against May's deal which they considered to be too "soft" (involving a risk of locking the UK into a customs union through the so-called Irish backstop). Remain MPs with political careers to look after, on the other hand, could signal purity to their Leave voters and local party officials by "converting" (accepting the result of the referendum) and supporting May's attempt to get a deal through.

4.7.4 Johnson's October 2019 Brexit deal

As discussed in Section 4.3, Prime Minister Johnson put a new Brexit deal before Parliament which passed its second reading on 22 October 2019 with a majority of 30.

Table 4.8 The probability of voting for the Withdrawal Agreement, breakdown by history of past rebellion

Outcome: VOTE	(1) Baseline	(2) First-time rebels	(3) Serial rebels	(4) Diff. p-value
REMAIN MP	0.371***	0.397***	0.399***	0.491
	(0.049)	(0.064)	(0.074)	
	[0.000]	[0.000]	[0.000]	
JUNIOR MP	0.227***	0.280***	0.189**	0.257
	(0.068)	(0.101)	(0.096)	
	[0.001]	[0.006]	[0.048]	
LEAVE VOTE SHARE	-0.154**	-0.115	-0.197*	0.298
	(0.072)	(0.116)	(0.101)	
	[0.034]	[0.321]	[0.052]	
Vote Dummies	YES	YES	YES	-
Controls	YES	YES	YES	-
N	662	306	356	-
Pseudo-R2	0.26	0.32	0.26	-

Note: The table reports Probit estimates (marginal effects evaluated at the mean of the explanatory variables) for the sample of Conservative backbenchers and the three Meaningful Votes combined. Column (1) replicates the full baseline results from Table 4.3, excluding the rebellion index control. Column (2) restricts the sample to MPs who had not rebelled prior to November 2017 (first-time rebels); column (3) restricts the sample to MPs who had rebelled at least once before (serial rebels). The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero if the MP rebelled by voting against. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; and *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, and the MP's win margin in the last election. The p-value reported in column (4) is associated with the one-sided null hypothesis that the marginal effect of the respective row variable is larger (smaller) in one sub-sample than in the other. Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; $^{*}p<0.10$, $^{**}p<0.05$, $^{***}p<0.01$

Table 4.9 The probability of voting for the Withdrawal Agreement for Remain and Leave MPs

Outcome: VOTE	(1) Baseline	(2) Leave MPs	(3) Remain MPs	(4) Diff. p-value
JUNIOR MP	0.211***	0.135	0.231***	0.233
	(0.069)	(0.118)	(0.060)	
	[0.002]	[0.254]	[0.000]	
LEAVE VOTE SHARE	-0.155**	-0.253**	0.008	0.013
	(0.069)	(0.100)	(0.061)	
	[0.026]	[0.011]	[0.893]	
Vote Dummies	YES	YES	YES	-
Controls	YES	YES	YES	-
N	662	354	308	-
Pseudo-R2	0.15	0.21	0.27	-

Note: The table reports Probit estimates (marginal effects evaluated at the mean of the explanatory variables) for the sample of Conservative backbenchers for the three Meaningful Votes combined. Column (1) replicates the baseline result from Table 4.3, excluding *REMAIN MP*. Column (2) restricts the sample to MPs who voted Leave in the 2016 referendum (Leave MPs). Column (3) restricts the sample to MPs who voted Remain in the referendum (Remain MPs). The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero if the MP rebelled. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; and *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. The p-value reported in column (4) is associated with the one-sided null hypothesis that the marginal effect of the respective row variable is larger (smaller) in one sub-sample than in the other. Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; $^{*}p<0.10$, $^{**}p<0.05$, $^{***}p<0.01$

It got no further because a general election was called. As explained, passing a second reading is not equivalent to passing one of the Meaningful Votes considered above, but some interesting patterns nevertheless should be noted. The 30 MP majority was achieved largely thanks to 24 Labour MPs defying their party and either voting for Johnson's deal (19) or abstaining (5). By comparing descriptive statistics, these rebel Labour MPs appear to be guided by motivations similar to those of the Conservative rebels analyzed above. Rebel Labour MPs had substantially higher constituency Leave vote shares than loyal Labour MPs (62.2% versus 50.1%), they were less likely to have campaigned for Remain (87.5% versus 98.2%), and less likely to be junior (33.3% vs

42.4%). Hence, we see patterns of rebellion by Labour MPs consistent with our findings for Conservative MPs.

4.8 Conclusions

We study the three Meaningful Votes that took place in the British House of Common between January and March 2019 in which the Conservative government's Withdrawal Agreement with the European Union was defeated decisively. Instrumental for that result was a major revolt on the Conservative backbench. We argue that the high-stakes situation can provide insights into why politicians revolt against their own parties more generally. We find evidence that personal preferences (ideology), constituency preferences and career concerns mattered. We also find (suggestive) evidence that the rebellion on the Conservative backbench was, in part, motivated by the prospect of bringing the May government down. An interesting question for future research is to study the electoral consequences of the rebellion for individual MPs. That is, do voters reward or punish them for the ways they voted on the highly contentious Brexit issue? A related question that also deserves attention is how the Conservative Party internally rewards or punishes rebellious MPs, i.e., how will the rebellion affect their long-term career prospects?

Appendix 4.A Definitions and sources

This appendix lists and defines the variables we use in the statistical analysis and gives the sources.

- *VOTE* is a dummy variable coded one if an MP voted for the government's deal and zero if they voted against; coded separately for each of the three votes. This coding takes into account that the Tellers, the Speaker and the deputy Speaker do not cast a vote. Note: Data retrieved April 2019. Source: House of Commons Votes

- *VOTE CHANGE 1-2* (*VOTE CHANGE 2-3*) is a dummy equal to one for MPs who voted against in the first (second) Meaningful Vote and for in the second (third) (zero otherwise). Note: Data retrieved April 2019. Source: House of Commons Votes

- *REMAIN MP* is a dummy variable coded one if the MP voted and campaigned to remain in the referendum and zero otherwise. Note: Data retrieved November 2018. Source: SkyNews Analysis

- *FRONTBENCH* is a dummy variable coded one if the MP holds a governmental position and zero otherwise. Note: Data retrieved November 2018. Source: House of Commons Library

- JUNIOR MP is a dummy variable coded one if the MP first entered Parliament either in 2015 or 2017 and zero otherwise. Note: Data retrieved November 2018. Source: House of Commons Library

- *LEAVE VOTE SHARE* records the (estimated) share of the electorate in each constituency who voted to leave the EU in the 2016 referendum. Note: Data retrieved November 2018. Source: Hanretty, 2017

- *FOREIGN* records the share of people residing within a constituency that have not been born within the UK. Data for March 2015. Note: Data retrieved November 2018. Source: Office for National Statistics

- *PUBLIC* records the share of people residing within a constituency employed in the public sector. Data for March 2015. Note: Data retrieved November 2018. Source: Office for National Statistics

- *EDUCATED* records the March share of people residing within a constituency that have a degree of higher education. Data for March 2015. Note: Data retrieved November 2018. Source: Office for National Statistics

- *POPULATION* records the number of people residing within a constituency. Data for June 2016. Note: Data retrieved November 2018. Source: House of Commons Library Local Data

- *WORKING AGE* records the share of people residing within a constituency that are between 16 and 64 years old. Data for June 2016. Note: Data retrieved November 2018. Source: House of Commons Library Local Data

- *UNEMPLOYED* records the unemployment rate within a constituency. Data for June 2016. Note: Data retrieved November 2018. Source: House of Commons Library Local Data

- *AGE* records the representative's age in years. Note: Data retrieved November 2018. Source: House of Commons Library

- *FEMALE* is a dummy variable coded one if the MP is female. Note: Data retrieved November 2018. Source: House of Commons Library

- *REBELLION* is an index variable which proxies for the number of times a representative has voted against the majority vote of the representative's party. Note: Data retrieved November 2018. Source: The Public Whip

- *WIN MARGIN* records, for each constituency, the difference between the vote share of the winning candidate and the vote share of the runner up. Note: Data retrieved November 2018. Source: House of Commons Library

- *JOHNSON GOVERNMENT SENIOR* is equal to one if the MP was appointed to a senior (Cabinet) position in the Johnson administration (zero otherwise). Note: Data retrieved July 31 2019. Source: BBC News

- *JOHNSON GOVERNMENT JUNIOR* is equal to one if the MP was appointed to a junior (non-cabinet) governmental position in the Johnson administration (zero otherwise). Note: Data retrieved July 31 2019. Source: BBC News

Appendix 4.B Additional data and estimation results

Table 4.10 Summary Statistics for sample of all Conservative MPs

Variable	(1) N	(2) Mean	(3) Std. Dev.	(4) Min.	(5) Max.
VOTE (Binary)	941	0.752	0.432	0	1
Main Determinants					
FRONTBENCH (Binary)	317	0.300	0.459	0	1
REMAIN MP (Binary)	317	0.546	0.499	0	1
JUNIOR MP (Binary)	317	0.300	0.459	0	1
LEAVE VOTE SHARE(%)	317	55.0	8.77	25.7	75.0
Constituency Controls					
FOREIGN (%)	317	8.86	6.94	2.30	52.0
POPULATION (No.)	317	100,324	11,371	58,873	140,264
UNEMPLOYED (%)	317	1.53	0.770	0.393	4.81
PUBLIC (%)	317	17.8	6.56	5.60	47.1
EDUCATED (%)	317	27.6	7.14	12.3	55.2
WORKING AGE (%)	317	60.8	2.79	51.4	73.6
MP Controls					
AGE (Yrs.)	317	51.6	9.85	27.0	78.0
FEMALE (Binary)	317	0.211	0.409	0	1
REBELLION (Index)	317	0.636	1.59	0	21.8
WIN MARGIN (pp)	317	23.2	13.1	0.066	49.7

Note: Appendix A lists definitions of the variables and provides details regarding the sources. The sample is used to estimate the specification in Table 4.3, column (4).

Table 4.11 The probability of voting for the Withdrawal Agreement in the three Meaningful Votes combined, Linear Probability Model

	A. All Conservatives			*B. Conservative Backbenchers*		
FRONTBENCH	0.305***	0.311***	0.329***	-	-	-
	(0.031)	(0.031)	(0.035)			
	[0.000]	[0.000]	[0.000]			
REMAIN MP	0.264***	0.256***	0.264***	0.346***	0.329***	0.341***
	(0.036)	(0.035)	(0.034)	(0.045)	(0.046)	(0.044)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
JUNIOR MP	0.122***	0.099**	0.146***	0.143***	0.115**	0.174***
	(0.038)	(0.039)	(0.047)	(0.045)	(0.049)	(0.062)
	[0.001]	[0.011]	[0.002]	[0.002]	[0.019]	[0.006]
LEAVE VOTE SHARE	0.0001	-0.081**	-0.069*	-0.005	-0.102**	-0.085*
	(0.016)	(0.034)	(0.037)	(0.023)	(0.045)	(0.048)
	[0.993]	[0.018]	[0.063]	[0.842]	[0.023]	[0.078]
Vote Dummies	YES	YES	YES	YES	YES	YES
Const. Controls	NO	YES	YES	NO	YES	YES
MP Controls	NO	NO	YES	NO	NO	YES
N	941	941	941	662	662	662
R2	0.30	0.32	0.33	0.26	0.28	0.30

Note: The table reports the results from a linear probability model estimated with Ordinary Least Squares (OLS) on the sample of all Conservative MPs (panel A) and for the sample of backbench MPs (panel B). The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero when the MP rebelled by voting against. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency; and *FRONTBENCH* is a binary variable equal to 1 if the MP holds a position in government. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; *p<0.10, **p<0.05, ***p<0.01

Table 4.12 The probability of voting for the Withdrawal Agreement in the three Meaningful Votes combined (Probit coefficients)

	Backbencher sample			Full Sample
Outcome: VOTE	(1) Probit	(2) Probit	(3) Probit	(4) OLS
FRONTBENCH	-	-	-	0.329***
				(0.035)
				[0.000]
REMAIN MP	1.14***	1.12***	1.22***	0.264***
	(0.170)	(0.174)	(0.170)	(0.034)
	[0.000]	[0.000]	[0.000]	[0.000]
JUNIOR MP	0.533***	0.433**	0.695***	0.146***
	(0.165)	(0.181)	(0.231)	(0.047)
	[0.001]	[0.017]	[0.003]	[0.002]
LEAVE VOTE SHARE	-0.005	-0.447**	-0.439**	-0.069*
	(0.083)	(0.0187)	(0.212)	(0.037)
	[0.949]	[0.017]	[0.038]	[0.035]
Vote Dummies	YES	YES	YES	YES
Const. Controls	NO	YES	YES	YES
MP Controls	NO	NO	YES	YES
N	662	662	662	941
(Pseudo-)R2	0.22	0.25	0.27	0.33

Note: Columns (1)-(3) report Probit estimates (rather than marginal effects) for the sample of Conservative backbenchers and column (4) reports OLS estimates for the sample of all Conservative MPs. The dependent variable (*VOTE*) is a binary variable equal to 1 whenever an MP voted in support of the Withdrawal Agreement and zero when the MP rebelled by voting against. *REMAIN MP* is a binary variable equal to 1 if the MP voted for remaining within the EU in the 2016 referendum; *JUNIOR MP* is a binary variable equal to 1 if the MP was elected to the House of Commons either in 2015 or 2017; *LEAVE VOTE SHARE* is the standardized share of voters who voted Leave in the referendum in 2016 in each constituency; and *FRONTBENCH* is a binary variable equal to 1 if the MP holds a position in government. All specifications include vote dummies. Constituency controls include population size, the unemployment rate, the share of constituents working in the public sector, the share of constituents with a higher education degree, and the share of constituents who are of working age. MP controls include gender, age, an index of the MP's history of rebellion, and the MP's win margin in the last election. Standard errors (in round brackets) are clustered at the constituency level; p-values are given in [square brackets]; *p<0.10, **p<0.05, ***p<0.01

Table 4.13 Breakdown of Meaningful Votes by Party and Government Positions (Alternative Affiliation Definition)

	First Vote			Second Vote			Third Vote		
	For	Against	Abstain	For	Against	Abstain	For	Against	Abstain
Panel A - Vote by Party									
Conservative	196	118	3	235	75	4	277	34	3
Labour	3	248	5	3	238	5	5	234	7
LD	0	11	0	0	11	0	0	11	0
SNP	0	35	0	0	35	0	0	34	1
DUP	0	10	0	0	10	0	0	10	0
Other	3	10	8	4	22	8	4	21	9
Total	*202*	*432*	*16*	*242*	*391*	*17*	*286*	*344*	*20*
Panel B - Conservatives by Govt. Position									
Frontbench	93	0	2	93	0	2	93	0	2
Backbench	103	118	1	142	75	2	184	34	1
Total	*196*	*118*	*3*	*235*	*75*	*4*	*277*	*34*	*3*

Note: This table shows the distribution of votes across the three Meaningful Votes taking into account that three Conservative MPs and seven Labour MPs resigned and became independent between the first and the second Meaningful Vote.

Table 4.14 The probability of voting for the Withdrawal Agreement in the three Meaningful Votess separately (alternative affiliation definition)

Outcome: VOTE	(1) 1st Vote	(2) 2nd Vote	(3) 3rd Vote	(4) Pooled	(5) Diff. p-value
REMAIN MP	0.556***	0.411***	0.164***	0.404***	0.000
	(0.061)	(0.058)	(0.043)	(0.047)	
	[0.000]	[0.000]	[0.000]	[0.000]	
JUNIOR MP	0.327***	0.211**	0.104**	0.223***	0.026
	(0.103)	(0.085)	(0.049)	(0.068)	
	[0.002]	[0.013]	[0.031]	[0.001]	
LEAVE VOTE SHARE	-0.150	-0.152*	-0.106*	-0.144**	0.371
	(0.121)	(0.086)	(0.057)	(0.071)	
	[0.217]	[0.077]	[0.066]	[0.044]	
Vote Dummies	NO	NO	NO	YES	-
Controls	YES	YES	YES	YES	-
N	221	217	218	656	-
Pseudo-R2	0.31	0.24	0.17	0.29	-

Note: Columns (1) to (3) report the results corresponding to Table 4.4 on a sample that including only MPs that were officially part of the Conservative party at the time of each vote. This, therefore, takes into account that three Conservative MPs resigned between the first and the second Meaningful Vote (see Table 4.13. We observe that this makes almost no difference to the results, except in the second Meaningful Vote where LEAVE VOTE SHARE is imprecisely estimated with a p-value of 12 percent. Column (4) reports the results for the combined sample (but in the second and third Meaningful Vote without the three MPs who resigned), corresponding to Table 4.3, column (3). We see that the results are very similar.

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