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Does Tax Policy Work When Consumers Have Imperfect Price Information? Theory and Evidence

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Does Tax Policy Work When Consumers Have Imperfect Price Information? Theory and Evidence

Abstract

We investigate how the pass-through rate of commodity taxes depends on competition in a setting where consumers have imperfect information about prices. We use a theoretical search model that has two key predictions: First, the larger the number of price sensitive consumers, the higher the pass-through rate. Second, there is a hump-shaped relationship between the average pass-through experienced by consumers and the number of sellers. We test our theoretical predictions by studying pass-through in the context of a tax decrease and increase in the German retail fuel market. We estimate pass-through of these tax changes to diesel and gasoline prices using a unique dataset containing the universe of price changes at fuel stations in Germany and France and a synthetic difference-in-differences strategy. Our empirical results are in line with our theoretical predictions. Finally, we show that our theoretical framework can encompass and reconcile a large number of empirical observations in previous studies.

Keywords: pass-through, carbon tax, VAT, consumer search, competition.

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1 Introduction

Understanding how and when firms pass through taxes to consumers is fundamental for the design of optimal tax policy. Pass-through determines the corrective effect of Pigouvian taxes, the effectiveness of unconventional fiscal policy to stimulate the economy and the distributional consequences of any commodity tax. Yet, our understanding of pass-through under imperfect competition is limited. Recently, Weyl and Fabinger (2013) made theoretical progress in settings with perfect information. But little is known about how pass-through behaves when consumers have imperfect information about prices, although imperfect information is ubiquitous.

In this paper, we propose a new theoretical framework to analyze commodity tax pass-through in oligopolistic markets where consumers have imperfect information about prices. We derive theoretical predictions about the pass-through rates as a function of the information consumers have about market prices and as a function of the number of sellers. We find that the more consumers are well informed about prices, the higher is the pass-through rate. We also show that there is a hump-shaped relationship between the number of sellers and pass-through. To test our predictions empirically, we study heterogeneities in the pass-through of a tax decrease and a subsequent tax increase in the German retail fuel market. We show that, as predicted by the theory, pass-through increases in how well consumers are informed about prices. We also find evidence for a hump-shaped relationship between pass-through and the number of fuel stations in a local market.

For our theoretical analysis, we adapt the consumer search model by Stahl (1989) to the analysis of tax pass-through. This model distinguishes between fully informed shoppers (who know all prices) and uninformed non-shoppers (who can search for prices sequentially). This framework allows us to introduce a novel notion of price sensitivity of demand to the analysis of tax pass-through: The larger the number of informed consumers, the more it pays for sellers to compete for them with their choice of prices. Price sensitivity of demand, as experienced by sellers, therefore depends on how many consumers have access to an information clearinghouse and are thus perfectly informed.

In equilibrium, firms set prices by randomizing according to a mixed strategy. Informed shoppers know all prices in the market, always buy from the lowest-price seller and therefore pay the minimum price. Uninformed non-shoppers draw the first price for free and then pay a search cost to draw more prices. In equilibrium, prices are chosen such that they do not search and thus pay the first price they draw. From an ex ante point of view, informed shoppers pay the expected minimum price, while uninformed non-shoppers pay the expected price.

The model has two key predictions about how competition affects pass-through. First, the larger the share of price sensitive consumers, the higher is the pass-through rate to all prices. Second, the larger the number of firms in the market, the larger is the pass-through rate to the expected minimum price, paid by informed shoppers. In contrast, the pass-through rate to the expected price, paid by uninformed non-shoppers, first increases and then decreases in the number of sellers. The latter effect can be explained by the fact that above a certain threshold, as more firms are active in the market, it becomes less and less likely for a particular firm to attract shoppers and so firms are more likely to charge a higher price and only serve uninformed non-shoppers. Thus, in a context with imperfect information about prices, a larger number of sellers does not monotonically lead to a more competitive outcome. How pass-through to the average price paid by consumers in the market varies with the number of firms depends on the share of informed and uninformed consumers in the market. These predictions are true for the pass-through of ad-valorem taxes, per unit taxes, as well as symmetric marginal cost shocks.

Next, we test our theoretical predictions by studying two important tax changes in the German retail fuel market. As part of the fiscal response to the COVID-19 pandemic, the German government announced a six-month temporary value-added tax (VAT) reduction on 3 June 2020, taking effect on 1 July on most products, including fuel. On 1 January 2021, the VAT rate returned back to its original level. At the same time, the government introduced a carbon tax on fuel.[1] We estimate pass-through of the tax de-

[1]For simplicity, we will frequently refer to the policy change on 1 July 2020 as the tax decrease and the change on 1 January 2021 as the tax increase.

crease as well as the two tax increases to diesel and gasoline prices using a unique dataset containing the universe of price changes at fuel stations in Germany and France before and after the policy change.

To estimate pass-through, we use the synthetic difference-in-differences (SDID) recently introduced by Arkhangelsky, Athey, Hirshberg, Imbens, and Wager (2020). This method combines the advantages of difference-in-differences (DID) and synthetic control (SC). To analyze how price sensitivity affects pass-through, we compare daily prices of the three main fuel types sold at fuel stations in Germany and France.

There is strong evidence suggesting that diesel drivers are on average more price sensitive than drivers fueling gasoline. Frequent drivers tend to use diesel cars. On average, diesel car users drive twice as many kilometres per year than gasoline drivers. By buying a car with a more expensive diesel engine, they make a fixed cost investment to decrease their marginal cost of driving. This suggests that diesel drivers have a greater incentive to become informed about fuel prices.[2] Using data on search querries from a smartphone app displaying fuel prices to users, we confirm empirically that the search intensity among diesel drivers is higher. Within gasoline, the evidence strongly suggests that customers of *E5* are less price sensitive than *E10* customers.

We find that the pass-through rate of the tax decrease (tax increase) is 79 (92) percent for diesel, whereas it is 52 (75) percent for *E10* and 34 (69) percent for *E5*. As predicted by the theoretical model, the higher the price sensitivity of consumers, the higher the pass-through rate. Since the same stations sell all three types of fuel, unobserved station characteristics cannot explain these differences.

Finally, we use the geolocation and brand information of fuel stations to compute the number of rival fuel stations within a local market. We then estimate how the pass-through rate varies with the number of rival stations. Consistent with our theoretical predictions, we find that the pass-through rate first increases and then decreases in the number of rival fuel stations within a local market. Empirically, this relationship seems to disappear when pass-through is very high.

[2]Johnson (2002) made a similar argument for why diesel drivers are more price sensitive.

Our paper makes two main contributions. First, we introduce a novel notion of price sensitivity to the theoretical analysis of pass-through in oligopolistic markets. We find that the more price sensitive consumers are on average, the higher is the pass-through rate. This is different to how another common notion of price sensitivity, the price elasticity of demand, affects pass-through. A classic result under perfect competition is that the higher the price elasticity of demand, the lower the pass-through rate. Weyl and Fabinger (2013) show that this result extends to models with imperfect competition.[3] Our notion of price sensitivity is different, in that there is no aggregate quantity response of consumers. Instead, we capture how likely it is that consumers seek out buying their fixed quantity from the cheapest seller.[4]

Second, we provide novel empirical evidence on the determinants of commodity tax pass-through and relate them to our theoretical predictions. A unique feature of our empirical setting is that close to all fuel stations sell all three types of fuel. This allows us to disentangle the two different aspects of imperfect competition: the fact that consumers are imperfectly informed about prices and the fact that the market is oligopolistic with a small number of competitors. We can therefore test how the pass-through rate differs for consumer groups that differ in their price sensitivity whilst holding the network of stations constant. We can also test how pass-through varies when we hold the price sensitivity constant and vary the number of competitors. In contrast to the previous literature, our setting allows us to disentangle these two mechanisms empirically within the same study. Finally, studying a tax decrease and a subsequent tax increase six months later strengthens the robustness of our results.

To the best of our knowledge, there are no previous empirical studies that combine the analysis of these two mechanisms. Furthermore, our explanation as to why

[3]More precisely, this holds true for the market-level price elasticity of demand. In oligopolistic markets, a higher price elasticity of demand decreases pass-through via an aggregate quantity response and increases pass-through by intensifying competition. Weyl and Fabinger (2013) show that which of these effects is larger depends on the relative elasticities of demand and supply and the curvature of demand. Previous work (see, e.g., Stern, 1987 or Hamilton, 1999) studied tax pass-through in a Cournot model. All of these studies focus on settings with perfect information. Instead, we focus on settings where consumers have imperfect information about prices.

[4]This can be thought of as the price sensitivity of the residual demand that a particular seller faces, whilst market demand remains unchanged.

pass-through increases when consumers are better informed is new to the literature. Reassuringly, our theoretical framework can encompass and reconcile previous empirical observations. Duso and Szücs (2017) find that cost pass-through is higher for competitive electricity tariffs, which consumers need to actively seek out, than for default tariffs. Kosonen (2015) finds that after a VAT decrease, Finnish hairdressers cut prices more for advertised services. Genakos and Pagliero (2019) find that tax pass-through by fuel stations on isolated Greek islands increases in the number of stations. Miller, Osborne, and Sheu (2017) find that cost pass-through in the cement industry decreases in the number of competitors. In our model, we predict a hump-shaped relationship between the pass-through rate and the number of competitors, which means that both empirical results can be consistent with our model.

More generally, we extend a growing empirical literature on pass-through of tax or cost changes. There are numerous studies that, as an intermediate or final step, estimate average pass-through rates.[5] However, few investigate their determinants. Notable exceptions are Hollenbeck and Uetake (Forthcoming) and Nakamura and Zerom (2010), who study the interplay between pass-through and market power. Hollenbeck and Uetake (Forthcoming) find that imperfect competition and log-convex demand is responsible for over-shifting in the legal marijuana industry. Nakamura and Zerom (2010) find that exchange rate pass-through is reduced by local costs and markup adjustments. Our study differs in that we analyze how informational frictions on the consumer side determine pass-through. This also gives policymakers a possible angle on how to increase the pass-through rate, for example by mandating price transparency.[6]

Within our setting, we can also study the speed of, and asymmetries in, pass-through. Like Benzarti, Carloni, Harju, and Kosonen (2020), we find higher pass-through

[5]Some studies focus on particular industries, such as energy markets (see, e.g., Fabra and Reguant, 2014, Li and Stock, 2019 or Ganapati, Shapiro, and Walker, 2020) or sin products (see, e.g., Dubois, Griffith, and O'Connell, 2020, Harding, Leibtag, and Lovenheim, 2012 or Conlon and Rao, 2020). Others estimate the average pass-through rate across a large number of industries (see, e.g., Benedek, De Mooij, Keen, and Wingender, 2019). The findings of these studies are mixed, as they include evidence for under-shifting (e.g. Benzarti and Carloni, 2019, Carbonnier, 2007), full pass-through (e.g. Benedek et al., 2019) and over-shifting (e.g. Besley and Rosen, 1999).

[6]Luco (2019), Ater and Rigbi (2019) and Montag and Winter (2020) study the effect of different mandatory price disclosure policies and find mixed results.

for the tax increase than for the tax decrease. Using monthly sales data for home appliances, Büttner and Madzharova (Forthcoming) show that VAT pass-through is full and relatively fast. Similarly, Fuest, Neumeier, and Stöhlker (2020) find full pass-through of the 2020 German temporary VAT reduction at supermarkets of the Rewe Group.[7] Our results indicate that although pass-through of both tax changes is fast, it remains incomplete even two months after the tax change.

Our results not only inform policymakers aiming to set optimal Pigouvian taxes, but also the use of unconventional fiscal policy to stimulate the economy. This describes the use of temporary tax cuts or pre-announced tax increases to stimulate inflation by targeting household expectations directly.[8] For temporary tax cuts to stimulate inflation expectations and consumption, consumers need to expect that prices will rise after the tax increases again. This is most likely the case if the temporary tax cut and the pre-announced tax increase are passed-through to consumers. Since we find that pass-through increases in the price sensitivity of consumers, our results indicate that targeting such measures at markets where the price sensitivity of consumers is high can increase the cost effectiveness of unconventional fiscal policy.

Finally, we extend the empirical literature on pricing in retail fuel markets. Whereas Houde (2012) models fuel stations as differentiated by station locations but abstracts from imperfect information, recent studies found that models of imperfect information and consumer search are well-suited to explain empirical findings in retail fuel markets.[9] We extend this literature by combining a theoretical model with incomplete information and granular data on fuel prices to study the pass-through of taxes in retail fuel markets.[10]

[7]Jacob, Müller, and Wulff (2021) find higher pass-through of the corporate tax by fuel stations in municipalities with fewer stations. This differs from unit and ad-valorem taxes as the corporate tax is levied on profits, with a partial deductibility of costs.

[8]See, for example, D'Acunto, Hoang, and Weber (2018), or D'Acunto, Hoang, and Weber (Forthcoming).

[9]These include Chandra and Tappata (2011), Byrne and de Roos (2017), Byrne and de Roos (Forthcoming) or Pennerstorfer, Schmidt-Dengler, Schutz, Weiss, and Yontcheva (2020).

[10]There is a large empirical literature on cost pass-through in retail fuel markets using error correction models and testing the rockets-and-feathers hypothesis, which focuses on asymmetric pass-through of increases and decreases (e.g. Bachmeier and Griffin, 2003, Deltas, 2008 or Verlinda, 2008) and the speed of pass-through (e.g. Johnson, 2002). Most of these studies do not provide a theoretical explanation for their findings. A notable exception is Borenstein, Cameron, and Gilbert (1997), who show that asymmetric pass-through could either be explained by tacit collusion or by imperfect information. For a review of the literature, see Eckert (2013). Furthermore, Deltas and Polemis (2020) shows that many of

The remainder of the paper is structured as follows: Section 2 outlines the theoretical model, Section 3 describes the industry, Section 4 gives an overview of the data and presents descriptive evidence, Section 5 discusses the empirical strategy, Section 6 presents the estimation results and Section 7 concludes.

2 Theoretical Model

Our aim is to analyze theoretically how pass-through varies with the price sensitivity of consumers and the number of sellers. We therefore set up a model where firms sell a homogeneous good to consumers who are either fully informed about prices or can search for lower prices. The model is based on the rich literature on consumer search in industrial organization, and in particular on the model by Stahl (1989). We extend this model by introducing marginal costs and an ad-valorem tax in order to be able to analyze tax pass-through.

2.1 Setup

There is a mass M of consumers. Each consumer has the same valuation v for the homogeneous good and inelastically demands one unit of the product. A fraction ϕ of consumers are fully informed shoppers and $1-\phi$ are non-shoppers, who can search sequentially. Shoppers know prices of all sellers and therefore always buy from the lowest price seller. If there is a tie, shoppers are shared equally among the lowest price sellers. Non-shoppers only know the distribution of prices and draw a first price for free. They can then choose to randomly draw prices of additional sellers at an incremental search cost s, in the hope of finding a lower price. Non-shoppers buy the good as soon as the price that they draw is weakly below their reservation price p_r, at which non-shoppers are indifferent between accepting the price and drawing a new price at search cost s, because the expected price savings of drawing another price are equal to the search cost s.

On the supply side, there is an infinite number of symmetric firms that can poten-

the conclusions from studies using error correction models to estimate pass-through rates may strongly depend on research design and data features.

tially enter the market. Each firm can enter the market for a fixed and sunk cost F and produce at a constant marginal cost of c. The number of entrants is denoted by N and firms are indexed by i. Finally, sales are subject to an ad-valorem tax τ.

The game proceeds in two stages. In the first stage, firms decide whether to enter the market. In the second stage, sellers first choose prices and consumers then make search and purchase decisions. To find the subgame perfect Nash equilibrium of the game, we solve it via backward induction.

Before proceeding any further, we should define some more notation. When discussing prices, we always refer to the price paid by consumers. We assume that sellers bear the initial incidence of a tax and then (partially) "pass through" the cost of the tax to consumers. It is a well known result from the theoretical literature that equilibrium prices should be equivalent, irrespective of whether the initial tax incidence is with buyers or sellers. The pass-through rate of marginal costs is $\rho_c = \frac{\partial p}{\partial c}$. Note, that the pass-through rate of a per unit tax is equivalent to the pass-through rate of marginal costs. The pass-through rate of the ad-valorem tax is

$$\rho_\tau = \frac{\partial p}{\partial \tau} \cdot \frac{1+\tau}{p} \,.$$

In the following, we focus on what determines the pass-through rate of the ad-valorem tax. As we show in Appendix A.3, the determinants of the pass-through rate of marginal costs or per unit taxes are qualitatively equivalent.

Finally, it is worth discussing the notion of price sensitivity in this model. Whereas many canonical models analyzing pass-through rates think of the sensitivity of consumers to prices in terms of the price elasticity of demand, our notion of price sensitivity is different. As described above, all consumers always inelastically demand a single unit of the good so long as the price is below their valuation. There is thus no response in the aggregate quantity if prices change.

Instead, we capture a different way of how consumers are sensitive to prices, namely through the share of shoppers ϕ and the incremental search cost of non-shoppers s. If there are more shoppers, then a larger share of consumers is going to buy from the lowest

price seller for sure. This decreases the expected profit of setting a price that is not the lowest price in the market. If the search cost of non-shoppers is lower, then non-shoppers are more willing to search for lower prices. This decreases the reservation price of non-shoppers and also leads to lower prices.

2.2 Stage 2: Equilibrium price distribution

In the following, we characterize the equilibrium while the analysis of the model is relegated to Appendix A. There exists no pure strategy equilibrium in prices. There is a unique symmetric mixed strategy equilibrium where all sellers draw a price from the interval $[\underline{p}, p_r]$ according to the distribution $F(p_i)$, where p_r is the reservation price of non-shoppers and $\underline{p}$ is the minimum price a seller will charge. Shoppers always buy from the lowest price seller, whereas non-shoppers draw a single price and buy at this price. In equilibrium, non-shoppers do not search sequentially, because any price they draw is below their reservation price.

The symmetric equilibrium pricing strategy is characterized by the equilibrium objects p_r, $\underline{p}$ and $F(p_i)$. The reservation price of non-shoppers is

$$p_r = \begin{cases} E[p] + s & \text{if } E[p] + s < \upsilon \\ \upsilon & \text{otherwise} \end{cases}.$$

If searching sequentially is sufficiently cheap, the reservation price of non-shoppers is the sum of the expected price at the next draw and the search cost s. With relatively high search costs, the reservation price of non-shoppers is simply the valuation of the good υ.

The minimum element of the support from which sellers draw prices in equilibrium is

$$\underline{p} = \frac{p_r}{\frac{\phi N}{1-\phi} + 1} + c\frac{1+\tau}{1+\frac{1-\phi}{\phi N}}.$$

The cumulative density function of the equilibrium pricing strategy is

$$F(p_i) = 1 - (\frac{p_r - p_i}{p_i - c(1+\tau)} \frac{1-\phi}{N\phi})^{\frac{1}{N-1}} .$$

The expected second stage profits (i.e. excluding the fixed and sunk cost of entry) of a seller are

$$E[\pi_i] = (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{N} M .$$

Two further objects are of interest for our analysis, namely the expected price and the expected minimum price. Since non-shoppers do not search in equilibrium, they always buy at the first price they draw and thus the expected price is also the average price paid by non-shoppers. In contrast, shoppers always buy from the lowest price seller and thus the expected minimum price is also the average price paid by shoppers.[11]

The expected price is

$$E[p] = \underline{p} + (\frac{1-\phi}{N\phi})^{\frac{1}{N-1}} \int_{\underline{p}}^{p_r} (\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}} dp .$$

The expected minimum price is

$$E[p_{min}] = \frac{1-\phi}{\phi}[p_r - E[p] + (p_r - c(1+\tau))c(1+\tau) \int_{\underline{p}}^{p_r} \frac{1}{(p - c(1+\tau))^2} F(p) dp] .$$

2.3 Stage 1: Equilibrium entry

Entry occurs so long as the expected second stage profits of the entrant are greater or equal to the fixed and sunk cost of entry F. No further entry occurs if the next potential entrant cannot expect to recoup her entry costs.

The equilibrium number of entrants N^* will thus be such that

$$(\frac{p_r}{1+\tau} - c)\frac{1-\phi}{F} M - 1 < N^* \leq (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{F} M . \quad (1)$$

[11] The average refers to the average price paid by shoppers and non-shoppers if this game is often repeated across time or space. At a given time and location there is, of course, only one minimum price and N prices.

Note that increasing the market size M (or decreasing the fixed cost F) directly translates into a higher number of active sellers and does not enter the equilibrium in any other way. At the same time, different numbers of active sellers lead to different intensities of competition. Thus, whenever we analyze how prices or pass-through vary with the number of active sellers we should think of this as variation in the local market size or the fixed cost of entry.

For the remainder of the analysis we will assume that there is no entry and treat the number of sellers as exogenous. This is because our empirical study is concerned with a short-term tax adjustment during which entry seems unlikely. In other applications it will make sense to endogenize the number of active sellers also for the analysis of pass-through. Unless otherwise stated, we focus on the case where $N^* \geq 2$, since for the informedness of consumers to matter there need to be at least two sellers active in the market.

2.4 Pass-through of an ad-valorem tax

We now turn to analyzing how ad-valorem taxes are passed through to consumers. We begin by studying how an increase in the ad-valorem tax τ affects the equilibrium pricing strategy. To simplify the analysis, we assume that the search cost s is sufficiently high, such that $p_r = v$. We relax this assumption in Appendix A.5 and simulate how pass-through rates evolve with sequential search.[12] We show that qualitatively our results hold when search costs are low.

Since the reservation price now corresponds to the valuation of the good, only the minimum element of the support and the density of the pricing strategy are affected by a change in ad-valorem taxes.

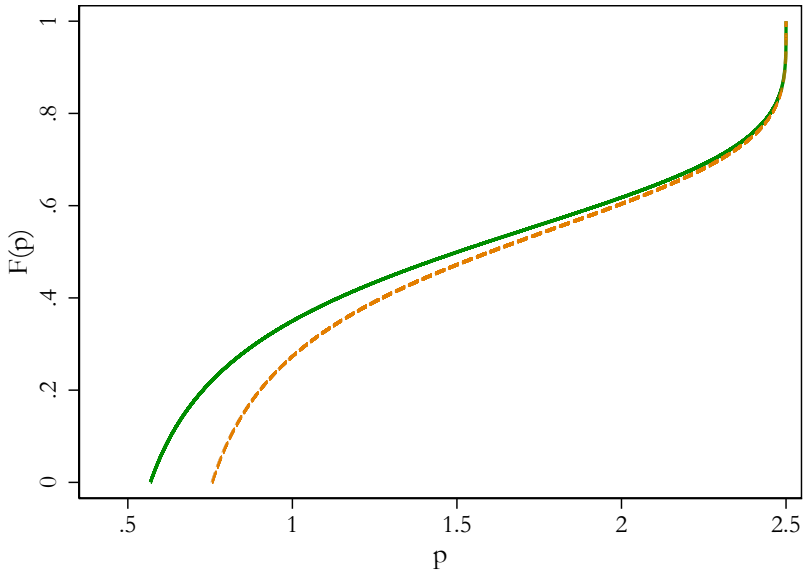
Proposition 1. *With $0 < \phi < 1$, for any $\hat{\tau} > \tau$ the minimum element of the support of the equilibrium pricing strategy $\underline{\hat{p}} > \underline{p}$ and the Nash equilibrium pricing strategy with τ first-order stochastically dominates (FOSD) the pricing strategy with $\hat{\tau}$, i.e. $\hat{F}(p) \leq$*

[12] An alternative simplification would be setting $N = 2$, which we consider to be less desirable for the purpose of this analysis.

$F(p) \quad \forall p.$

This means that if the share of shoppers is strictly positive, an increase in the ad-valorem tax τ leads to a shift in the support of prices from which sellers draw in equilibrium towards higher prices. It also means that, for each price on this support, the likelihood that a drawn price is lower than said price decreases if the ad-valorem tax rate increases to $\hat{\tau}$.

Figure 1: Ad-valorem tax pass-through to the equilibrium pricing strategy



Note: The Figure shows simulation results of how the distribution from which sellers draw prices in the symmetric Nash equilibrium changes if the ad-valorem tax increases from τ to $\hat{\tau}$. The solid line corresponds to the distribution under τ. The dashed line corresponds to the distribution under $\hat{\tau}$. Parameter values: $\upsilon = 2.5$, $s = 0.75$, $c = 0.4$, $\tau = 0.1$ and $\hat{\tau} = 0.6$.

As the share of shoppers converges to zero, the Nash equilibrium converges towards a degenerate distribution at the monopoly price, the classical result by Diamond (1971). The monopoly price corresponds to the valuation of the good, υ.

Since the minimum element of the support of prices and the density function monotonously move towards higher prices, other moments of interest, such as the expected price $E[p]$, which is the average price paid by non-shoppers, and the expected minimum price $E[p_{min}]$, which is the average price paid by shoppers, also increase. Thus, if ad-valorem taxes increase then the expected price paid increases for all consumers.

2.5 The effect of price sensitivity on the pass-through rate

We now turn to analyzing how the pass-through rate of an ad-valorem tax τ varies with the price sensitivity of consumers.

Proposition 2. *If the share of shoppers $\phi = 0$, pass-through of the ad-valorem tax $\rho_\tau = 0$. If $\phi = 1$, there is full pass-through, i.e. $\rho_\tau = 1$. As $\phi \to 1$, the pass-through rate $\rho_\tau \to 1$.*

Let us begin by analyzing two extreme cases. As we saw already, if there are no shoppers at all the Nash equilibrium is a degenerate distribution at the monopoly price, which is independent of the ad-valorem tax. Thus, if there are no shoppers, pass-through is zero. On the other hand, as the share of shoppers converges to one, the Nash equilibrium converges to the classical result by Bertrand (1883), where the Nash equilibrium is a degenerate distribution at $c(1+\tau)$. Thus, if all consumers are shoppers, there is full pass-through of the ad-valorem tax.

Finally, for all values of ϕ between zero and one, we can show that the pass-through rate of the ad-valorem tax to the lower bound of the equilibrium price strategy is strictly increasing in ϕ. We can also show that the rate at which an increase in the ad-valorem tax from τ to $\hat{\tau}$ reduces the probability that a drawn price is below a particular price p, i.e. from $F(p)$ to $\hat{F}(p)$, strictly increases in the share of shoppers. Thus, the pass-through rate of the ad-valorem tax increases in the share of shoppers and converges to full pass-through as the share of shoppers converges to one.

2.6 The effect of the number of sellers on the pass-through rate

So far, we saw that a higher share of informed consumers increases the intensity of competition and leads to higher pass-through. However, the model also contains a second dimension of competition, the number of active sellers. This is considered more often in empirical applications, since it is more salient and easier to observe than the informedness of consumers. We therefore ask how pass-through varies with the number of active sellers.

Proposition 3. *With $0 < \phi < 1$, as $N \to \infty$ the pass-through of τ to the minimum*

element of the equilibrium price support converges to full pass-through, i.e. $\rho_{\tau,\underline{p}} \to 1$.

As the number of sellers increases, competition for shoppers becomes more intense and so the minimum price that sellers consider charging in the symmetric Nash equilibrium converges towards $c(1+\tau)$. As this occurs, the pass-through rate of the ad-valorem tax to $\underline{p}$ increases.

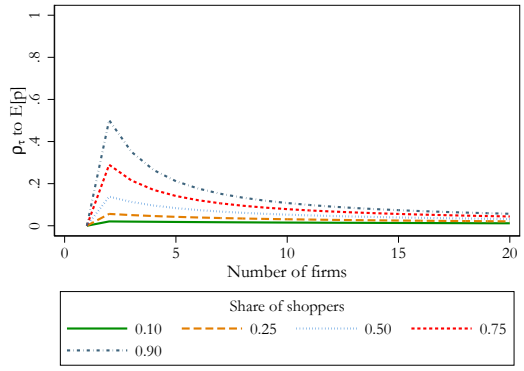
Showing how an increase in N affects the pass-through rate of ad-valorem taxes to $F(p)$, $E[p]$ and $E[p_{min}]$ analytically turns out to be more difficult. Instead, we resort to simulating how the pass-through rate varies with N.

In a setting without taxes or marginal costs but for a wider class of demand functions, Stahl (1989) shows that for a sufficiently high N', for $N > N'$ the equilibrium price distribution converges to a degenerate price distribution at the monopoly price as $N \to \infty$. At the same time, we know that as N increases from one to two, prices in the symmetric Nash equilibrium move from a degenerate distribution at the monopoly price to a competitive price distribution that includes prices below the monopoly price. Thus, the expected price first decreases and then increases again as $N \to \infty$. We also showed that as prices converge to the monopoly price, the pass-through rate converges to zero. Therefore, we expect the pass-through rate of ad-valorem taxes to $E[p]$ to first increase and then decrease as $N \to \infty$.

When we analyzed how pass-through varies with the share of shoppers, $E[p]$ (paid by non-shoppers) and $E[p_{min}]$ (paid by shoppers), as well as pass-through rates to these prices, always moved in the same direction. As $N \to \infty$, this is different. When s is sufficiently high such that $p_r = v$, $E[p_{min}]$ monotonously decreases in N and the pass-through rate of the ad-valorem tax to $E[p_{min}]$ monotonously increases.[13] This is because although each individual seller is more likely to charge higher prices, with an increase in N and a decrease in $\underline{p}$, it is overall more likely that some seller will set a lower price to attract shoppers.

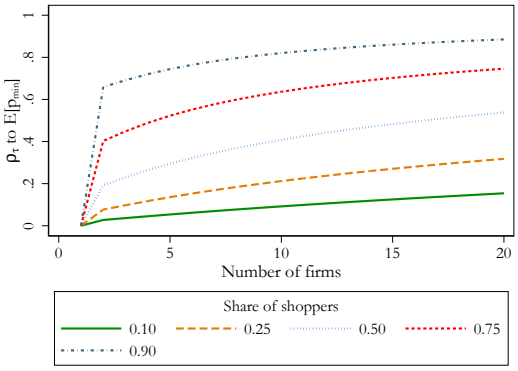
[13] As we show in Appendix A.5, for some values of ϕ there is an intermediate range of values in which ρ_c to $E[p_{min}]$ decreases in N, after which it increases again. This is because $\underline{p}$ is a function of p_r.

Figure 2: Pass-through of τ to $E[p]$



Parameter values: $\upsilon = 2.5$, $c = 0.4$, $\tau = 0.2$ and $\hat{\tau} = 0.22$.

Figure 3: Pass-through of τ to $E[p_{min}]$

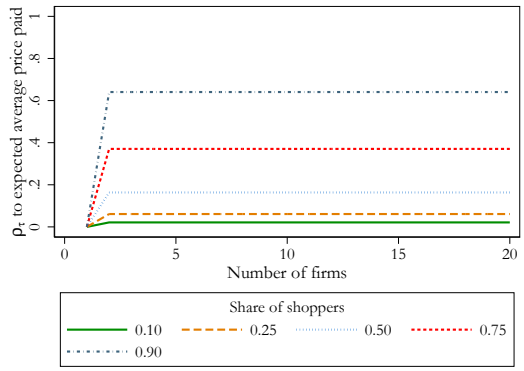


Parameter values: $\upsilon = 2.5$, $c = 0.4$, $\tau = 0.2$ and $\hat{\tau} = 0.22$.

The simulation results in Figures 2 and 3 are in line with our expectations. As N increases, pass-through of the ad-valorem tax to the expected price first increases and then decreases. Pass-through to the expected minimum price always decreases.

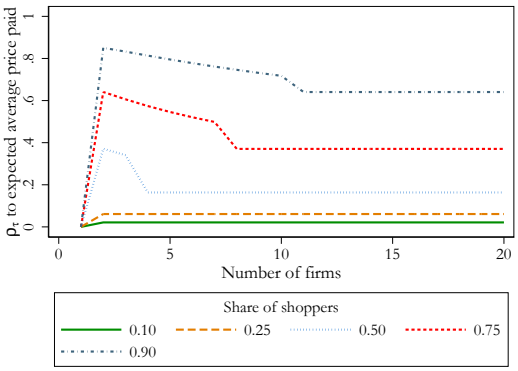
Finally, since prices paid by shoppers and non-shoppers evolve differently, we may be interested in how ad-valorem taxes are passed through to the expected average price paid by consumers in the markets. Fortunately, since both consumers types consume the same quantities and we know the share of each type of consumer, this can easily be considered.

Figure 4: ρ_τ to $E[\phi p_{min} + (1-\phi)p]$, $p_r = \upsilon$



Parameter values: $\upsilon = 2.5$, $c = 0.4$, $\tau = 0.2$ and $\hat{\tau} = 0.22$.

Figure 5: ρ_τ to $E[\phi p_{min} + (1-\phi)p]$, p_r endogenous



Parameter values: $\upsilon = 2.5$, $s = 0.75$, $c = 0.4$, $\tau = 0.2$ and $\hat{\tau} = 0.22$.

The simulation in Figure 4 shows that when search costs are so high that $p_r = \upsilon$, pass-through of ad-valorem taxes first increases in N and then stays constant, because

the decrease in pass-through to $E[p]$ and the increase in pass-through to $E[p_{min}]$ cancel each other out. Figure 5 shows that if search costs s are sufficiently low such that p_r is endogenous, pass-through to the expected average price paid first increases in N, then decreases in N and, as $p_r \to \upsilon$ when $N > 2$ and $N \to \infty$, ad-valorem tax pass-through remains constant when N is sufficiently large.

Thus far, when analyzing pass-through, we studied short-run responses in prices and thus held the number of sellers constant. Although our empirical application focuses on a temporary decrease in the VAT, and so is unlikely to induce entry, it is nevertheless worth discussing long-run responses. As we saw in the analysis of the entry stage in Section 2.3, an increase in the ad-valorem tax reduces the equilibrium number of sellers in the market. If the pre-change N is such that pass-through increases in N (i.e. very low levels of N), long-run pass-through is lower than short-run pass-through. If the pre-change N is such that pass-through decreases in N (i.e. sufficiently high N), long-run pass-through is higher than short-run pass-through.

3 The Retail Fuel Market

We now turn to the description of the retail fuel market in Germany. In 2019, total revenues from retail fuel sales were worth 92 billion Euro or approximately 3 percent of German GDP. In addition to its standalone value to the economy, this market has large externalities on the rest of the economy. Fuel prices are a key determinant of travel costs, commuting costs and, more broadly, the cost of personal transportation.

3.1 Diesel vs. gasoline

The first important distinction to make within fuels for passenger vehicles is between diesel and gasoline.[14] In Germany, diesel has a volume share of 44 percent of fuel for passenger vehicles with combustion engines and gasoline accounts for the remaining 56

[14]Since fuel stations do not report prices for truck diesel to the Market Transparency Unit, we only focus on fuel prices for passenger vehicles.

percent.[15] Substituting between these two types of fuel is very costly, both on the demand and supply side.[16] In the short-term, these can be considered as separate markets.

Drivers of diesel and gasoline cars differ in how much they drive. Whereas only 32 percent of registered passenger vehicles in Germany have a diesel engine, compared to 66 percent that run on gasoline, frequent drivers often buy diesel cars.[17] On average, gasoline passenger vehicles drive $10,800$ kilometers, whereas diesel passenger vehicles drive $19,500$ kilometers per year.[18]

The reason why frequent drivers buy diesel cars whereas less frequent drivers buy cars with a gasoline engine is that buying a diesel car is more expensive, but the cost of fuel at the pump is lower. Buying a diesel car is therefore a fixed cost investment to lower the marginal cost of driving. Drivers that select into buying a diesel engine thus do so based on their cost sensitivity and their incentive to save on fuel costs due to the distances they drive every year.

We verify this claim using data on search queries in 2015 from a major smartphone app displaying fuel prices to users in Germany. Figure 6 shows the daily number of price searches by fuel type on a major German smartphone app per 1,000 diesel or gasoline vehicles in circulation. The ratio of price searches to the number of vehicles in circulation is around 54 percent higher for diesel than for gasoline. This shows that the search intensity among drivers of diesel-run vehicles is significantly higher than among drivers of gasoline-run vehicles. It therefore strongly suggests that diesel drivers are more price sensitive.

A frequently made observation is that commercial vehicles usually run on diesel and this may affect the average price sensitivity of drivers by fuel type. Although we showed that drivers of diesel vehicles search more, it is worth briefly discussing why commercial

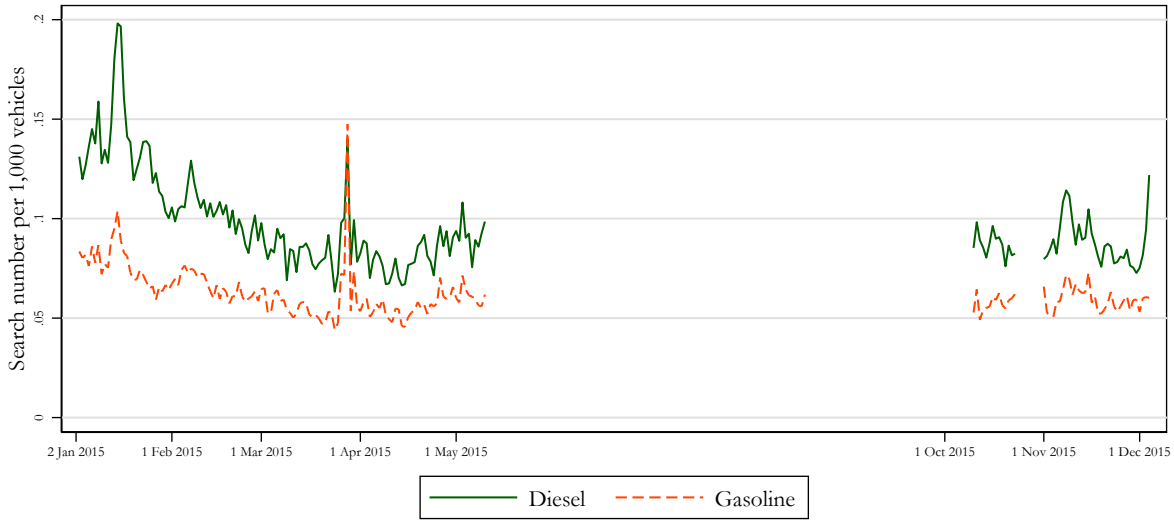
[15]This is based on 2018 figures from *Verkehr in Zahlen 2019/2020*, published by the Federal Ministry of Transportation. To the best of our knowledge, these are the most recent administrative figures concerning the passenger vehicle market only.

[16]On the demand side, this would usually require buying a new vehicle. On the supply side, readjusting the ratio of diesel and gasoline made from a barrel of crude oil is possible, but only to a limited extent and at a high cost.

[17]This is based on April 2020 figures on registered passenger vehicles in Germany, published by the German Federal Motor Transport Authority.

[18]This is based on 2018 figures from *Verkehr in Zahlen 2019/2020*, published by the Federal Ministry of Transportation.

Figure 6: Consumer search patterns (Germany)



Notes: The Figure shows the daily number of price searches by fuel type on a major German smartphone app per 1,000 diesel or gasoline vehicles in circulation. The data is available for January to May and October to December 2015. The solid line corresponds to the search intensity for diesel. The dashed line corresponds to the search intensity for gasoline.

vehicles are not a concern. First, as of 1 January 2021 there were around 15 million passenger vehicles with a diesel engine, but, including those with a gasoline engine, only 5.1 million commercial passenger vehicles (Kraftfahrt-Bundesamt, 2021). At the very least, 66 percent of passenger cars with a diesel engine are therefore owned by private individuals. In addition, commercial vehicle drivers may also have an incentive to reduce fuel costs, such as those receiving a lump-sum (or distance-based) fuel allowance or those that are self-employed. The fact that many commercial vehicles run on diesel therefore does not call into question our finding that drivers of vehicles that run on diesel are, on average, more price sensitive than drivers of vehicles running on gasoline.

3.2 *E5* vs. *E10*

Within gasoline, there is differentiation according to the octane rating and the share of ethanol. Standard gasoline (commonly referred to as *Super*) has an octane rating of 95. It has a volume share of 95.4 percent of the gasoline market.[19] *Super Plus* accounts for the remaining volume and is gasoline with an octane rating of 98, required by some high-

[19]This is based on 2019 figures from the monthly oil statistics, published by the Federal Office for Economic Affairs and Export Control.

performance vehicles. We do not consider *Super Plus* for the remainder of our analysis.[20]

Within *Super*, we can further distinguish according to the ethanol share. Standard gasoline has a 5 percent share of ethanol and is thus commonly referred to as *E5*. In 2011, a new type of gasoline was introduced in Germany with a 10 percent ethanol share, referred to as *E10*. The aim of increasing the share of ethanol is to reduce greenhouse gas emissions and decrease the amount of fossil fuel used in transportation. Although *E5* and *E10* are not taxed differently, *E10* is usually around 4 to 5 Eurocent cheaper than *E5*. This is partly driven by the relative prices of crude oil and ethanol on the world market and partly by a minimum quota of biofuels that need to be sold by fuel stations every year.

After the introduction of *E10* in 2011, there was controversy about whether biofuels damage the engine. Although biofuels can pose a significant threat to the engine of a vehicle that is not certified to be compatible with *E10*, around 90 percent of gasoline-run vehicles, including all vehicles produced after 2012, are compatible with *E10*.[21] According to the German Automobile Association, *E10* is around 1.5 percent less efficient than *E5*.[22] This cannot fully account for the observed difference in *E5* and *E10* prices. All fuel stations in Germany are required to sell both types of fuel. Nevertheless, in 2019 *E5* still had a volume share of 85.6 percent within *Super* and *E10* only of 14.4 percent. Overall, many motorists who could buy less expensive *E10* choose not to do so and buy *E5* instead. Reasons for this could include preferences or a lack of information, which point towards a lower price sensitivity of *E5* customers compared to *E10* customers.

Recent findings by the German Automobile Association confirm this view. According to a survey conducted in Fall 2020, the most cited reason for fueling *E10* was its lower price (72 percent among respondents fueling *E10*), followed by concerns for the environment (37 percent). Amongst respondents stating that they do not fuel *E10*, the

[20] *Super Plus* is a niche product in a different product market. Outside high-performance sports vehicles, most vehicles do not receive any additional benefit from fueling *Super Plus*. At the same time, it is always significantly more expensive than *Super* and the price difference can be up to 15 Eurocent at the same fuel station and time. This is also why fuel stations do not have to report prices of *Super Plus* to the Market Transparency Unit in Germany.

[21] A full list of compatible vehicles can be found at https://www.dat.de/e10/.

[22] See https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/benzin-und-diesel/e10-tanken/.

most cited reason not to do so were technical concerns (51 percent among respondents not fueling *E10*), followed by uncertainty about the cost and benefits (23 percent).[23]

Overall, the evidence therefore strongly suggests that among drivers of gasoline cars, the more price sensitive drivers become informed and buy *E10*, whereas the less price sensitive drivers buy *E5*.

3.3 Taxes and input costs

The largest share of the fuel price consists of taxes. A lump-sum energy tax of 65.45 Eurocents per liter is levied on gasoline (47.04 Eurocents per liter for diesel).[24] In addition, there is a 19 percent value-added tax which is levied on the net price of diesel and gasoline, including the energy tax. This value-added tax was temporarily reduced to 16 percent between July and December 2020. For simplicity, we will refer to this event as the "tax decrease".

On 1 January 2021, at the same time as the value-added tax was raised back to 19 percent, the German Federal Government also introduced a carbon price of 25 Euro per emitted tonne of CO_2 on oil, gas and fuel. For *E5* and *E10*, this translates into a per unit tax of 6 Eurocents per liter (7.14 Eurocents including VAT). For diesel, the per unit tax is 6.69 Eurocents per liter (7.96 Eurocents including VAT).[25] Likewise, we will refer to this event as the "tax increase". Since the increase in the VAT and the introduction of the carbon emissions price happened simultaneously and affected the same stations, we cannot separately identify the pass-through rate of the two. Instead, we jointly estimate their pass-through rate. This does not raise concerns regarding the theoretical predictions, as we showed that the predictions on the determinants of pass-through are qualitatively the same for ad-valorem taxes and per unit taxes.

Crude oil accounts for another important share of the fuel price and is the most important source of price fluctuations. A barrel (42 gallons) of crude oil can be refined

[23]The full survey results can be found at https://www.adac.de/news/umfrage-e10-tanken/.

[24]An additional fuel storage fee of 0.27 Eurocents per liter is levied on gasoline and 0.30 Eurocents per liter on diesel.

[25]Further details can be found in the "Brennstoff-Emissionshandelsgesetz" (2020 Fuel Emissions Trading Act).

into around 19 gallons of gasoline, 12 gallons of diesel, as well as 13 gallons of other products, such as jet fuel, petroleum coke, bitumen or lubricants.[26] Gasoline and diesel are the most valuable components of refined crude oil.

4 Data and Descriptive Evidence

We now turn to our empirical analysis. We begin by describing our dataset and then present descriptive evidence on the differences in pass-through between fuel types.

4.1 Data

Our dataset contains all price changes for close to all fuel stations in Germany and France, as well as several characteristics of these stations.[27] In Germany, stations report price changes in real-time to the Market Transparency Unit at the German Federal Cartel Office. Tankerkönig, a price comparison website, provides access to this data, as well as to station characteristics, to researchers.[28] Similarly, price changes in France have to be reported by stations to a government agency, which makes this data available to researchers.[29] Furthermore, we add data on the daily price of crude oil, the principal input product for diesel and gasoline, at the port of Rotterdam. Finally, we use data on daily regional mobility patterns from the COVID-19 Community Mobility Report provided by Google.

Our analysis of the tax decrease starts on 1 May 2020 and goes until 31 August 2020. For the tax decrease, we analyze data between 1 November 2020 and 28 February 2021. In this section, we report descriptive statistics for the analysis of the tax increase in summer 2020. We report the same descriptive statistics for the tax decrease in winter 2020/21 in Appendix B.

[26] These are approximate shares which can vary by context and type of crude oil. The total volume of products refineries produce (output) is greater than the volume of crude oil that refineries process (input) because most of the products they make have a lower density than the crude oil they process. See https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-inputs-and-outputs.php.

[27] In France, fuel stations selling less than $500m^3$ per year are exempt from reporting price changes.

[28] See https://creativecommons.tankerkoenig.de/.

[29] See https://www.prix-carburants.gouv.fr/rubrique/opendata/.

Table 1: Summary statistics

	Germany pre-VAT cut	Germany post-VAT cut	France pre-VAT cut	France post-VAT cut
A. Station characteristics				
Number of stations	14,627	14,612	8,960	8,975
Median comp. nr. (5km markets)	4	4	2	2
Share of local monopolists	13%	13%	20%	19%
B. Prices, *E5*				
Mean price	1.21	1.27	1.30	1.36
Mean price net of taxes and duties	.36	.44	.40	.44
Mean retail margin	.13	.16	.17	.16
C. Prices, *E10*				
Mean price	1.18	1.23	1.27	1.32
Mean price net of taxes and duties	.34	.40	.39	.43
Mean retail margin	.11	.13	.16	.15
D. Prices, diesel				
Mean price	1.05	1.07	1.20	1.25
Mean price net of taxes and duties	.41	.45	.39	.43
Mean retail margin	.18	.17	.16	.15
E. Mobility data				
Retail & recreation	-22.2%	-2.4%	-32.4%	6.6%
Workplaces	-21.9%	-20.7%	-27.8%	-26.2%

Notes: "pre-VAT cut" and "post-VAT cut" refer to fuel stations in Germany and France before and after the reduction of the VAT rate, respectively. The pre-VAT phase goes from 1 May until 31 June 2020. The post-VAT phase starts on 1 July 2020.

Using the data on price changes, we construct daily weighted average prices. Table 1 shows the summary statistics for the analysis of the tax reduction. The price level is generally higher in France than in Germany. Gross prices in France increase by around 5 to 6 Eurocent between the pre- and post-tax cut periods. In Germany, gross prices increase by about 2 Eurocent for diesel and 5 to 6 Eurocent for *E5* and *E10*. At the same time, the increase in the net price in Germany is between 4 and 8 Eurocent, depending on the fuel type, which is larger than in France, and suggests that the tax reduction was not completely passed on to consumers.

We also calculate retail margins by subtracting taxes, duties and the share of the price of crude oil that goes into the production of diesel and gasoline, respectively.[30] Although these retail margins still contain different cost types, such as the cost of refining or transportation costs, the main source of input cost variation, the price of crude oil, is

[30]For a detailed description of the calculation of prices and margins, see Appendix B.

eliminated. Table 1 shows that retail margins declined by about 1 Eurocent for France after the tax reduction. Although there is a modest decrease in retail margins for diesel in Germany after the tax reduction, there is an increase in the retail margin of around 17.6 percent for *E10* and 20.4 percent for *E5*.[31]

To capture regional changes in demand over time, we use the daily percentage change in visits to retail and recreation, as well as to the workplace, from the COVID-19 Community Mobility Report. With the former, we intend to capture local changes in the propensity of using a car for leisurely activities, including going on vacation. With the latter, we aim to capture local changes in the propensity to use a car for professional activities. Both of these variables are measured as the percentage change of activities compared to the median value for the corresponding day of the week during the five-week period 3 January to 6 February 2020. The data is disaggregated for 96 sub-regions in France and 16 regions in Germany. We use the geolocation of each fuel station to match the measures of local mobility to each station.

Table 1 shows that mobility patterns in France and Germany are similar. Whereas visits to retail and recreational facilities were around 22 to 32 percent lower in May to June compared to the baseline beginning of the year, in July to August, the number of such visits returned close to their pre-pandemic levels. At the same time, in both countries visits to workplaces were around 20 to 28 percent lower in May to August compared to the baseline.

Our dataset also contains a number of station characteristics, such as the exact geolocation, and, for Germany, the brand of a station. We use this data to measure the number of firms active in a local market. We define each market as a catchment area around a focal fuel station. We exploit the geolocation of each station to calculate the driving distance between stations using the road network.[32] Finally, we count the number of rival stations that are within a 3, 5 or 10 km catchment area around a focal station. Based on our market definition, we can also compute the share of stations that are without

[31]Percentage changes are different from what you would calculate from the retail margins in the table because of rounding of margins in the table.

[32]By using the road network, we avoid classifying fuel stations that are close by air distance but not by road as competing with each other.

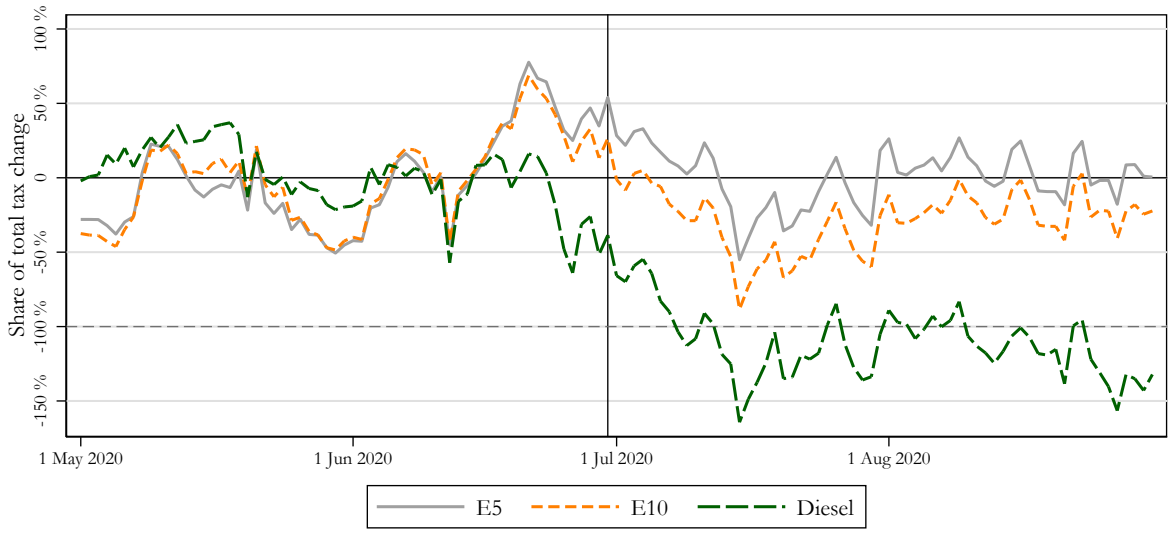
any competitor in their local market, i.e. the share of local monopolists. Table 1 shows that the median number of competing fuel stations within a 5 km catchment area is 4 in Germany and 2 in France. 13 percent of stations in Germany are local monopolists within a 5 km catchment area, compared to 19 to 20 percent in France.

We report summary statistics using the weights in the SDID in Appendix B. Results on average fuel prices, retail margins and stations characteristics remain analogous when stations in France are weighted by the SDID weights.

4.2 Descriptive evidence on heterogeneous pass-through

Before econometrically estimating pass-through of the tax changes on prices and retail margins, we study the pass-through of the policy changes descriptively. We can thereby gain first insights into whether pass-through differs between markets with very price sensitive consumers (diesel) and markets with less price sensitive consumers (*E5*). Let us begin by first looking at the VAT reduction on 1 July 2020.

Figure 7: Tax decrease: Price change as share of total tax change

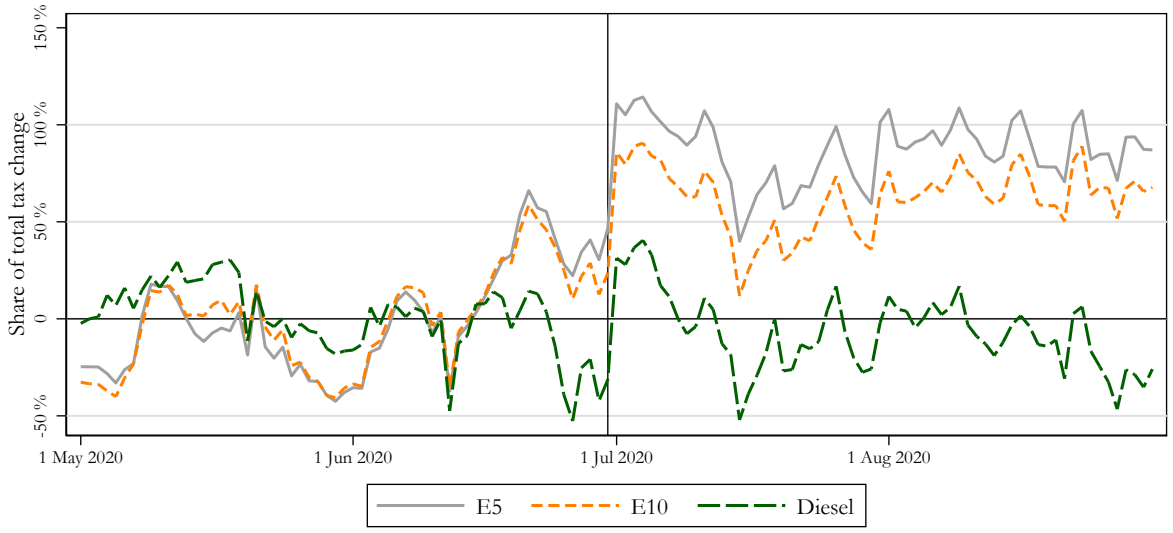


Notes: The solid line shows the nonparametric estimate of the daily average pass-through rate to prices for *E5*. The short-dashed and long-dashed lines show analogous estimates for *E10* and diesel, respectively. To estimate pass-through, we first subtract the average pre-period (1 May until 30 June 2020) price in Germany (France) from the daily average price in Germany (France). Next, we compute the difference between demeaned average prices in Germany and France. Finally, we divide this difference by 3 Eurocents for *E5* and *E10* and by 2.7 Eurocents for diesel, which would be the difference under full pass-through. The vertical solid line marks the starting date of the tax decrease. The horizontal dashed line indicates the full pass-through.

Figure 7 shows nonparametric estimates of the pass-through rate of the tax decrease to fuel prices. As we would expect, prior to the tax reduction, there is no pass-through of the tax decrease for any fuel type, as it has not yet occured. The evolution of fuel prices evolves similarly for the three fuel types, which suggests that differences in pass-through rates after the tax decrease are not driven by pre-trends. The evolution of prices after the tax decrease suggests that pass-through was relatively fast, stabilized after around two weeks, and that it was highest for diesel and lowest for *E5*. The difference in pass-through between fuel types is in line with our theoretical prediction that pass-through increases if there are more price sensitive consumers in the market.

Although we can see that there are differences in the evolution of prices between France and Germany in the pre-period, these appear to be idiosyncratic. The findings described above can clearly be seen even before correcting for some of the idiosyncratic shocks. However, the absolute magnitudes of pass-through in this graph should be treated with caution and we provide more precise estimates of these in the following sections.

Figure 8: Tax decrease: Margin change as share of total tax change

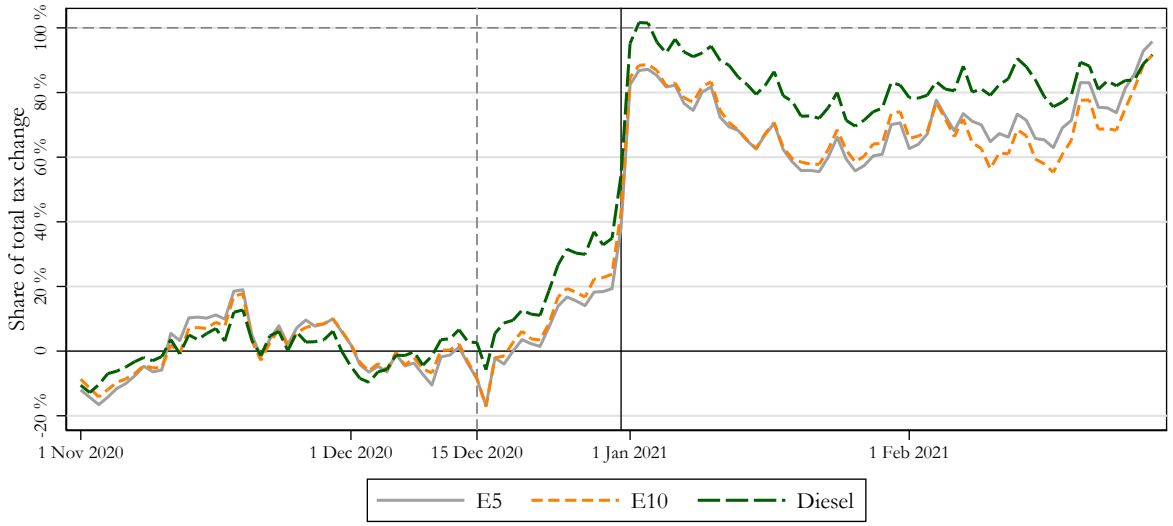


Notes: The solid line shows the nonparametric estimate of the daily average pass-through rate to retail margins for *E5*. The short-dashed and long-dashed lines show analogous estimates for *E10* and diesel, respectively. To estimate pass-through, we first subtract the average pre-period (1 May until 30 June 2020) retail margin in Germany (France) from the daily average retail margin in Germany (France). Next, we compute the difference between demeaned average retail margins in Germany and France. Finally, we divide this difference by 3 Eurocents for *E5* and *E10* and by 2.7 Eurocents for diesel, which would be the difference under full pass-through. The vertical solid line marks the starting date of the tax decrease.

Figure 8 plots the analogous graph for retail margins. Consistent with what we

saw for prices, there is no pass-through of the tax decrease to retail margins prior to the tax decrease. In the post-period, retail margins appear to increase the most for *E5* and remain unchanged for diesel.

Figure 9: Tax increase: Price change as share of total tax change

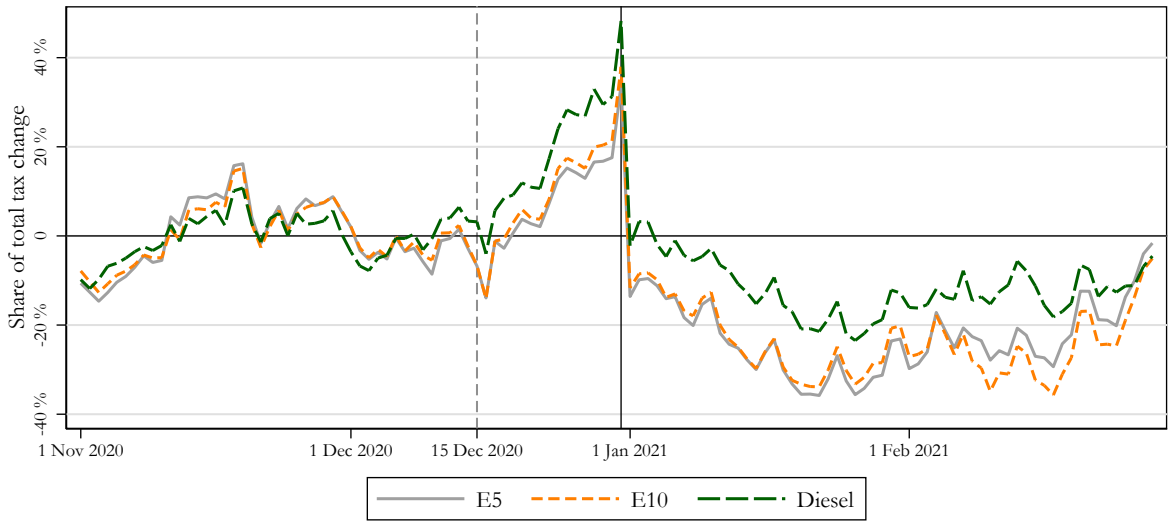


Notes: The solid line shows the nonparametric estimate of the daily average pass-through rate to prices for *E5*. The short-dashed and long-dashed lines show analogous estimates for *E10* and diesel, respectively. To estimate pass-through, we first subtract the average pre-period (1 November until 15 December 2020) price in Germany (France) from the daily average price in Germany (France). Next, we compute the difference between demeaned average prices in Germany and France. Finally, we divide this difference by 10 Eurocents for *E5* and *E10* and by 11 Eurocents for diesel, which would be the difference under full pass-through. The vertical solid line marks the starting date of the VAT increase and carbon emissions price in Germany. The horizontal dashed line indicates the full pass-through.

In Figure 9, we present nonparametric estimates of the pass-through rate by fuel type for the tax increase in winter 2020/21. As for the tax decrease, there is no anticipatory pass-through of the tax increase for most of the pre-increase period. In contrast to the tax decrease, there seem to be anticipatory effects in passing through the tax increases in the last two weeks of December. In our econometric analysis, we therefore drop the second half of December 2020, since this already appears to be partially treated. Finally, there is a sharp increase in the implied pass-through rate around 1 January 2021, after which this stays stable. Differences in pass-through between diesel and other types of fuel are very pronounced. As in summer 2020, pass-through appears to be highest for diesel. This is also consistent with our theoretical predictions. From the descriptive evidence, differences in pass-through between *E5* and *E10* seem less strong. We provide

more precise estimates on this in the upcoming sections.

Figure 10: Tax increase: Margin change as share of total tax change



Notes: The solid line shows the nonparametric estimate of the daily average pass-through rate to retail margins for *E5*. The short-dashed and long-dashed lines show analogous estimates for *E10* and diesel, respectively. To estimate pass-through, we first subtract the average pre-period (1 November until 15 December 2020) retail margin in Germany (France) from the daily average retail margin in Germany (France). Next, we compute the difference between demeaned average retail margins in Germany and France. Finally, we divide this difference by 10 Eurocents for *E5* and *E10* and by 11 Eurocents for diesel, which would be the difference under full pass-through. The vertical solid line marks the starting date of the VAT increase and carbon emissions price in Germany.

Figure 10 shows how the tax increase is passed through to retail margins. Since stations seem to have begun increasing prices already in the second half of December 2020, even though the tax increase only occured on 1 January 2021, there appears to be an increase in retail margins worth up to 30 percent of the subsequent tax change for diesel in the last week of December 2020 and around 20 percent for *E5* and *E10*. After the tax increase, the descriptive evidence suggests that the decrease in retail margins was lowest for diesel. This is consistent with what we see for prices.

The results in Figures 9 and 10 suggest that in the second half of December 2020, there are some anticipatory effects of the tax increase coming into effect on 1 January 2021 across all fuel types. A visual analysis of Figures 7 and 8 suggests that there could be anticipatory effects for *E5* and *E10* already in the second half of June 2020, but that these are less pronounced than in winter. Our preferred specification is therefore to account for anticipatory effects in winter but not in summer. In Appendix D, we show

that our main empirical findings are robust to changing these assumptions. In Appendix A, we briefly discuss theoretically why anticipatory price increases could arise before a tax increase and a tax decrease.

5 Empirical Strategy

So far, we saw descriptively that pass-through of the two tax changes appears to be different across fuel types. At the same time, we saw that there were some idiosyncratic differences in the evolution of fuel prices between Germany and France. To cut through the noise and estimate pass-through rates, we use a synthetic difference-in-differences (SDID) strategy.

5.1 Synthetic difference-in-differences

The general idea of SDID is quite simple. As with difference-in-differences, we use fuel prices at French stations as the control group and so the treatment effect is the change in the difference between average fuel prices at fuel stations in Germany and France between pre- and post-treatment periods. In contrast to DID, weights of fuel stations in the control group, as well as weights of the pre-treatment periods are chosen as to match the pre-treatment trends in the treatment group.[33] In this sense it is similar to synthetic control methods. Arkhangelsky et al. (2020) report that SDID performs weakly better than DID and SC methods.

The estimation proceeds in two steps. In the first step, we compute the unit and time weights that minimize the difference in pre-treatment trends between the treated and control units and the difference in outcomes between pre- and post-treatment periods for the unexposed units. In the second step, we estimate a difference-in-differences model using the unit and time weights from the first step. We estimate standard errors using the jackknife method.[34]

[33]On average, fuel prices are higher at stations in France than in Germany. Since SDID matches the pre-treatment trends in prices instead of the price level, as shown in Appendix D control stations that receive a higher SDID unit weight are not clustered in a particular region in France.

[34]We use the jackknife method instead of bootstrapping, as the latter is computationally too intensive

To estimate the average pass-through rate of the tax changes on fuel prices, we compare stations in Germany and France, before and after the tax change. In particular, we solve the following minimization problem:

$$(\hat{\tau}^{sdid}, \hat{\mu}, \hat{\alpha}, \hat{\beta}) = \underset{\tau,\mu,\alpha,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} \left(Y_{it} - \mu - \alpha_i - \beta_t - Tax_{it}\tau\right)^2 \hat{w}_i^{sdid} \hat{\lambda}_t^{sdid} \right\} \tag{2}$$

where $\hat{\tau}^{sdid}$ is the estimated effect of the policy change, and $\hat{w}_i^{sdid}$ and $\hat{\lambda}_t^{sdid}$ are the SDID unit and time weights, respectively.[35] Y_{it} is the logarithm of the price of gasoline or diesel at fuel station i at date t, and Tax_{it} is a dummy variable that equals one for stations affected by the tax change at date t. For the analysis of the tax reduction, these are fuel stations in Germany from 1 July 2020 onwards. For the analysis of the subsequent tax increase, these are fuel stations in Germany from 1 January 2021 onwards. The variables α_i and β_t correspond to fuel station and date fixed effects, respectively.

To use the synthetic difference-in-differences method, we require a balanced sample. We therefore restrict our sample to fuel stations in France and Germany for which we have a price observation on every day in our sample. This is the case for 83 percent of fuel stations in Germany and 62 percent in France for the analysis of tax reduction, and for 83 percent of stations in Germany and 74 percent in France for the analysis of the tax increase. In Appendix D, we also estimate a DID model using the full, unbalanced sample.

Finally, we also want to assess the speed at which the tax changes are passed-through to consumers and verify that the parallel trends assumption holds. We therefore estimate time-varying effects of the tax changes using the following model:

$$ln(p_{it}) = \sum_{j=-k}^{8} \beta_j Tax_{it} + \mu_i + \gamma_t + \epsilon_{it} \tag{3}$$

where $ln(p_{it})$ is the logarithm of the price of gasoline or diesel at fuel station i at date t. The regression is weighted by the SDID unit and time weights, and we control for fuel

in our case. The jackknife method is a linear approximation of the bootstrap and gives a conservative estimate of the variance when the panel is large and the number of treated units is high.

[35] We estimate the model using the *synthdid* package by Arkhangelsky et al. (2020). A more detailed description of the algorithm can be found in Appendix C.

station and date fixed effects. The coefficient β_j captures the effect of the tax change in a period t on fuel prices in Germany in a week $t + j$, with $j \in [-k, 8]$.[36]

5.2 French fuel stations as a control group

To identify the effect of the tax change on fuel prices, two main assumptions must be satisfied. First, there should be no transitory shocks that would differentially affect fuel stations in Germany and France before and after the change in tax, other than the policy change itself. Second, there should be no spillover effects from the tax decrease or the tax increase in Germany onto the fuel market in France.

Station fixed effects control for any time-invariant differences between fuel stations in France and Germany, and date fixed effects capture the transitory shocks, such as fluctuations in the price of crude oil, that identically affect French and German stations. The two countries are similar in their geographic location, size, and wealth. Since in our analysis we also focus on relatively narrow windows around the reforms, this should alleviate concerns on transitory shocks differentially affecting French and German fuel stations.

To further strengthen our claim that the effects are not confounded by certain transitory shocks, we now discuss the most obvious candidates. On the demand side, public and school holidays in France and Germany are highly correlated. Travel restrictions put in place due to COVID-19 were lifted simultaneously in the two countries. Starting from 15 June 2020, residents of the Schengen Area and the United Kingdom could freely cross the territories of France and Germany again. Most holidaymakers within Europe typically travel across several countries in the EU, and as France and Germany are both popular travel destinations in close geographic proximity, demand shocks likely hit fuel stations in the two countries in a similar way.[37]

Transitory supply shocks should affect French and German fuel stations in a similar way. Due to their geographic proximity, the fuel stations in France and Germany procure

[36]For the analysis of the tax reduction, $k = 7$. For the analysis of the tax increase, $k = 5$.

[37]In addition, we directly account for demand-related shocks by including regional information on the daily mobility to work and to retail and recreational places as control variables into our empirical specification. The results are reported in the Appendix.

most of their crude oil from similar sources.[38] The two countries are also members of the European Single Market, which implies harmonized border checks, common customs policy, and identical regulatory procedures on the movement of goods within the EU.

No major reforms were implemented in France during our analysis period. In general, there are no fuel price-setting regulations in Germany and France, and both countries have mandatory disclosure of fuel prices, which reaffirms our choice of France as a suitable control group.

Furthermore, the SDID algorithm allows us to place higher weight on French fuel stations whose pre-trends are very similar to the pre-trends of stations in Germany and place lower weight on French stations whose pre-trends are very dissimilar. This should further alleviate any remaining concerns about French stations as a control group.

Finally, our analysis of the two episodes of a change in tax, the temporary VAT rate reduction in July 2020 and the subsequent increase in the VAT rate with simultaneous introduction of a carbon emissions price in January 2021, alleviates a concern that some confounding factor could drive the results. If we find similar heterogeneities in pass-through for the VAT increase in January 2021 as for the VAT decrease in July 2020, a transitory shock confounding our estimates in July 2020 would also have to be present in January 2021 and at that point work in the opposite direction. To illustrate this point: if we thought that we overestimate the pass-through rate for diesel in July 2020, because France is hit by a positive transitory demand in July 2020, which does not affect Germany, then also overestimating pass-through for diesel in January 2021 would now require France to be hit by a negative demand shock in January 2021, which does not affect Germany. Overall, this seems implausible. Finding consistent heterogeneities in pass-through rates between the July 2020 and January 2021 tax changes therefore suggests that we are robustly estimating actual differences in pass-through.

[38] We additionally account for potentially differential pass-through of oil cost shocks to fuel prices by allowing crude oil price affect fuel prices differently depending on the country. The results are reported in the Appendix.

6 Results

In Section 2, we showed theoretically how the pass-through of a tax depends on the price sensitivity of consumers and the number of sellers. Descriptively, we showed that the heterogeneities in the pass-through rate between fuel types are in line with our theoretical predictions. In this section, we provide further evidence on this and also study how pass-through depends on the number of sellers empirically.

6.1 Price sensitivity and tax pass-through

We first study how the pass-through of a tax varies with the price sensitivity of consumers. Theoretically, we showed that the higher the price sensitivity of consumers, the higher will be the pass-through rate of a tax. To test this prediction empirically, we estimate the effects of the tax changes in Germany on *E5*, *E10* and diesel prices, and compare the estimated pass-through rates across fuel types.

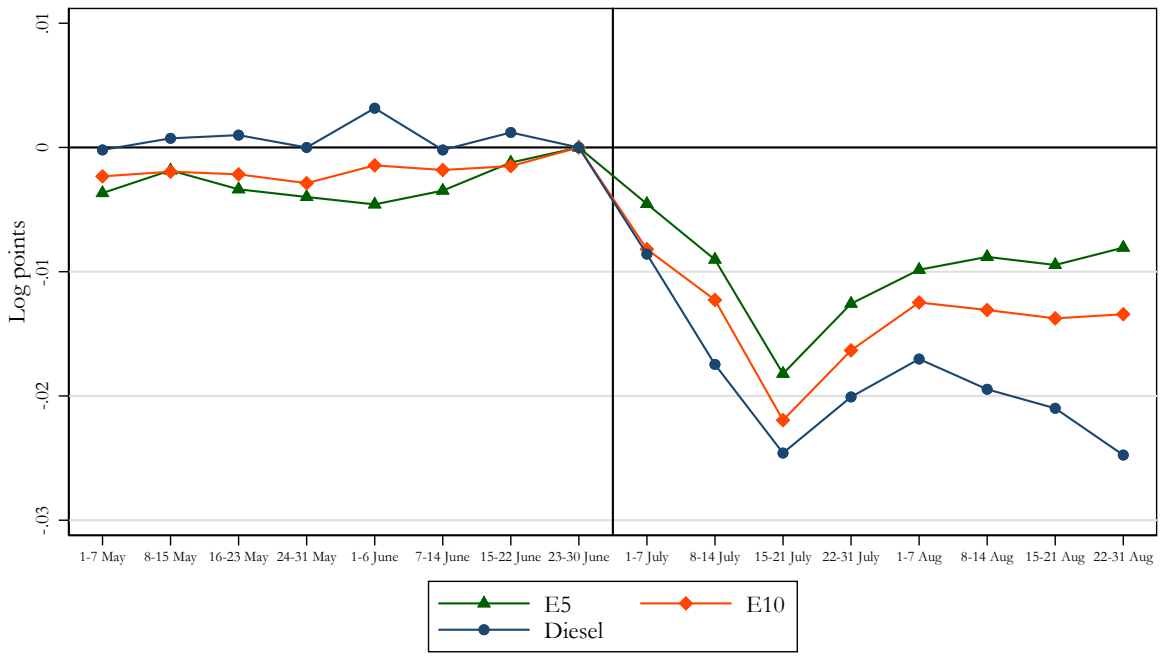
We begin our analysis of the tax changes by plotting their time-varying effects by fuel type.

Figure 11 shows the time-varying effect of the tax decrease on the logarithm of prices for *E5*, *E10* and diesel.[39] The estimation is based on 1 May to 31 August 2020. The vertical line marks the beginning of the tax decrease in Germany. Prior to the tax reduction, the trends in log fuel prices are similar between France and Germany. After the tax reduction, log prices of all fuel types decline at fuel stations in Germany compared to fuel stations in France. The effect of the tax reduction is highest for diesel and lowest for *E5*, and is relatively fast. These results are consistent with the descriptive evidence and the theoretical predictions.

Figure 12 shows the time-varying effect of the tax increase. The analysis is based on the pre-treatment period of 1 November to 15 December 2020 and the post-treatment period of 1 January to 28 February 2021. As we saw in the descriptive analysis, there are anticipatory effects of the tax increase in the second half of December 2020. Since these days appear to be already partially treated, we drop them from the analysis.

[39] Figures with the time-varying effects on retail margins are reported in Appendix D.

Figure 11: Dynamic effect of the tax decrease on log fuel prices



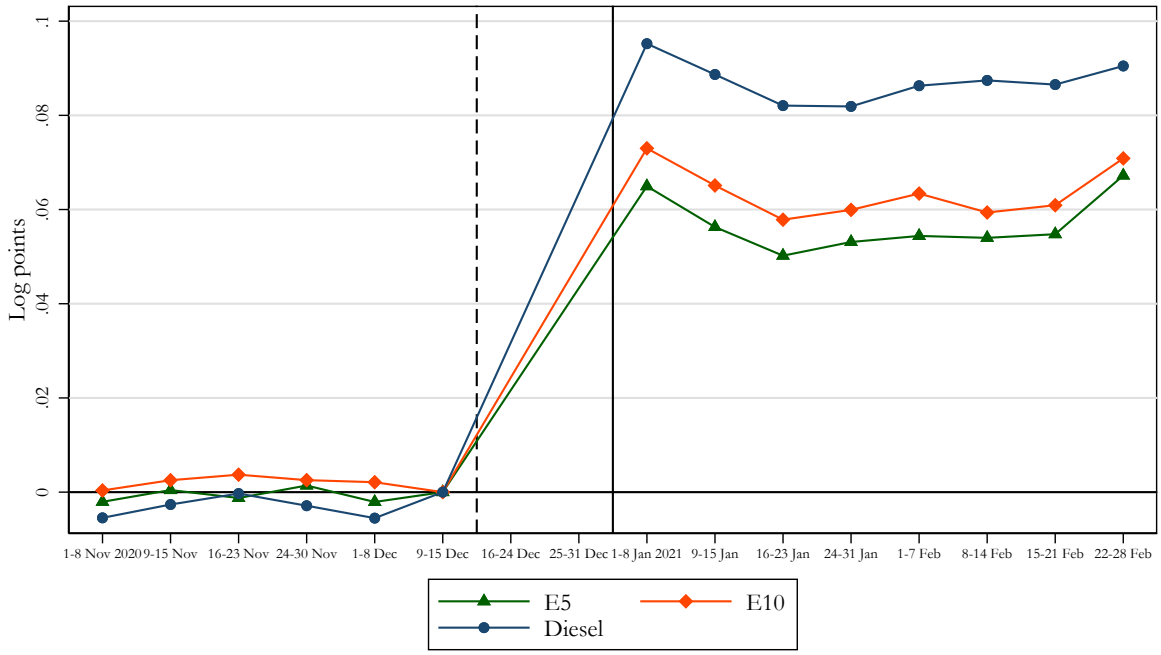
Notes: The graph shows the time-varying effect of the tax decrease on the log prices for *E5*, *E10* and diesel. The analysis period goes from 1 May until 31 August 2020. For the time-varying treatment effects, we estimate the model in Equation 3, weighted by the SDID unit and time weights. The vertical line marks the starting date of the tax decrease in Germany.

Prior to the tax increase, the trends in the logarithm of fuel prices are similar between France and Germany. After the tax increase, log prices at fuel stations in Germany increase compared to those in France for all fuel types. Pass-through of the tax increase is almost immediate. Fuel prices increase by about 6 to 9 percent in the first week of January 2021 compared to the week ending on 15 December 2020. Similarly to our results for the tax reduction, the price increase is highest for diesel and lowest for *E5*, with *E10* in between.[40]

Next, we estimate the average treatment effect of the tax changes on the logarithm of prices for *E5*, *E10* and diesel. Table 2 shows the results of estimating the SDID model described in Equation 2. The outcome variable in all columns is the logarithm of price for each fuel type, including taxes and duties. Columns (1) to (3) correspond to the effect of the tax decrease. Columns (4) to (6) correspond to the effect of the subsequent tax

[40]Note, that relative pass-through rates cannot directly be inferred from Figure 12, as the percentage increase in prices for full pass-through is different between fuel types. We estimate pass-through rates in Table 2.

Figure 12: Dynamic effect of the tax increase on log fuel prices



Notes: The graph shows the time-varying effect of the tax increase on log prices for *E5*, *E10* and diesel. The pre-treatment period goes from 1 November until 15 December 2020 and the post-treatment period from 1 January to 28 February 2021. For the time-varying treatment effects, we estimate the model in Equation 3, weighted by the SDID unit and time weights. The vertical solid line marks the beginning of the tax increase in Germany.

Table 2: Effect of the tax change on log prices (percent)

	E5	E10	Diesel	E5	E10	Diesel
	(1)	(2)	(3)	(4)	(5)	(6)
Tax change	-.0085***	-.0130***	-.0199***	.0565***	.0627***	.0889***
	(.0013)	(.0013)	(.0015)	(.0015)	(.0019)	(.0020)
Pass-through rate	34%	52%	79%	69%	75%	92%
	[24%, 43%]	[42%, 62%]	[67%, 91%]	[66%, 73%]	[71%, 79%]	[88%, 96%]
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Station fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,736,145	1,968,984	2,176,362	1,485,120	1,712,984	1,945,736

Notes: Columns (1) to (3) present average treatment effect estimates of the VAT reduction on E5, E10, and diesel log prices, respectively. Columns (1) to (3) use data from 1 May to 31 August 2020. Columns (4) to (6) present average treatment effect estimates of the VAT increase and CO_2 emissions tax on E5, E10, and diesel log prices, respectively. Columns (4) to (6) use data from 1 November to 15 December 2020 for pre-treatment period, and from 1 January to 28 February 2021 for post-treatment period. 95% confidence intervals on pass-through rates are reported in parentheses. Standard errors are computed using the jackknife method and are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

increase. In all columns, we control for fuel station and date fixed effects.[41]

The results in Columns (1) to (3) of Table 2 show that the tax decrease led to a decline in prices of all fuel products. The average price for *E5* decreases by 0.85 percent after the tax reduction, whilst average prices for *E10* and diesel decrease by 1.3 and 1.99 percent, respectively.[42]

To estimate pass-through of the tax reduction, we start by considering the case of full pass-through. Under full pass-through, we expect prices for each fuel product to decrease by about 2.52 percent.[43] An estimated decline of 1.99 percent in diesel prices is therefore relatively close to full pass-through. Around 79 percent of the tax decrease is passed on to consumers who refuel with diesel. For *E10*, the pass-through rate is 52 percent. Finally, we estimate that 34 percent of the tax decrease is passed through to

[41]In Appendix D, we show the geographic distribution of stations that receive a higher than average SDID unit weight in France for the case of the tax decrease and tax increase. Control stations with disproportionately higher SDID weights are scattered throughout France and do not appear to cluster in a particular region.

[42]In Appendix D, we report the results when we additionally control for regional mobility for retail and recreational purposes and to workplaces, and allow the changes in the crude oil price to differentially affect fuel prices in France and Germany. Our results are robust to the inclusion of these additional controls.

[43]With a decrease in the VAT rate from 19 percent before the VAT decrease to 16 percent after the VAT decrease, this is $\frac{1.16-1.19}{1.19} * 100 \approx -2.52\%$.

consumers of *E5*. For all fuel products, pass-through of the tax reduction is fast and relatively high, but incomplete.

The results in Columns (4) to (6) of Table 2 show the effect of the subsequent VAT rate increase and the introduction of a carbon price on log fuel prices. Since the increase in the VAT and the introduction of the carbon emissions price happened simultaneously and affected the same stations, we cannot separately identify the pass-through rate of the two. Instead, we jointly estimate their pass-through rate. This does not raise concerns regarding the theoretical predictions, as we showed that the predictions on the determinants of pass-through are qualitatively the same for ad-valorem taxes and per unit taxes.[44]

Columns (4) to (6) of Table 2 show that the tax increase led to an increase in prices of all fuel products. The average price of *E5* increases by about 5.65 percent, whereas *E10* and diesel prices increase by about 6.27 and 8.89 percent after the change in the VAT rate and carbon tax introduction, respectively.

Next, we estimate the pass-through rate of the tax increase. Under full pass-through, we would expect an increase in prices by 8.15 percent for *E5*, 8.37 percent for *E10* and 9.66 percent for diesel.[45] We find a joint pass-through rate of the tax increase of 69 percent for *E5*, 75 percent for *E10* and 92 percent for diesel. As for the tax decrease, pass-through is fast but incomplete and it is lowest for fuel types with fewer price sensitive consumers and higher for fuel types with more price sensitive consumers. In Appendix D, we report results for the tax decrease and tax increase using DID model. The ranking of pass-through rates across different fuel types and their magnitude remain robust to using this alternative specification.

As predicted by the theory, we find that the pass-through rate for diesel is highest and it is the lowest for *E5*. An advantage of our setting is that all fuel stations in Germany

[44]The only necessary adjustment is that we need to translate the per unit tax on carbon emissions into a percentage value, such that we can calculate how large the percentage increase in prices would be if the VAT rate and the carbon emissions tax were fully passed through.

[45]Under full pass-through, a change in the VAT rate from 16 to 19 percent would increase the fuel price by $\frac{1.19-1.16}{1.16} * 100 \approx 2.59$ percent. To estimate by what percentage the fuel price would increase if the carbon emissions price was fully passed through, we divide the gross per liter price on carbon emissions for each fuel type by the average fuel price in Germany in the last week of 2020.

are required by law to sell all three types of fuel and so differences in the pass-through rates cannot be explained by supply-side factors, such as fuel station characteristics. Table 2 reports the 95 percent confidence interval on pass-through rates for the different fuel types. For both the tax decrease and subsequent tax increase, we can see that the difference between the pass-through rate for diesel and the two types of gasoline is statistically significant at the 5 percent level. Confidence intervals for the pass-through rate of *E5* and *E10* overlap, however, their ranges still strongly suggest that there is an important economic difference between the pass-through rates for *E5* and *E10*. Overall, our empirical results confirm the predictions in Proposition 2.

Across fuel types, the pass-through rate of the increase is above the pass-through rate of the decrease. Although this is not the focus of our study, these results are consistent with recent findings on asymmetric VAT pass-through by Benzarti et al. (2020).

Based on the descriptive price plots in Section 4, our preferred specification and the presented results so far correspond to accounting for anticipatory effect in winter 2020/21 but not in summer 2020. In Appendix D, we report results when we instead account for anticipatory effects in summer but not in winter. Even though pass-through estimates change when we use this alternative specification, the relationship between tax pass-through and price sensitivity is robust with respect to anticipatory effects. The pass-through remains highest for diesel and lowest for *E5*.

6.2 Number of sellers and tax pass-through

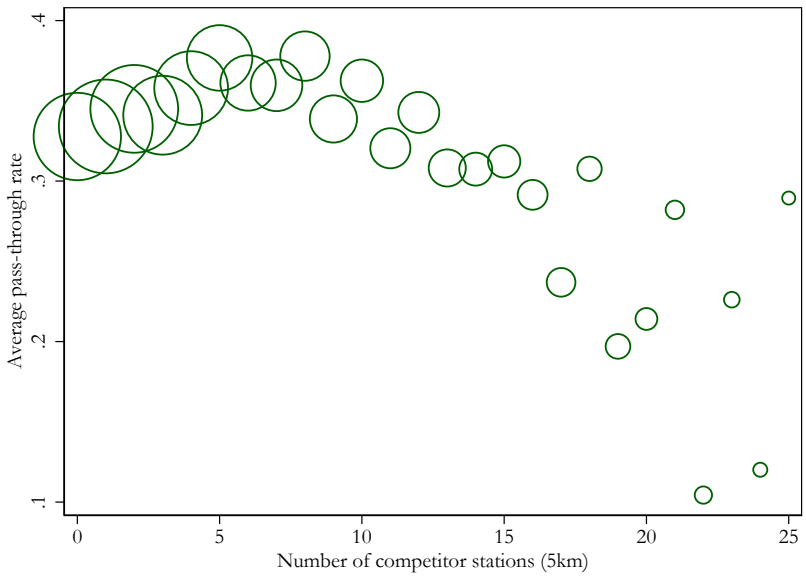
Finally, we study how the pass-through rate varies with the number of sellers in the market. In Section 2, we used simulations to show that theoretically there is a hump-shaped relationship between the number of sellers in the market and tax pass-through.

To verify this empirically, we study differences in the pass-through rate of the tax decrease across fuel stations with different numbers of competitors in their market. An important feature of our setting is that we can do this comparison within fuel type and so hold an important source of variation in price sensitivity fixed. We begin by estimating a pass-through rate for every station in Germany for each fuel type. For each station

in Germany and fuel type, we estimate the model in Equation 2 adding an interaction term between the treatment period and the station's fixed effect.[46] The station-specific treatment effect is then the sum of the average treatment effect and this additional interaction. Finally, we group stations by the number of competitors in their market and calculate the average pass-through rate for each group.[47]

Figure 13 shows the relationship between the pass-through rate and the number of competitors of a focal station for *E5*. Each circle corresponds to the average pass-through rate for stations with a particular number of competitors within 5 km catchment area.[48] The size of a circle is proportional to the total number of stations with a given number of competitors. Figure 13 shows that the average pass-through is relatively low for local monopolists, and increases in the number of rivals, up to around six competitor stations. With more than six competitor stations, the average pass-through declines in the number of competitors.

Figure 13: Average pass-through by number of competitor stations, E5



Notes: Each circle plots the average pass-through rate for a group of stations with a particular number of competitors within a 5 km catchment area. The number of competitor stations is trimmed at the top percentile.

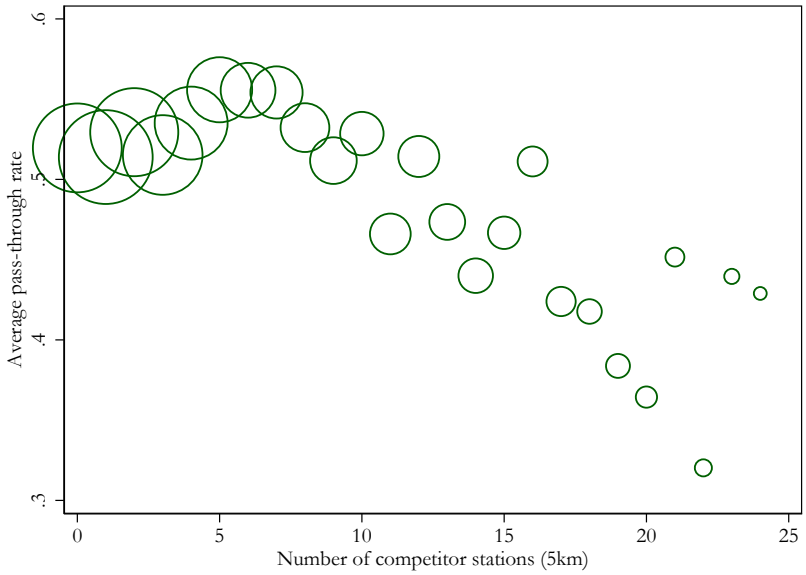
[46] We use the same time and unit weights for each station-specific treatment effect and estimate this only once.

[47] In Appendix D, we show the analogous relationship between the pass-through rate of the tax increase and the number of competitors of a focal station.

[48] The pattern is similar for alternative radii.

Figure 14 shows the relationship between the pass-through rate and the number of competitors of a focal station for *E10*. Similar to *E5*, we observe a hump-shaped relationship between the pass-through rate and the number of competitors. The average pass-through rate is relatively low for local monopolists, peaks in the group of stations that have around six to eight competitors and then falls again in the number of competitors.

Figure 14: Average pass-through by number of competitor stations, E10

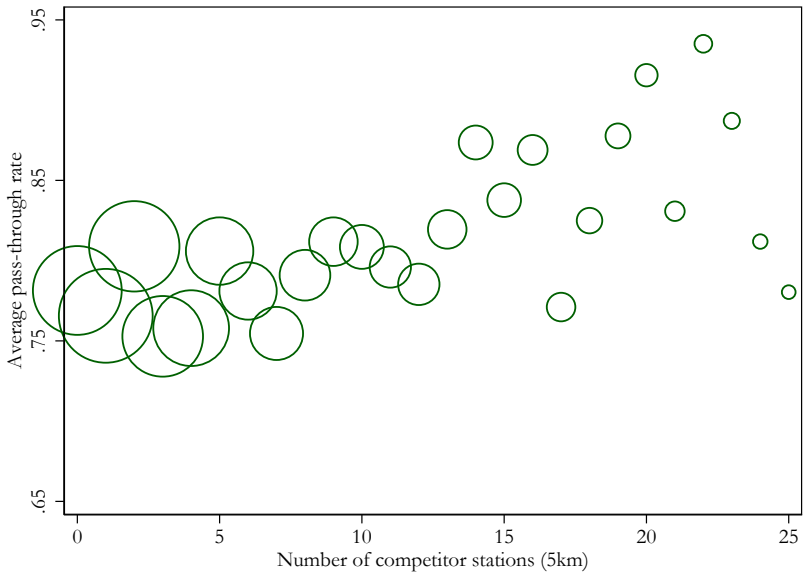


Notes: Each circle plots the average pass-through rate for a group of stations with a particular number of competitors within a 5 km catchment area. The number of competitor stations is trimmed at the top percentile.

Figure 15 shows the relationship between the pass-through rate for diesel and the number of competitors of a focal station. In contrast to what we see for *E5* and *E10*, the relationship between the pass-through rate and the number of competitors is mostly flat and, in parts, even increasing.

Since the theoretical model predicts a hump-shaped relationship between the number of sellers and the pass-through rate, one possibility could be that for diesel we only observe the upward-sloping part of the hump. Another possibility could be that the hump-shaped relationship becomes weaker for higher pass-through rates.

Figure 15: Average pass-through by number of competitor stations, diesel



Notes: Each circle plots the average pass-through rate for a group of stations with a particular number of competitors within a 5 km catchment area. The number of competitor stations is trimmed at the top percentile.

We repeat this analysis for the tax increase in winter 2020/21 in Appendix D. For *E5*, we find a hump-shaped relationship as for the tax decrease. For *E10* and diesel, the relationship between the number of sellers and the pass-through rate is flat or even mildly increasing, as it was for diesel in summer 2020. This suggests that if pass-through is very high on average, the number of sellers has less of an impact on pass-through rates than if pass-through is at an intermediate level.

7 Conclusion

In this paper, we investigated what determines pass-through of commodity taxes when consumers have incomplete information about prices. We began by setting up a theoretical search model in which there are some consumers that react strongly to lower prices and others that do not. By modelling the price sensitivity of consumers as the share of consumers that react strongly to lower prices, we introduced a novel notion of price sensitivity to the tax pass-through literature, which usually analyzes price sensitivity in the context of the price elasticity of demand. We show that this new way of modelling

price sensitivity reverses the predictions on how price sensitivity affects pass-through. In our setting, the higher the price sensitivity of consumers, the higher the pass-through rate, because more price sensitive consumers let the market converge towards Bertrand competition.

In the second part of our analysis, we used data on fuel prices at all fuel stations in Germany and France to study how a temporary tax decrease and subsequent tax increase six months later, was passed through to consumers. In both cases, we find that pass-through is higher in markets with more price sensitive consumers.

These findings have important implications for economic policy. Whether the corrective goal of a Pigouvian tax or subsidy can be achieved hinges on whether the agents that should change their behavior also bear the incidence of the measure. Similarly, unconventional fiscal policy can only be effective in stimulating demand if consumers expect tax cuts to be passed through by firms. Finally, tax pass-through determines the distributional consequences of taxes and subsidies.

By showing how price sensitivity affects pass-through when consumers are imperfectly informed, we shed light on a novel explanation of what determines tax pass-through. Our findings are relevant beyond fuel markets and should be considered in any market where consumers do not know all prices. In these cases, policymakers should try to assess the extent to which information asymmetries exist, take these into consideration when predicting the effect of new taxes, and potentially accompany this with complementary measures targeting consumer behavior directly.

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Appendix

A Appendix to Section 2: Theoretical Model

A.1 Stage 2: Equilibrium price distribution

Lemma 1. *There is no pure strategy Nash equilibrium in prices in the second stage if $N \geq 2$ sellers entered the market in the first stage.*

Proof. Suppose that all N sellers chose to set the same price strictly above the constant marginal cost c. Then, all sellers receive a share $\frac{1}{N}$ of shoppers and non-shoppers. This cannot be a stable equilibrium because all sellers have an incentive to marginally undercut the common price and attract all shoppers. All sellers setting the price at the constant marginal cost c can also not be a stable equilibrium because sellers can profitably deviate by setting a higher price and only serving uninformed consumers.

Finally, suppose that sellers play pure strategies in which at least one seller chooses a lower price than the other sellers. This seller then serves all shoppers, as well as its share of uninformed consumers. This cannot be an equilibrium because the lowest price seller can always marginally increase its price without losing the shoppers to another seller.

□

Lemma 2. *There are no mass points in the equilibrium pricing strategies.*

Proof. Suppose that any price was played with positive probability. This would mean that there is a positive probability of a tie for shoppers at that price. This cannot be an equilibrium because a seller could profitably deviate from that strategy by charging a marginally lower price with the same probability and capture all shoppers in that case.[49]

□

Lemma 3. *There is a unique symmetric mixed strategy Nash equilibrium where all sellers*

[49] For a more detailed proof, see Varian (1980).

draw a price from the distribution $F(p_i)$ *on the interval* $[\underline{p}, p_r]$*, where*

$$\underline{p} = \frac{p_r}{\frac{\phi N}{1-\phi}+1} + c\frac{1+\tau}{1+\frac{1-\phi}{\phi N}}\,,$$

$$p_r = \begin{cases} E[p]+s & \text{if } E[p]+s < \upsilon \\ \upsilon & \text{otherwise} \end{cases}\,,\ \text{and}$$

$$F(p_i) = 1 - (\frac{p_r - p_i}{p_i - c(1+\tau)}\frac{1-\phi}{N\phi})^{\frac{1}{N-1}}\,.$$

The expected second stage profits (i.e. excluding the fixed and sunk cost of entry) of a seller are

$$E[\pi_i] = (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{N}M\,.$$

The expected price is

$$E[p] = \underline{p} + (\frac{1-\phi}{N\phi})^{\frac{1}{N-1}}\int_{\underline{p}}^{p_r}(\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}}dp\,.$$

The expected minimum price is

$$E[p_{min}] = \frac{1-\phi}{N\phi}[p_r - E[p] + (p_r - c(1+\tau))c(1+\tau)\int_{\underline{p}}^{p_r}(p - c(1+\tau))^2F(p)dp]\,.$$

Proof. We begin by deriving the reservation price of non-shoppers, p_r. Non-shoppers can search sequentially at an incremental search cost s. A necessary condition for search to occur, irrespective of the price initially drawn, is that the sum of the expected price at the next draw and the sequential search cost does not exceed the valuation of the good. If this is fulfilled, non-shoppers with a particular first draw of p search as long as the expected gain of searching is greater than s. Thus, search occurs so long as

$$s < p - \int_{\underline{p}}^{p_{max}} pf(p)dp\,. \tag{4}$$

The reservation price of non-shoppers is such that they are exactly indifferent be-

tween continuing to search and buying at that price. No consumer buys at a price above the reservation price of non-shoppers. At the same time, sellers that do not sell to shoppers want to charge non-shoppers their reservation price. The maximum of the support of prices from which sellers draw in equilibrium is therefore $p_{max} = p_r$. Following Stahl (1989), a consistent reservation price $p_r \leq \upsilon$ must therefore satisfy

$$H(p_r; \phi, N, s) \equiv p_r - \int_{\underline{p}}^{p_r} pf(p)dp - s = 0\,. \tag{5}$$

Stahl (1989) shows that H has a unique root or none at all for a general class of demand functions which include linear demand. Thus, in this case there is no other symmetric mixed strategy Nash equilibrium of the pricing game.

As explained before, if the sum of the expected price at the next draw and the sequential search cost exceed the valuation υ, search never occurs. In this case, the reservation price is simply the valuation of the good. The equilibrium reservation price of non-shoppers is thus

$$p_r = \begin{cases} E[p] + s & \text{if } E[p] + s < \upsilon \\ \upsilon & \text{otherwise} \end{cases}. \tag{6}$$

Since it is never an equilibrium strategy for any seller to choose a price above the reservation price of non-shoppers, there is no sequential search in equilibrium.

Next, we turn to finding the lowest price sellers may draw in equilibrium, $\underline{p}$. Any price drawn with positive probability in equilibrium should yield the same expected profit. The expected profit of setting the price at $\underline{p}$ therefore has to equal the expected profit of setting the reservation price, thus

$$E[\pi(\underline{p})] = E[\pi(p_r)]\,. \tag{7}$$

Since we established that there are no mass points in the equilibrium pricing strategies, the probability of a tie is zero. A seller setting its price at $\underline{p}$ will therefore attract all

shoppers and its share of non-shoppers that randomly visit its store. A seller setting its price at p_r will never attract any shoppers and only serve its share of non-shoppers. We can therefore re-write the expected profits as

$$(\frac{\underline{p}}{1+\tau} - c)(\phi + \frac{1-\phi}{N})M = (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{N}M\,. \tag{8}$$

We can simplify this expression and re-arrange it to yield an expression for the lowest price sellers may draw in equilibrium

$$\underline{p} = \frac{p_r}{\frac{\phi N}{1-\phi} + 1} + c\frac{1+\tau}{1 + \frac{1-\phi}{\phi N}}\,. \tag{9}$$

The last ingredient necessary to characterize the distribution from which sellers draw prices in equilibrium is the density function of the distribution. To derive the density function, we can again exploit the equiprofit condition that

$$E[\pi(p_i)] = E[\pi(p_r)] \qquad \forall \quad p_i \in [\underline{p}, p_r]\,. \tag{10}$$

With probability $(1 - F(p_i))^{N-1}$ a seller choosing price p_i has the lowest price of all N sellers and will thus sell to all shoppers and its share of non-shoppers. With probability $1 - (1 - F(p_i))^{N-1}$ there is another seller charging a lower price and thus seller i only sells to its share of non-shoppers. Expected profits can be written as

$$(\frac{p_i}{1+\tau} - c)(\phi + \frac{1-\phi}{N})(1 - F(p_i))^{N-1}M + (\frac{p_i}{1+\tau} - c)(\frac{1-\phi}{N})(1 - (1 - F(p_i))^{N-1})M = (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{N}M\,. \tag{11}$$

We can solve this equation for the equilibrium density function according to which each seller i draws its prices from the support $[\underline{p}, p_r]$

$$F(p_i) = 1 - (\frac{p_r - p_i}{p_i - c(1+\tau)}\frac{1-\phi}{N\phi})^{\frac{1}{N-1}}\,. \tag{12}$$

For a given number of entrants N and a given set of exogenous parameters, Equations 6, 9 and 12 uniquely identify the symmetric mixed strategy Nash equilibrium in prices.

We can derive the expected second stage profit of each seller i in this equilibrium. Since the expected profit of each seller in the symmetric equilibrium is the same for any price chosen with positive probability, the expected profit of seller i drawing a price from the equilibrium price distribution is

$$E[\pi_i] = E[\pi(p_r)] = (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{N}M\,. \tag{13}$$

Finally, we can derive the expected prices paid by non-shoppers and shoppers, namely the expected price and the expected minimum price.

The expected price is

$$E[p] = \int_{\underline{p}}^{p_r} pf(p)dp = p_r - \int_{\underline{p}}^{p_r} F(p)dp\,, \tag{14}$$

after integrating by parts. We can then insert the equilibrium price distribution and simplify the expression, which yields

$$E[p] = \underline{p} + (\frac{1-\phi}{N\phi})^{\frac{1}{N-1}} \int_{\underline{p}}^{p_r} (\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}} dp\,.$$

To derive the expected minimum price we begin by setting up the probability density function of the minimum price. This can be written as

$$f_{min}(p) = N(1 - F(p))^{N-1} f(p)\,. \tag{15}$$

After inserting $F(p)$ and simplifying the expression, this yields

$$f_{min}(p) = \frac{p_r - p}{p - c(1+\tau)} \frac{1-\phi}{\phi} f(p)\,. \tag{16}$$

The expected minimum price is then

$$E[p_{min}] = \int_{\underline{p}}^{p_r} p f_{min}(p) dp = \int_{\underline{p}}^{p_r} p \frac{p_r - p}{p - c(1+\tau)} \frac{1-\phi}{N\phi} f(p) dp \,. \tag{17}$$

After adding and subtracting $c(1+\tau)$ in the numerator of the first fraction and further simplifications, we get that

$$E[p_{min}] = \frac{1-\phi}{\phi} [\int_{\underline{p}}^{p_r} p \frac{p_r - c(1+\tau)}{p - c(1+\tau)} f(p) dp - E[p]] \,.$$

Finally, we can use integration by parts and rearrange terms to get the following expression for the expected minimum price:

$$E[p_{min}] = \frac{1-\phi}{\phi} [p_r - E[p] + (p_r - c(1+\tau)) c(1+\tau) \int_{\underline{p}}^{p_r} \frac{1}{(p - c(1+\tau))^2} F(p) dp] \,.$$

□

A.2 Stage 1: Equilibrium entry

Lemma 4. *Under free entry and with a sufficiently large number of symmetric potential entrants, such that the number of potential entrants always exceeds the number of firms that can be supported by the market, in equilibrium an integer number of N^* firms enter the market, such that*

$$(\frac{p_r}{1+\tau} - c) \frac{1-\phi}{F} M - 1 < N^* \leq (\frac{p_r}{1+\tau} - c) \frac{1-\phi}{F} M \,.$$

Proof. Suppose that there is a large number of symmetric firms which are sequentially asked whether they want to enter the market at the fixed and sunk cost F, knowing how many firms decided to enter before them. Firms are going to decide to enter the market so long as their expected second stage profits are at least as high as the fixed and sunk cost F. In equilibrium, the first N firms asked to enter will accept and firm $N+1$ and all firms following thereafter will reject if, and only if, the expected second stage profits

of firms $1, ..., N$ are equal to F or higher and the expected second stage profits of firm $N+1$ are lower than F.

To derive the condition for the equilibrium number of firms entering the market, we use the expression for the expected second stage profit of firm i in Equation 13. We calculate the expected second stage profits with N and $N+1$ entrants and re-arrange these to yield a condition on the equilibrium number of entrants. In equilibrium, an integer number of N firms enter the market, such that

$$(\frac{p_r}{1+\tau} - c)\frac{1-\phi}{F}M - 1 < N^* \leq (\frac{p_r}{1+\tau} - c)\frac{1-\phi}{F}M\,. \tag{18}$$

□

A.3 Pass-through of marginal costs

Next, we analyze how marginal costs or per unit taxes are passed through to consumers. Many of the results and intuitions regarding ad-valorem taxes directly translate to marginal costs (or per unit taxes).

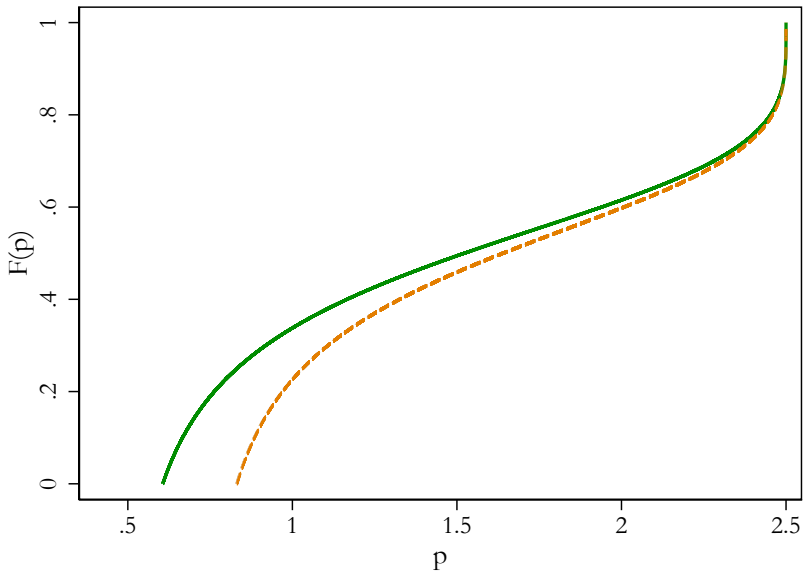
Proposition 4. *With $0 < \phi < 1$, for any $\hat{c} > c$ the minimum element of the support of the equilibrium pricing strategy $\underline{\hat{p}} > \underline{p}$ and the Nash equilibrium pricing strategy with c first-order stochastically dominates (FOSD) the pricing strategy with $\hat{c}$, i.e. $\hat{F}(p) \leq F(p) \quad \forall p$.*

Analogous to the explanation for ad-valorem taxes, this means that if the share of shoppers is strictly positive, an increase in c leads to a shift in the support of the prices from which sellers draw in equilibrium towards higher prices. Furthermore, for each price on the equilibrium pricing support the likelihood that a drawn price is below said price decreases if marginal costs increase from c to $\hat{c}$.

As for the pass-through of ad-valorem taxes, the pass-through of marginal costs converges to zero as the share of shoppers converges to zero.

Since the minimum element of the support of prices and the density function monotonously move towards higher prices, other moments of interest, such as the expected price $E[p]$ and the expected minimum price $E[p_{min}]$ also increase.

Figure 16: Marginal cost pass-through to the equilibrium pricing strategy



Note: The Figure shows simulation results of how the distribution from which sellers draw prices in the symmetric Nash equilibrium changes if marginal costs increase from c to $\hat{c}$. Parameter values: $\upsilon = 2.5$, $s = 0.75$, $\tau = 0.2$, $c = 0.4$, and $\hat{c} = 0.6$.

We now turn to analyzing how the pass-through rate of marginal costs or per unit taxes vary with the price sensitivity of consumers and the number of active sellers.

Proposition 5. *If the share of shoppers $\phi = 0$, marginal cost pass-through $\rho_c = 0$. If $\phi = 1$, there is full pass-through, i.e. $\rho_c = 1 + \tau$. As $\phi \to 1$, the pass-through rate $\rho_c \to 1 + \tau$.*

We can begin by looking at the cases when there are no shoppers and when there are only shoppers. If there are no shoppers, all sellers choose the monopoly price and pass-through of marginal costs is zero. If all consumers are shoppers, there is full pass-through of marginal costs or per unit taxes.[50]

For all values of ϕ between zero and one, we can show that the pass-through rate of marginal costs to the lower bound of the equilibrium price strategy is strictly increasing in the share of shoppers. We can also show that the rate at which an increase in marginal costs from c to $\hat{c}$ reduces the probability that a drawn price is below a particular price p,

[50] Although an increase in the marginal cost from c to $\hat{c}$ leads to an increase of $(\hat{c} - c)(1 + \tau)$ to consumers, we would still classify this case as full pass-through (instead of over-shifting) since the producer price only increases by $\hat{c} - c$.

i.e. from $F(p)$ to $\hat{F}(p)$, strictly increases in the share of shoppers. Thus, the pass-through rate of marginal costs increases in the share of shoppers.

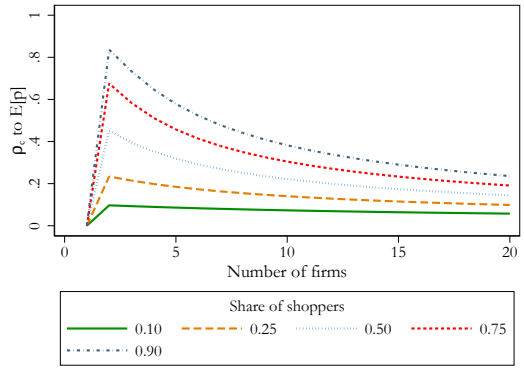
Let us now consider how the pass-through of marginal costs varies with the number of active sellers. As we will see, all of our results and intuitions with respect to ad-valorem tax pass-through extend to marginal costs.

Proposition 6. *With $0 < \phi < 1$, as $N \to \infty$ the pass-through of c to the minimum element of the equilibrium price support converges to full pass-through, i.e. $\rho_{c,\underline{p}} \to 1 + \tau$.*

As the number of sellers increases, competition for shoppers becomes fiercer and the pass-through rate of marginal costs to $\underline{p}$ increases.

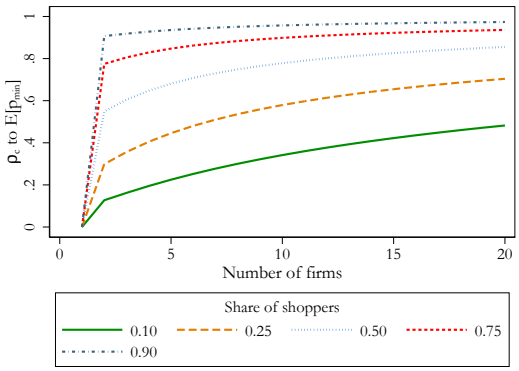
Furthermore, we also expect pass-through of marginal costs to $E[p]$ to first increase and then decrease, whereas pass-through to $E[p_{min}]$ should always increase as $N \to \infty$. The same reasoning as laid out for ad-valorem taxes applies.

Figure 17: Pass-through of c to $E[p]$



Parameter values: $\upsilon = 2.5$, $\tau = 0.2$, $c = 0.4$ and $\hat{c} = 0.44$.

Figure 18: Pass-through of c to $E[p_{min}]$

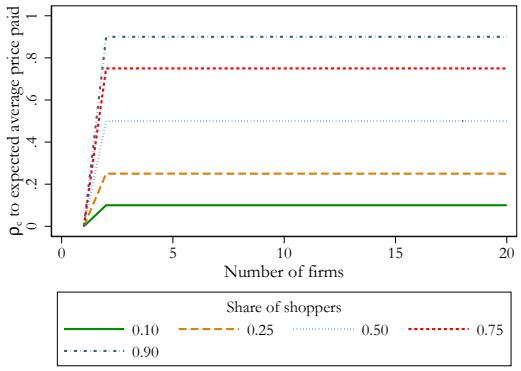


Parameter values: $\upsilon = 2.5$, $\tau = 0.2$, $c = 0.4$ and $\hat{c} = 0.44$.

The simulation results in Figures 17 and 18 are very similar to those for ad-valorem tax pass-through. As N increases, pass-through of c to the expected price first increases and then decreases. Pass-through to the expected minimum price always decreases.

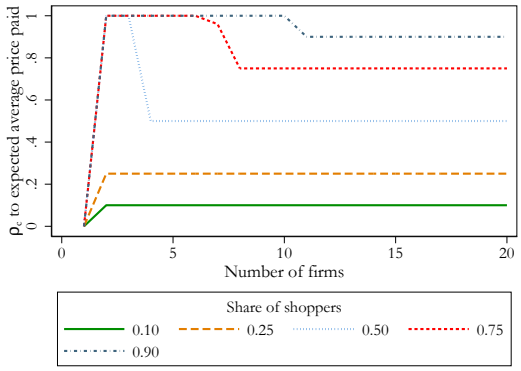
Finally, we consider how c is passed through to the expected average price paid by consumers in the markets.

Figure 19: ρ_c to $E[\phi p_{min} + (1-\phi)p]$, $p_r = \upsilon$



Parameter values: $\upsilon = 2.5$, $\tau = 0.2$, $c = 0.4$ and $\hat{c} = 0.44$.

Figure 20: ρ_c to $E[\phi p_{min} + (1-\phi)p]$, p_r endogenous



Parameter values: $\upsilon = 2.5$, $s = 0.75$, $\tau = 0.2$, $c = 0.4$ and $\hat{c} = 0.44$.

The simulation in Figure 19 shows that when sequential search costs are so high that $p_r = \upsilon$, pass-through of marginal costs first increases in N and then stays constant, because the decrease in pass-through to $E[p]$ and the increase in pass-through to $E[p_{min}]$ cancel each other out. Figure 20 shows that if sequential search costs s are sufficiently low such that p_r is endogenous, pass-through to the expected average price paid first increases in N, then decreases in N and, as $p_r \to \upsilon$ when $N > 2$ and $N \to \infty$, marginal cost pass-through remains constant when N is sufficiently large.

A.4 Proof of Propositions

Proof of Proposition 1. First, we assess the pass-through of τ to $\underline{p}$ if $0 < \phi < 1$.[51] Taking the first derivative with respect to τ, we find that

$$\frac{\partial \underline{p}}{\partial \tau} = c(1 + \frac{1-\phi}{\phi N})^{-1} > 0\,.$$

Thus, with $0 < \phi < 1$, pass-through of τ to the minimum element of the support of the equilibrium pricing strategy is strictly positive.

Next, we assess the pass-through of the ad-valorem tax to $F(p)$ if $0 < \phi < 1$. Taking

[51] $\underline{p}$ is not defined for $\phi = 0$ or $\phi = 1$.

the first derivative with respect to τ, we find that

$$\frac{\partial F(p)}{\partial \tau} = -(\frac{1-\phi}{\phi N})^{\frac{1}{N-1}} \frac{1}{N-1} (\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}} \frac{c}{p - c(1+\tau)} < 0\,.$$

Thus, with $0 < \phi < 1$, for any $\hat{\tau} > \tau$ $\hat{F}(p) \leq F(p) \quad \forall p \in [\underline{p}, p_r]$.

□

Proof of Proposition 2. Let us begin by examining the case where $\phi = 0$. In this case, the price equilibrium is a degenerate distribution at the monopoly price, with $\underline{p} = p_r = \upsilon$. An increase in τ is fully absorbed by sellers, since these already fully extract the entire valuation from consumers.

Next, we examine the case where $\phi = 1$. In this case, the price equilibrium is a degenerate distribution at the perfectly competitive price, with $\underline{p} = p_r = c(1+\tau)$. An increase in the ad-valorem tax τ is now fully passed through to consumers, as sellers already operate at zero profits and absorbing some of the marginal cost would mean that they would be making losses.

Finally, we study the case where $0 < \phi < 1$.

Let us begin by analyzing how the pass-through rate changes with ϕ

$$\frac{\partial^2 \underline{p}}{\partial \tau \partial \phi} = c(1 + \frac{1-\phi}{\phi N})^{-2} \frac{1}{\phi^2 N} > 0\,.$$

Thus, with $0 < \phi < 1$, the pass-through of τ to the minimum element of the support of the equilibrium pricing strategy strictly increases in ϕ.

Next, we consider how the effect of an increase from τ to $\hat{\tau}$ on the cumulative density function of the pricing strategy changes if ϕ increases

$$\frac{\partial^2 F(p)}{\partial \tau \partial \phi} = (\frac{1}{N-1})^2 (\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}} \frac{c}{p - c(1+\tau)} (\frac{1-\phi}{\phi N})^{\frac{1}{N-1}-1} \frac{1}{\phi^2 N} > 0\,.$$

Thus, for higher ϕ, an increase from τ to $\hat{\tau}$ decreases the probability that prices are below a certain p more strongly.

□

Proof of Proposition 3. To see how the pass-through rate of a value-added tax τ to the minimum element of the support varies with N, we study the limit to which the pass-through rate converges as $N \to \infty$. We find that

$$\lim_{N\to\infty} \rho_{\tau,\underline{p}} = \lim_{N\to\infty} \frac{\partial \underline{p}}{\partial \tau} \cdot \frac{1+\tau}{\underline{p}} = \frac{c(1+\tau)}{c(1+\tau)} = 1\,.$$

Thus, with $N \to \infty$, pass-through of a value-added tax to the minimum element of the support of the equilibrium pricing strategy converges to full pass-through.

□

Proof of Proposition 4. We begin by assessing the pass-through of marginal costs to $\underline{p}$ if $0 < \phi < 1$. Taking the first derivative with respect to c, we find that

$$\frac{\partial \underline{p}}{\partial c} = (1+\tau)(1+\frac{1-\phi}{\phi N})^{-1} > 0\,.$$

Thus, with $0 < \phi < 1$, pass-through of marginal costs to the minimum element of the support of the equilibrium pricing strategy is strictly positive.

Next, we assess the pass-through of marginal costs to $F(p)$ if $0 < \phi < 1$. Taking the first derivative with respect to c, we find that

$$\frac{\partial F(p)}{\partial c} = -(\frac{1-\phi}{\phi N})^{\frac{1}{N-1}} \frac{1}{N-1} (\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}} \frac{1+\tau}{p - c(1+\tau)} < 0\,.$$

Thus, with $0 < \phi < 1$, for any $\hat{c} > c$, $\hat{F}(p) \leq F(p) \quad \forall p \in [\underline{p}, p_r]$.

□

Proof of Proposition 5. Again, we begin by examining the case where $\phi = 0$. In this case, the price equilibrium is a degenerate distribution at the monopoly price, with $\underline{p} = p_r = \upsilon$. An increase in marginal costs is fully absorbed by sellers, since these already fully extract the entire valuation from consumers.

Next, we examine the case where $\phi = 1$. In this case, the price equilibrium is a degenerate distribution at the perfectly competitive price, with $\underline{p} = p_r = c(1+\tau)$. An

increase in c is now fully passed through to consumers.[52]

Finally, we study the case where $0 < \phi < 1$.

Let us begin by analyzing how the pass-through rate changes with ϕ

$$\frac{\partial^2 \underline{p}}{\partial c \partial \phi} = (1+\tau)(1+\frac{1-\phi}{\phi N})^{-2}\frac{1}{\phi^2 N} > 0\,.$$

Thus, with $0 < \phi < 1$, the pass-through of c to the minimum element of the support of the equilibrium pricing strategy strictly increases in ϕ.

Next, we consider how the effect of an increase from c to $\hat{c}$ on the cumulative density function of the pricing strategy changes if ϕ increases

$$\frac{\partial^2 F(p)}{\partial c \partial \phi} = (\frac{1}{N-1})^2(\frac{p_r - p}{p - c(1+\tau)})^{\frac{1}{N-1}}\frac{1+\tau}{p-c(1+\tau)}(\frac{1-\phi}{\phi N})^{\frac{1}{N-1}-1}\frac{1}{\phi^2 N} > 0\,.$$

Thus, for higher ϕ, an increase from c to $\hat{c}$ decreases the probability that prices are below a certain p more strongly.

□

Proof of Proposition 6. To see how the pass-through rate of marginal costs to the minimum element of the support varies with N, we study the limit to which the pass-through rate converges as $N \to \infty$. We find that

$$\lim_{N\to\infty} \rho_{c,\underline{p}} = \lim_{N\to\infty} \rho_{c,\underline{p}}(1+\tau)(1+\frac{1-\phi}{\phi N})^{-1} = 1+\tau\,.$$

Thus, with $N \to \infty$, pass-through of marginal costs to the minimum element of the support of the equilibrium pricing strategy converges to full pass-through.

□

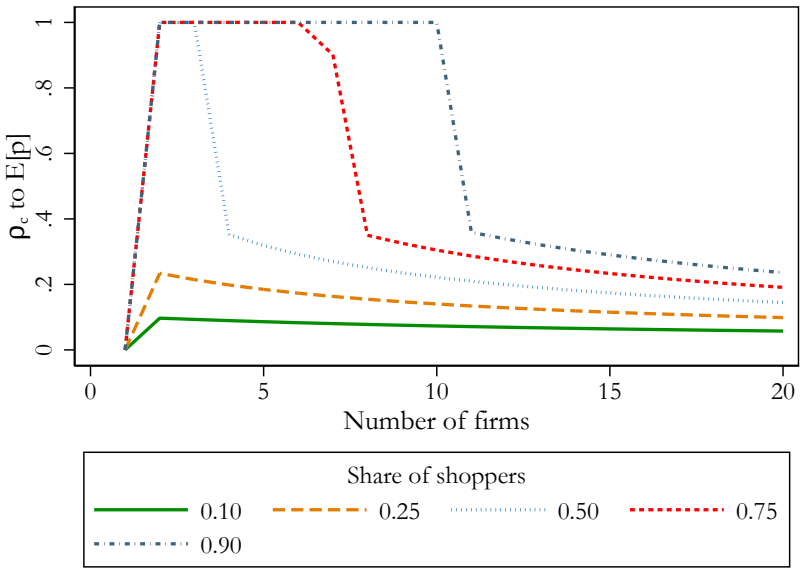
[52] Although an increase in the marginal cost from c to $\hat{c}$ leads to an increase of $(\hat{c}-c)(1+\tau)$ to consumers, we would still classify this case as full pass-through (instead of over-shifting) since the producer price only increases by $\hat{c}-c$.

A.5 Allowing for sequentially searching non-shoppers

In this section, we simulate how the pass-through of marginal costs and ad-valorem taxes to the expected price and the expected minimum price vary with the share of shoppers and the number of sellers, if we allow non-shoppers to search sequentially. We find that the qualitative results remain unchanged to a situation where non-shoppers cannot search sequentially.

A.5.1 Marginal cost pass-through

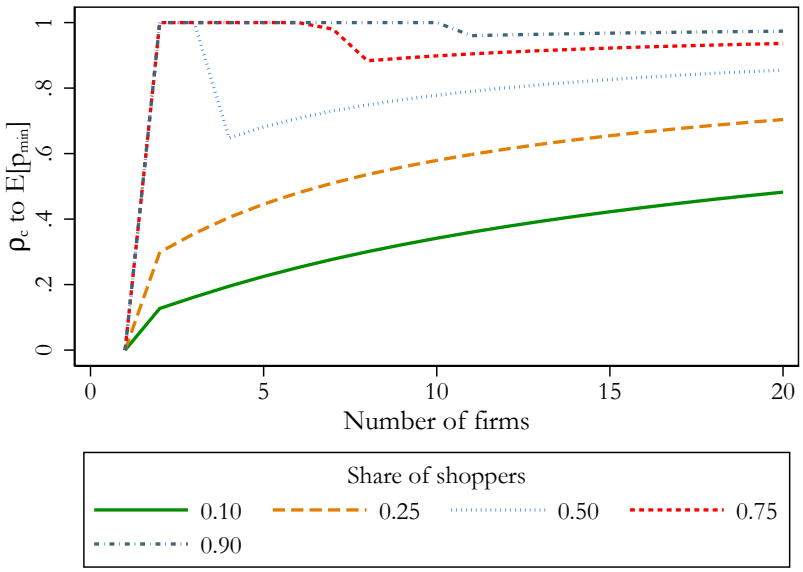
Figure 21: Marginal cost pass-through to the expected price



Note: The Figure shows simulation results of how the pass-through of marginal costs to the expected price varies with the share of shoppers and the number of active sellers. We fix the following parameter values for these simulations: $\upsilon = 2.5$, $s = 0.75$, $\tau = 0.2$, $c = 0.4$ and $\hat{c} = 0.44$.

The higher the share of shoppers, the higher is the pass-through rate of marginal costs to the expected price. For a given share of shoppers, marginal cost pass-through to the expected price first increases and then decreases in the number of sellers.

Figure 22: Marginal cost pass-through to the expected minimum price

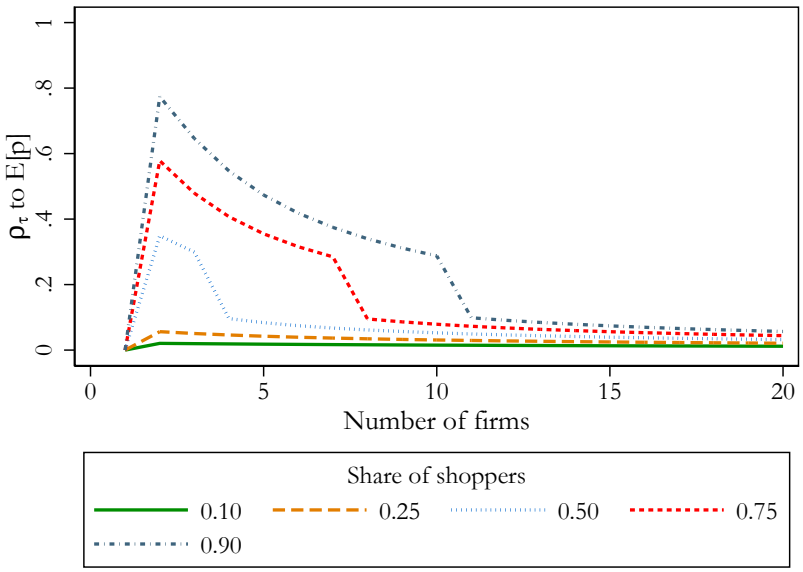


Note: The Figure shows simulation results of how the pass-through of marginal costs to the expected minimum price varies with the share of shoppers and the number of active sellers. We fix the following parameter values for these simulations: $v = 2.5$, $s = 0.75$, $\tau = 0.2$, $c = 0.4$ and $\hat{c} = 0.44$.

The higher the share of shoppers, the higher is the pass-through rate of marginal costs to the expected minimum price. For sufficiently low shares of shoppers and holding the share of shoppers fixed, marginal cost pass-through to the expected minimum price increases in the share of shoppers. This is as in the case without sequentially searching non-shoppers. For sufficiently high shares of shoppers, the pass-through rate first increases in the number of sellers, then decreases and then increases again. This is different to when we do not allow for sequentially searching non-shoppers.

A.5.2 Ad-valorem tax pass-through

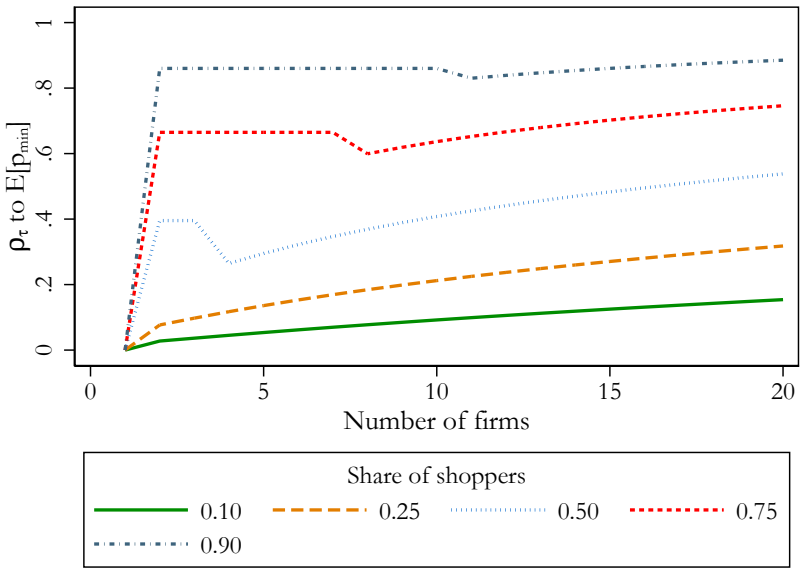
Figure 23: Ad-valorem tax pass-through to the expected price



Note: The Figure shows simulation results of how the pass-through of an ad-valorem tax to the expected price varies with the share of shoppers and the number of active sellers. We fix the following parameter values for these simulations: $v = 2.5$, $s = 0.75$, $c = 0.4$, $\tau = 0.2$ and $\hat{\tau} = 0.22$.

The higher the share of shoppers, the higher is the pass-through rate of an ad-valorem tax to the expected price. For a given share of shoppers, ad-valorem tax pass-through to the expected price first increases and then decreases in the number of sellers.

Figure 24: Ad-valorem tax pass-through to the expected minimum price



Note: The Figure shows simulation results of how the pass-through of an ad-valorem tax to the expected minimum price varies with the share of shoppers and the number of active sellers. We fix the following parameter values for these simulations: $v = 2.5$, $s = 0.75$, $c = 0.4$, $\tau = 0.2$ and $\hat{\tau} = 0.22$.

The higher the share of shoppers, the higher is the pass-through rate of an ad-valorem tax to the expected minimum price. For sufficiently low shares of shoppers and holding the share of shoppers fixed, ad-valorem tax pass-through to the expected minimum price increases in the share of shoppers. This is as in the case without sequentially searching non-shoppers. For sufficiently high shares of shoppers, the pass-through rate first increases in the number of sellers, then decreases and then increases again. This is different to when we do not allow for sequentially searching non-shoppers.

A.6 Dynamics and anticipatory effects

Since we analyze pass-through in a static model, we abstract from how expectations about future prices affect current price setting. Nevertheless, we briefly discuss how expectations may lead to anticipatory effects if extended to a dynamic framework. In particular, anticipatory price increases before a tax increase and a tax decrease are not at odds with the more long-term relationship between price sensitivity, competition, and pass-through that we focus on in this paper.

First, let us extend our model and consider a dynamic framework in which there

are not only informed shoppers and uninformed non-shoppers, but within both groups also patient consumers (who could buy before or after the tax change) and impatient consumers (who cannot or do not want to wait).

Let us now consider how an anticipatory price increase could occur before a large pre-announced tax decrease. In this case, all patient consumers wait until the next period. Sellers cannot compete for patient consumers before the tax decrease and so are left with impatient consumers that do not have the option to wait. Within the group of shoppers and non-shoppers, patient consumers are more price sensitive since, also in the absence of a tax change, they have the option to wait. Before a large pre-announced tax decrease, the more price sensitive consumer groups within shoppers and non-shoppers drop out. Compared to a situation without a tax change, equilibrium prices therefore increase and quantities decrease.

Finally, let us consider how an anticipatory price increase could occur before a large pre-announced tax increase. In this case, the option of waiting for another period becomes worse for patient consumers. Therefore, patient consumers become more likely to accept a particular price draw before the tax increase than if there is no pre-announced tax change. For impatient consumers, nothing changes. Patient consumers therefore are willing to accept higher prices than without a large pre-announced tax increase and are more likely to buy in the current period, whereas impatient consumers behave just as they do without a pre-announced tax increase. Compared to a situation without a tax change, equilibrium prices therefore increase and quantities also increase.

B Appendix to Section 4: Data and descriptive evidence

B.1 Data

B.1.1 Details on constructing the price and margin data set

We construct the price panel at fuel stations in France and Germany as follows. For each fuel station in our data set, we observe a fuel price every time it is changed along with a precise time and date stamp of a change. On average, fuel stations in Germany change fuel prices 15 times a day, whereas there is typically one price change a day at French fuel stations. Based on the distribution of price changes at German fuel stations, we construct hourly fuel prices from 6 am until 10 pm for each day between 1 May and 31 August 2020 and between 1 November 2020 and 28 February 2021. For France, we keep a fuel price at 5 pm for our empirical analysis since fuel prices do not change frequently over the day.

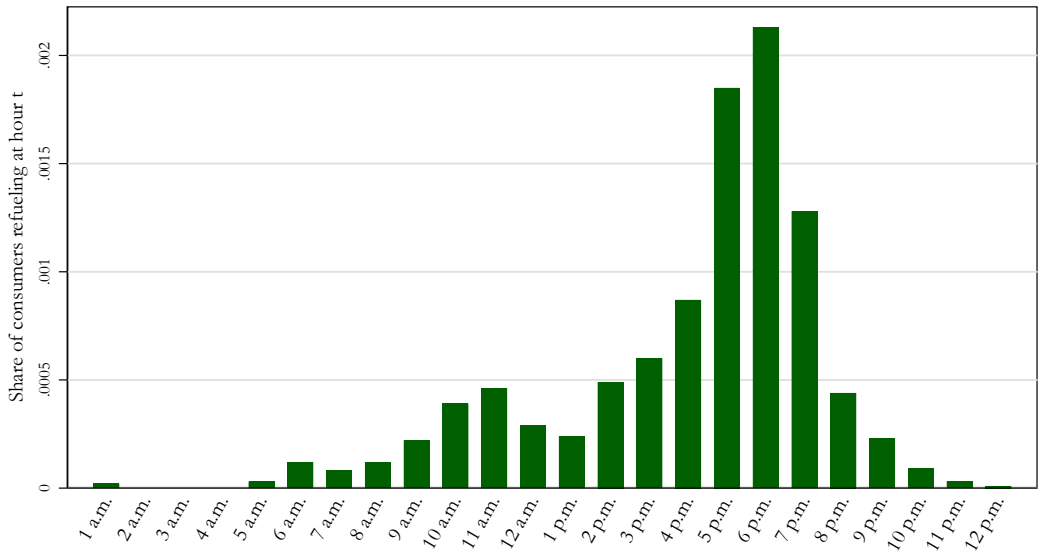
For German fuel stations, we compute daily weighted average prices from the hourly distribution of price changes that we observe. To construct the weights, we use the data on hourly fueling patterns reported in a representative survey among drivers for the German Federal Ministry of Economic Affairs. Figure 25 shows shares of motorists in Germany who fuel at a given time period during a day. We further re-weight the hourly shares to produce weights for the hours between 6 am and 10 pm.

We also compute retail margins. To compute retail margins, we subtract taxes and duties in France and Germany, as well as an estimate of the input cost of crude oil.

In Germany, taxes and duties consist of the value-added tax, a lump-sum energy tax, and a fee for oil storage. The lump-sum energy tax is at 0.6545 Euro per liter for *E5* and *E10* gasoline, and at 0.4704 Euro per liter for diesel. The fee for oil storage is at 0.0027 Euro per liter for *E5* and *E10*, and at 0.0030 Euro per liter for diesel.[53] Before the VAT reduction, the VAT rate on retail fuel was 19 percent. Between 1 July 2020 and 31 December 2020, this was temporarily reduced to 16 percent. On 1 January 2021, the VAT rate was raised back to 19 percent. At the same time, the German Federal Government introduced a CO_2 price of 25 Euro per emitted tonne of CO_2 on oil, gas and

[53] See https://www.avd.de/kraftstoff/staatlicher-anteil-an-den-krafstoffkosten/.

Figure 25: Daily fueling patterns (Germany)



Notes: The Figure shows shares of drivers in Germany who fuel at a given hour of a day. Data is based on a representative survey of motorists in Germany, commissioned by the German Federal Ministry of Economic Affairs.

fuel.[54]

In France, the VAT rate on retail fuel is 20 percent, with the exception of Corsica Island, where it is 13 percent. In addition to the VAT, fuel products in France are subject to a lump-sum tax of 0.60 to 0.70 Euro per liter, depending on the metropolitan region and fuel product type.[55]

We obtain daily data on the Brent price of crude oil at the port of Rotterdam from the US Energy Information Administration. A barrel (42 gallons) of crude oil is on average refined into around 19 gallons of gasoline, 12 gallons of diesel, and 13 gallons of other products, such as jet fuel, petroleum coke, and still gas. Among products different from gasoline and diesel, only jet fuel (of which around 4.3 gallons are refined from a barrel of crude oil) yields sizable commercial value.[56]

Assuming that among the other products only jet fuel is of high value, we split the price of a barrel into the cost of producing gasoline, diesel, and jet fuel to compute a share

[54]For *E5* and *E10*, this translates into a per unit tax of 6 Eurocent per liter (7.14 Eurocent including VAT). For diesel, the per unit tax is 6.69 Eurocent per liter (7.96 Eurocent including VAT). Further details can be found in the "Brennstoff-Emissionshandelsgesetz" (2020 Fuel Emissions Trading Act).

[55]See http://www.financespubliques.fr/glossaire/terme/TICPE/.

[56]See https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil.php.

of the Brent price that corresponds to a particular fuel product. Around 54 percent of the Brent oil price per barrel corresponds to the production of 19 gallons of gasoline, and around 34 percent - to the production of 12 gallons of diesel, which we further transform into the input cost per liter of gasoline and diesel. We therefore compute retail margins of *E5*, *E10*, and diesel by subtracting taxes and duties, as well as the approximate input cost of crude oil from the observed fuel price.

B.1.2 Summary statistics for winter 2020/21

In Table 3, we report summary statistics for the time window around the tax increase. Our analysis is based on the pre-treatment period of 1 November to 15 December 2020 and post-treatment period of 1 January to 28 February 2021. Table 3 shows that the price level is generally higher in France than in Germany. Gross prices increase in France by around 9 to 10 Eurocent between pre- and post-tax increase. In Germany, gross prices increase by about 16 to 19 Eurocent, depending on the fuel type. At the same time, net prices in Germany increase between 5 and 7 Eurocent. This is smaller than in France and suggests that the increase in the VAT and the introduction of CO_2 tax were not completely passed on to consumers.

Table 3 also shows mobility patterns in France and Germany. In both countries, visits to workplaces were around 16 to 29 percent lower in November 2020 to February 2021 compared to their pre-pandemic levels. At the same time, visits to retail and recreational facilities were around 40 percent lower in France and 29 to 57 percent lower in Germany than in the baseline period of 3 January to 6 February 2020.

Table 3: Summary statistics

	Germany pre-treatment	Germany post-treatment	France pre-treatment	France post-treatment
A. Station characteristics				
Number of stations	14,554	14,491	8,832	9,146
Median comp. nr. (5km markets)	4	4	2	2
Share of local monopolists	13%	13%	19%	19%
B. Prices, *E5*				
Mean price	1.23	1.40	1.35	1.45
Mean price net of taxes and duties	.41	.46	.44	.52
Mean retail margin	.13	.11	.16	.17
C. Prices, *E10*				
Mean price	1.19	1.35	1.32	1.41
Mean price net of taxes and duties	.37	.42	.43	.51
Mean retail margin	.09	.07	.15	.15
D. Prices, diesel				
Mean price	1.05	1.24	1.23	1.33
Mean price net of taxes and duties	.43	.50	.42	.50
Mean retail margin	.16	.15	.14	.15
E. Mobility data				
Retail & recreation	-28.8%	-56.8%	-40.7%	-37.8%
Workplaces	-16.1%	-28.9%	-25.1%	-24%

Notes: "pre-treatment" and "post-treatment" refer to fuel stations in Germany and France before and after the increase of the VAT rate and introduction of carbon emissions tax, respectively. The pre-treatment phase goes from 1 November until 15 December 2020. The post-treatment phase goes from 1 January until 28 February 2021.

B.1.3 Summary statistics using SDID weights

In Table 4, we report summary statistics for the analysis of the tax decrease restricted to the balanced sample used in the SDID analysis. The analysis is based on the pre-treatment period of 1 May to 30 June 2020 and post-treatment period of 1 July to 31 August 2020. In the last two columns, we report summary statistics where we weigh fuel stations in the control group by the station weights they receive in the SDID analysis. In contrast to the summary statistics in Table 1, Table 4 is based on the balanced panel which is required for the estimation with SDID. Due to the sample restriction, the total number of stations in Germany and France is lower than in Table 1.

Table 4 shows that characteristics of the unweighted and weighted control groups are similar. As in the summary statistics based on the full sample in Table 1, relative increase in retail margins in Germany remains highest for *E5* and lowest for diesel when we restrict the sample to a balanced panel.

Table 5 reports analogous summary statistics for the analysis of the tax increase. The last two columns correspond to the control group weighted by the weights in SDID. Table 5 is based on the balanced panel used in the estimation by SDID, so the number of stations is lower than in Table 3 that reports summary statistics for the full sample. Across unweighted and weighted control groups, price characteristics and mobility indicators are similar. As in the summary statistics based on the full sample, Table 5 shows that relative decline in margins in Germany after the tax increase is lowest for diesel.

Table 4: Summary statistics, tax decrease

	DE pre-change	DE post-change	FR pre-change	FR post-change	FR, weighted pre-change	FR, weighted post-change
A. Station characteristics						
Number of stations	12,171	12,171	5,523	5,523	5,523	5,523
Median comp. nr. (5km markets)	4	4	3	3	2	2
Share of local monopolists	11%	11%	15%	15%	16%	16%
B. Prices, *E5*						
Mean price	1.21	1.27	1.29	1.34	1.28	1.35
Mean price net of taxes and duties	.36	.44	.38	.43	.38	.43
Mean retail margin	.13	.16	.15	.15	.15	.16
C. Prices, *E10*						
Mean price	1.18	1.23	1.26	1.32	1.26	1.33
Mean price net of taxes and duties	.34	.40	.38	.43	.38	.43
Mean retail margin	.11	.13	.15	.15	.15	.16
D. Prices, diesel						
Mean price	1.05	1.07	1.19	1.24	1.20	1.24
Mean price net of taxes and duties	.41	.45	.38	.42	.39	.43
Mean retail margin	.18	.17	.15	.14	.16	.15
E. Mobility data						
Retail & recreation	-22.3%	-2.4%	-34.1%	1.4%	-34.2%	0%
Workplaces	-21.8%	-20.5%	-29.6%	-27.6%	-29.5%	-27.8%

Notes: DE (FR) "pre-change" and "post-change" refer to fuel stations in Germany (France) before and after the reduction of the VAT rate, respectively. The pre-VAT change phase goes from 1 May until 30 June 2020. The post-VAT change phase starts on 1 July 2020. All columns are based on the balanced panel, which is used in the estimation by SDID. Columns labeled with "FR, weighted" correspond to summary statistics on stations in France, when these are weighted by the SDID unit weights.

Table 5: Summary statistics, tax increase

	DE pre-change	DE post-change	FR pre-change	FR post-change	FR, weighted pre-change	FR, weighted post-change
A. Station characteristics						
Number of stations	12,077	12,077	6,632	6,632	6,632	6,632
Median comp. nr. (5km markets)	4	4	3	3	3	3
Share of local monopolists	11%	11%	17%	17%	9%	9%
B. Prices, *E5*						
Mean price	1.24	1.40	1.34	1.44	1.36	1.46
Mean price net of taxes and duties	.41	.46	.43	.51	.44	.53
Mean retail margin	.13	.11	.15	.15	.17	.17
C. Prices, *E10*						
Mean price	1.19	1.35	1.32	1.41	1.32	1.41
Mean price net of taxes and duties	.37	.42	.43	.50	.43	.50
Mean retail margin	.09	.07	.15	.15	.15	.15
D. Prices, diesel						
Mean price	1.05	1.24	1.23	1.33	1.23	1.32
Mean price net of taxes and duties	.43	.50	.41	.50	.41	.49
Mean retail margin	.16	.15	.14	.14	.14	.14
E. Mobility data						
Retail & recreation	-28.9%	-56.8%	-41.8%	-38.7%	-41.5%	-38.3%
Workplaces	-16.1%	-28.8%	-26.4%	-24.9%	-25.8%	-24.7%

Notes: DE (FR) "pre-change" and "post-change" refer to fuel stations in Germany (France) before and after the increase of the VAT rate and introduction of carbon emissions tax, respectively. The pre-treatment phase goes from 1 November until 15 December 2020. The post-treatment phase goes from 1 January until 28 February 2021. All columns are based on the balanced panel, which is used in the estimation by SDID. Columns labeled with "FR, weighted" correspond to summary statistics on stations in France, when these are weighted by the SDID unit weights.

C Appendix to Section 5: VAT Pass-through Estimation

C.1 Synthetic difference-in-differences

In the following, we give a brief overview of the SDID method developed by Arkhangelsky et al. (2020).

Consider a balanced panel with N units, T time periods, and outcomes denoted by Y_{it}. Units from 1 to N_{co} and time periods from 1 to T_{pre} are not exposed to the binary treatment $W_{it} \in \{0, 1\}$. Units from N_{tr} to N and time periods from T_{post} to T are exposed to the treatment. To compute the SDID estimator $\hat{\tau}^{sdid}$, the SDID method proceeds via the following algorithm:

1. Compute the regularization parameter according to Equation (20)
2. Compute the unit weights $\hat{w}_i^{sdid}$ solving the minimization problem in Equation (19)
3. Compute the time weights $\hat{\lambda}_t^{sdid}$ solving the minimization problem in Equation (21)
4. Compute the SDID estimator $\hat{\tau}^{sdid}$ by solving the following minimization problem:

$$(\hat{\tau}^{sdid}, \hat{\mu}, \hat{\alpha}, \hat{\beta}, \hat{\gamma}) = \underset{\tau,\mu,\alpha,\beta,\gamma}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} \left(Y_{it} - \mu - \alpha_i - \beta_t - X_{it}\gamma - W_{it}\tau\right)^2 \hat{w}_i^{sdid} \hat{\lambda}_t^{sdid} \right\}$$

where X_{it} is a vector of controls.[57]

In Steps 1 to 2, the unit weights are computed by solving

$$(\hat{w}_0, \hat{w}^{sdid}) = \underset{w_0 \in \mathbb{R}, w \in \Omega}{\arg\min}\, l_{unit}(w_0, w), \text{ where} \tag{19}$$

$$l_{unit}(w_0, w) = \sum_{t=1}^{T_{pre}} \left(w_0 + \sum_{i=1}^{N_{co}} w_i Y_{it} - \frac{1}{N_{tr}} \sum_{i=N_{co}+1}^{N} Y_{it} \right)^2 + \xi^2 T_{pre} ||w||_2^2,$$

[57] See Arkhangelsky et al. (2020) for further details.

$$\Omega = \left\{ w \in \mathbb{R}_+^N : \sum_{i=1}^{N_{co}} w_i = 1, w_i = N_{tr}^{-1} \text{ for all } i = N_{co}+1, .., N \right\}.$$

ξ is the regularization parameter and w_0 is the intercept. The regularization parameter matches a one period change in the outcome for the control units in the pre-treatment period and is set to

$$\xi^2 = \frac{1}{N_{co} T_{pre}} \sum_{i=1}^{N_{co}} \sum_{t=1}^{T_{pre}} (\Delta_{it} - \bar{\Delta})^2, \text{ where} \tag{20}$$

$$\Delta_{it} = Y_{i,(t+1)} - Y_{it}, \text{ and } \bar{\Delta} = \frac{1}{N_{co}(T_{pre}-1)} \sum_{i=1}^{N_{co}} \sum_{t=1}^{T_{pre}-1} \Delta_{it}.$$

In Step 3, the time weights are computed by solving

$$(\hat{\lambda}_0, \hat{\lambda}^{sdid}) = \underset{\lambda_0 \in \mathbb{R}, \lambda \in \Lambda}{\arg\min}\, l_{time}(\lambda_0, \lambda), \text{ where} \tag{21}$$

$$l_{time}(\lambda_0, \lambda) = \sum_{i=1}^{N_{co}} \left(\lambda_0 + \sum_{t=1}^{T_{pre}} \lambda_t Y_{it} - \frac{1}{T_{post}} \sum_{t=T_{pre}+1}^{T} Y_{it} \right)^2,$$

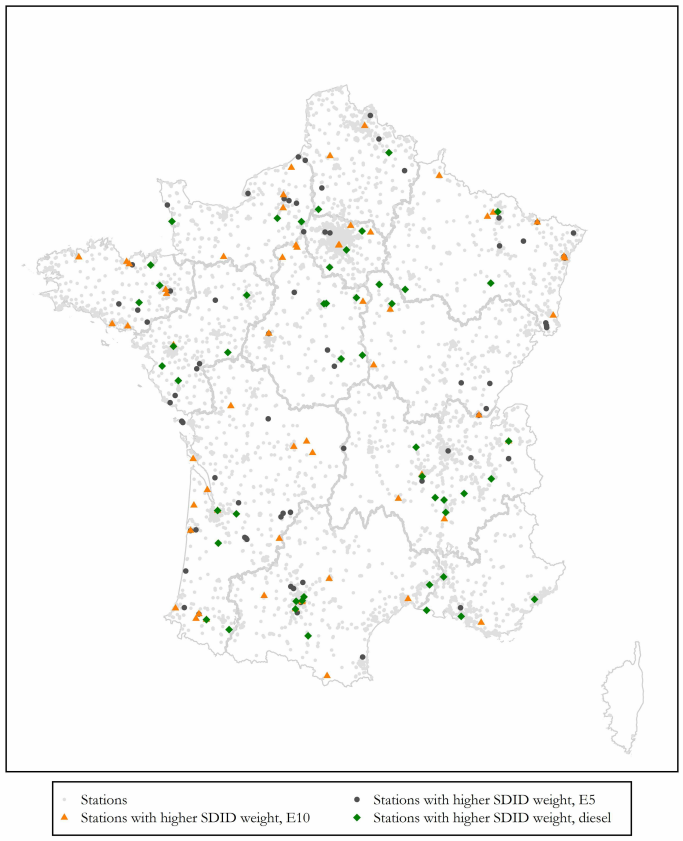
$$\Lambda = \left\{ \lambda \in \mathbb{R}_+^T : \sum_{t=1}^{T_{pre}} \lambda_t = 1, \lambda_t = T_{post}^{-1} \text{ for all } t = T_{pre}+1, .., T \right\}.$$

D Appendix to Section 6: Empirical Results

D.1 Geographical distribution of station weights in the SDID

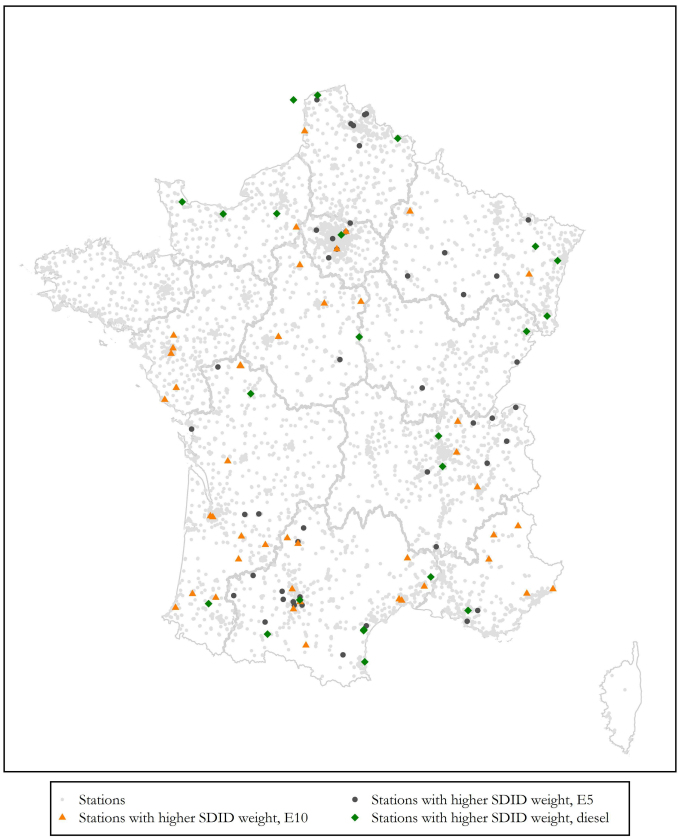
Figures 26 and 27 show the geographical distribution of stations in France. In Figure 26, we highlight stations that receive a disproportionally high weight in the SDID pass-through estimation of the tax decrease for *E5*, *E10* and diesel. Analogously, in Figure 27 we highlight stations that receive a disproportionately high weight in the SDID pass-through estimation of the tax increase. The control stations with higher SDID weights are scattered throughout France and there does not appear to be any regional cluster that particularly influences the estimation results.

Figure 26: France: distribution of fuel stations by SDID unit weights (tax decrease)



Notes: The Figure shows the geographic distribution of fuel stations in France for the analysis of the tax decrease. Stations with a disproportionally high unit weight in the SDID pass-through estimation for *E5*, *E10* or diesel are highlighted.

Figure 27: France: distribution of fuel stations by SDID unit weights (tax increase)



Notes: The Figure shows the geographic distribution of fuel stations in France for the analysis of the tax increase. Stations with a disproportionally high unit weight in the SDID pass-through estimation for *E5*, *E10* or diesel are highlighted.

D.2 Robustness: Pass-through estimation with additional controls

In Table 6, we report results on the effect of the tax change on *E5*, *E10* and diesel prices when we control for regional mobility for retail and recreational purposes and to workplaces, and allow the changes in the crude oil price to differentially affect fuel prices in France and Germany. Overall, the point estimates of the pass-through rates are very similar (no deviation of more than 2 percentage points) to our main estimation results in Table 2.

The coefficients in Columns (1) to (3) correspond to the effect of the tax decrease on *E5*, *E10* and diesel prices, and the coefficients in Columns (4) to (6) correspond to the effect of the subsequent tax increase.

The results in Columns (1) to (3) show that the tax decrease led to a decline in prices of all fuel products, which is statistically significant at the 1 percent level and economically significant. The average price for *E5* decreases by 0.88 percent after the VAT reduction, whilst average prices for *E10* and diesel decrease by 1.27 and 2.01 percent, respectively.

Under full pass-through, we would expect prices for each fuel product to decrease by about 2.52 percent. An estimated decline of 2.01 percent in diesel prices is therefore relatively close to full pass-through. Around 80 percent of the tax decrease is passed on to consumers who buy diesel. For *E10*, the pass-through rate is 50 percent. Finally, we estimate that 35 percent of the tax decrease is passed through to consumers of *E5*.

The results in Columns (4) to (6) show that the subsequent tax increase led to an increase in prices of all fuel products. The average price of *E5* increased by about 5.8 percent, whereas *E10* and diesel prices increase by about 6.5 and 8.8 percent after the tax increase, respectively.

Next, we estimate the pass-through rate of the tax increase. Under full pass-through, we would expect an increase in prices by 8.15 percent for *E5*, 8.37 percent for *E10* and 9.66 percent for diesel. We find a joint pass-through rate of the VAT increase and the carbon emissions price of 71 percent for *E5*, 77 percent for *E10* and 91

Table 6: Effect of the tax change on log prices (percent)

	E5	E10	Diesel	E5	E10	Diesel
	(1)	(2)	(3)	(4)	(5)	(6)
Tax change	-.0088***	-.0127***	-.0201***	.0577***	.0647***	.0878***
	(.0012)	(.0012)	(.0013)	(.0015)	(.0016)	(.0014)
Pass-through rate	35%	50%	80%	71%	77%	91%
	[25%, 45%]	[41%, 60%]	[70%, 90%]	[67%, 74%]	[73%, 81%]	[88%, 94%]
Retail & recreation	Yes	Yes	Yes	Yes	Yes	Yes
Workplaces	Yes	Yes	Yes	Yes	Yes	Yes
DE × oil price	Yes	Yes	Yes	Yes	Yes	Yes
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Station fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,736,145	1,968,984	2,176,362	1,485,120	1,712,984	1,945,736

Notes: Columns (1) to (3) present average treatment effect estimates of the VAT reduction on E5, E10, and diesel log prices, respectively. Columns (1) to (3) use data from 1 May to 31 August 2020. Columns (4) to (6) present average treatment effect estimates of the VAT increase and CO_2 emissions tax on E5, E10, and diesel log prices, respectively. Columns (4) to (6) use data from 1 November to 15 December 2020 for pre-treatment period, and from 1 January to 28 February 2021 for post-treatment period. 95% confidence intervals on pass-through rates are reported in parentheses. Standard errors are computed using the jackknife method and are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

percent for diesel. This is very close to the pass-through of 69 percent for *E5*, 75 percent for *E10* and 92 percent for diesel, estimated without the additional controls.

D.3 Robustness: Anticipatory effects

In Table 7, we estimate pass-through rates if we change the assumptions on anticipatory effects. In Columns (1) to (3), we estimate the pass-through rate of the tax decrease if we drop the second half of June 2020 from the control period. In this case, the gap between pass-through rates between *E5*, *E10* and diesel widens, but the order remains the same. This is not our preferred estimation strategy, since we do not think that there is sufficient evidence for an anticipatory pass-through of the tax decrease in June 2020. We would therefore treat the point estimates of the pass-through rate with caution. Reassuringly, however, our main results, which is the heterogeneity of pass-through with respect to the price sensitivity of consumers, does not change.

In Columns (4) to (6), we report the estimates of the pass-through rate for the tax

Table 7: Effect of the tax change on log prices (percent)

	E5	E10	Diesel	E5	E10	Diesel
	(1)	(2)	(3)	(4)	(5)	(6)
Tax change	.0037***	-.0051***	-.0223***	.0531***	.0544***	.0811***
	(.0014)	(.0018)	(.0009)	(.0040)	(.0031)	(.0029)
Pass-through rate	-15%	20%	88%	65%	65%	84%
	[-25%, -4%]	[7%, 34%]	[81%, 95%]	[56%, 75%]	[58%, 72%]	[78%, 90%]
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Station fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,524,420	1,728,864	1,910,952	1,690,320	1,952,760	2,219,160

Notes: Columns (1) to (3) present average treatment effect estimates of the VAT reduction on E5, E10, and diesel log prices, respectively. Columns (1) to (3) use data from 1 May to 15 June for pre-treatment period, and 1 July to 31 August 2020 for post-treatment period. Columns (4) to (6) present average treatment effect estimates of the VAT increase and CO_2 emissions tax on E5, E10, and diesel log prices, respectively. Columns (4) to (6) use data from 1 November to 31 December 2020 for pre-treatment period, and from 1 January to 28 February 2021 for post-treatment period. 95% confidence intervals on pass-through rates are reported in parentheses. Standard errors are computed using the jackknife method and are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

increase if we include the second half of December 2020 into the control period. In this case, the point estimate of the pass-through rate for *E5* decreases from 69 percent to 65 percent, for *E10* from 75 to 65 percent and for diesel from 92 percent to 84 percent. This is expected, since we can graphically see important anticipatory effects of the tax pass-through in the second half of December 2020 and so including this time period into the control period necessarily leads to an underestimate of the pass-through rate. The difference between gasoline and diesel remains similar to our main results. The difference between *E5* and *E10* disappears. Although not accounting for anticipatory effects would slightly modify the results, the overall conclusions remain the same. Overall, however, the important anticipatory effects that are obvious in the data lead us to believe that excluding the second half of December 2020 from the analysis is preferable.

D.4 Robustness: Difference-in-differences analysis

Using the SDID requires us to restrict our analysis to a balanced subsample of our data. To make sure that our main results are not driven by this sample restriction, we repeat the analysis by estimating the following DID using the full, unbalanced panel:

$$Y_{it} = \beta_0 + \beta_1 \text{Tax}_{it} + \alpha X_{it} + \mu_i + \gamma_t + \epsilon_{it}\,, \tag{22}$$

where Y_{it} is the logarithm of the price of gasoline or diesel at a fuel station i at date t, and Tax_{it} is a dummy variable that equals one for stations affected by the tax change at date t. As for the SDID specification, we also include results of a specification where we include a vector of controls, X_{it}, with regional mobility for retail and recreational purposes, mobility to work, and an interaction term of crude oil price with an indicator of stations in Germany. μ_i and γ_t correspond to fuel station and date fixed effects, respectively.

Table 8 shows the results of estimating the regression model presented in Equation 22 using the logarithm of price as an outcome variable for the analysis of the tax decrease. The coefficients in Columns (1) to (3) correspond to the effect of the tax decrease on *E5*, *E10* and diesel prices without mobility controls. Columns (4) to (6) show the effects when we control for mobility.

For *E5*, the pass-through rate is 31 percent, and around 49 and 93 percent of the tax decrease is passed on to consumers who refuel with *E10* and diesel, respectively. This is very close to the pass-through rates of 34, 52 and 79 percent for *E5*, *E10* and diesel, respectively, estimated using the SDID method for the balanced subsample. The ranking of pass-through rates with respect to fuel types and their magnitude therefore are robust to using this alternative specification.

Table 8: Effect of the tax decrease on log prices (percent)

	E5	E10	Diesel	E5	E10	Diesel
Tax decrease	-.0069***	-.0115***	-.0237***	-.0079***	-.0123***	-.0233***
	(.0003)	(.0002)	(.0002)	(.0003)	(.0002)	(.0002)
Retail & recreation				.0016***	.0033***	.0039***
				(.0005)	(.0004)	(.0003)
Workplaces				.0131***	.0115***	-.0017***
				(.0004)	(.0004)	(.0003)
DE × oil price	.1952***	.1624***	.0394***	.2245***	.1919***	.0451***
	(.0053)	(.0033)	(.0030)	(.0053)	(.0033)	(.0031)
Pass-through rate	27%	46%	94%	31%	49%	93%
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Station fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,150,748	2,332,890	2,725,295	2,149,177	2,329,576	2,721,105
Adjusted R^2	0.889	0.887	0.952	0.890	0.887	0.952
Mean price	1.24	1.21	1.06	1.24	1.21	1.06

Notes: Columns (1) to (3) present estimates without mobility control variables on E5, E10, and diesel log prices, respectively. Columns (4) to (6) present estimates on E5, E10, and diesel log prices from estimation with mobility controls. All columns use data from 1 May to 31 August 2020. Standard errors clustered at the fuel station level are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

We also estimate the effect of the tax increase with the DID specification in Equation 22 using the full, unbalanced panel.

Table 9 shows the results of estimating the regression model presented in Equation 22 using the logarithm of price as an outcome variable for the analysis of tax increase. The coefficients in Columns (1) to (3) correspond to the effect of the VAT rate increase and the CO_2 tax on *E5*, *E10* and diesel prices without mobility controls. Columns (4) to (6) show the effects when we control for mobility. In all columns, we control for an interaction term of crude oil price with an indicator of stations in Germany.

For *E5*, the pass-through rate is 69 percent. For *E10* and diesel, the pass-through is 72 and 84 percent, respectively. This is close to the pass-through rates of 69, 75 and 92 percent for *E5*, *E10* and diesel, respectively, estimated using the SDID method for the balanced subsample. The ranking of pass-through rates with respect to fuel types and their magnitude remain robust to using this alternative specification.

Table 9: Effect of the tax increase on log prices (percent)

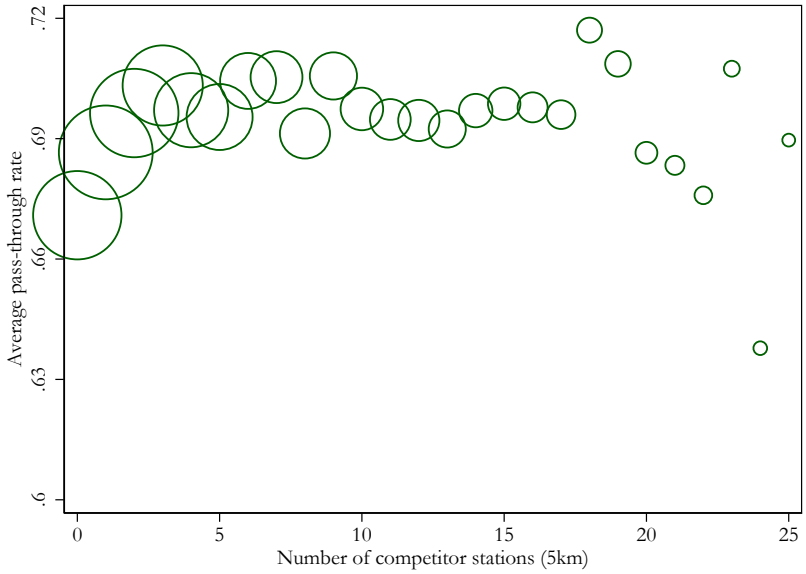
	E5	E10	Diesel	E5	E10	Diesel
Tax increase	.0561***	.0610***	.0831***	.0560***	.0602***	.0813***
	(.0003)	(.0002)	(.0002)	(.0003)	(.0002)	(.0002)
Retail & recreation				-.0013**	-.0039***	-.0054***
				(.0006)	(.0004)	(.0003)
Workplaces				.0010**	.0004	-.0030***
				(.0004)	(.0004)	(.0003)
DE × oil price	.0801***	.0229***	.0807***	.0783***	.0193***	.0778***
	(.0035)	(.0026)	(.0019)	(.0032)	(.0025)	(.0019)
Pass-through rate	69%	73%	86%	69%	72%	84%
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Station fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,808,265	1,985,213	2,322,408	1,807,129	1,982,431	2,318,890
Adjusted R^2	0.949	0.950	0.973	0.949	0.951	0.973
Mean price	1.33	1.28	1.15	1.33	1.28	1.15

Notes: Columns (1) to (3) present estimates without mobility control variables on E5, E10, and diesel log prices, respectively. Columns (4) to (6) present estimates on E5, E10, and diesel log prices from estimation with mobility controls. All columns use data from 1 November until 15 December 2020 for pre-treatment and from 1 January until 28 February 2021 for post-treatment. Standard errors clustered at the fuel station level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

D.5 Number of sellers and tax pass-through for tax increase

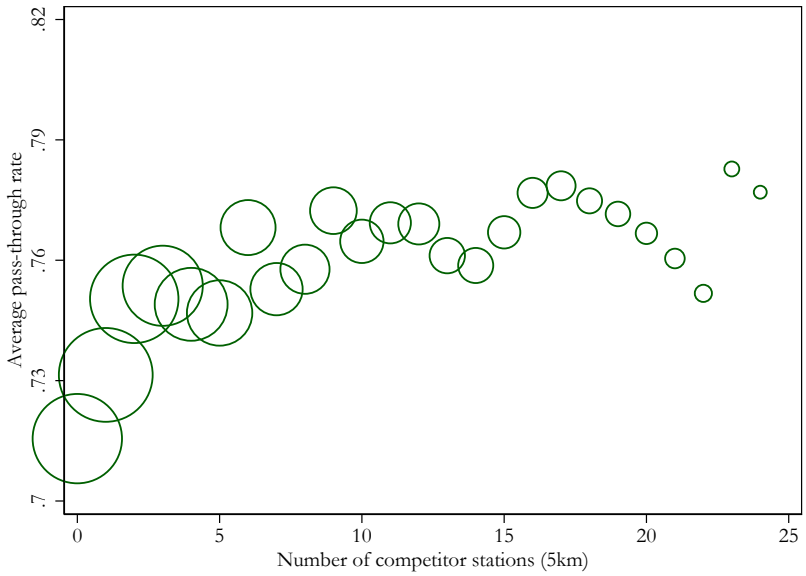
Figures 28 to 30 show the relationship between the pass-through rate of the tax increase and the number of competitors of a focal station within 5 km catchment area for *E5*, *E10* and diesel. As for the tax decrease, there appears to be a mild hump-shamped relationship between the number of competitors and the pass-through rate for *E5*. For *E10* and diesel, we seem to only observe the upward-sloping part of the hump. Interestingly, as for the tax decrease, the hump-shaped relationship between the number of competitors and the pass-through rate appears to weaken for higher pass-through rates.

Figure 28: Average pass-through by number of competitor stations, E5



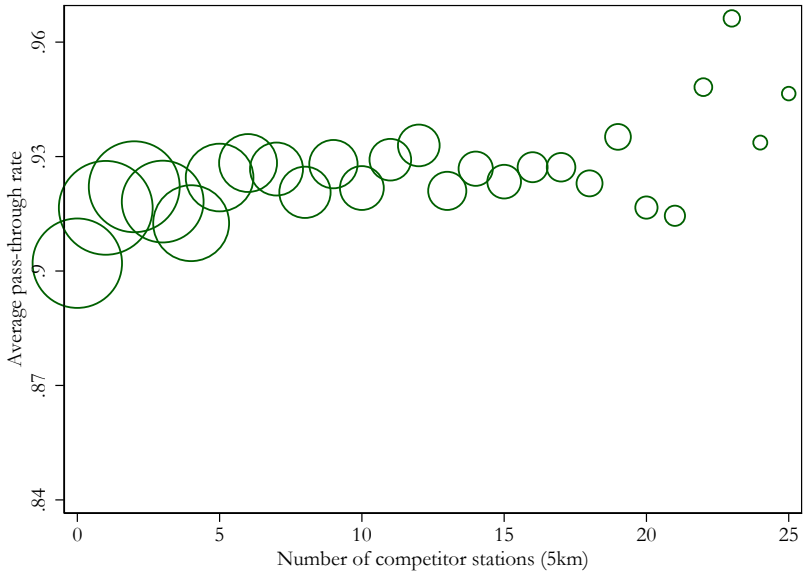
Notes: Each circle plots the average pass-through rate for a group of stations with a particular number of competitors within 5 km catchment area. The number of competitor stations is trimmed at the top percentile.

Figure 29: Average pass-through by number of competitor stations, E10



Notes: Each circle plots the average pass-through rate for a group of stations with a particular number of competitors within 5 km catchment area. The number of competitor stations is trimmed at the top percentile.

Figure 30: Average pass-through by number of competitor stations, diesel



Notes: Each circle plots the average pass-through rate for a group of stations with a particular number of competitors within 5 km catchment area. The number of competitor stations is trimmed at the top percentile.