Reference Pricing as a Deterrent to Entry: Evidence from the European Pharmaceutical Market*

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Abstract

This paper empirically and theoretically analyzes the impact of external reference pricing (ERP) on launch delays in the market for pharmaceutical products. Governments that implement ERP use prices in other countries as negotiation benchmarks to bring down the cost of prescription drugs. By doing so, they limit the ability of firms to price discriminate across countries and create an incentive to withhold drugs from countries with lower willingness to pay. Using data on pharmaceutical sales in European countries from 2002 to 2012, we document the presence of widespread launch delays across Europe — up to three years on average in some Eastern European countries. To distinguish between strategic delays caused by ERP and delays that arise for unrelated reasons, we develop a dynamic structural model of entry that allows for externalities in price, which we estimate using a novel moment inequality approach. We find that removing ERP would reduce delays in low-income European countries by as much as one year per drug. We also estimate that removing strategic delays by compensating firms through lump-sum transfers would cost around €500 million per year.

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1 Introduction

In October of 2018, the US Department of Health and Human Services (HHS) published a policy proposal called International Pricing Index Model for Medicare Part B. If enacted, the policy would tie reimbursement for Medicare Part B drugs to international prices. The proposal has two main motivations. First and foremost, it is an attempt to rein in the rise of drug prices — a main concern for governments around the world. Second, it is an attempt to reduce the disparity in drug prices between the US and the rest of the world. The International Pricing Index Model is a form of external reference pricing (ERP), a class of policies defined by the WHO as the practice of benchmarking drug prices by using prices in foreign countries. Even though external reference pricing has never been adopted in the US, it is commonly used by governments abroad. ERP has an obvious appeal: it is simple, it guarantees that prices will be in line with other countries, and it can reduce spending. Firms however, worry about the limitations that ERP imposes on their ability to optimally price discriminate across countries with different willingness to pay.

The debate over the effects of reference pricing has important implications for policy. Using ERP carries virtually no negative repercussions for the home country, but it can impose an externality on foreign countries. Firms will have an incentive to delay entry in low-income countries whose prices are referenced by high-income countries whenever the externality imposed through reference pricing outweighs the revenue earned by expanding into additional markets. Drugs are frequently unavailable in many markets for several years after receiving marketing approval, so the welfare loss generated by ERP could be very large (Reich, 2000).

In this paper, we develop a structural model of entry with price externalities across markets and use it to provide an estimate of the impact of ERP on launch delays. In the model, firms maximize profits by choosing an optimal entry sequence, conditional on demand and price conditions in each country. To isolate the impact of reference pricing we exploit the fact that ERP operates through a very specific channel. On the margin, ERP generates delays when additional expected revenue from launching in one more country is outweighed by the expected loss from lower prices in the countries that reference its price.

We estimate the model using data on sales of pharmaceutical products across all Member States of the European Economic Area (EEA).[1] The EEA is a good testing environment for our theoretical model. Most European countries adopt ERP among the criteria used to set prices. Moreover, the EEA includes countries with highly heterogeneous income, which creates the potential for strategic delays. Finally launch delays occur in almost all European countries, though some of these delays are likely due to factors other than reference pricing: prior to entry, governments and drug manufacturers engage in negotiations that can last many months, and individual member states can also delay the entry of products they consider unsafe.

We begin our exercise by estimating demand and price in each country. We use a ran-

[1] The EEA includes all EU member states plus Norway, and Iceland. We also include Switzerland, which is not formally part of the EEA, but has a series of bilateral trade agreements with the EU that allow it to participate in the market.

dom utility nested logit model for demand, and estimate prices using a flexible parametric function that tries to capture the decision process of the government. The function predicts equilibrium prices as a weighted average of the reference price and an internal *government price* — which represents the price that would have been granted in the absence of reference pricing. The weight assigned to the reference price is a country-specific parameter in the pricing model. Consistent with previous research, we find that allowing this additional degree of heterogeneity is important, as several countries do not follow their stated ERP guidelines perfectly (Leopold et al., 2012a).

Our estimated demand and price primitives suggest that the externality generated by reference pricing is large enough to justify strategic delays. In simulations that compare the expected revenue of various entry sequences we find that firms earn higher revenue when delaying entry in most low income countries. For over 70% of drugs, delaying entry in at least one country yields higher expected revenue.

Quantifying the impact of ERP requires isolating delays due to reference pricing from other sources of delays, such as the time needed to negotiate pricing and reimbursement conditions. We model delays that are not generated by ERP using a binary stochastic process. Every period, firms draw a shock for each country where they apply for entry. If it comes up negative, entry is postponed until the next period, when a new shock is drawn.

The structure of the delay shocks accurately reflects the regulatory constraints faced by firm, but also presents a novel challenge to estimation because it implies that firm strategies are unobserved. Situations when a firm applied and was delayed are observationally equivalent to situations in which the firm did not apply at all. This would not be an issue if we were able to solve the model. However, fully solving the model is not possible. There is no analytic solution, and the cardinality of the action space of the firm makes a numerical approach unfeasible (for a set of N countries over a T-period horizon, the firm can choose between T^N possible strategies).

In order to overcome this obstacle, we develop a novel moment inequality estimator. Our approach does not require solving the model or computing the value function, though it can only provide bounds on the parameters of the model. Our inequalities rely on a revealed preference argument. We assume that firms are maximizing expected profits and compare the expected profits of the observed entry sequence to the counterfactual profits of playing a different strategy. Since the firm's strategy is observed only up to a random shock our inequalities will not always hold for individual firms: the realization of the random delay shocks in the data might prevent the firm from achieving the desired entry sequence. Using a generalized version of the law of large numbers for non-identical, independently distributed random variables we show that these differences disappear if we consider average payoffs across many firms. Hence, our estimator generates moment conditions based on the payoff of the average drug. In our empirical application we find that these moment conditions can only provide a lower bound on the parameter of interest. We calculate an upper bound by exploiting the fact that the approval date is the earliest time at which the firm could have sent an entry application.

Our results imply that, over the period from 2002 to 2012, replacing ERP with a pricing

mechanism that does not link prices across countries would reduce delays in a set of lower-income Eastern European countries by up to 55%, or roughly 12 months per drug on average.[2] Several possible alternatives to ERP have been proposed, from transitioning to a centralized European cost-effectiveness evaluation system (Drummond, 2003), to two-part pricing systems with barriers preventing reference pricing and import-export of pharmaceutical products across countries (Towse et al., 2015). The exact policy would affect firm profits and consumer welfare but not strategic delays, so our counterfactual has broad external validity.

We also estimate that firms gain on average around €18 million by engaging in strategic delays, relative to what they would earn if they disregarded the incentives of ERP and applied for entry in all countries at the same time. This is a large figure, though not as a percentage of the average lifetime earnings of drugs in the European market. Two factors contribute to mitigating the impact of ERP. First, in the current equilibrium prices in lower-income European countries are only marginally lower than prices in the higher-income countries that use ERP aggressively.[3] Second, countries that grant lower prices also tend to be somewhat slower in reviewing pricing and reimbursement applications. We suggest that the European Union could remove strategic delays by offering to compensate firms for ERP-generated revenue losses by offering lump-sum transfers. We calculate that, given an average of 27 new drugs per year, the overall budget impact of this policy would be around €500 million per year.

Our paper contributes to three main strands of economic literature. First, it belongs to a growing body of work, both empirical and theoretical, studying how price regulation affects access to pharmaceutical products. The empirical side of this literature usually analyzes the impact of government policy on launches using a reduced-form framework (Danzon et al., 2005; Danzon and Epstein, 2012; Kyle, 2007; Kyle and Qian, 2013; Cockburn et al., 2016). A notable exceptions is Duso et al. (2014), which examines the welfare impact of parallel trade in Germany.[4] On the theory side, this literature has focused on simulating the impact of reference pricing on firm strategy (e.g. Borja, 2014; Toumi et al., 2013; Stargardt and Schreyögg, 2006; Houy and Jelovac, 2015), or establishing conditions under which regulation that limits price discrimination is beneficial or harmful to welfare (e.g. Birg, 2016; Brekke et al., 2007, 2015, 2016; Matteucci and Reverberi, 2017). Our contribution is that we explicitly model the impact of reference pricing on firm incentives and develop an estimation strategy to isolate the effect of this policy on launch delays.

Second, our paper is related to a series of studies on the impact of regulation that links prices to endogenous market benchmarks. For example, both Medicare Part B and Medicaid tie drug reimbursements to the average of reported private market prices. Duggan and Scott Morton (2006) show that in the case of Medicaid this regulation creates a distortion that leads

[2] By distinguishing between Eastern Europe and Western Europe we do not mean to associate any value to the geographic location of these sets of countries. Rather, we draw this demarcation for convenience. Countries in Eastern Europe share certain traits that make their bundling convenient for our purpose: they have lower income (and prices), and smaller market size than virtually all countries in Western Europe, with the exception of Portugal and Greece.

[3] This is almost certainly an equilibrium result. Young et al. (2017) find that prices in Eastern European countries are higher-than-expected when compared to income levels, and argue that if reference pricing were removed, firms would almost certainly be willing to grant lower prices in Eastern Europe.

[4] Another methodologically related paper is Chaudhuri et al. (2006), which uses structural techniques to estimate the impact of patent policy on patient welfare in the Indian market for quinolones.

to higher prices in the private market. Another set of policies with a similar effect are so-called "price-linked" subsidies, i.e. subsidies that are linked to market prices. Jaffe and Shepard (2017) and Decarolis (2015) show that these types of subsidies can distort premiums in health exchanges and Medicare Part D respectively. More generally, price externalities across firms have been detected in the absence of government intervention. Grennan (2013) and Grennan and Swanson (2016) show that knowing how much rival hospitals paid for medical devices can affect future prices. Our paper shows that if pricing strategies are constrained, firms can also respond along different margins (i.e. by manipulating their entry strategy).

Our third and final contribution is to the growing empirical literature on partial identification, which includes several papers (Katz, 2007; Crawford and Yurukoglu, 2012; Eizenberg, 2014; Ho and Pakes, 2014; Illanes, 2016; Dickstein and Morales, 2018; Wollmann, 2018; Morales et al., 2017). Our starting point are the revealed preference inequalities formalized in Pakes (2010) and Pakes et al. (2015). We extend their framework by allowing for unobserved restrictions to the choice set. We then show how to recover bounds on the model parameters when these restrictions are the result of a stochastic shock whose distribution is known up to a parameter vector.[5] The two approaches are not nested however, as our setting does not include a structural error term. In terms of the empirical setting, the paper that is closest to us is Morales et al. (2017), who also considers a single-agent dynamic model where previous entry decisions affect future profits. Our setting differs in that our inequalities allow for a stochastic component in the strategy of the firm, at the cost of a restriction on the structural error. More generally, our approach is conceptually different from previous papers because rather than identifying the set of parameter values for which the firm's observed strategy is optimal, we identify the set of parameters consistent with the firm's observed profits.

The rest of the paper proceeds as follows. Section 2 discusses the relevant features of the European pharmaceutical market, and describes the data. Section 3 presents preliminary evidence in support of the hypothesis that firms are delaying launches in response to external reference pricing. We present our theoretical model of entry in Section 4. The estimation is then divided in two parts. Our empirical model and estimation results for demand and price are in Section 5, while Section 6 contains the dynamic analysis. We discuss the implications of our results for counterfactuals and policy analysis in Section 7. Finally, in Section 8 we provide some concluding remarks, and a discussion of the paper's limitations.

2 Overview of the European Pharmaceutical Market

2.1 *Marketing Approval and Price Regulation of Pharmaceutical Products in Europe*

New drugs can only be sold after being reviewed for efficacy and safety. The European Medicines Agency (EMA) oversees this process in the European Economic Area. While marketing approval for new drugs is generally granted by a regulatory authority whose jurisdiction is limited to one country (i.e. the FDA in the United States, or the PMDA in Japan), member states of the European Economic Area have been relying on a shared approval pro-

[5] The conditions we derived are sufficient for partial identification in our empirical setting, though possibly not necessary. We leave further generalizations of this framework to future work.

cess since 1995 — the year the EMA was founded. Though national drug agencies still exist, their effort is now organized and regulated by the EMA.

Pharmaceutical companies seeking approval for their products can choose between three possible procedures. The *centralized procedure* is administered by the EMA itself, and grants automatic approval in all EEA Member States. It is available to all drugs, and compulsory for certain classes of drugs, including biologics.[6] Drugs for which the centralized procedure is not mandatory can also go through two additional channels. If the drug already has a marketing authorization from any EEA member state, the firm can use the *mutual recognition procedure* to extend it to any other member state using a fast-track procedure taking no longer than 90 days (European Parliament, 2001).[7] The other alternative is the *decentralized procedure*. In this case, the firm submits an application to multiple countries at the same time and designs one as the Reference Member State in charge of reviewing it (European Parliament, 2004).

The centralized marketing approval process ensures that the cost of seeking additional marketing approvals all but disappears as soon as firms receive marketing approval from any country in Europe (or from the EMA). This eliminates one of the most common explanations for launch delays. However, firms may still experience delays because individual countries retain the ability to regulate prices independently from one another.

Most European countries provide some form of single-payer coverage, meaning the government bears the vast majority of prescription drug costs. Even where the government does not directly insure patients (e.g. Germany, Netherlands, Switzerland), it still negotiates a price cap with manufacturers. Thus, all governments impose strict restrictions on drug prices, with the primary goal of controlling spending.

Pricing restrictions typically only apply to drugs that are paid for by the government through the public health insurance system. However, since European citizens overwhelmingly access health care through government-funded programs, the exclusion of a product from public formularies results in its de-facto exclusion from the national market (European Commission, 2012).[8] The ability to effectively deny entry provides governments with the necessary leverage to demand lower prices.

Firms petition for reimbursement status by submitting pricing and reimbursement applications to each government. The time required to review an application and negotiate a price can vary significantly across countries. In theory, Directive 89/105/EEC (informally known as the Transparency Directive) states that governments can take no longer than 180 days to review a pricing and reimbursement application (Council of European Communities, 1988). In practice however, this limit is often surpassed, both because of enforceability issues, and because governments can stop the clock by asking for additional information. Data on turnaround times for applications is scarce, but survey evidence from the late 1990s and early 2000s indicates

[6]The full list of drugs that must receive approval by the EMA includes: human medicines containing a new active substance to treat HIV or AIDS, cancer, diabetes, neurodegenerative diseases, auto-immune and other immune dysfunctions, and viral diseases; medicines derived from biotechnology processes; advanced-therapy medicines, such as gene-therapy, somatic cell-therapy or tissue-engineered medicines; and medicines seeking orphan designation.

[7]Other countries can to refuse the extension by claiming that doing so would create significant risks for public health, although this does not happen very frequently.

[8]The only exceptions to this rule tend to be generic drugs, whose low price tag makes them a cost-effective option even in the absence of government coverage.

that the average varies substantially, from 0 days in UK and Germany, to over two years in Poland (OECD 2008; PICTF, 2006).

The requirements of pricing and reimbursement applications vary across countries, though firms must generally include both a clinical dossier detailing the medical benefits of the drug, as well as an economic report with projected sales and a proposed price. The government then uses this information as inputs into the pricing decision. In theory, the government strives to set prices that reflect the value of each drug and reward the firm's innovative efforts, while at the same time keeping spending under control. In practice, estimating the value of a drug is a complicated and costly exercise. Most countries use ERP as a way to set prices that are approximately consistent with what other governments are paying.

It is important to stress however, that ERP is not the only policy instrument used by countries in setting prices. Countries often rely on a variety of other methods, including Health Technology Assessments, internal reference pricing (which links prices of molecules within a pre-specified equivalence class), and price freezes/cuts. These policies will still be in place when a reference price cannot be observed, or is higher than what the government is able (or willing) to pay.

Finally, governments ultimately care more about overall pharmaceutical spending than prices. Price-volume agreements that protect spending such as clawback policies are common, meaning that the outcome of the negotiation between the government and the firm is usually not a set list price, but rather a price schedule that depends on volume (Carone et al., 2012). Prices and volumes will also be correlated if the government is willing to provide more favorable coverage to firms that give better pricing conditions.

2.2 *Overview of External Reference Pricing*

In 2012 all European countries indicated ERP as one of the criteria used in setting prices except Denmark, Germany, Sweden, and the UK.[9] Both the pharmaceutical industry and policymakers have acknowledged the externality generated by ERP and its role in producing launch delays for new pharmaceutical products (EFPIA, 2014; Carone et al., 2012). However, governments remain reluctant to abandon the policy, because of the savings they claim it generates.

The two most important aspects of ERP policies are the reference basket (i.e. the basket of countries whose prices are sampled), and the formula used to compute the reference price. For both, there is significant variation across countries.[10] Some governments (e.g. Austria, Belgium, Finland, Hungary, and Poland) require firms to submit prices from all other countries in the European Union. Others only reference similar countries, both in terms of geographical proximity, size, and income level — for example, Estonia references Hungary, Latvia, and Lithuania, while France references Germany, Italy, Spain, and the UK. In terms of the reference formula, most countries use the average across the reference basket, but a few (e.g. Latvia,

[9] Since then, Denmark and Germany have adopted ERP as well.

[10] Contrary to cross-country variation, over time variation in ERP policies is much more scarce. The biggest policy change happened in 2010 when Greece switched its reference function in an effort to lower prices. Other changes are tied to the entry of new Member States in the European Union or in the Eurozone. These occurred in Austria, Belgium, Finland, and Italy (all of whom reference EU member states); and Spain (which references countries in the Eurozone). Finally, Portugal, Hungary, and Poland made small adjustments to their reference baskets at various points. Please refer to the Online Appendix for more details.

Poland, and Romania) use the lowest price, while others still use slight variations: Bulgaria, Greece, and Norway use the average of the three lowest prices in the basket. Table 1 offers an overview of cross-country variation in reference baskets and formulas.[11]

The stringency with which each country adheres to their stated ERP guidelines may vary across countries. Some governments state that ERP is only used to "inform" the pricing decision, meaning that we might expect prices to be affected by ERP but not necessarily to be perfectly aligned with the reference pricing benchmark. In other instances, governments may push for prices that are below the benchmark if they expect to sell higher volumes than the referenced countries.[12] Countries whose governments claim to only use ERP informally include Belgium, Finland, France, Italy, Poland, and Spain.

We use the reference basket and formulas to estimate reference prices in our model, but we exclude a few additional characteristics of ERP policies that can also vary across countries. We briefly list them here for completeness. First, countries update the reference prices with varying frequency, from as little as every 6 months (e.g. Greece, and Slovenia), to as many as 60 (Finland). Second, countries can use raw ex-factory prices, or apply a PPP adjustment (all Scandinavian countries do so). Third, not all countries apply ERP to the same set of drugs. Most countries apply ERP only to drugs that are reimbursed through the national health insurance system, but some apply it to all new innovative drugs (e.g. France), and others to all drugs, regardless of reimbursement status (e.g. Greece).

2.3 Data and Summary Statistics

The main source of data for the empirical analysis is the MIDAS database maintained by IQVIA (formerly IMS Health), a global information company specializing in the health care sector. The data covers sales of all pharmaceutical products for European countries from 2002 to 2012.[13] It consists of a quarterly panel of volume and revenue sales divided by country. Products are defined by a combination of molecule, firm, product name, form, strength, and package. IQVIA collects this information by surveying pharmacies and hospitals.

To the best of our knowledge, this database represents the most comprehensive source of data on sales in the European pharmaceutical market. Nonetheless, it has a few important limitations, which we discuss below.

First, the data does not provide any information on the approval dates of drugs. Instead, we collect approval dates for all EMA-approved medications from the EMA's website, and the approval date of all mutual recognition applications from an internet database maintained by the Heads of Medicines Agencies (HMA).[14]

[11] The table shown in the paper represents a snapshot of reference baskets and formulas in 2012. It was built by combining several published sources (Carone et al., 2012; European Federation of Pharmaceutical Industries and Associations, 2014; Kanavos et al., 2011; Leopold et al., 2012b; Wilsdon et al., 2013) with unpublished IMS reports. For the analysis used in the paper we generated yearly tables to capture some small changes that happened in a few countries with regard to their reference basket and the formula used.

[12] According to several informal conversations of the authors with industry insiders, these sort of arguments appear to be popular in countries such as Italy, where the prices of smaller markets are included in the reference function.

[13] We are missing data entirely for Cyprus, Iceland, Lichtenstein, and Malta. A few other countries have partially missing data. See the Online Appendix for more details.

[14] Both datasets are publicly available. The HMA is a network of the heads of the European national authorities

Table 1: REFERENCE PRICE BASKETS AND FORMULAS FOR EEA COUNTRIES

Country	Code	Reference Basket																											Formula
		AT	BE	BG	CZ	DK	EE	FI	FR	DE	EL	HU	IE	IT	LV	LT	LX	NL	NO	PL	PT	RO	SK	SL	ES	SE	CH	UK	
Austria	AT		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	Average
Belgium	BE	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	Average
Bulgaria	BG	X			X		X					X								X	X	X	X						Average of 3 lowest
Czech Republic	CZ						X		X		X	X		X		X					X				X				Average of 4 lowest +3%
Denmark	DK																												
Estonia	EE											X			X	X													Minimum
Finland	FI	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	Average
France	FR									X				X											X			X	Average
Germany	DE																												
Greece	EL	X	X	X	X			X	X	X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	Average of 3 lowest
Hungary	HU	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Minimum
Ireland	IE	X	X			X		X	X	X								X							X			X	Average
Italy	IT	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X		X	Average
Latvia	LV						X									X													Minimum
Lithuania	LT				X		X					X			X						X		X						Average -5%
Luxembourg*	LX																												
Netherlands	NL		X						X	X																		X	Average
Norway	NO	X	X			X		X		X			X					X								X		X	Average of 3 lowest
Poland	PL	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	Minimum
Portugal	PT													X										X	X				Average
Romania	RO	X	X	X	X	X				X	X	X		X		X				X			X		X				Minimum
Slovakia	SK	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	X	X		X	Average
Slovenia	SL	X							X	X																			Average -5%
Spain	ES	X	X				X	X	X	X	X		X	X	X	X	X	X			X		X	X					Average
Sweden	SE																												
Switzerland	CH	X				X			X	X								X										X	Average
United Kingdom	UK																												

* Luxembourg only references the drug's country of origin.

Second, IMS reports ex-factory revenue sales, which do not usually incorporate rebates and discounts that are sometimes granted by individual payers. While in the US estimates of discounts for brand drugs oscillate between 20-40% during the period we consider (see Congressional Budget Office, 2005; Aitken et al., 2016), discounts tend to be much lower in Europe (Danzon, 2003; Danzon and Furukawa, 2006). According to industry insiders, average rebates for patent-protected brand drugs are rarely above 10%.[15] Unfortunately, there is currently no available data on pharmaceutical rebates in Europe, so in our paper we simply use the prices implied by the IMS data.[16]

Third, the data contains some missing information for certain countries and years. Because of the externalities generated by reference pricing, missing data points can affect non-missing observations as well. To minimize the impact of missing data we resort to imputation using a variety of techniques.[17]

We integrate the IMS data with a few additional sources. On top of the aforementioned EMA and HMA data on approval dates, we collect GDP and population data from Eurostat, as well as data on the incidence of diseases in each European country from the Global Burden of Disease Study. We use that information to build the market size variable for the demand estimation. We also use quarterly exchange rates from the European Central Bank to convert sales data from countries that use currencies other than the Euro.

We observe around 6,000 molecules and 3,000 firms in our data. Most of these molecules are old off-patent and generic products with negligible yearly sales, and many are only available in one or two countries. We are interested in new, on-patent products whose potential market spans multiple European countries. Hence, we select a subsample of drugs that satisfy the following three criteria: the drug was first launched on or after January 1st, 1995; it had at least one new launch in a European country on or after January 1st, 2002; and it was either approved by the EMA using the centralized procedure, successfully completed at least one Mutual Recognition Application (MRA) between 1995 and 2012, or is a patent-protected brand drug sold in at least 10 countries by 2012.

Our final selection comprises 481 drugs (we define a drug as the combination of a molecule, a firm, and a therapeutic class).[18] Most of the products we select received approval from the EMA through the centralized procedure or applied for mutual recognition. We also include a few drugs that we were not able to match with the EMA and HMA data on approval dates, but that we observe being sold in many European countries.[19] Unsurprisingly, drugs in our main

in charge of the regulation of medicinal products for human and veterinary use in the European Economic Area. The data can be found at http://mri.cts-mrp.eu/Human

[15] Author estimation based on several conversations with industry insiders.

[16] As an aside, contracts that combine list prices with hidden discounts could circumvent ERP and restore the ability to use price discrimination. However, this does not seem to be the case even though these contracts are theoretically available. One possible reason why rebates are underutilized in Europe is that governments have higher transparency requirements than private firms, due to the necessity to account for their spending. Hence hiding discounts might be more difficult. Another possibility is that firms know that if they were to avoid ERP by using large discounts, government might find ways to force them to reveal those discounts.

[17] Please refer to the Online Appendix for a detailed description of the data cleaning and imputation process.

[18] All molecules in our main sample are sold by a single firm, but can sometimes be available in different therapeutic classes. In these cases, IMS reports separate observations for each therapeutic class. We keep this distinction since our demand estimation relies on therapeutic classes to define markets.

[19] For these products we impute the European approval date as the date of the fifth launch. We do not use the first launch because in many instances products that apply through the mutual recognition procedure start selling

Table 2: SUMMARY STATISTICS

		Full Sample	Main Sample	Dynamic Sample
# therapeutic classes		241	109	44
# firms		2,944	168	47
# molecules		6,354	475	86
Class-firm-mol combinations		55,134	481	87
Class-firm combinations			375	84
Diffusion	mean	2.1	20.1	21.3
	median	1	22	24
Yearly sales	mean	€3,547,665	€115,427,475	€121,977,298
	median	€92,489	€39,214,276	€46,340,438
Approval Method	EMA		312	24
	MRP		127	46
	Other		42	17

This table reports summary statistics for the IMS MIDAS database. The full sample includes all prescription drugs in the data. The main sample includes prescription drugs that satisfy the criteria laid out in section 2.3. The dynamic sample includes a subset of main sample drugs whose patent expired by December 31st, 2012. Yearly sales refer to the entire EEA territory.

sample experience much greater sales and diffusion relative to the average drug in the data (see Table 2). The median drug in our main sample is available in 22 countries (by the end of 2012), and collects yearly sales of €38.6 million across all European markets. For comparison, the median product in the full sample is sold in only 1 country, and earns less than €100,000 every year.

We also select a subsample of drugs within our main sample whose patent expired prior to December 31st, 2012. This smaller group is used in the dynamic analysis, when our methodology requires that we are able to compute the overall expected payoff of a drug until the time its patent expires.[20] This smaller sample consists of 87 drugs and has similar characteristics relative to the main sample of drugs in terms of sales and diffusion across European countries. The only main difference is in how these drugs were approved. Most of the drugs in our main sample were approved by the EMA using the centralized procedure. However, a majority of the drugs in the dynamic sample chose the Mutual Recognition Procedure.

While virtually all countries experience some launch delays relative to a drug's approval date, the magnitude of these delays varies substantially across countries. Figure 1 contains a series of maps that display the fraction of drugs launched in each country within the first 6 years of the marketing approval date.[21] The maps clearly show how some countries, particu-

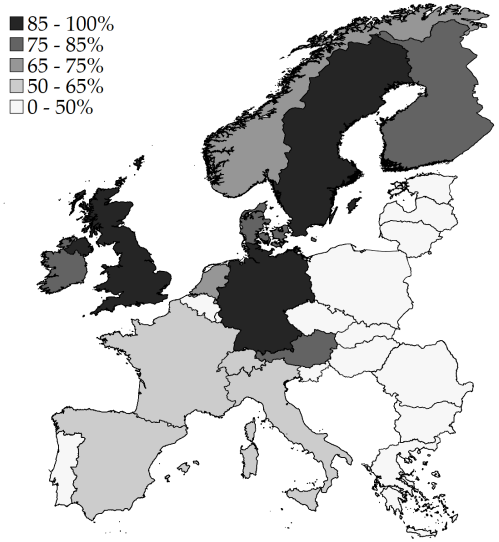
in the reference member state a year or two in advance relative to the rest of Europe.

[20]Since patent expiration dates can vary slightly across countries, we set period T as the latest expiration date among those of France, Italy, and Spain. Patents generally expire roughly at the same time in most countries, since they are administered by the European Patent Office. However, some countries can choose to grant extensions to individual patents. In our data we also occasionally observe earlier than expected patent expiration dates for some Eastern European countries. We choose these three countries because they are the three largest markets that use ERP. Therefore, when their patent protection expires, the strategic incentives to delay launches should become close to zero. Empirically, we observe only a total of 11 country launches occurring after period T, which suggests that our approximation is accurate.

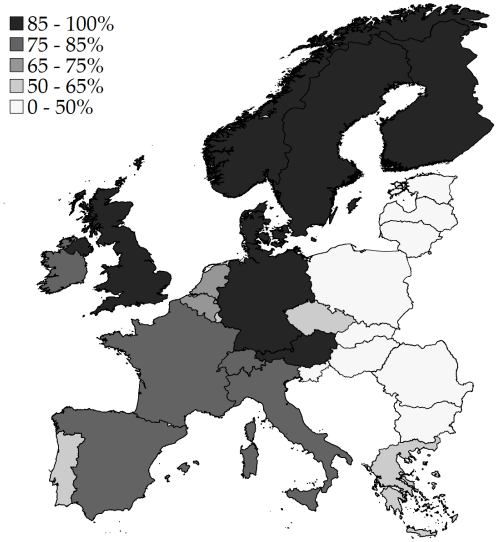
[21]We select a balanced subsample of 142 drugs that received approval through the centralized procedure on or

Figure 1: DIFFUSION OF EMA-APPROVED DRUGS IN EUROPEAN COUNTRIES

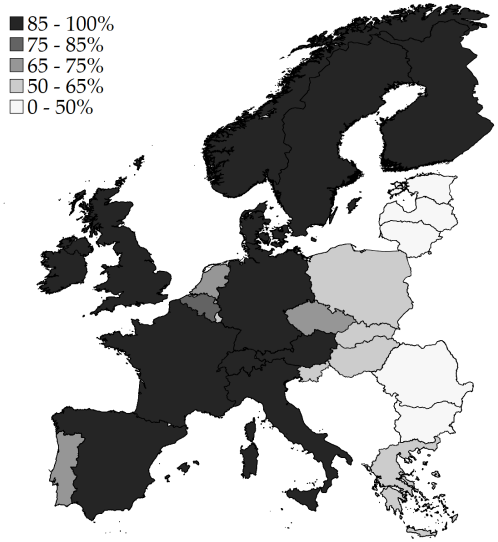
(a) 1 year after approval

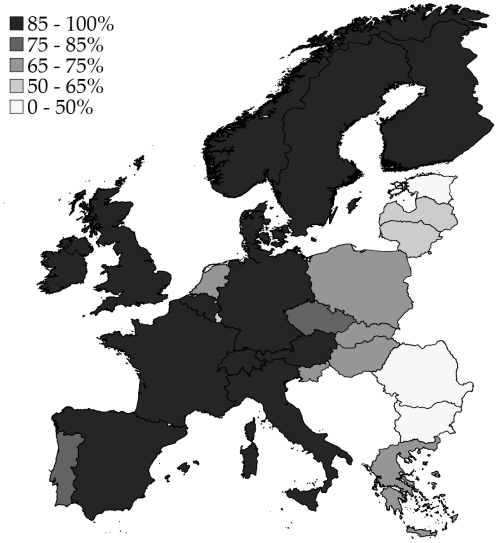


(b) 2 years after approval

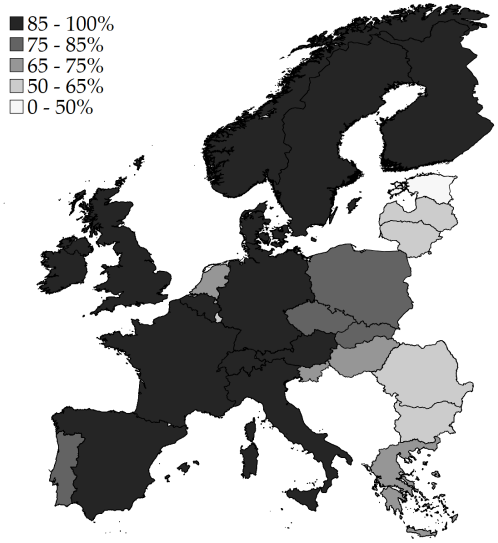


(c) 3 years after approval

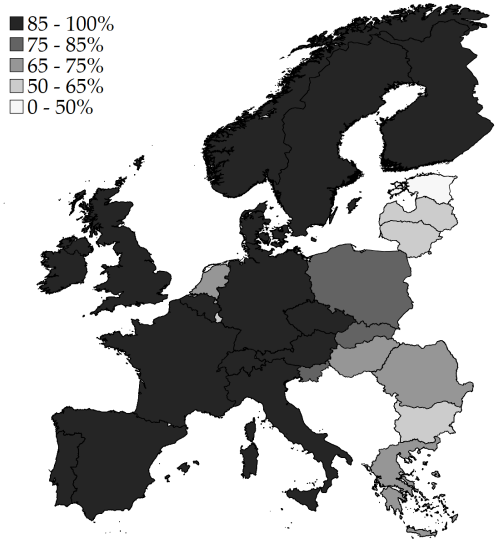




(d) 4 years after approval

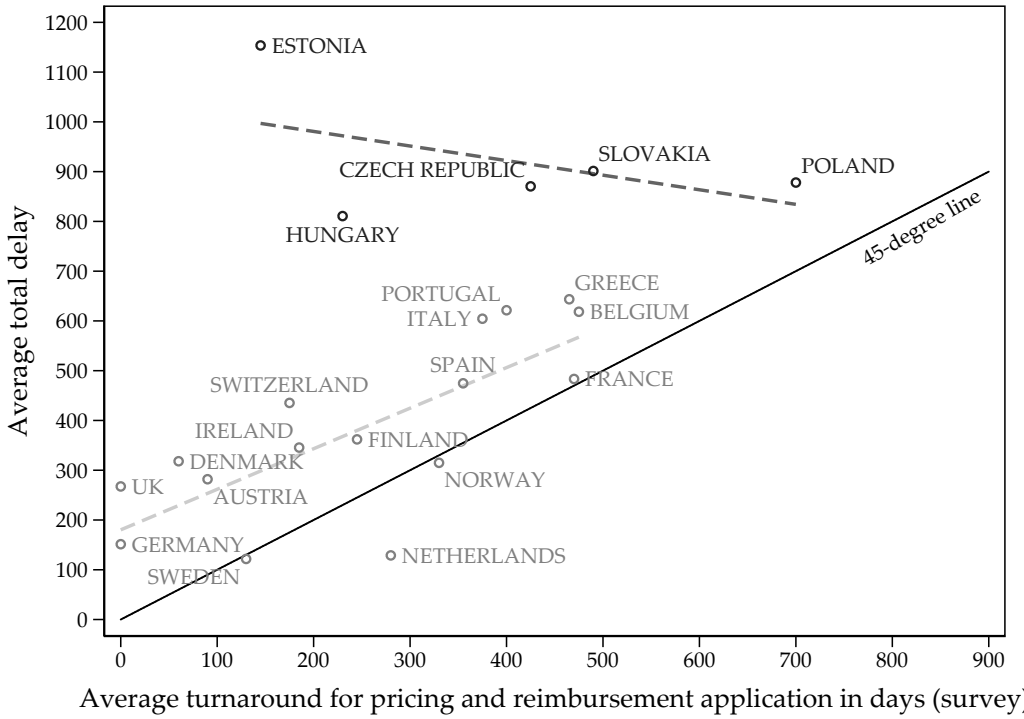


(e) 5 years after approval



(f) 6 years after approval

Figure 2: AVERAGE APPLICATION TURNAROUND VS. AVERAGE LAUNCH DELAY



larly in Eastern Europe, are lagging behind the rest of the continent in terms of their access to medication. Six years after the original approval of a product, Bulgaria, Estonia, Latvia, and Lithuania are the nations with the lowest diffusion rates, followed by Romania and Hungary.[22]

One of the main alternative explanations for these delays is the time required to obtain approval for government reimbursement. However, evidence from a 2004 survey of manufacturers suggests that the average turnaround time for a pricing and reimbursement application is too low to justify overall observed delays (PICTF, 2006). In Figure 2 we plot average application delays by country from the survey against average observed delay in our data. The plot shows that in virtually all cases, our average observed delays are greater than the turnaround times for pricing and reimbursement applications, and sometimes dramatically so.[23] In the plot we also distinguish between Western European countries (where delays are relatively short), and Eastern European countries (where many drugs experience very long delays). The pattern exhibited by these two groups of countries are very different. For Western European countries the two measures are strongly correlated, which is what we would expect if the timing of the

before December 31st, 2006 (out of the 481 in our main sample) to ensure that we can observe the first 6 years of their life-cycle in our data.

[22]The Netherlands also appear to have very low diffusion rates. Rather than reflecting a real empirical phenomenon, this result is caused by missing data. Our coverage for the Netherlands starts in 2007 and includes only retail sales (and not sales through the hospital channel), which means that many products never appear in the data because they are only available in hospitals or they had already exited the market in 2007. Unfortunately, the sample selected to draw this figure draw heavily on this earlier cohort of drugs, exacerbating the problem. In reality, the Netherlands have one of the highest (and fastest) diffusion rates, comparable to those of Germany or Sweden.

[23]The survey did not report turnaround time information for Bulgaria, Latvia, Lithuania, Luxembourg, Romania, and Slovenia. Our estimate for total average delay in the Netherlands is likely affected by missing data as in the case of Figure 1.

launch largely depended on the turnaround for pricing and reimbursement applications. For Eastern European countries, the two measures are completely uncorrelated, which is what we would expect if the timing of the launch depended instead on factors other than turnaround times on applications — such as a firm's strategic choice.

3 Preliminary Evidence of the Impact of ERP

In this section we present suggestive evidence that delay patterns observed in Europe are inconsistent with models that do not incorporate reference pricing. The presence of delays does not represent, in and of itself, enough evidence that firms are responding strategically to reference pricing. Many models can justify delays: they could be caused by fixed costs of entry, capacity constraints, or because firms can only send a limited number of entry applications to each country. We show that the comparative statics of these models are inconsistent with the delay patterns observed in the data, which are instead consistent with reference pricing.

We begin by introducing a stylized model of entry. Suppose a monopolistic firm has a license to sell a new drug in two countries. The drug has a lifetime of two periods, after which a generic enters, and profits fall to zero. For simplicity, assume that prices are set through an exogenous mechanism, so the firm's only choice variable is the launch sequence, which we denote as (s_1, s_2), where s_j is the period in which the product is launched. We also assume that demand and prices are constant over time, and that there are no costs of production. Denote demand and price in country j as q_j and p_j respectively and assume WLOG that $p_1 > p_2$.

Within this framework we consider four possible motivations for delays: reference pricing, fixed costs of entry, capacity constraints, and limits to the number of launches that can be successfully completed in each period.

External reference pricing. In this scenario, assume that differential pricing can only be sustained for one period. After that, if the drug is available abroad, governments take notice of each other's prices and demand the lowest one. In this scenario, the optimal strategy can either be to launch immediately in both countries or wait until the second period before launching in the country with a lower price.[24] Let the profits of a given launch sequence (s_1, s_2) be expressed as $\pi(s_1, s_2)$. Then

$$\begin{aligned} \pi(1,2) &= p_1 q_1 + (p_1 q_1 + p_2 q_2) \\ \pi(1,1) &= (p_1 q_1 + p_2 q_2) + (q_1 + q_2) p_2 \end{aligned}$$

Hence, a delay will occur if and only if

$$\pi(1,1) > \pi(1,2) \iff q_1 (p_1 - p_2) > q_2 p_2 \tag{1}$$

The LHS of this equation represents the revenue loss caused by reference pricing in the second period, while the RHS represents the additional sales from anticipating entry in country 2.

[24] Any other possible strategy is clearly suboptimal: launching in the country with a high price in the first period is better than both not launching at all, and launching in the country with a lower willingness to pay. Moreover, since prices adjust after one period, there are no downsides to launching everywhere in the second and last period.

Notice that since the loss depends on the difference in price between country 1 and country 2, delays in country 2 should be inversely correlated with prices even after controlling for revenue.

Fixed costs of entry. In this scenario, assume that in order to enter in a country the firm must pay a stochastic fixed cost of entry $\xi_{jt} \sim F_{j\xi}\left(\theta_{j\xi}\right)$. We can treat the entry problem in each country separately. In period 1, the firm decides whether to delay or not based on

$$\max\left\{2p_jq_j - \xi_{j1}; p_jq_j - \mathbb{E}\left[\xi_{j2}\right]\right\}$$

In particular, there will be a delay in country j in period 1 if and only if

$$\xi_{j1} > p_jq_j - \mathbb{E}\left[\xi_{j2}\right] \tag{2}$$

According to this model, the probability of delay should respond to revenue, but should *not* depend on price once revenue is accounted for.

Capacity constraints. In this scenario, assume that the firm has unlimited capacity in period 2, but can only produce a fixed amount $\bar{q} < q_1 + q_2$ in period 1. In this scenario, the firm would sell first in the country with a higher price, that is, country 1. Then, if $\bar{q} > q_1$ it would sell the remaining units in country 2. Delays in country 2 arise if $\bar{q} < q_1$. This model too, predicts that delays should be inversely correlated with price even after accounting for revenue.

Limited number of applications. In this scenario, we assume that firms can launch in at most one country in each period. In the first period, the firm will choose to launch in country j if and only if

$$p_jq_j = \max_{k\in\{1,2\}}\left\{p_kq_k\right\} \tag{3}$$

Like in the model with fixed costs of entry, prices shouldn't matter after accounting for revenue.

While delays can arise in all four variations of the model, each scenario predicts different delay patterns. In the scenarios that justify delays using fixed costs of entry and limits to the number of applications, revenue is the only variable that affects the decision of the firm to delay entry. Conversely, the variations that explain delays using external reference pricing and capacity constraints suggest that prices can affect delays even after controlling for revenue. Under the ERP regime, launching in a small country with a higher price may be more desirable than launching in a country with higher expected revenue, but a lower unit price. More generally, holding revenue constant, delays are more likely in countries with lower prices because a lower price generates a bigger externality. In the scenario with capacity constraints prices matter because in the absence of other costs, the firm would like to sell their stock wherever they can get a higher unit price for it.

In the data, we find that delays are inversely correlated with prices, even after controlling for revenue (Table 3). We test this hypothesis by regressing delays on revenue and price:

Table 3: IMPACT OF PRICE AND REVENUE ON DELAYS

	(1)	(2)	(3)	(4)	(5)	(6)
$\ln\left(\text{Yearly Rev}_{ij}\right)$	-2.716^{***}	-3.663^{***}	-2.756^{***}	-3.769^{***}	-2.756^{***}	-3.757^{***}
	(-0.091)	(-0.097)	(-0.092)	(-0.097)	(-0.092)	(-0.096)
$\ln\left(\text{avg}\left(P_{ijt}\right)\right)$	-0.172^{**}	-1.509^{***}				
	(-0.087)	(-0.472)				
$\ln\left(P_{ijt_0}\right)$			-0.173^{**}	-6.015^{***}		
			(-0.088)	(-0.727)		
$\ln\left(\max\left\{P_{ijt}\right\}\right)$					-0.164^{*}	-8.771^{***}
					(-0.087)	(-0.719)
Drug F.E.	N	Y	N	Y	N	Y
R^2	0.09	0.38	0.09	0.38	0.09	0.39
N	8,819	8,819	8,819	8,819	8,819	8,819

$$\text{Delay}_{ij} = \alpha_i + \ln\left(\text{Yearly Rev}_{ij}\right) + \ln\left(p_{ij}\right) + \varepsilon_{ij}$$

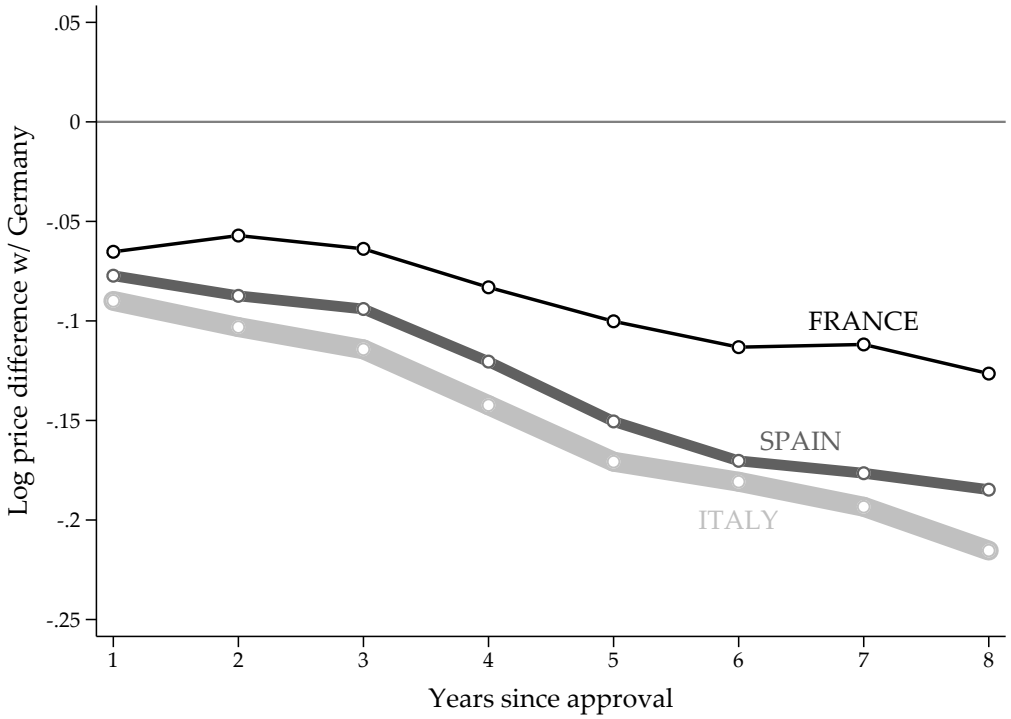
To address the issue that revenue will mechanically be lower in countries where entry is delayed, we use average yearly revenue. With price, the main concern is that what we observe in the data is a combination of a country's true underlying price and the reference price. We test three different measures of price: average price, price at launch, and maximum price. Each has some advantages and disadvantages. Average price is more robust to year-to-year fluctuations but will also suffer the most from the impact of reference pricing. Price at launch and maximum price are less likely to be influenced by reference pricing but are also potentially more noisy.

Our results show that while the exact measure of price matters for the magnitude of the correlation, all three measure are significantly and negatively correlated with delays. This suggests that the models with fixed costs of entry and limits to the number of applications are not capturing the full story behind delays.

Distinguishing between reference price and capacity constraints is harder just by looking at the correlation of price and delays because both models predict that delays are more likely to occur in countries with lower prices even after controlling for revenue. The ideal test of the capacity constraint model would require data on capacity, which is usually hard to come by. Instead, we use total output as a proxy for capacity and exploit the fact that some drugs have declining sales towards the end of their life-cycle. In the data, we can see the year in which the firm reached peak output and calculate the fraction of countries where the product is not yet available after output has already started declining. We select a sample of drugs approved by the European Medicines Agency through the centralized procedure, and for which peak output is reached before 2012. We find that in this sample of drugs, approximately 22% of launches are missing at the end of the year in which peak output is achieved.[25] This suggests that capacity constraints cannot entirely explain delays.

[25]Calculations not shown. See the Online Appendix for a more thorough explanation of this analysis.

Figure 3: CHANGE IN PRICES OVER TIME AND ACROSS COUNTRIES



Finally, we run an indirect test of the model using reference pricing by looking at how prices change across countries that use ERP and countries that don't. To do so, we run the following regression:

$$\ln\left(p_{ijt}\right) = \theta_i + \gamma_{ja} + \delta_t + \varepsilon_{ijt}$$

where γ_{ja} is a fixed effect for country and drug age, measured in years starting from the approval year. We also include drug fixed effects θ_i and year fixed effects δ_t. We focus on the four largest countries in the Eurozone: France, Germany, Italy, and Spain. Germany does not use ERP, while the three other countries do. To check whether prices diverge over time we plot the difference between the γ_{ja} coefficients for Germany and those of the the three other countries (Figure 3). The results show that relative prices in France, Spain and Italy fall over time relative to Germany. This is consistent with the additional downward pressure that we would expect to see through the external reference pricing channel: as the product is launched in more countries, prices fall wherever ERP is used relative to countries where ERP is not used.

4 A DYNAMIC MODEL OF ENTRY WITH EXTERNALITIES IN PRICE

In this section we extend the stylized model introduced in the previous section to obtain a statistical model for structural estimation.

A pharmaceutical firm l owns a set $\mathcal{I}_l$ of patent-protected molecules (indexed by i) with a marketing authorization for sale in a finite set $\mathcal{N}_i \subseteq \mathcal{N} = \{1, \ldots, N\}$ of markets (European countries), indexed using the subscript j.[26] The patent on each molecule i has an expiration

[26] Even though in theory all drugs can easily be approved for all countries in the EEA, we allow for the possibility

date, T_i periods into the future, at which point generic alternatives are allowed to enter and profits are driven to zero.[27] The firm's objective is to maximize profits over the life-cycle of their products. We denote the last period of the firm as $T_l = \max_{i \in \mathcal{I}_l} T_i$.

In each period, the firm is solving a two-part problem:

1. In what countries should the products be launched?
2. What prices should be set in each country?

We are interested in understanding strategic launch delays, which are the outcome of the first part of the problem. Of course, the optimal launch strategy will depend on the equilibrium prices that are set in each country. Firms, however, have limited agency in determining these prices, because drug spending is subject to strict government regulation. Therefore, we do not explicitly model the price-setting stage, but instead use a flexible parametric function to predict equilibrium prices.[28]

We start by introducing some notation. Denote the *launch sequence* of firm l as $S_l = \{s_{ij}\}_{j \in \mathcal{N}_i, i \in \mathcal{I}_l}$, where s_{ij} denotes the period of entry of product i in country j. Furthermore, we denote the launch sequence at the end of a given period t as $S_{lt} = \{s_{ijt}\}_{j \in \mathcal{N}_i, i \in \mathcal{I}_l}$ where

$$s_{ijt} = \begin{cases} s_{ij} & \text{if } s_{ij} \leq t \\ 0 & \text{otherwise} \end{cases}$$

Once a product has entered, we assume that it cannot be voluntarily withdrawn.[29] Under this assumption, knowing S_{lt} is enough to know $S_{l\tau}$ for all $\tau < t$. We similarly denote the launch sequence of other firms as S_{-l}. Occasionally, we will also use the shorthand S or S_t to indicate the launch sequences of all firms. Which sequence maximizes profits depends on demand and prices. The demand system and the price-setting equation are primitives that the firm takes as given when making entry decisions. We describe each in turn before specifying the dynamic entry model.

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that the drug might not be able to enter in all countries. In some occasions, governments can ban drugs if they are concerned about side effects. Hence, we only assume that a drug can enter in a country if we observe sales in the data.

[27] This assumption can be relaxed in many ways without significantly altering the model. The key result that has to hold is that there are no more strategic incentives to delay once the product has lost patent protection. This is almost certainly the case because once a product loses patent protection, governments can rely on much more effective price-cutting measures, and no longer need to resort to external reference pricing.

[28] We remain agnostic with respect to possible micro-foundations of this function, which do not matter for the results of this paper or for the counterfactual. We show in Appendix A.3 that the equation can be derived from a static Nash Bargaining model.

[29] Empirically, we only observe products being withdrawn because the EMA has decided to revoke the marketing authorization upon reviewing post-clinical evidence, or after demand falls for several periods, suggesting that the product is no longer economically or therapeutically viable. In both cases we assume that the choice is not taken by the firm.

4.1 Demand System

We base demand on the logit random utility model.[30] Markets are defined by country, year, and therapeutic class.[31] We aggregate products within a therapeutic class at the molecule-brand status level. We define three possible brand statuses: originator product (i.e. the brand sold by the patent-holder or main manufacturer), non-originator brand (usually a parallel traded product), and generic. The utility of consumer ℓ, in country j, from consuming drug i (molecule m), belonging to therapeutic class κ, in year t is given by

$$u_{i(m,\kappa)\ell(j)t} = \delta_{ijt} + \nu_{i\ell t} \tag{4}$$

To obtain more realistic substitution patterns we also add a nesting structure at the molecule level. The error term $\nu_{i\ell t}$ is parametrized as

$$\nu_{i\ell t} = \left(\zeta_{m,\kappa} + (1 - \sigma_\kappa)\, \varepsilon_{i\ell t}\right)$$

where m indicates the molecule of drug i, σ_κ lies on the unit interval, $\varepsilon_{i\ell t}$ is distributed according to a standard Extreme Value Type 1 distribution and $\zeta_{m,\kappa}$ is an error term whose distribution satisfies the property that $\nu_{i\ell t}$ is distributed according to an Extreme Value Type 1 distribution as long as $\varepsilon_{i\ell t}$ is also EV1 (Cardell, 1997).[32]

We parametrize δ_{ijt} as

$$\delta_{ijt} = \alpha_{ij} + \beta_i \text{age}_{it} + \eta_i NF_{ijt} + \xi_{ijt} \tag{5}$$

Our specification incorporates two important empirical features of drug demand in our data: heterogeneity in preferences across countries, and growing demand over time.[33] α_{ij} captures a country-specific preference for each drug, which could reflect differences in prescribing guidelines or disease burden.[34] The β_i coefficient accounts for drug-specific time trends, which could be generated by physician learning or the slow diffusion of information. We measure age starting with the approval date of the drug. For non-originator products we also keep track of the number of selling firms as a separate control variable NF_{ijt}.[35] Finally, we add a drug-country-

[30] Variations on the logit model are commonly used to describe the pharmaceutical market. Duso et al. (2014) and Stern (1996) use a two-level nested logit model to model demand for oral anti-diabetics and a set of four therapeutic classes (gout, sedatives, minor tranquilizers, and oral anti-diabetics) respectively. Dunn (2012) uses a random-effect logit model (micro-BLP) to describe the market for anti-cholesterol drugs using individual data. In our case, we found that adding a more sophisticated nesting structure did not substantially improve model fit (we experimented with adding an upper level at the ATC4 level or at the market level, separating the outside option from all other products). We did not have enough data to implement a random-effect logit model.

[31] For details on the definition and construction of therapeutic classes, see the Online Appendix.

[32] For the nested logit model to make sense, σ_κ must lie on the unit interval. We do not implement this restriction in the estimation, but instead opt to abandon the nesting structure in favor of a simple logit whenever the parameter falls outside the limits set by the theory.

[33] Demand for drugs can differ substantially across countries because of heterogeneity in prescribing guidelines, incidence of disease, and patient preferences. Moreover, possibly because drugs are generally considered experience goods (Crawford and Shum, 2005), demand for most products increases over the life-cycle.

[34] Even though the impact of disease burden is mostly reflected through market size, therapeutic classes can sometimes encompass large clusters of disease. For example, oncologics are divided in three large therapeutic classes (targeted therapies, cytotoxics, and hormonal therapies).

[35] Virtually all originator products are sold by a single firm in each country, though the firm is not necessarily the same across countries. However, most molecules face multiple brand and generic competitors, which we aggregate in order to avoid excessive entry and exit.

year random shock, ξ_{ijt}, so that the model can fit the data. We do not include a coefficient for price, since we do not observe the price that patients pay. Instead, we include realized demand as a control in the price function, implicitly assuming that any relationship between price and volume sold is mediated by the government. In general, patients in European countries only pay a fraction of the cost of prescription drugs, so any degree of price elasticity that is picked up in the data is likely driven by the government.[36]

Inverting market shares (and normalizing the utility of the outside option to 0) yields the standard estimating equation for nested logit models:

$$\ln\left(\frac{s_{ijt}}{s_{0jt}}\right) = \alpha_{ij} + \beta_i \text{age}_{it} + \eta_i NF_{ijt} + \sigma_m \ln\left(\frac{s_{ijt}}{s_{mjt}}\right) + \xi_{ijt} \tag{6}$$

where s_{0jt} is the share of the outside good, and s_{ijt} and s_{mjt} are the market share of the product, and the overall market share of the molecule nest respectively.[37] We denote the demand function generated by this model as $D_{ijt}\left(S_t, \xi_{jt}^{\kappa}\right)$, where $\xi_{jt}^{\kappa} = \left\{\xi_{ijt}\right\}_{i\in\kappa}$ is the vector of shocks for all products in therapeutic class κ.

4.2 Price-Setting Equation

Drug prices are set in negotiations between firms and governments. The exact form of these negotiations is hard to capture in an explicit model. The government is trying to reconcile several goals, such as providing access to valuable medications and rewarding costly innovation, while at the same time facing a budget constraint. Since we do not have any information on the government's objective function we opt for a more agnostic approach, and model prices using a flexible control function.

Our price-setting equation includes two components. The first component is what we call *government price*, p_{ijt}^{gov}. This is the price that is agreed upon between the firm and the government in the absence of reference pricing. We write the government price as a function of product and country fixed effects, as well as three additional control variables that are meant to capture the potential effect of other price-control policies implemented by the government. First, we include an indicator for whether the firm has headquarters in country j. Kyle (2006) shows that this variable is important to determine probability of launch; we include it to check whether we can detect a significant effect on price. Second, we include a flexible function of the number of other molecules available in the same market. There are several reasons why this variable should matter, all of which suggest it should have negative sign: the availability

[36] All European governments provide universal health insurance coverage. Cost-sharing for drugs tends to be very low. Drugs administered in an inpatient setting are usually completely free. Cost-sharing of outpatient prescription drugs is disciplined by a variety of regulations that weaken the relationship between the price paid by the government and that paid by the patient. In a few countries outpatient drugs are also completely free (Netherlands, Scotland). Some countries use copays that are common to all drugs, regardless of price (Austria, Germany, Ireland, Italy, UK). Others have coinsurances but relatively low caps on the amount that each patient can spend each year/month (Belgium, Finland, Spain, Sweden). Finally, countries that have coinsurances without caps either have low coinsurances for the most valuable products (France, Greece, Poland), or allow for a variety of exemptions to protect sick and low-income individuals (Denmark, Portugal) (Barnieh et al., 2014; Panteli et al., 2016; Thomson and Mossialos, 2010).

[37] See Appendix A.1 for the derivation. We think of the outside good as an aggregate of non-drug therapies (doctor visits, surgery, etc.) or drugs in other classes.

of alternatives should decrease the additional welfare generated by a drug, competitive pressure could bring prices down, and finally, governments sometimes benchmark prices to the lowest price available within a group of substitutable drugs (a practice called internal reference pricing). Third, we include total realized demand for the drug. This variable could also capture a variety of channels, most of which would suggest a negative sign. For example, governments might use soft nudges to steer patients away from expensive drugs to save money. Governments also make widespread use of price-volume agreements meant to prevent budget overshooting. These could take the form of lower prices for drugs whose demand is expected to be higher, as well as volume rebates for drugs with unexpectedly high demand (Carone et al., 2012).

The specification of the government price is

$$p_{ijt}^{\text{gov}}\left(D_{ijt}\left(S_t, \xi_{jt}^{\kappa}\right)\right) = \theta_i \cdot \gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\left(S_t, \xi_{jt}^{\kappa}\right)\right)\right) \tag{7}$$

where θ_i and γ_j are the product and country fixed effects, Z_{ijt} is the matrix of controls, and $D_{ijt}\left(S_t, \xi_{jt}^{\kappa}\right)$ the realized demand, which depends on the random shocks of the products in class κ: $\xi_{jt}^{\kappa} = \left\{\xi_{ijt}\right\}_{i\in\kappa}$. We interpret this equation as a price-schedule, rather than a set list price.

The second component of the price-setting equation is the *reference price*. The reference price is not directly observed, but reference price functions F_{jt}^{ref} and baskets R_{jt} are reported by various sources.[38] Nonetheless, some details regarding the implementation of these functions require additional assumptions: we need to establish how soon governments see prices that have been set in other countries, and whether ERP is applied before or after volume discounts. We assume that governments see prices with a 1-period lag, and that ERP is applied before volume discounts.[39] Therefore, the reference pricing function that we implement empirically is given by

$$p_{ijt}^{\text{ref}}\left(S_t, D_{ijt}\left(\cdot\right)\right) = F_{jt}^{\text{ref}}\left(\left\{p_{ikt-1}\left(S_t, D_{ijt}\left(\cdot\right)\right)\right\}_{k\in\left(R_{jt}\cap E_{it-1}\right)}\right) \tag{8}$$

where E_{it-1} is the set of countries where product i is sold as of time $t-1$ (this set can be obtained from information in S_t).

To combine these two components, we assume that whenever the governments observes a reference price that is inferior to the government price, the equilibrium price is set as a weighted average of the government price and the reference price. We let the weight be country-specific in order to capture eventual heterogeneity in the application of reference pric-

[38] Table 1 shows the reference baskets and prices for 2012. See the Online Appendix for more details on reference functions in previous years, and on the exact sources of reference price functions and baskets.

[39] We think this is the most natural sequence, since ERP is used to set the initial price, while volume discounts can only be applied at the end of the year. This sequence implies that for the purposes of ERP, governments use the initial prices (i.e. *before* volume adjustments), though in our data we observe the final price (inclusive of eventual volume discounts). As a result, we calculate prices without the volume component when calculating reference prices.

ing guidelines. The overall price-setting equation is then given by

$$p_{ijt}\left(S_t, D_{ijt}\left(\cdot\right)\right) = \begin{cases} p_{ijt}^{\text{gov}}\left(S_t, D_{ijt}\left(\cdot\right)\right) & \text{if } p_{ijt}^{\text{ref}}\left(\cdot\right) \geq p_{ijt}^{\text{gov}}\left(\cdot\right) \\ \left(1-\mu_j\right) p_{ijt}^{\text{gov}}\left(S_t, D_{ijt}\left(\cdot\right)\right) + \mu_j p_{ijt}^{\text{ref}}\left(S_t, D_{ijt}\left(\cdot\right)\right) & \text{if } p_{ijt}^{\text{ref}}\left(\cdot\right) < p_{ijt}^{\text{gov}}\left(\cdot\right) \end{cases} \tag{9}$$

4.3 Entry Dynamics

We now turn to dynamic choices. The firm operates in a single-agent, discrete-time, finite-horizon environment. Its goal is to maximize profits by choosing the order and timing of entry in each country, conditional on demand and price primitives (over which it has perfect information).[40]

Firms face stochastic shocks in the form of random entry delays. Formally, a delay shock is a binary Bernoulli random variable ρ_{ijt}, with country-specific parameter ψ_j, independently distributed across countries, years, and drugs. If $\rho_{ijt} = 1$, then drug i cannot enter in country j until period $t+1$ (when a new shock is drawn). These shocks help capture variation in delays that cannot be explained through the reference pricing channel. Delays caused by ERP will arise when firms voluntarily decide to withhold one of their products because they expect that doing so will result in higher overall revenues. Launch delays that occur for any other reason will be soaked up by delay shocks.[41]

Each period unfolds as follows. At the beginning, the firm chooses a set of countries where it will send entry applications. We represent this action as a binary vector $A_{lt} = \left\{a_{ijt}\right\}_{j\in\mathcal{N}_i, i\in\mathcal{I}_l}$ where $a_{ijt} = 1$ whenever the firm chooses to launch product i in country j. More generally, we denote *a strategy* for firm l in the extended-form problem as a map

$$\mathcal{A}_{lt} : \mathcal{S} \to \{0,1\}^{T_l - t + 1}$$

where $\mathcal{S}$ is the set of all possible values of the launch sequence S_l, and $\mathcal{A}_{lt}$ generates a set of binary vectors A_{lt} with an action profile for each period until T_l. The launch sequence of the firm as of period t represents the state variable of the problem. While the launch sequence of other firms has the potential to affect expected revenue (by stealing market share and potentially affecting prices), we assume that strategies are not conditional on the actions of other firms.[42] After the vector of binary shocks for the current period $\left\{\rho_{ijt}\right\}$ is realized, the value of the state variable updates, governments set prices, and finally, products are sold, and profits are realized.

[40] Notice that revenue and profits are equivalent, since the model assumes that all costs are zero.

[41] The main source of delays other than ERP is probably the time required to review price and reimbursement applications and to complete price negotiations. However, other sources may exist as well: firms may need to wait for certain negotiations to be resolved before engaging in additional launching because of capacity constraints to their negotiating workforce; or countries may block the entry of products they consider potentially dangerous for a number of years.

[42] This assumption is necessary to obtain identification from the model. Allowing firms to react to each other is desirable, but makes counterfactual scenarios hard to compute, since our data does not allow us to make inferences about reactions off the equilibrium paths.

The firm's problem at time t is to pick a strategy to maximize

$$V_t\left(S_{lt-1}, S_{-lt-1}\right) = \max_{\mathcal{A}_{lt}=\{A_{l\tau}(S_{l\tau-1})\}_{\tau=t}^{T}} \sum_{S_l}\left(\sum_{S_{-l\tau}}\left(\sum_{\tau=t}^{T}\beta^{\tau-t}\Pi_\tau\left(S_l, S_{-l}\right)\right)\cdot\mathcal{P}\left(S_{-l}\middle|\, S_{-lt-1}, \mathcal{A}_{-lt}\right)\right)\cdot\mathcal{P}\left(S_l\middle|\, S_{lt-1}, \mathcal{A}_{lt}\right) \tag{10}$$

where β is the discount factor, $\Pi_\tau\left(S_l, S_{-l}\right)$ is the expected period profit of the firm, for a given realization of the launch sequence (both the own sequence and the sequence of competitors), and $\mathcal{P}\left(S_l\middle|\, S_{lt-1}, \mathcal{A}_{lt}\right)$ and $\mathcal{P}\left(S_{-l}\middle|\, S_{-lt-1}, \mathcal{A}_{-lt}\right)$ are the probabilities of S_l and S_{-l} conditional on S_l and S_{lt-1}, for given strategies $\mathcal{A}_{lt}$ and $\mathcal{A}_{-lt}$ of the firm and its competitors.

The expected period payoff is defined as

$$\Pi_\tau\left(S_l, S_{-l}\right) = \sum_{i\in\mathcal{I}_l}\mathbb{E}_{\xi_{jt}^r}\left[\sum_{j\in S_{l\tau}} p_{ij\tau}\left(S_t, D_{ijt}\left(\cdot\right)\right) D_{ij\tau}\left(\cdot\right)\right] \tag{11}$$

where the expectation is taken over the possible realizations of the stochastic error in the demand system.

5 Estimates of Demand and Price Primitives

5.1 *Demand Estimation*

We estimate demand from equation 6. The independent variables can be easily constructed from the IMS data, with the exception of age, for which we use approval date from the EMA or the Heads of Medicines Agencies.[43] To measure market size, we use data from the Global Burden of Disease Study. We use a map from ATC4 to GBD indication constructed by Costinot et al. (2016) to calculate the number of patients that might potentially use drugs in a certain therapeutic class.[44] We then scale up the number of patients to obtain a number for standard units and construct market shares from data on sales volumes.[45]

Identification of demand system parameters

Two potential identification issues arise. First, $\ln\left(\frac{s_{ijt}}{s_{mjt}}\right)$ (i.e. the within-molecule market share of product i) is correlated with the error term ξ_{ijt}, so we need instruments to recover a consistent value for σ_m. We use three. First, we use the total number of other firms that are selling the same product (distinguishing between brand/parallel traded products and generics). This

[43] We manage to match over 90% of molecules in our main sample to an approval date. In the handful of cases for which we do not have a match, we use the fifth-earliest launch date from the IMS MIDAS database as a proxy for the approval date. In the sample we were able to match, the fifth-earliest launch occurs after the approval date in 95% of the cases. Notice that any measurement error in the actual approval date will not impact demand estimation, since it will be absorbed by the country-drug fixed effect.

[44] We thank the authors of the paper for sharing the map with us ahead of publication.

[45] The scaling number is chosen to be the smallest number such that the outside option has at least 1% market share in all countries and years. In that sense, our estimate can be thought of as a lower bound on the actual market size. We pick a different scaling number for each therapeutic class.

is because in a logit model, the within-molecule share will be mechanically related to the number of alternative options. Second, we use years since the patent on molecule m expired. This instrument is motivated by the fact that market shares tend to shift to generic manufacturers over time after loss of exclusivity. Third, we use the average within-molecule market share of parallel traded products for other molecules within the same country j.[46] This instrument is meant to capture the average propensity of a government to shift individuals towards parallel traded products.

The second issue is that firms might be able to observe ξ_{ijt} prior to entry. This leads to a classic selection problem common to many IO settings: countries where entry is recorded would have unobservably high values of ξ_{ijt}, leading to a biased estimator. In practice however, there are several attenuating circumstances that suggest selection is a second-order concern in this case. First, firms never exit voluntarily, so we do not need to worry about exit selection. Second, since we control for drug-country-specific preferences, our model will pick up the average preference of each country. The remaining concern is then that demand prior to entry could be lower than our model predicts, because firms may wait until demand reaches a certain threshold before entering. If that were the case, we would expect our α_{ij} coefficients to be biased upwards. In the dynamic estimation, a higher α_{ij} coefficient makes firm i more likely to enter in country j. Therefore, this type of selection bias would lead us to underestimate the extent of strategic delays.

Results

We estimate a separate equation for each of the 109 therapeutic classes that contain at least one of the products in our main sample using linear regressions with instruments. The actual value of the estimated coefficients does not have an intuitive economic interpretation. Instead, we are more concerned with the ability of the model to fit and predict demand accurately. Virtually all regressions achieve an R^2 coefficient of 0.8 or higher. This is both a result of our very flexible model, and a reflection that demand for most drugs tends to be well-behaved, without many fluctuations.

5.2 Price and ERP parameters

We estimate the pricing function using equation 9. Our data almost certainly has measurement error: our prices are yearly averages, which could shroud higher frequency fluctuations, and IQVIA collects their data from pharmacies and hospitals whose reporting systems may not be entirely accurate. We include a measurement error term η_{ijt} that is i.i.d. across countries, drugs and years. For simplicity, we do not include any additional sources of error.[47] Since our price function is multiplicative, we also assume that η_{ijt} is multiplicative (i.e. additive in logs).

[46] We identify as parallel traders all non-originator firms who sell a product sharing the same molecule and product name as the original product.

[47] Introducing any other source of error in the price would potentially lead to insurmountable estimation issues due to the propagation of this error through the reference pricing channel.

Denoting p_{ijt} as the model-predicted price, and p^o_{ijt} as the observed price we obtain

$$\ln\left(p^o_{ijt}\right) = \begin{cases} \ln\left(p^{\text{gov}}_{ijt}\left(\cdot\right)\right) + \eta_{ijt} & \text{if } p^{\text{ref}}_{ijt}\left(\cdot\right) \geq p^{\text{gov}}_{ijt}\left(\cdot\right) \\ \ln\left(\left(1-\mu_j\right) p^{\text{gov}}_{ijt}\left(\cdot\right) + \mu_j p^{\text{ref}}_{ijt}\left(\cdot\right)\right) + \eta_{ijt} & \text{if } p^{\text{ref}}_{ijt}\left(\cdot\right) < p^{\text{gov}}_{ijt}\left(\cdot\right) \end{cases}$$

Our estimation routine searches the vector of parameters that minimizes the difference between the model prediction and the data. Since the price function includes a fixed effect for each product and country (there are 481 distinct products in our main sample), the total number of parameters is quite large, slowing down estimation. To improve the speed and efficiency of the procedure we match log differences in price (the key property of this ratio is that it does not depend on the product fixed effect θ_i, which we prove in Appendix A.2). Since log differences do not depend on the product fixed effect θ_i, this strategy drastically reduces computation time. We match $\ln\left(\frac{p_{ijt}}{p_{ikt+1}}\right)$, where j and k are two (randomly selected) countries, and we look at the difference in the price of product i in these two countries over consecutive periods.[48] The estimating equation in differences is

$$\ln\left(\frac{p^o_{ijt}}{p^o_{ikt+1}}\right) = \ln\left(\frac{p_{ijt}\left(\cdot\right)}{p_{ikt+1}\left(\cdot\right)}\right) + \eta_{ijt} - \eta_{ikt+1}$$

and our routine minimizes the sum of squares of the two error terms:

$$O\left(\gamma_j, \mu_j, \beta_Z, \beta_D\right) = \sum_{i,j,k,t}\left[\ln\left(\frac{p_{ijt}\left(\cdot\right)}{p_{ikt+1}\left(\cdot\right)}\right) - \ln\left(\frac{p^o_{ijt}}{p^o_{ikt+1}}\right)\right]^2 \tag{12}$$

We restrict the μ_j parameters to the unit interval. A negative value of μ_j does not make sense; a value of μ_j greater than 1 — while theoretically possible — raises the possibility of negative prices in counterfactual predictions, which is undesirable.

Identification of the pricing equation

The main threat to identification in the estimation of the pricing equation is the potential presence of cross-country correlations in the error term η_{ijt}. For example, in the case of an EU-wide demand or cost shock we would expect prices of all drugs to be affected similarly. The fear is that our model might erroneously interpret this as the work of reference pricing. To make sure this does not happen, instead of calculating reference prices using *observed* prices in the previous period, we we calculate them using *predicted* prices. Hence, μ is identified through comovements between observed prices and predicted reference prices. This ensures that η_{ijt} does not affect reference prices, and therefore cannot generate a spurious correlation between prices of different countries.

The variation in predicted reference prices that identifies μ_j comes from two possible sources. First, the reference price will change if the value of Z_{ijt} changes in any of the countries where

[48] We compare prices of different countries to avoid differencing out the country fixed effect. In order to minimize the number of observations lost through the differencing process, we occasionally consider $\frac{p_{ij2012}}{p_{ik2002}}$ as a moment. By doing so we only lose one observation per drug, instead of one observation per drug-country.

the product is already available. Second, it will change when the drug launches in a new country. Hence, one of the key sources of variation that pins down μ_j is the exact timing of entry of drugs across countries. It is important that this variation is plausibly exogenous with respect to changes in prices in country j. What helps us is the fact that the entry application process injects significant randomness in the timing of entry of new products. The delays generated by government negotiations can be significant and are likely orthogonal to prices and strategic considerations. Indeed, while most drugs follow relatively similar launch patterns, there is substantial variation in the exact order of drug launches, to the point where virtually no two drugs follow the same exact entry sequence. The fact that entry sequences have a stochastic component also helps us identify the other components of the pricing equation. For virtually every country there are at least a few drugs that begin their launch sequence there. Since governments cannot observe a reference price at the beginning of the launch sequence, this variation helps us identify the components of the government price function.

In calculating the change in the reference price we also leverage the fact that we know the reference function and basket, and the assumption that governments see prices with a one-period lag. These two factors affect when the reference price reacts to a change in prices abroad and the degree to which it is affected. For example, a drug's Italian reference price will adjust in the period after a drug is launched in Poland, while the French reference price will not — Poland is in Italy's reference basket, but not in France's. Moreover, the extent to which the Italian reference price moves will depend on the number of countries where the product is already available: Italy references 24 countries and uses average as their reference function.

Results

We report price estimation results for the vector of parameters $(\hat{\gamma}_j, \hat{\mu}_j, \hat{\beta}_Z, \hat{\beta}_D)$. Since our estimation is in logs, we report coefficients for $\ln(\gamma_j)$, which are more easily interpretable as proportional changes in relative terms with respect to a benchmark (in this case, the omitted coefficient used as a benchmark is $\ln(\gamma_{\text{GERMANY}})$).

The first column of Table 4 shows the coefficients for $\ln(\gamma_j)$. The point estimates roughly match our intuition: countries with lower income tend to pay lower prices, with one main exception: Poland has a higher coefficient than many other countries with higher income. However, it uses the minimum price in Europe as its reference, and its coefficient on μ_j is very close to 1. This suggests that the government may be willing to grant higher prices, knowing that reference rules will bring them down very quickly.[49]

The second column shows estimates for μ_j, which is the coefficient measuring how strictly each country adheres to its own ERP guidelines. We observe significant heterogeneity across countries in this respect. Thirteen countries have coefficients above 0.85, meaning that our model estimates that they closely follow reference pricing guidelines. However, five countries

[49] Luxembourg and Norway (the two richest countries in Europe) are also outliers. Norway is relatively isolated in the reference pricing matrix, because it is only referenced by Finland. Hence granting a lower price to Norway might carry relatively little consequences for firms. This effect is not captured explicitly by our model, but is incorporated in the country fixed effect. Luxembourg is harder to explain, though its status as a relatively small country might give rise to all sort of irregularities and exceptions. Many drugs do not even record sales in Luxembourg, so it is possible that selection might play a role here.

Table 4: PRICE ESTIMATION RESULTS

Country	$\ln(\gamma_j)$		μ_j	
Austria	-0.105	(0.021)	0.330	(0.207)
Belgium	-0.123	(0.021)	0.195	(0.240)
Bulgaria	-0.203	(0.106)	1.000	(0.003)
Denmark[b]	-0.084	(0.016)	0	
Estonia	-0.185	(0.060)	1.000	(0.150)
Finland	-0.135	(0.021)	0.262	(0.322)
France	-0.095	(0.019)	0.000	(0.267)
Germany[a,b]	0		0	
Greece	-0.094	(0.042)	1.000	(0.052)
Hungary	-0.263	(0.080)	0.984	(0.216)
Ireland	-0.078	(0.068)	0.592	(0.352)
Italy	-0.177	(0.036)	1.000	(0.151)
Latvia	-0.244	(0.043)	0.875	(0.273)
Lithuania	-0.244	(0.048)	1.000	(0.100)
Luxembourg[c]	-0.239	(0.024)	0	
Netherlands	-0.207	(0.021)	0.001	(0.182)
Norway	-0.169	(0.020)	1.000	(0.310)
Poland	-0.061	(0.089)	0.914	(0.145)
Portugal	-0.194	(0.041)	0.999	(0.271)
Romania	-0.281	(0.148)	1.000	(0.081)
Slovenia	-0.247	(0.020)	0.999	(0.101)
Spain	-0.160	(0.023)	1.000	(0.204)
Sweden[b]	-0.108	(0.017)	0	
Switzerland	-0.004	(0.015)	0.000	(0.010)
UK[b]	-0.193	(0.016)	0	
Controls				
Log quantity sold	-0.025	(0.003)		
Home-Firm Indicator	0.051	(0.019)		
At least 1 other molecule in class	-0.009	(0.044)		
At least 2 other molecules in class	0.005	(0.026)		
At least 5 other molecules in class	-0.024	(0.023)		
At least 10 other molecules in class	-0.005	(0.015)		

[a] The price level is normalized to Germany's.

[b] Denmark, Germany, Sweden, and the UK do not use reference pricing during the period 2002-2012, so we set μ_j to zero.

[c] Luxembourg references the price of the country of origin of the drug. We don't know country of origin, so we simply assume that μ_j is equal to 0.

This table reports coefficients from the price estimating equation (equation 12). $\ln\left(\gamma_j\right)$ is the country fixed effect, in log terms, normalized with respect to the coefficient of Germany. μ_j represents the weight assigned to the reference price. See Section 4.2 for a detailed description of the price function and control variables. Standard errors are calculated using nonparametric bootstrap with sampling at the drug level.

have coefficients below one-third, which suggests that they either do not follow their guidelines all that closely, or that they apply them only to selected drugs. In particular France, the Netherlands, and Switzerland do not appear to use reference pricing at all, with coefficients that are estimated to be almost exactly zero.

Almost all the coefficients on the control variables in the welfare function behave as expected. Higher quantity sold is associated with lower prices. Prices tend to be approximately 5% higher in countries where the firm has headquarters. Finally, having a higher number of competitors in the same class is associated with slightly lower prices, though the relationship appears to be nonlinear and noisy.

One important result that emerges from the analysis is that the price level (as indicated by $\ln(\gamma_j)$) in Western European countries that follow reference pricing closely is only marginally higher than the price level of Eastern European countries. This suggests that in the current equilibrium firms may be under pressure to keep prices higher in Eastern European countries to reduce the size of the externality generated by ERP, an interpretation consistent with recent empirical work by Dubois et al. (2018) for the US and Canadian pharmaceutical market.

5.3 Simulation-Based Evidence of Optimal Delays

Our price estimation results suggest that ERP affects equilibrium prices, but is the implied externality strong enough to generate delays? To test this hypothesis we simulate firm revenue from various entry sequences and compare it to the payoff obtained from having products launch immediately in every country.

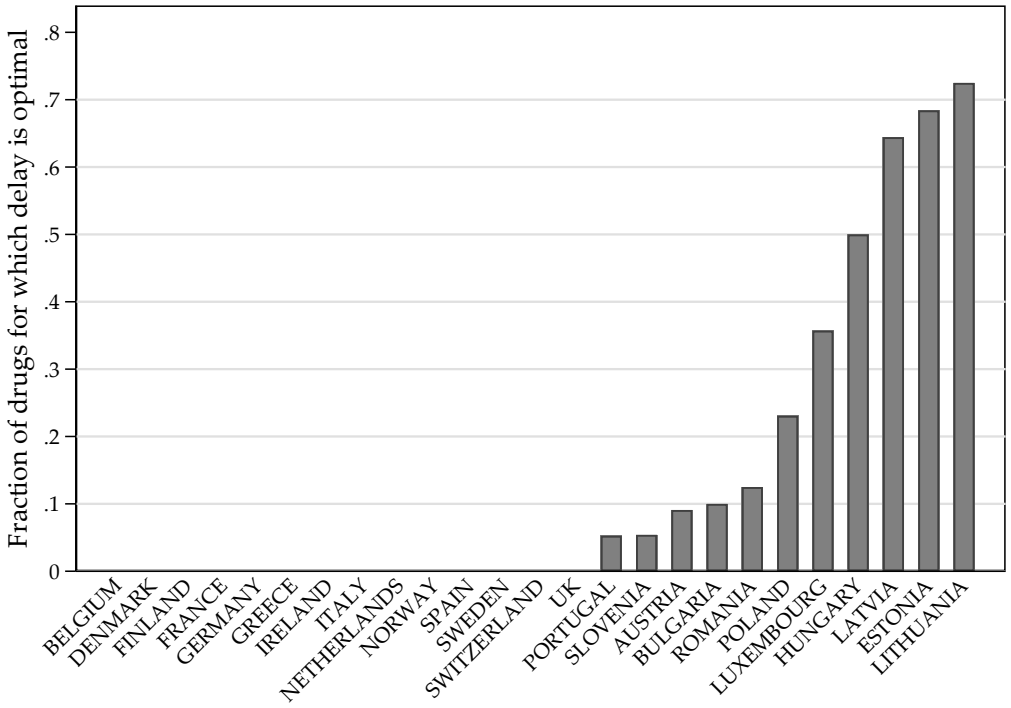
For each of the 87 drugs in our dynamic product sample we simulate entry sequences — denoted as S^{jr} — that consist in launching in all countries immediately, except for country j, where the drug is launched after r periods. We then calculate the fraction of drugs for which delaying in country j is optimal for at least one value of r.[50] In doing our calculations, we set $\beta = 0.95$. Figure 4 plots the results. We find that delays are optimal in countries with lower income. Only two higher-income countries would experience delays according to this simulation: Austria, and Luxembourg. Luxembourg is a very small market, so it's not surprising that for some drugs it would be optimal to exclude it. The model also predicts a delay for one drug in Austria. In this case, the drug in question was indeed launched with a long delay and earned a very small amount in sales. Even though Austria tends to have high price levels relative to most other countries, it can affect the prices of countries with higher price levels (for example Ireland).[51]

Note that no information about delays or launch sequences was used in generating the figure, which is purely based on price and demand estimates. Even so, the patterns we uncover

[50] In some cases, drug i is already in country j in 2002, which makes it impossible to simulate revenue under a counterfactual delay. We exclude those drugs from our calculations.

[51] Delaying entry in Romania and Bulgaria is optimal for a surprisingly low number of drugs, given our price and demand estimates. This is because prior to acquiring EU membership in 2007, Bulgaria and Romania where only referenced by a few other Eastern European countries. Thus, our model predicts that entering in Romania and Bulgaria only has a small effect on prices prior to 2007. In the data, we do not find a significant difference in the average delays before and after EU entry in these two countries. This is not too surprising however, as entry in the EU also removes several bureaucratic obstacles that might have generated idiosyncratic delays. Hence, the net effect of EU membership on launch delays could be close to 0.

Figure 4: OPTIMALITY OF STRATEGIC DELAYS BY COUNTRY



are remarkably consistent with the entry patterns from Figure 1 (Section 2.3). This confirms the intuition that firm behavior adheres to the incentives laid out by the regulatory environment and supports the idea that our model captures the relevant features of this market.

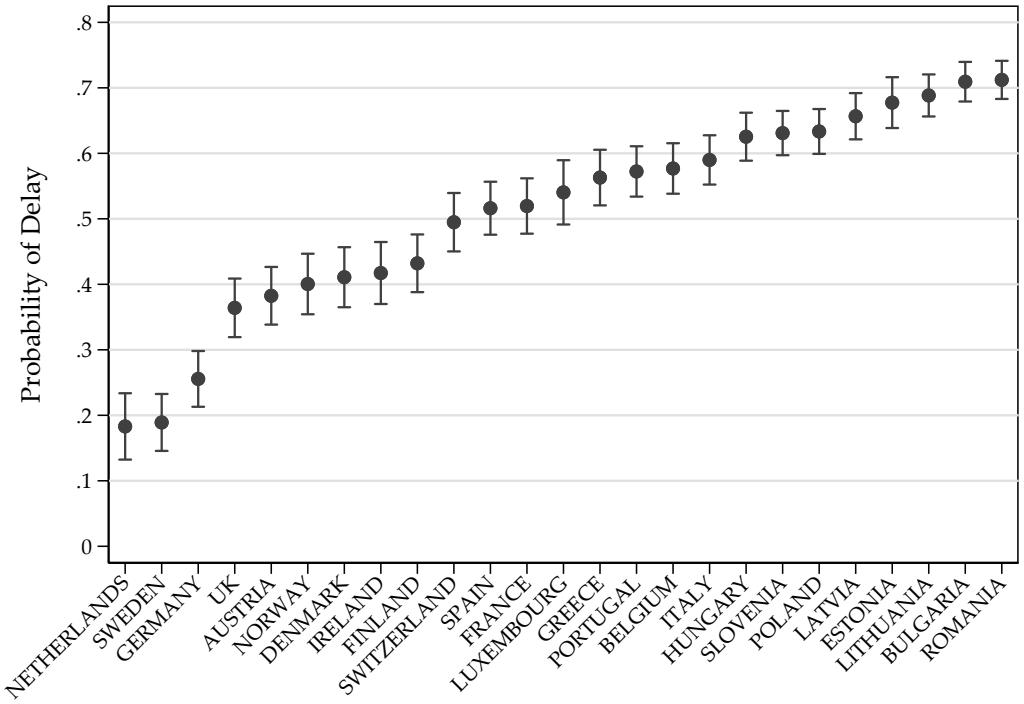
6 DYNAMIC ANALYSIS

With estimates of demand and price primitives in hand, we now turn our attention to the parameters governing idiosyncratic delays. While these parameters will absorb all delays that are not justified from a revenue standpoint, their primary source is likely the time that it takes for the government to approve a pricing and reimbursement application.

Traditional estimation method are unfeasible in our case. First, the model does not have an analytic solution due to the complicated net of price externalities. Second, the state space (N^T possible entry sequences for N countries and T periods) is too large to solve the problem numerically. Third, firm strategies are unobserved: we see when drugs enter, but not when firms send applications. In other words, an application that was not sent is observationally equivalent to an application that was rejected.

To avoid having to make unrealistic restrictions to the choice set we derive restrictions on the parameter set by constructing two sets of moment inequalities. The first set uses data on entry and approval dates. We exploit the intuition that firms can only apply after they have received marketing approval for a product. Hence, the average probability of an idiosyncratic delay is bounded above by the average probability of overall delay implied by the data. The second set uses information contained in the expected revenue of the observed entry sequence. The estimator rejects parameter values for which we can find strategies that yield higher ex-

Figure 5: PROBABILITY OF OVERALL DELAYS BY COUNTRY



pected revenue than what firms obtained in the data.

The second set of moment inequalities is novel. We introduce a methodology that does not require observing the firm's strategy. We show that, conditional on some assumptions, simply observing the total revenue earned by the firm is sufficient to derive restrictions on model parameters.

6.1 Moment Inequalities based on Entry Data

We use entry and approval data to recover an upper bound on the delay parameters. Our distributional assumption on the random delay shocks is that in each period the probability of an application for entry in country j being delayed is ψ_j. Let $\left(1-\bar{\psi}_j\right)$ be the probability that product i will enter in country j in a given year. This is the combination of the probability that the firm will apply, times the probability of the application being accepted. Hence, for all j, $\bar{\psi}_j \geq \psi_j$.

To estimate $\bar{\psi}_t$ we can simply calculate the probability of a delay by using data on approval dates and launch dates: suppose that a product approved in year 0 enters France in year 2. Then, the expected probability of entry is $1/3$: the product had three opportunities to enter — in years 0, 1, and 2 — and registered one success, in year 2.[52]

[52]Our assumption is that delays are country-specific, so we use the full sample of 481 drugs to estimate them in order to minimize noise. Note that this assumption also implies that we could obtain a tighter bound by choosing a partition P of the set of all drugs, calculating a subset-specific upper bound $\bar{\psi}_j^p$ for all $p \in P$, and choosing $\bar{\psi}_j^{p,\min} = \min_p \bar{\psi}_j^p$ to be the upper bound. We show in the Online Appendix that doing so can yield a lower upper bound for $\bar{\psi}_j$.

Figure 5 plots our estimates for $\bar{\psi}_j$ for all European countries, together with 95% confidence intervals.[53] We find that the probability of a delay ranges from 0.18 in the Netherlands and Sweden to 0.71 in Bulgaria and Romania. The countries with the highest probability of delay are all located in Eastern Europe, though there isn't much difference between, for example, Italy, a country for which we did not detect any incentive to engage in delays, and Hungary, a country for which half of all drugs have a potential incentive to delay (see Figure 4).

6.2 Moment Inequalities based on Revenue Data

Identification in moment inequalities grounded in revealed preference is based on the idea that the firm's strategy is only optimal for a certain range of value of the unknown parameters, and therefore contains information that can be used to restrict the feasible parameter space.

We cannot follow the same logic in our setting, because firm strategies are unobserved (e.g. if we observe entry in France with a 2-year delay, we don't know whether the firm applied starting in year 0, year 1, or year 2). As a result, we can't compute the expected revenue of the firm's observed strategy for arbitrary values of the unknown parameter. However, in the data we still know how much the firms earned — i.e. the revenue earned for the true value of the parameter. It is important to note that this is a draw from the distribution of the revenue random variable, and not the *expected* revenue. However, we can aggregate realized revenue *across* drugs to generate a sample analog for the expected revenue of the average firm. We use this information to obtain identification and build inequalities in a way that is similar to the rest of the literature: we compare the revenue earned by the firm in the observed data and calculate counterfactual revenue under alternative strategies for arbitrary values of the parameter.

Formally, let $\mathcal{A}^{\star}_{lt}$ denote the optimal strategy of firm l starting in period t. By definition, $\mathcal{A}^{\star}_{lt}$ is the solution to the dynamic programming problem of the firm as expressed in equation 10. In other words, for all possible strategies $\mathcal{A}'_{lt}$, $\mathcal{A}^{\star}_{lt}$ satisfies

$$\tilde{V}_t\left(\mathcal{A}^{\star}_{lt}; S_{lt-1}, S_{-lt-1}\right) \geq \tilde{V}_t\left(\mathcal{A}'_{it}; S_{lt-1}, S_{-lt-1}\right) \tag{13}$$

where

$$\tilde{V}_t\left(\mathcal{A}_{lt}; S_{lt-1}, S_{-lt-1}\right) = \mathbb{E}\left[\sum_{\tau=t}^{T} \beta^{\tau-t} \Pi_\tau\left(S_l, S_{-l}\right) \middle| \mathcal{A}_{lt}, S_{lt-1}, S_{-lt-1}\right] \tag{14}$$

is the expected payoff of the agent conditional on playing strategy profile $\mathcal{A}_{lt}$ (the expectation is taken over the possible realizations of the launch sequences of all products, as in equation 10).

Under the assumption that firms maximize expected returns we can use equation 13 to build "revealed preference" inequalities as in Pakes et al. (2015). In the data we observe a certain number of firms with molecules in specific therapeutic classes (each firm-class combination constitutes one observation for us, since molecules in different therapeutic classes do not affect each other). The *expected* payoff of the observed launch sequence S^{o}_{l} of firm l starting

[53] We follow instructions laid out by Brown et al. (2001) in building approximate confidence intervals for these parameters.

at period t is

$$V_t\left(S_l^o, S_{-l}^o\right) = \sum_{\tau=t}^{T} \beta^{\tau-t} \Pi_\tau\left(S_l^o, S_{-l}^o\right)$$

Notice that $\Pi_\tau\left(S_l^o, S_{-l}^o\right)$ is an object that we can recover through simulations, since it only depends on the shocks $\xi_t^\kappa = \left\{\xi_{jt}^\kappa\right\}$.[54] We recover the distribution of ξ_t^κ from demand estimation and use it to simulate ξ_t^κ. Then, the average of $V_t\left(S_l^o, S_{-l}^o\right)$ converges to the average of the expected payoff of each firm when playing the optimal strategy.

Theorem 1. *For any $\varepsilon > 0$, we can find M' such that*

$$\frac{1}{M}\sum_{i=1}^{M}\left(V_t\left(S_l^o, S_{-l}^o\right) - \tilde{V}_t\left(\mathcal{A}_{lt}^\star; S_{lt-1}, S_{-lt-1}\right)\right) < \varepsilon$$

for all $M > M'$.

We provide a rigorous proof of this Theorem in Appendix A.4. Intuitively, if firms are playing the optimal strategy, then the observed launch sequences are draws from the probability distributions $\mathcal{P}\left(S_l \middle| S_{lt-1}, \mathcal{A}_{lt}^\star\right)$ and $\mathcal{P}\left(S_{-l} \middle| S_{-lt-1}, \mathcal{A}_{-lt}^\star\right)$. This distribution need not be the same for all firms: each may face a different initial state S_{lt-1}, and different demand or price primitives. However, since the random shocks used in the model are independently distributed across drugs, we can invoke a generalized version of the law of large number for non-identical independent random variables to prove that the sample average across firms converges to the average expected payoff.

Theorem 1 suggests that we can write moment inequalities based on the average payoff obtained by the firms in our sample:

$$\frac{1}{M}\sum_{i=1}^{M}\tilde{V}_t\left(\mathcal{A}_{lt}^\star; S_{lt-1}, S_{-lt-1}\right) \geq \frac{1}{M}\sum_{i=1}^{M}\tilde{V}_t\left(\mathcal{A}_{lt}'; S_{lt-1}, S_{-lt-1}\right) \tag{15}$$

The left-hand side of this inequality is approximated by $\frac{1}{M}\sum_{i=1}^{M} V_t\left(S_l^o, S_{-l}^o\right)$. To compute the right-hand side we use simulation. The expected payoff of any deviation $\mathcal{A}_{lt}'$ can be written as an integral over the possible realization of the launch sequence S_l, holding S_{-l} fixed

$$\tilde{V}_t\left(\mathcal{A}_{lt}'; S_{lt-1}, S_{-lt-1}\right) = \sum_{S_{-l}}\sum_{S_l}\sum_{\tau=t}^{T}\beta^{\tau-t}\Pi\left(S_l, S_{-l}\right)\mathcal{P}\left(S_l \middle| S_{lt-1}, \mathcal{A}_{lt}'\right)\mathcal{P}\left(S_{-l} \middle| S_{-lt-1}, \mathcal{A}_{-lt}^\star\right)$$

We approximate $\tilde{V}_t\left(\mathcal{A}_{lt}'; S_{lt-1}, S_{-lt-1}\right)$ by simulating the distribution of $\mathcal{P}\left(S_l \middle| S_{lt-1}, \mathcal{A}_{lt}'\right)$. For a given guess of the parameter vector ψ, and for each drug $i \in \mathcal{I}_l$ draw $\left\{\nu_{ijt}^r\right\}_{r=1}^{nsim}$ to calculate simulated entry paths $\left\{S_l^r\right\}$. The average simulated payoff is

$$V_t^{sim}\left(\mathcal{A}_{lt}'; S_{lt-1}, S_{-lt-1}, \psi\right) = \frac{1}{nsim}\sum_{r=1}^{nsim}\left[\sum_{\tau=t}^{T}\beta^{\tau-t}\Pi\left(S_l^r, S_{-l}\right)\right]$$

[54] This error is unobserved by both the firm and the econometrician by assumption. There is no additional error from price since the residual is assumed to be measurement error.

The difference between $\tilde{V}_t\left(\mathcal{A}'_{lt}; S_{lt-1}, S_{-lt-1}\right)$ and $V_t^{sim}\left(\mathcal{A}'_{lt}; S_{lt-1}, S_{-lt-1}, \psi^0\right)$ — for the true parameter vector ψ^0 — is simulation error, which can be eliminated by choosing $nsim$ large enough, and the error in the realization of S_{-lt-1} (which is only one of many possible draws). When we aggregate across firms, the error in S_{-lt-1} will disappear for a large enough sample of drugs.

We define empirical moment conditions as

$$\mu\left(\mathcal{A}'_{lt}, \psi\right) = \min\left\{0, \frac{1}{M}\left(\sum_{i=1}^{M} V_t\left(S_l^o, S_{-l}^o\right) - V_t^{sim}\left(\mathcal{A}'_{lt}; S_{lt-1}, S_{-lt-1}, \psi\right)\right)\right\}$$

The estimation identifies a set Ψ^I of parameters that satisfy

$$\Psi^I = \left\{\psi \,:\, \sum_{\mathcal{A}'_t} \mu\left(\mathcal{A}'_{lt}, \psi\right) = 0\right\}$$

Ex-ante, we expect these inequalities to be more effective in finding a lower bound on the probability of an idiosyncratic delay ψ. To see why, assume that the expected revenue conditional on playing the optimal strategy are monotonically decreasing in ψ (i.e $\frac{\partial \tilde{V}\left(\mathcal{A}^\star(\psi), \psi; \cdot\right)}{\partial \psi} < 0$).[55] Then, it is impossible to find an alternative strategy A' such that

$$\tilde{V}_t\left(A', \psi'; S_{lt-1}, S_{-lt-1}\right) > \tilde{V}_t\left(\mathcal{A}^\star_{lt}\left(\psi^0\right), \psi^0; S_{lt-1}, S_{-lt-1}\right)$$

for $\psi' > \psi^0$.[56] It will still be possible to find A' such that $V\left(A', \psi'\right) > V\left(A^\star\left(\psi^0\right), \psi^0\right)$ for $\psi' < \psi^0$.[57]

Empirical Implementation The computational demands of moment inequality estimation grow exponentially with the number of parameters. At a high computational cost, we would be able to estimate bounds for each country j. In practice, we think a sensible compromise is to estimate separate parameters for two groups of countries.

We select the groups based on the the results of our dynamic simulations, as well as reduced form patterns. The first group, consists of countries where we believe strategic delay incentives to be low, includes all Western European countries. The second group, includes all Eastern European countries. The classification is fairly clear cut: Eastern European countries

[55] We do not have a formal proof of this statement. However, this is intuitively true: firms should be better off when the probability of a delay is lower, as they have better control over which entry sequence will be realized. For example, if the probability of delay were 0, the firm would be able to choose the profit-maximizing entry strategy. An increase in the probability of delay would reduce the likelihood of achieving the profit-maximizing entry sequence, therefore expected revenue would fall.

[56] To see why, notice that by assumption $V\left(A^\star\left(\psi^0\right), \psi^0\right) > V\left(A^\star\left(\psi'\right), \psi'\right)$ for all $\psi' > \psi^0$. Moreover, by definition of $A^\star(\cdot)$, $V\left(A^\star\left(\psi'\right), \psi'\right) > V\left(A', \psi'\right)$ for all ψ'.

[57] We could obtain an upper bound from data on expected revenue by showing that for a given value of ψ, no strategy will ever yield expected revenue as high as what the firm obtained in the data. The problem is that the firm achieves the highest possible expected revenue when playing the optimal strategy, and the reason we resort to moment inequalities is precisely that we cannot compute this strategy. However, we can find functions of data and parameters that always returns a value greater than the expected revenue under the optimal strategy. We describe this approach in the Online Appendix, including an example of a function that satisfies these requirements, but that unfortunately only yields an upper bound that is already ruled out from the moment inequalities that use entry data.

all have much lower income and market size relative to the vast majority of Western European countries. Moreover, our dynamic simulation suggests that at least some firms have an incentive to delay entry in each of these countries. Conversely, Western European countries have higher income, larger markets, and our simulation suggests that there is little reason to delay entry in Western Europe on purpose. There are a few exceptions to this rule that is worth mentioning. First, the economic fundamentals of both Greece and Portugal (i.e. per capita GDP and price level) are closer to those of Eastern Europe than to some of the other Western European countries. However, neither one appears to be particularly prone to strategic delays in simulations — Portugal is the only country of the two for which we simulate a delay incentive, for a single drug. Luxembourg is the only Western European country for which we simulate meaningful strategic delays. However, overall delays in Luxembourg do not seem to be dramatically different than those of other Western European countries, so we decided to keep it in the first block of countries.

We assign a separate parameter to each group, ψ_{WE} for Western Europe, and ψ_{EE} for Eastern Europe. To introduce some more flexibility in the model we also parametrize the moment inequality so that ψ_{WE} and ψ_{EE} can be interpreted as the proportion of the overall probability of delay that is due to idiosyncratic reasons. In other words, we let

$$\psi_j = \bar{\psi}_j \times \psi_g$$

where $g \in \{WE, EE\}$ and $\psi_g \in [0,1]$. Intuitively, if $\psi_g = 0$, it means that all delays are strategic, while if $\psi_g = 1$ it means that all delays are idiosyncratic.[58] We estimate an identified set for these parameters by building moment conditions based on equation 15, and checking the range of parameters that satisfies it for a series of possible strategies $\mathcal{A}'_{lt}$. Calculating $V_t\left(S^o_l, S^o_{-l}\right)$ and $V^{sim}_t\left(\mathcal{A}'_{lt}; S_{lt-1}, S_{-lt-1}, \psi\right)$ does not require observing drugs from their original launch, but it does require observing them until period T_l. Hence we perform this analysis on the dynamic sample (see Table 2 for details).

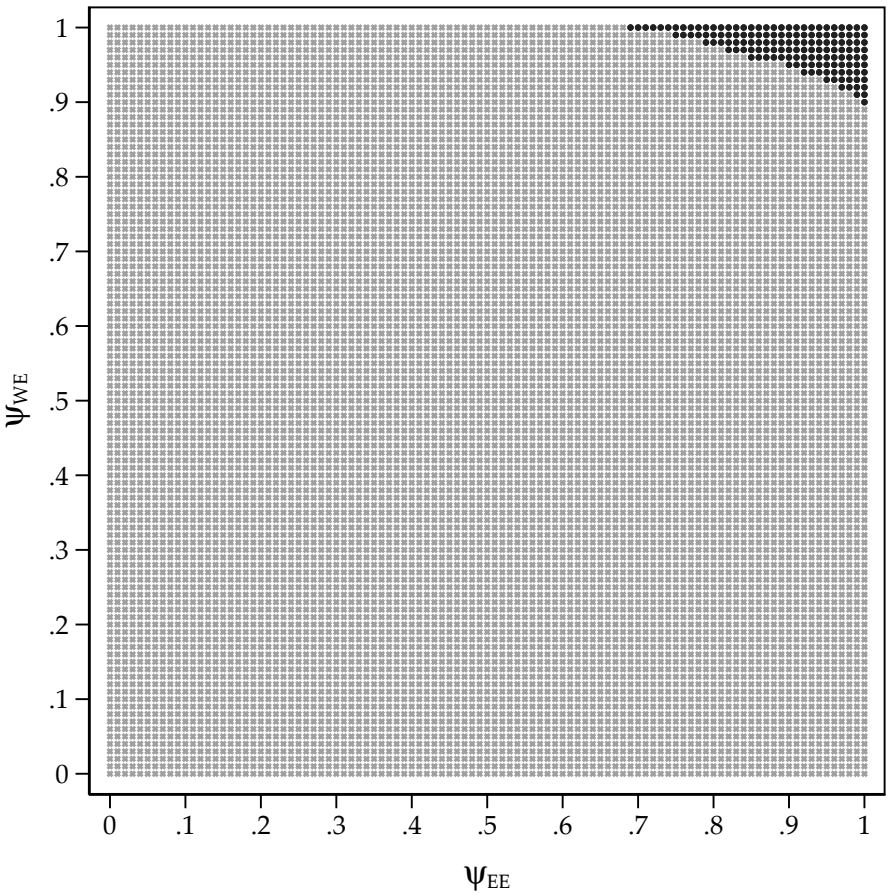
The choice of $\mathcal{A}'_{lt}$ that will yield the tightest bound is whatever strategy we can construct that comes closes to the optimal strategy. In order to find the best possible approximation, we conduct additional simulation exercises where we compute the optimal entry period for each drug and country when firms are restricted to sequences that delay entry in up to 2 countries (these are natural extensions of the sequences we simulated in section 5.3). We then take the optimal entry periods for all drugs i and countries j and test strategies where firms send entry applications up to k periods in advance. We set $k \in \{0,1,2,3\}$, so we test 4 possible strategies in total.[59]

Figure 6 shows our results. The darker area is the identified set. We notice two things. First, consistent with our initial assessment, we are much more successful at rejecting values

[58] This choice is motivated by the fact that, especially for Western European countries, overall delays are strongly correlated with average turnaround time for a pricing and reimbursement application (Figure 2). By taking this approach we maintain some heterogeneity across Western European countries, which we think is important, given that probability of delay varies significantly across Western Europe. The adjustment is less important for Eastern Europe, which has more homogeneous delay probability rates.

[59] We also test a variety of simpler strategies, such as applying right away in all countries, or applying k periods before observed entry s^o_{ij}. These strategies yield looser bounds.

Figure 6: IDENTIFIED SET OF ψ_{WE} AND ψ_{EE}



for Western Europe. Second, considering that the inequalities can only deliver a lower bound, we can actually reject a fairly large proportion of the overall set of possible values for ψ_{WE} and ψ_{EE}.

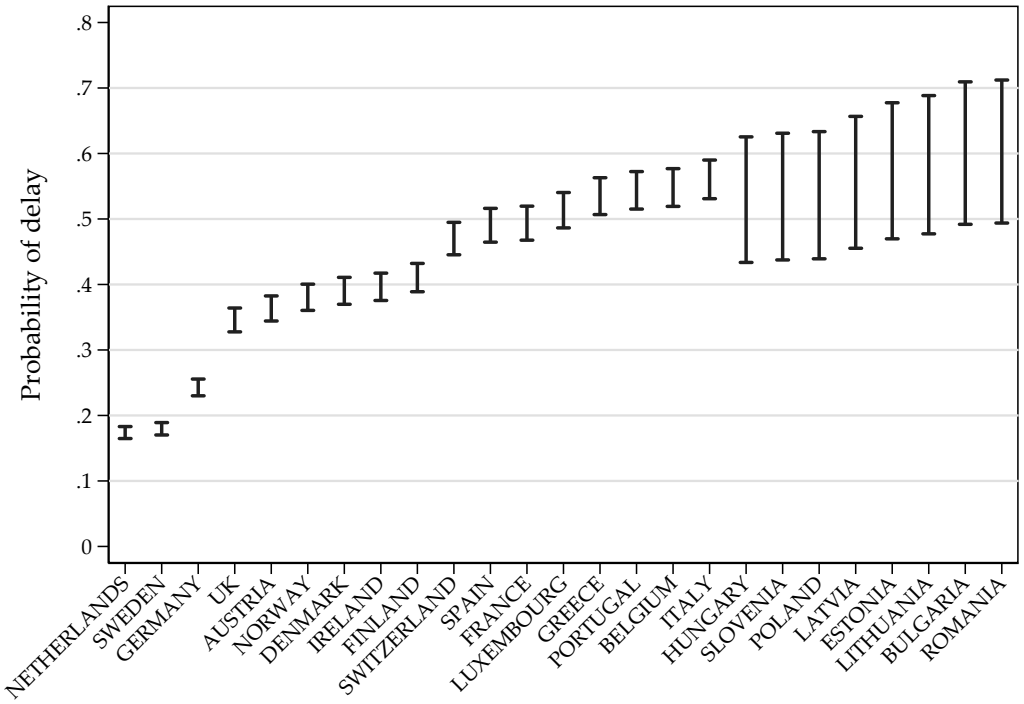
The two extremes of the identified set are $(\psi_{WE}, \psi_{EE}) = (1, 0.69)$, and $(\psi_{WE}, \psi_{EE}) = (0.90, 1)$. Using these two pairs we can construct identified sets by country. We use 0.69 as the value of ψ_{EE} and 0.90 as the value for ψ_{WE}. The results are shown in Figure 7. Notice that the identified sets for Western European countries are fairly small: in some cases, they are actually contained within the confidence intervals for $\bar{\psi}_j$ shown in Figure 5).

7 COUNTERFACTUAL: DELAYS IN THE ABSENCE OF ERP

7.1 Delays in the absence of ERP

Using our estimates, we can simulate how delays would change in the absence of ERP. In this scenario, firms no longer have any incentive to delay entry in any country, so the optimal strategy is to apply for entry right away in all countries. Hence, the only delays arise through the stochastic shock channel. Notice that this counterfactual exercise does *not* depend on the specific pricing rule adopted to replace ERP, as long as it eliminates externalities across countries (this would also involve imposing limits on parallel trade, for example by carving out

Figure 7: IDENTIFIED SET OF ψ_j BY COUNTRY



an exclusion for patent-protected pharmaceuticals). Therefore, we do not need to rely on our pricing model to work out the implications of this counterfactual. This strengthens the external validity of our estimates, because it means that our final result does not depend on the ability of our pricing model to accurately predict prices out of equilibrium.

To estimate the impact of the reform, we focus on Eastern European countries and hold $\psi_{WE} = 1$. We do this because all our results suggest that the relevant delays are in our group of Eastern European countries. Figure 8 plots the range of possible delays in implied by the identified sets of ψ_j. We measure the impact of delays in country-years per drug (e.g. 4 country-years of delay means a total of 4 years of delays across all countries in Eastern Europe. Since we have 8 Eastern European countries in our data, the average delay in each country would be 6 months).

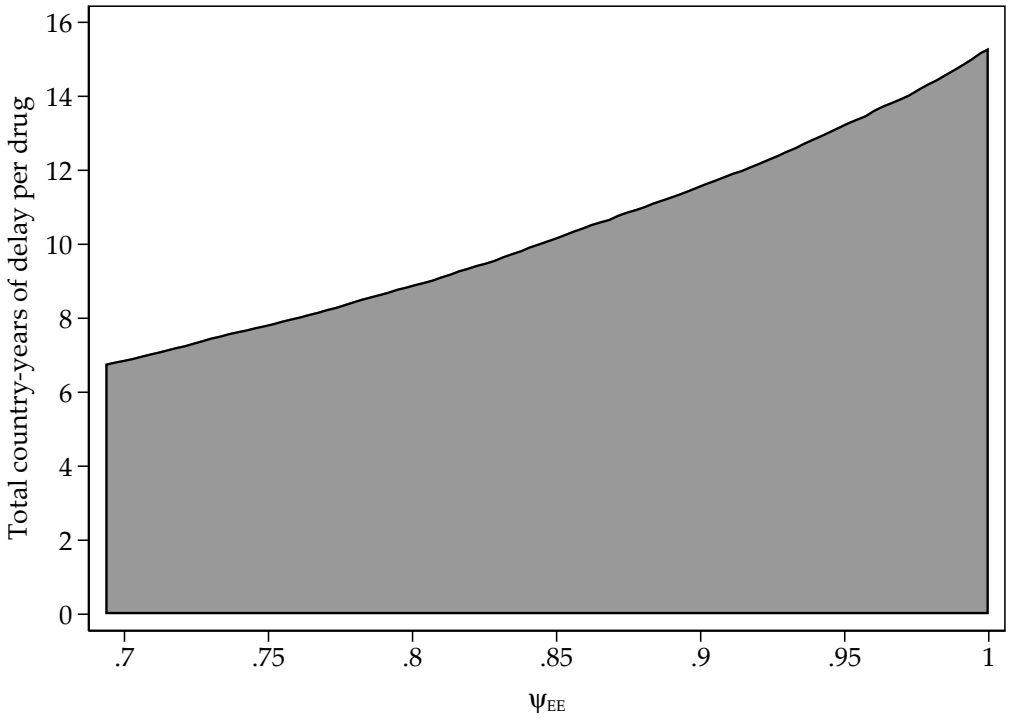
The parameter at the upper bound of the interval implies that idiosyncratic delays match observed delays (i.e. $\psi_{EE} = 1$). Under this scenario, the average drug should expect a total of 15.3 country-years of delays. At the lower bound of the interval, firms would instead expect a total of 6.8 country-years of delays, a reduction of approximately 55% in delays. In terms of years of delay per country and per drug, the total number is slightly above one year.

7.2 Policy Analysis: implications of the impact of ERP on revenue

Using our model, we can also calculate how much money firms would lose by disregarding the negative impact of reference pricing and applying for entry in all countries right away.[60]

[60]Notice that this is different than estimating how much revenue firms lose because of ERP, which would ultimately depend on what policy is chosen to replace ERP, and on how prices would adjust in the new equilibrium.

Figure 8: RANGE OF POTENTIAL DELAYS IN THE ABSENCE OF ERP



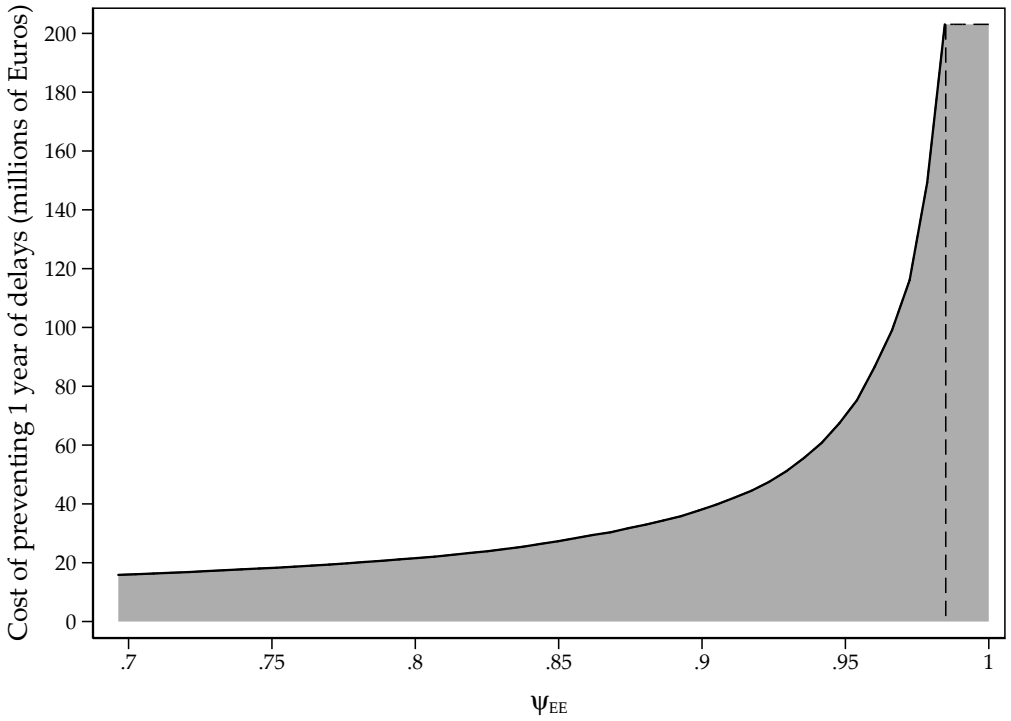
This number is helpful to understand how large is the incentive to engage in strategic delays. To calculate it we simulate expected revenue of the "naive" strategy of applying everywhere right away and compare it to observed revenue. As was the case in the construction of the moment inequalities, we need to average across drugs to eliminate the noise generated by the realization of the delay shocks. What we recover is the a consistent estimate of the average revenue loss across all drugs.[61]

We estimate this loss to be approximately €18 million for the average drug. This is not a small sum, and it provides further confirmation that an incentive to delay exists and is large enough to justify a strategic reaction from firms (especially considering that this amount is about as large as the overall revenue that firms earn in lower-income European countries). At the same time, 18 million is only a small fraction of the average lifetime expected revenue for the drugs in our sample. There are two reasons that contribute to keeping this number low. First, prices in several Western European countries are only marginally higher than in Eastern Europe. This reduces the impact of reference pricing when it is applied. Second, our estimates suggest that countries with lower prices also have a higher probability of stochastic delays. Hence, even when firms launch everywhere at the same time, drugs tend to enter later in these countries, which also contributes to reduce the impact of ERP.

The fact that the revenue loss is not unreasonably large suggests that instead of removing ERP, the European Union could compensate firms with lump sum transfers in exchange for

[61] The distribution of drug revenue is highly skewed, which means that the average is not necessarily the most informative moment that we could look at. However, given our data, we can only look at the average (instead of, say, the median) because we need to aggregate across drugs in order to remove the residual error that comes from the random realization of the delay shocks in the data.

Figure 9: COST OF REDUCING DELAYS BY 1 DRUG-YEAR IN EASTERN EUROPEAN COUNTRIES



In this figure we plot the range estimate of the cost of reducing delays by 1 drug-year in all 8 Eastern European countries in our sample. The y-axis is truncated above because the curve tends to infinity as ψ_{EU10} approaches 1, which is the value for which all delays are idiosyncratic, in which case subsidies cannot affect delays.

forgoing strategic delays. This solution has the advantage that it does not require EU Member States to give up the prerogative to manage drug pricing independently (which stems directly from the Treaty of Lisbon).[62] Subsidies could be handed out by a centralized European agency upon confirmation that an entry application has been sent and approved for entry in all European countries. The overall budget impact of this policy would be small according to our estimates. On average, during the period between 1995 and 2017, around 27 new drugs received approval in the EEA. Hence, the overall impact of this subsidy would be less than €500 million per year, which would represent a very small fraction of the overall budget of the EU, which in 2016 was around €150 billion. It is also worth noting that from the point of view of a social planner, the lump sum constitutes a transfer, so any gains from early access, however small, would improve the overall welfare in the system.[63] We leave the question of whether or not such a mechanism satisfies incentive-compatibility constraints to future research, and simply assume that it can be implemented at no significant additional cost here (perhaps by having a third-party estimate demand and prices).

Figure 9 plots a distribution of the cost of reducing delays by 1 country-year for all countries

[62] Article 168 of the Treaty on the Functioning of the European Union (i.e. the Treaty of Lisbon) explicitly states that "Union action in the field of public health shall fully respect the responsibilities of the Member States for the definition of their health policy and for the organization and delivery of health services and medical care and the allocation of the resources assigned to them."

[63] This conclusion might not hold in a model where additional frictions or dynamic considerations exist (e.g a shadow cost of raising governments funds, or dynamic implications on the incentives to invest in R&D). However, the size of the subsidy is small enough that these additional considerations will likely be second-order.

in Eastern Europe over the range of the identified set of ψ_{EU10}. The purpose of this figure is not to argue whether paying the subsidy is worth it, but rather to illustrate the implied tradeoff. A larger probability of idiosyncratic delays implies that subsidies have a smaller impact on overall delays, hence the cost increases. At the upper bound, all delays are idiosyncratic, and therefore subsidies cannot affect the entry sequence of any drug. However, for more reasonable values of the parameter, the cost to increase access is not prohibitive. At the lower bound, given that roughly 80 million people live in Eastern Europe, the overall cost comes down to roughly 23 cents per person.

8 Conclusion and Next Steps

This paper studies the extent to which external reference pricing policies contribute to the disparity in access to prescription drugs across countries. ERP generates complex incentives for firms who might benefit from strategically delaying entry in countries with low willingness to pay for drugs. Using a novel moment inequality approach, we characterize the impact of these policies on launch delays and on firm revenue. Our methodology allows us to obtain identification even though the firm's actions are unobserved, thus contributing to a growing body of literature showing how moment inequalities can make even the most complicated models tractable.

We hope that our work can also prove useful for policy. While policymakers and industry insiders are both aware of the externality generated by ERP, our paper is (to the best of our knowledge) the first to isolate the impact of ERP on launch delays from that of other policies. Our counterfactual estimates suggest that if reference pricing was removed delays would fall by up to 12 months per drug in the average Eastern European country.

Several proposals to replace reference pricing with alternative systems have been suggested (Kanavos et al., 2011; OECD Health Policy Studies, 2008; Towse et al., 2015; Vogler et al., 2015). If pricing reform proves difficult, or politically unfeasible, our paper proposes an alternative solution that does not require any changes to the current pricing system. Instead, firms could be induced to forgo strategic delays through a system of lump-sum transfers. We calculate that the overall budget impact of this policy would be around half a billion euros per year.

Our analysis also has some limitations. First, our demand model does not include a source of structural error. As we discuss in Section 5.1, unobservable demand shocks would likely lead us to underestimate the impact of strategic delays. Hence, this omission may lead us to underestimate the impact of reference pricing.

Second, we assume that our price model predicts exact prices. Introducing a structural error in the price estimation would create an insurmountable econometric challenge, since this error would propagate through reference pricing channel in ways that would be difficult to account for. One possible avenue to relax this assumption might be to assume that the structural error on price is known to the firm, but not to foreign governments. This would prevent the error from propagating across countries. However, the intuition behind the model would not change much. This type of error could help justify earlier-than-predicted entry, but the opposite (later-than-predicted entry) is usually much more common in the data.

Third, we assume that firms act as single agents even though our demand and price models imply that the actions of other firms affect revenue. Our demand model implies that entry of a competitor will negatively affect the market shares of all other products within the therapeutic class, and our price function suggests that entry of a competitor may have a negative impact on price. This introduces a certain degree of internal inconsistency in the model, though empirically, these effects may not be large enough to elicit a strategic reaction — in particular, the effect of competitors on price is very noisy according to our estimation results. Allowing for multiple agents is unfortunately not feasible in the current environment, as the expected revenue of alternative strategies in the moment inequality can only be computed holding the strategy of other firms fixed. This is a more general problem in the moment inequality literature, which has limited applications in dynamic multiple agent problems.

Finally, there are also elements that we do not model explicitly. We take the regulatory environment as exogenous. Presumably, the government could choose the reference pricing function according to some optimal decision-making criterion. We ignore this possibility here. The question of why reference pricing is effective in lowering prices is also interesting. Experience suggests that governments do not need to resort to ERP if they want to implement price cuts (we observe several instances of temporary price cuts in the data that do not seem to be related to reference pricing). Indeed, there is some evidence that reference pricing is sometimes used only as a pretense for cuts that would have occurred anyway. For example, Greece changed its reference pricing function in 2010 to a formula that resulted in roughly 10-20% lower prices across the board. It is likely that these cuts would have been mandated regardless due to the financial situation of the country at the time. These considerations go beyond the scope of the paper (we believe it is reasonable to assume that these changes are exogenous from the point of view of the firm) but might provide fertile ground for future research.

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Appendices

A Theoretical Derivations

In this Appendix we derive some results from the main body of the paper, and present a few complementary results that are not crucial to the results of the paper, but add robustness to the framework we use.

A.1 Logit Model

The utility of consumer ℓ, in country j, from consuming drug i (molecule m), belonging to therapeutic class κ, in year t is given by

$$u_{i(m,\kappa)\ell(j)t} = \delta_{ijt} + \left(\zeta_{m,\kappa} + (1-\sigma_\kappa)\,\varepsilon_{i\ell t}\right)$$

where $\zeta_{m,\kappa}$, is common for all $i \in m$, and distributed according to the unique distribution such that if $\varepsilon_{i\ell t}$ is an extreme value random variable, then so is $\zeta_g + (1-\sigma)\,\varepsilon_{i\ell t}$ (Cardell, 1997). δ_{ijt} is parametrized as in Equation 5.

With this setup, one can show that the country j market share of *i within subset set m* is given by

$$s^m_{ijt} = \frac{\exp\left(\frac{\delta_{ijt}}{1-\sigma_\kappa}\right)}{D_m\left(\mathbf{X}_{mt}\right)} \tag{A.1}$$

where

$$D_m\left(\mathbf{X}_{mt}\right) = \sum_{k\in m} \exp\left(\frac{\delta_{kjt}}{1-\sigma_\kappa}\right)$$

and the market share of set *m within the overall market* is given by

$$s_{m/jt} = \frac{D_m\left(\mathbf{X}_{mt}\right)^{1-\sigma_\kappa}}{1 + \sum\limits_{h\in G_\kappa} D_h\left(\mathbf{X}_{ht}\right)^{(1-\sigma_\kappa)}} \tag{A.2}$$

where G_κ is the set of all molecules in class κ. Hence, the *overall market share of drug i* is

$$s_{ijt} = \frac{\exp\left(\frac{\delta_{ijt}}{1-\sigma_\kappa}\right) D_m\left(\mathbf{X}_{mt}\right)^{-\sigma_\kappa}}{1 + \sum\limits_{h\in G_\kappa} D_h\left(\mathbf{X}_{ht}\right)^{(1-\sigma_\kappa)}} \tag{A.3}$$

Derivation of the estimating equation Notice that the share of the outside option can be expressed as

$$s_{0jt} = \frac{1}{1 + \sum\limits_{h\in G_\kappa} D_h\left(\mathbf{X}_{ht}\right)^{(1-\sigma_\kappa)}} \tag{A.4}$$

Consider the log ratio of the market share of item i in group m to the outside good. According to the model, this can be expressed as

$$\ln\left(s_{ijt}\right) - \ln\left(s_{0jt}\right) = \left(\frac{\delta_{ijt}}{1-\sigma_\kappa}\right) - \sigma_\kappa\sigma \ln\left(D_m\left(\mathbf{X}_{mt}\right)\right)$$

Combining equations A.2 and A.4 we also obtain

$$\ln\left(D_m\left(\mathbf{X}_{mt}\right)\right) = \frac{\ln\left(s_{m/jt}\right) - \ln\left(s_{0jt}\right)}{1-\sigma_\kappa}$$

Hence we can write

$$\ln\left(s_{ijt}\right) - \ln\left(s_{0jt}\right) = \frac{\delta_{ijt}}{1-\sigma_\kappa} - \frac{\sigma_\kappa}{1-\sigma_\kappa\sigma}\left(\ln\left(s_{m/jt}\right) - \ln\left(s_{0jt}\right)\right)$$

which implies

$$\begin{aligned}
\left(1-\sigma_\kappa\right)\left(\ln\left(s_{ijt}\right) - \ln\left(s_{0jt}\right)\right) &= \delta_{ijt} - \sigma_\kappa\left(\ln\left(s_{m/jt}\right) - \ln\left(s_{0jt}\right)\right) \\
\implies \left(1-\sigma_\kappa\right)\ln\left(s_{ijt}\right) - \ln\left(s_{0jt}\right) &= \delta_{ijt} - \sigma_\kappa \ln\left(s_{m/jt}\right) \\
\implies \ln\left(s_{ijt}\right) - \ln\left(s_{0jt}\right) &= \delta_{ijt} + \sigma_\kappa \ln\left(\frac{s_{ijt}}{s_{m/jt}}\right)
\end{aligned} \tag{A.5}$$

A.2 Derivation of price estimating equation A.2

Let $p_{ijt}\left(\cdot\right)$ be defined as in equation 9. Then, for any $j, k \in \mathcal{N}_i$

$$\ln\left(\frac{p_{ijt}\left(\cdot\right)}{p_{ikt+1}\left(\cdot\right)}\right) = \begin{cases}
\ln\left(\frac{\gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\right)\right)}{\gamma_k \cdot \exp\left(\beta_Z Z_{ikt+1} + \beta_D \ln\left(D_{ikt+1}\right)\right)}\right) & \text{if } p^{\text{ref}}_{ijt}\left(\cdot\right) \geq p^{\text{gov}}_{ijt}\left(\cdot\right) \wedge \\
& p^{\text{ref}}_{ikt+1}\left(\cdot\right) \geq p^{\text{gov}}_{ikt+1}\left(\cdot\right) \\
\ln\left(\frac{\gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\right)\right)}{\left(1-\mu_k\right)\gamma_k \cdot \exp\left(\beta_Z Z_{ikt+1} + \beta_D \ln\left(D_{ikt+1}\right)\right) + \mu_k \tilde{p}^{\text{ref}}_{ikt+1}\left(\cdot\right)}\right) & \text{if } p^{\text{ref}}_{ijt}\left(\cdot\right) \geq p^{\text{gov}}_{ijt}\left(\cdot\right) \wedge \\
& p^{\text{ref}}_{ikt+1}\left(\cdot\right) < p^{\text{gov}}_{ikt+1}\left(\cdot\right) \\
\ln\left(\frac{\left(1-\mu_j\right)\gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\right)\right) + \mu_j \tilde{p}^{\text{ref}}_{ijt}\left(\cdot\right)}{\gamma_k \cdot \exp\left(\beta_Z Z_{ikt+1} + \beta_D \ln\left(D_{ikt+1}\right)\right)}\right) & \text{if } p^{\text{ref}}_{ijt}\left(\cdot\right) < p^{\text{gov}}_{ijt}\left(\cdot\right) \wedge \\
& p^{\text{ref}}_{ikt+1}\left(\cdot\right) \geq p^{\text{gov}}_{ikt+1}\left(\cdot\right) \\
\ln\left(\frac{\left(1-\mu_j\right)\gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\right)\right) + \mu_j \tilde{p}^{\text{ref}}_{ijt}\left(\cdot\right)}{\left(1-\mu_k\right)\gamma_k \cdot \exp\left(\beta_Z Z_{ikt+1} + \beta_D \ln\left(D_{ikt+1}\right)\right) + \mu_k \tilde{p}^{\text{ref}}_{ikt+1}\left(\cdot\right)}\right) & \text{if } p^{\text{ref}}_{ijt}\left(\cdot\right) < p^{\text{gov}}_{ijt}\left(\cdot\right) \wedge \\
& p^{\text{ref}}_{ikt+1}\left(\cdot\right) < p^{\text{gov}}_{ikt+1}\left(\cdot\right)
\end{cases} \tag{A.6}$$

where $\tilde{p}^{\text{ref}}_{ijt}\left(\cdot\right)$ is such that $p^{\text{ref}}_{ijt}\left(\cdot\right) = \tilde{p}^{\text{ref}}_{ijt}\left(\cdot\right) \cdot \theta_i$, and $\tilde{p}^{\text{ref}}_{ijt}\left(\cdot\right)$ is not a function of θ_i.

The proof of this Theorem hinges on showing that the reference price can be written as a linear function of the drug fixed effect. Intuitively, this result follows from the fact that the reference price can be written as a weighted average of government prices, which are all linear functions of the drug fixed effect. To prove the result of the theorem, we first prove the following Lemma:

Lemma 2. *Denote*

$$\lambda_{ijt} = \gamma_j \exp\left(\beta_Z Z_{ijt-1}\right)$$

and let $\lambda_{it} = \left\{\lambda_{ijt}\right\}_{j \in \mathcal{N}_i}$. *Then, there exists a set of weights* $\omega_{ijkt}\left(S_{t-1}, \{\lambda_{i\tau}\}_{\tau=1}^{t}\right)$ *such that for any drug* i, *country* j, *and year* t

$$p_{ijt}^{ref} = \sum_{\tau=1}^{t} \sum_{k \in R_{j\tau}} \omega_{ijkt}\left(S_{t-1}, \{\lambda_{i\tau}\}_{\tau=1}^{t}\right) p_{ik\tau-1}^{gov}\left(D_{ijt}\left(\xi_{jt}\right)\right)$$

Proof. This Lemma states that we can write p_{ijt}^{ref} as a linear function of government prices in all previous periods, using weights that depend only on the current entry sequences of all firms and structural parameters of the model other than the drug fixed effect. We use induction over t, where t indexes time starting with the year after the product was first approved (in the year of approval there cannot be any reference prices).

Consider $t = 1$. We want to show that for all j,

$$p_{ijt}^{\text{ref}} = \sum_{k \in R_{j1}} \omega_{ijk1}\left(S_0, \lambda_{i0}\right) p_{ik0}^{\text{gov}}\left(D_{ij1}\left(\xi_{j1}\right)\right) \tag{A.7}$$

The definition of the reference price is

$$p_{ij1}^{\text{ref}}\left(E_{i0}, D_{ij1}\left(\xi_{j1}\right)\right) = F_{j1}^{\text{ref}}\left(\left\{p_{ik0}\left(D_{ij1}\left(\xi_{j1}\right)\right)\right\}_{k \in \left(R_{j1} \cap E_{i0}\right)}\right)$$

Since reference pricing cannot be applied at time $t = 0$, the prices that can be referenced must be government prices:

$$p_{ik0}\left(D_{ij1}\left(\xi_{j1}\right)\right) = p_{ik0}^{\text{gov}}\left(D_{ij1}\left(\xi_{j1}\right)\right)$$

Then, if F_{j1}^{ref} is a linear function, like an average, equation A.7 is satisfied for constant weights. F_{j1}^{ref} can also be the minimum function, or the average of the three lowest prices, which are not linear.[64] These functions however, can be expressed as weighted averages, where the weights will depend on the relative ranking of the volume adjusted country government prices, which in turn will depend on λ_{ij0}.

In these cases weights can be constructed as follows. Recall that $E_{i0} = \left\{j : s_{j0} \neq 0\right\}$ is the set of countries where the product is available in period 0. This set can be obtained from information contained in S_0. We assume WLOG that E_{i0} is not empty (if it is, then there can be no possible reference and the case of $t = 1$ is identical to $t = 0$). Let n_k denote the rank of $k \in E_0$ in increasing order of λ_{i1}. In other words, if $n_k = 1$, then

$$\lambda_{ik1} = \min\left\{\lambda_{i\ell 1} : \ell \in \left(R_{j1} \cap E_0\right)\right\}$$

and, more generally,

$$\lambda_{ik1} = \min\left\{\lambda_{i\ell 1} : \ell \in \left(R_{j1} \cap E_0\right) \wedge n_\ell \geq n_k\right\}$$

[64] See Figure **??**.

Hence, the country that ranks first is the one with the lowest government price, the one that ranks second has the second-lowest price, etc. Finally, let $m_{ij1} = \min\{|E_0|, 3\}$, where the operator $|\cdot|$ indicates the cardinality of a set.

If F_{j1}^{ref} is the average of the three lowest prices, the weights can be written as

$$\omega_{ijk1}(S_0, \lambda_{i0}) = \begin{cases} 1 & \text{if } n_k = 1 \\ 0 & \text{otherwise} \end{cases}$$

If F_{j1}^{ref} is the average of the three lowest prices instead, construct the weights as

$$\omega_{ijk1}(S_0, \lambda_{i0}) = \begin{cases} \frac{1}{m_{ij0}} & \text{if } n_k \leq m_{ij0} \\ 0 & \text{otherwise} \end{cases}$$

These weights are written as a function of S_0 and λ_{i0} only, hence they satisfy the premise of the proposition.

To conclude the proof, suppose that the assertion of the proposition is true for $\tau \in \{1, \ldots, t-1\}$, and show that it must hold for t as well. This is easy to prove. We can walk through the same exact steps as we did for $t = 1$, but substituting $p_{ikt-1}\left(E_{it-1}, D_{ijt}\left(\xi_{jt}\right)\right)$ for λ_{i1}. This will give us weights for p_{ijt}^{ref} as a linear function of the prices in the previous period. By construction, prices in the previous period are a weighted average of government prices and reference prices. The reference prices are themselves linear functions of adjusted government prices by the inductive assumption. Since the sum of linear functions is also linear, the proposition must hold for period t as well. ■

The Lemma gives us a way to write the reference price as a weighted average of government prices. Since government prices are a multiplicative function of θ_i, so are reference prices. Hence we can write

$$p_{ijt}^{\text{ref}}(\cdot) = \tilde{p}_{ijt}^{\text{ref}}(\cdot) \cdot \theta_i$$

where $\tilde{p}_{ijt}^{\text{ref}}$ is not a function of θ_i. Then, we can write

$$p_{ijt}(\cdot) = \begin{cases} \theta_i \gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\right)\right) & \text{if } p_{ijt}^{\text{ref}}(\cdot) \geq p_{ijt}^{\text{gov}}(\cdot) \\ \theta_i \gamma_j \cdot \exp\left(\beta_Z Z_{ijt} + \beta_D \ln\left(D_{ijt}\right)\right) + \mu_j \tilde{p}_{ijt}^{\text{ref}}(\cdot)\,\theta_i & \text{if } p_{ijt}^{\text{ref}}(\cdot) < p_{ijt}^{\text{gov}}(\cdot) \end{cases}$$

which shows that $p_{ijt}(\cdot)$ is a multiplicative function of θ_i. Hence, when we consider $\frac{p_{ijt}}{p_{ikt+1}}$, θ_i will appear in both the denominator and the numerator and we can eliminate it, giving us the result in equation A.6.

■

A.3 Foundations for the Price-Setting Equation

In the main body of the paper we do not provide a micro foundation of the price setting equation from a utility- or revenue-based optimization model. The characteristics of such a model

are less relevant for our paper. However, in this section we provide two possible sets of assumptions that could justify an estimation equation identical to the one we use.

Foundations as a static Nash Bargaining Model

We assume that the firm and the government play a Nash Bargaining game. The game is repeated every period, but for simplicity the two parties only split the static welfare gains from the current period. In reality, prices impose dynamic constraints through reference pricing that both agents should take into account. To eliminate these dynamic considerations one could assume that the government is a myopic agent and that the firm's bargaining unit is only tasked with carrying out the negotiation, without concerns for the future ramifications of the agreed-upon price.[65]

The equilibrium price in a standard Nash Bargaining model is given by

$$p^{\star} = \arg\max_{p} \left[\Delta W_{ijt}\right]^{b_j} \times \left[\Delta \Pi_{ijt}\right]^{1-b_j}$$

where ΔW_{ijt} represents the change in the welfare of the government from having drug i available, $\Delta \Pi_{ijt}$ represents the incremental change in revenue, and b_j is the bargaining power of country j. Notice that the interpretation of ΔW_{ijt} is not necessarily welfare, but could more generally be described as the objective function of the government agent tasked with completing the negotiation.

Under our assumptions of static bargaining, $\Delta \Pi_{ijt}$ is simply the potential revenue in country j, and since demand is price inelastic, we can divide through by demand to recast the problem as a negotiation over the unit price of the product (instead of total revenue). We abstract away from marginal costs of production since for brand drugs they are a negligible fraction of prices. The simplified problem can be written as

$$p^{\star} = \arg\max_{p} \left[\Delta w_{ijt} - p\right]^{b_j} \times \left[p\right]^{1-b_j}$$

where the interpretation of Δw_{ijt} is the average change in the welfare function from obtaining an additional unit of drug i. The standard Nash bargaining solution, can then be written as

$$p^{\star} = \Delta w_{ijt} \left(1 - b_j\right)$$

This price denotes the equilibrium in the absence of reference pricing, and represents the *government price* p_{ijt}^{gov}.

To account for the impact of reference pricing we propose that the government can negotiate more effectively by eliciting a signal about what prices are charged abroad. We incorporate this possibility in the model by assuming that the signal (i.e. the reference price) affects the

[65] There are several reasons why short-term considerations could in fact play a major role for most government agencies. First, the main goal of pharmaceutical agencies is to keep spending within the limits of their budget, which is often specifically carved out for prescription drugs thus limiting the ability to generate trade-offs such as paying more for cost-effective drugs that would save money in other areas of health care, such as inpatient care. Turnover of government officials might also contribute to the failure of adopting long-term strategies. On the pharmaceutical company side, most firms have a separate bargaining unit for each country. Informal conversations with industry insiders seem to suggest that these unit operate in relative independence from one another.

bargaining weight assigned to the government. The reference price p_{ijt}^{ref} is calculated as described in the main body of the paper.[66] Given p_{ijt}^{ref}, we write the bargaining weight of the government as

$$B_{ij}\left(p_{ijt}^{\text{ref}}\right) = b_j + \left(1 - b_j\right)\mu_j \left(1 - \frac{p_{ijt}^{\text{ref}}}{p_{ijt}^{\text{gov}}}\right) \cdot \mathbb{I}\left\{p_{ijt}^{\text{ref}} < p_{ijt}^{\text{gov}}\right\}$$

where $p_{ijt}^{\text{gov}} = \Delta w_{ijt}\left(1 - b_j\right)$ is a function of model parameters that reflects the price that the government would have obtained without using reference pricing. We define the bargaining weight of the firm as $1 - B_{ij}\left(p_{ijt}^{\text{ref}}\right)$.

The function $B_{ij}\left(\cdot\right)$ has several attractive properties. First, it reduces to the base case whenever $p_{ijt}^{\text{ref}} < p_{ijt}^{\text{gov}}$. This has the intuitive implication that observing a reference price that is higher than the country's own internal benchmark does not affect negotiations. Second, the bargaining weight is inversely proportional to the reference price, meaning that a lower reference price lets the government extract a greater discount. Third, as long as $\mu_j \in (0,1)$ the bargaining weight is also lies on the unit interval, which insures an interior solution for the first-order condition.

The first-order condition of the Nash Bargaining problem with the specified bargaining weights is

$$\begin{aligned}[p]: \quad & \left(\Delta w_{ijt} - p\right)^{-1+b+\mu_j - b_j\mu_j - \frac{\mu_j p_{ijt}^{\text{ref}}}{\Delta w_{ijt}}} \cdot \\ & \left(\left(1 - b_j\right)\left(1 - \mu_j\right)\Delta w_{ijt} + \mu_j p_{ijt}^{\text{ref}} - \Delta w_{ijt}\right) p^{-b_j\left(1-\mu_j\right) + \mu_j\left(1 - \frac{p_{ijt}^{\text{ref}}}{\Delta w_{ijt}}\right)} = 0\end{aligned}$$

and has three roots:

$$\begin{aligned} p_1^\star &= 0 \\ p_2^\star &= \Delta w_{ijt} \\ p_3^\star &= \left(1 - \mu_j\right)\left(1 - b_j\right)\Delta w_{ijt} + \mu_j p_{ijt}^{\text{ref}} \end{aligned}$$

Notice that $p_{ijt}^{\text{ref}} \leq \left(1 - b_j\right)\Delta w_{ijt}$ whenever the reference price binds. Hence, $p_1^\star < p_3^\star < p_2^\star$.

The second-order condition is given by

$$\begin{aligned}SOC: \quad & p^{-1-b\left(1-\mu_j\right)-\mu_j\left(1 - \frac{p_{ijt}^{\text{ref}}}{\Delta w_{ijt}}\right)} \cdot \left(\Delta w_{ijt} - p\right)^{-2+b_j+\mu_j - b_j\mu_j - \frac{\mu_j p_{ijt}^{\text{ref}}}{\Delta w_{ijt}}} \cdot \\ & \left(\Delta w_{ijt}\left(1 - b_j\right)\left(1 - \mu_j\right) + \mu_j p_{ijt}^{\text{ref}}\right)\left(-b_j \Delta w_{ijt}\left(1 - \mu_j\right) + \mu_j\left(p_{ijt}^{\text{ref}} - \Delta w_{ijt}\right)\right)\end{aligned}$$

[66] As a side note, the reference price does not necessarily need to be linked to other prices, but can be anything else that might affect negotiations.

and, for $p \in (0, \Delta w_{ijt})$, is proportional to

$$\begin{aligned} SOC &\propto \left(\Delta w_{ijt}\left(1-b_j\right)\left(1-\mu_j\right)+\mu_j p_{ijt}^{\text{ref}}\right)\left(-b_j \Delta w_{ijt}\left(1-\mu_j\right)+\mu_j\left(p_{ijt}^{\text{ref}}-\Delta w_{ijt}\right)\right) \\ &\propto \left(-b_j \Delta w_{ijt}\left(1-\mu_j\right)+\mu_j\left(p_{ijt}^{\text{ref}}-\Delta w_{ijt}\right)\right)<0 \end{aligned}$$

Hence the objective function is maximized for $p = p_3^\star$. The two other roots of the first-order condition are also roots for the second-order condition, therefore they represent points of inflection.

The final solution to this bargaining problem is therefore made up of two equations:

$$p_{ijt} = \begin{cases} \left(1-b_j\right)\Delta w_{ijt} & \text{if } p_{ijt}^{\text{ref}} \geq \left(1-b_j\right)\Delta w_{ijt} \\ \left(1-\mu_j\right)\left(1-b_j\right)\Delta w_{ijt}+\mu_j p_{ijt}^{\text{ref}} & \text{if } p_{ijt}^{\text{ref}} < \left(1-b_j\right)\Delta w_{ijt} \end{cases}$$

This solution will have the same form of our estimating equation as long as $\left(1-b_j\right)\Delta w_{ijt}$ can be written as a function of the observables we have included in our parametric function for the government price.

A.4 Proof of Theorem 1

To prove the theorem we will rely on the strong law of large numbers applied to non-identical, independent random variables. For this reason it will be useful to define the payoff of firm l as a random variable. We will then show that the set of these random variables (one for each firm l) satisfies the Kolmogorov criterion, which in turn implies the strong law of large numbers.

Let $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}; S_{lt-1}, S_{-lt-1}\right)$ denote the payoff of the firm starting in period t, conditional on the value of state variable in period $t-1$ and on firm l following strategy $\mathcal{A}_{lt}$. Note that by definition, $\mathbb{E}\left[\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}; S_{lt-1}, S_{-lt-1}\right)\right] = \tilde{V}_t\left(\mathcal{A}_{lt}; S_{lt-1}, S_{-lt-1}\right)$.

For the proof of the Theorem we need the following Lemma and Corollary.

Lemma 3. *Let $\Pi\left(S_l, S_{-l}\right)$ be defined as in equation 11. Then $\Pi\left(S_l, S_{-l}\right)$ is finite.*

Proof. We prove that $\Pi_\tau\left(S_l, S_{-l}\right)$ is finite by showing that period profits are bounded. The realization of period profits depends on ξ_{jt}. Define

$$\Pi_\tau\left(S_l, S_{-l}, \xi_{j\tau}\right) = \sum_{i \in \mathcal{I}_l} \sum_{j \in S_{i\tau}} p_{ij\tau}\left(S_{l\tau-1}, S_{-l\tau}, D_{ij\tau}\left(\xi_{j\tau}\right)\right) \cdot D_{ij\tau}\left(S_{-l\tau}, \xi_{j\tau}\right)$$

For any given product i and country j, we can write demand as

$$D_{ij\tau}\left(S_{-l\tau}, \xi_{j\tau}\right) = MS_{j\tau} \cdot \frac{\exp\left(\alpha_{ij} + \beta_i \text{age}_{i\tau} + \eta_i NF_{ij\tau} + \xi_{j\tau}\right)}{1 + \sum_{\ell \in E_{-l\tau}} \exp\left(\alpha_{\ell j} + \beta_\ell \text{age}_{\ell\tau} + \eta_\ell NF_{\ell j\tau} + \xi_{j\tau}\right)}$$

where $MS_{j\tau}$ is the market size in country j in period τ. Hence, $D_{ij\tau}\left(S_{-l\tau}, \xi_{jt}\right) \in \left(0, MS_{j\tau}\right)$.

Price is bounded above by the government price:

$$p_{ij\tau}\left(S_{l\tau-1}, S_{-l\tau}, D_{ij\tau}\left(\xi_{j\tau}\right)\right) \leq p_{ij\tau}^{\text{gov}}\left(S_{l\tau-1}, S_{-l\tau}, D_{ij\tau}\left(\xi_{j\tau}\right)\right)$$

Moreover, using the definition of government price in equation 7 we can rewrite

$$p_{ij\tau}^{\text{gov}}\left(S_{l\tau-1}, S_{-l\tau}, D_{ij\tau}\left(\xi_{j\tau}\right)\right) \cdot D_{ij\tau}\left(\xi_{j\tau}\right) = p_{ij\tau}^{\text{gov}}\left(S_{l\tau-1}, S_{-l\tau}, 1\right) \cdot \left(D_{ij\tau}\left(\xi_{j\tau}\right)\right)^{1+\beta_D}$$

Hence, the period payoff of a single drug in any given country is bounded above by

$$p_{ij\tau}^{\text{gov}}\left(S_{l\tau-1}, S_{-l\tau}, 1\right) \cdot \left(MS_{j\tau}\right)^{1+\beta_D}$$

and bounded below by 0. This implies that the period payoff in any given country and period is finite, and therefore $\Pi_\tau\left(S_l, S_{-l}\right)$ is also finite. ■

Corollary 4. $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}; S_{lt-1}, S_{-lt-1}\right)$ *has finite variance.*

Proof. This lemma follows directly from Lemma 3. $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}; S_{lt-1}, S_{-lt-1}\right)$ is defined as the discounted sum of the expected period payoffs. By Lemma 3 the expected period payoffs are finite. Let

$$\Pi^{UB} = \max_{\left(S_l, S_{-l}\right)} \Pi_\tau\left(S_l, S_{-l}\right)$$

Then, the support of $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}; S_{lt-1}, S_{-lt-1}\right)$ is bounded above by $(T-t) \cdot \Pi^{UB} < \infty$.

Since $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}; S_{lt-1}, S_{-lt-1}\right)$ is also bounded below by 0, it must have finite variance. ■

At this point we are ready to prove Theorem 1.

Proof of Theorem 1. For any given drug i, $V_t\left(S_l^o, S_{-l}^o\right)$ represents a draw from the distribution of $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}^\star; S_{lt-1}, S_{-lt-1}\right)$. By Corollary 4, $\text{Var}\left(\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}^\star; S_{lt-1}, S_{-lt-1}\right)\right) < \infty$. Moreover, the random variables $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}^\star; S_{lt-1}, S_{-lt-1}\right)$ are independently distributed. Thus, our premise satisfies the Kolmogorov criterion, which implies that the strong law of large numbers applies to the sequence of random variables $\tilde{\mathbf{V}}_{lt}\left(\mathcal{A}_{it}^\star; S_{lt-1}, S_{-lt-1}\right)$, and the sample average of the realized payoffs will converge to the average of their expected values. Formally, for any $\varepsilon > 0$, we can find M' such that

$$\frac{1}{M}\sum_{i=1}^{M}\left(V_t\left(S_l^o, S_{-l}^o\right) - \tilde{V}_t\left(\mathcal{A}_{lt}^\star; S_{lt-1}, S_{-lt-1}\right)\right) < \varepsilon$$

for all $M > M'$. This concludes the proof.

■