Information Frictions and the Law of One Price: "When the States and the Kingdom became United"*

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Abstract

How do information frictions distort international trade? This paper exploits a unique historical experiment to estimate the magnitude of these distortions: the establishment of the transatlantic telegraph connection in 1866. I use a newly collected data set based on historical newspaper records that provides daily data on information flows across the Atlantic together with detailed, daily information on prices and trade flows of cotton. Information frictions result in large and volatile deviations from the Law of One Price. What is more, the elimination of information frictions has real effects: Exports respond to information about foreign demand shocks. Average trade flows increase after the telegraph and become more volatile, providing a more efficient response to demand shocks. I build a model of international trade that is consistent with the empirical evidence. In the model, exporters use the latest news about a foreign market to forecast expected selling prices when their exports arrive at the destination. Their forecast error is smaller and less volatile the more recent the available information. I estimate the welfare gains from information transmission through the telegraph to be roughly equivalent to those from abolishing a 6% ad valorem tariff.

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1 Introduction

The "Law of One Price" (LOP) states that the price for identical goods in different locations should not differ by more than their transport costs. However, empirical studies document frequent and large deviations from the LOP (for example, Froot et al. 1995). Understanding the nature of the frictions that inhibit arbitrage across markets is one of the central objectives in international trade. Anderson and van Wincoop (2004) and Head and Mayer (2013) summarize the literature by observing that direct barriers to trade (for example transport costs and trade tariffs) have been found to be of minor importance. Therefore researchers have shifted their attention to more indirect barriers.

This paper focuses on information frictions as a potential explanation for "missing trade" (Trefler 1995) and deviations from the LOP. Information is essential for the efficient functioning of markets, but in reality often limited or costly (Jensen 2007; Stigler 1961). For example, exporting firms have to spend considerable time and money to learn about preferences of consumers in foreign countries and often fail while trying (Albornoz et al. 2010), especially if preferences are changing over time and production and export decisions have to be made in advance (Hummels and Schaur 2010; Evans and Harrigan 2005; Collard-Wexler 2013). The distortions from information frictions are hard to measure, as information flows are usually unobserved and also notoriously responsive to the trading environment.

I use an historical experiment to circumvent these empirical pitfalls: the construction of the transatlantic telegraph connection in the 19th century. The telegraph connection provides an exogenous and large reduction in information frictions. Before 28 July 1866, mail steam ships took between seven and 15 days to transmit information between the United States and Great Britain. The transatlantic cable reduced this information delay to a single day. The timing of the connection was exogenous and not anticipated, because due to a series of technological setbacks over the course of ten years it remained unclear until the very end whether this new technology could ever succeed. It came as a big surprise when it not only worked, but also did so reliably and quickly. This paper is, to my knowledge, the first in the trade literature to observe actual information flows, which are based on news about foreign prices reported in historical newspapers.[1] The information flows are used to measure the impact of information on prices and exports, and to derive micro foundations for exporters' behavior under information frictions, which I use to estimate the welfare effects of deviations from the LOP.

This paper focuses on cotton, the most important traded good between Great Britain and the United States in the mid-19th-century. The dominance of "King Cotton" in trade provides a unique setting to study information frictions, because historical newspapers published detailed and meticulous market reports on cotton. No other prices and trades were reported at a daily frequency. Surprisingly, these rich data have never been systematically digitized. I use market reports from newspapers on both sides of the Atlantic – *The New York Times* and the *Liverpool Mercury* – to construct a new, daily data set that includes cotton prices in New York and Liverpool, export flows and freight cost between the two ports, stock levels in both markets and detailed information flows for the period from one year before until one year after the telegraph connection. The use of this data set has several advantages: First, using export as well as

[1] Previous papers using exogenous variation in information frictions used the presence of mobile phone coverage (Jensen 2007; Aker 2010), internet kiosks (Goyal 2010) or even the transatlantic telegraph connection (Ejrnaes and Persson 2010), but none of these papers observed information flows directly. Observing information ("news") and relating them to prices is much more common in the finance literature (for example Cutler et al. 1989, Koudijs 2013).

price data makes it possible to understand whether information has a real effect on trade, as opposed to only distributing profits across agents. Second, it is possible to study the impact of information frictions on a durable good. Jensen (2007) provides evidence that information reduces spoilage of fish, a highly perishable good, but it is not clear whether the same is true for a storable commodity. Third, shipping time makes imports predetermined, which allows me to identify the supply and demand functions that are needed for the welfare estimation.

Using these detailed data, I am able to document six Reduced Form Findings: (1) The telegraph caused a better adherence to the Law of One Price, as the mean and volatility of the cross-Atlantic price differences fell. (2) Within the pre-telegraph period, faster steam ships had a similar effect and reduced deviations from the Law of One Price. In contrast, within the post-telegraph period, temporary technical failures of the connection led to increased deviations from the Law of One Price. (3) New York prices responded to news from Liverpool. Before the telegraph, only Liverpool prices lagged by ten or more days were relevant in determining New York prices. After the telegraph, the transmission of shocks across prices was reduced to almost real-time.[2] (4) Market participants base their search for arbitrage opportunities on the latest news from Liverpool. (5) Information frictions had real effects on trade flows and are not just a reallocation of profits across market participants, because exports responded to news about Liverpool prices.[3] (6) After the telegraph, exports were on average higher, and more volatile.

In order to establish a causal relationship between these findings and the telegraph, I use two complementary strategies. First, I show the findings are robust to a number of alternative explanations (for example transport cost variations, supply irregularities in the aftermath of the American Civil War, fluctuations within bounds given by trade cost in no trade periods, change in the market structure of merchants, futures or forward trading, and anticipation effects). Second, to rule out any confounding trends that happened over time, I use another source of exogenous variation in information flows *within* the period before the telegraph was established: the irregular passage times of steam ships across the Atlantic, which were driven by weather conditions.

I present a partial equilibrium model of trade under information frictions that provides a micro foundation for the empirical findings and can be used to measure the welfare cost of information frictions. In the model, as in 19th century trade, intermediaries act as arbitrageurs across geographic markets. They buy cotton from suppliers at a centralized exchange in New York and ship it to Liverpool, where they sell it to cotton millers, again at a centralized market place. Aggregate demand from cotton millers follows a stochastic, autocorrelated process. Shipping takes time, so merchants have to make their export decision before they know the realization of the demand shock,[4] and will base it on the prices they *expect* to generate in Liverpool upon delivery of their shipment. Frictions affect the information available to

[2] A related paper by Ejrnaes and Persson (2010) estimates faster shock transmission after the telegraph using weekly wheat prices. However, their price series exhibits a gap of 15 years around the time of the establishment of the telegraph connection, which makes it difficult to distinguish the effect of the telegraph from other confounding trends such as the introduction of futures trading in the 1870s.

[3] To my knowledge, my paper is the first to provide evidence that the telegraph had real effects on exports. An earlier paper by Ejrnaes and Persson (2010) does not observe trade flows, takes real effects as given and estimates the welfare gains from the transatlantic telegraph using estimated demand and supply elasticities from other studies that are based over yearly rather than weekly time horizons.

[4] Aggregate demand shocks cannot be fully insured away, as borrowing cotton from future harvests is impossible. Furthermore, since futures trading had not yet been established, the risk could also not be reallocated across market participants, for example from merchants to "speculators", so merchants had to bear the full market risk of their ex-ante export decision.

merchants when they construct these conditional expectations: If frictions are low, market conditions in Liverpool are observed up to the current date. If frictions are high, lagged information about market conditions in Liverpool have to be used to predict future selling prices. In this model, merchants optimally choose exports taking their information as given.[5]

In the model I study the implications of storability for the operation of markets with information frictions. Storage moderates the impact of information frictions, but it can not eliminate it. The model shows why: For example, consider a positive demand shock in Liverpool. In this case it is not optimal to release enough stock to fully eliminate the effect of the demand shock, because prices in Liverpool need to increase in order to incentivize additional exports to replenish stock next period. But if prices in Liverpool go up, then it is not optimal to release the stock from storage in the current period. In equilibrium it is optimal to distribute the effect of a demand shock over time by increasing exports by a small amount over a long time period, so replenishment of stock takes longer than shipping time.[6]

I calibrate the model to match the historical data *after* the telegraph was introduced. Then I conduct a counterfactual analysis by increasing information frictions to simulate the effect of the telegraph. The resulting predictions are consistent with the reduced form evidence: The volatility of trade flows increases after the telegraph connection, because exports follow expected demand shocks in Liverpool.[7] With better information, expected demand shocks are more volatile. To see this, consider two extremes: Without any information, expected demand is equal to a constant, the unconditional mean, which has zero variance. With perfect foresight, expected demand is actual demand and has the variance of the demand shock. In between, more information increases the variance of expected demand, as expected demand follows actual demand more closely.

Average exports are lower before the telegraph connection, because periods of high demand are systematically underestimated with information frictions. An asymmetry arises from restricting exports to be positive:[8] While periods of low demand are also systematically overestimated with information frictions, in these periods it is never profitable to export. As a result, average exports increase after the telegraph, because in periods of high demand exports are higher. The distorted export flows are reflected in the difference of prices across the Atlantic: After the telegraph, the average and the volatility of the cross-Atlantic price difference falls.

The model provides an analytical solution for the lower bound of the deadweight loss arising from distorted trade flows under information frictions based on Harberger Triangles: The deadweight loss from information frictions is a function of the squared observed price difference between New York and Liverpool (taking into account the shipping lag) as well as the slopes of the demand and supply curves. The reduction in the absolute observed price difference after the construction of the telegraph connection correspond to the abolishment of an ad valorem tariff of around 6%. To measure how this translates into welfare gains, the slopes of the supply and demand functions need to be estimated. This estimation is

[5] This is different from Allen (2014), who models information frictions as a costly search across markets, and merchants optimally decide on how much information to acquire.

[6] Only an infinite amount of stock can fully smooth aggregate demand shocks, a result that is well known in the commodity storage literature, e.g. Williams and Wright (1991); Deaton and Laroque (1996).

[7] To my knowledge, this is the first paper in this literature to model information directly as the way how conditional expectations are formed.

[8] In models without time lag due to shipping, negative exports can be interpreted as imports. However, with time-consuming shipping, negative exports are “imports from a future period”, an unrealistic assumption.

usually difficult due to the simultaneous determination of quantity and prices, and a valid instrument cannot always be found. I propose a novel identification strategy that exploits the fact that exports are predetermined once they arrive in Liverpool, since shipping takes time for transatlantic cotton trade. This breaks the simultaneity problem under the assumption of i.i.d. demand shocks. For the case of autocorrelated demand shocks, I split the unobserved demand shock into a part that is known at the time of exporting and a part that consists of demand innovations that occur while the good is being shipped. The former can be controlled for using the lagged demand function, while the latter part is exogenous to exports.

Combining the estimated parameters with the observed price differences, I estimate the welfare gain from the telegraph to be equal to 8% of the annual export value of American cotton. About 80% of this gain comes from the reduced variance of the cross-Atlantic price difference as cotton is allocated more efficiently across days and weeks within a year, while the rest is due to increased average trade and a reduced average price difference. There was one unusually large demand shock in the pre-telegraph period; excluding it reduces the welfare gains to 6.6%.

What are the implications of this paper for today's modern world, when optical glass fiber cables have long since replaced the copper wires of the telegraph? The historical example of the transatlantic telegraph provides a micro foundation for how exporters (or equivalently producers) use information about demand shocks to forecast demand and decide ex-ante on export (or production) quantities. Exporters and firms still face this problem today, and new emerging technologies such as the real-time analysis of "Big Data" have the potential to provide firms with immediate information about consumer behavior (McAfee and Brynjolfsson 2012). My model can be used to assess the welfare effects from these technologies. The model also illustrates that technologies that reduce the time lag between the production decision and consumption, such as faster transport and better supply chain management, are complementary to information technologies that improve the precision to forecast consumer demand (see also Hummels and Schaur 2010, 2013; Evans and Harrigan 2005; Aizenman 2004; Harrigan 2010). In fact, firms successfully managing their supply chain focus on both of these dimensions (e.g. Ferdows et al. 2004 describes Spanish textile manufacturer Zara).

This paper contributes to an emerging literature on information frictions in trade. Information frictions can take different forms: One branch of the literature focuses on the information frictions in the search and matching process of buyers and sellers across international markets. Rauch and Trindade (2002) show that social networks help to overcome these frictions and increase trade.[9] Other papers focus on the role of information technology to overcome these frictions. For example, Jensen (2007) and Aker (2010) use mobile phone coverage, while Goyal (2010) and Brown and Goolsbee (2002) use internet based price comparisons to explain better equalization of prices across locations. This paper contributes to this strand of the literature in several ways: I observe data on information flows and can relate this to outcomes; I demonstrate that information has real effects by observing exports and not only price differences; I provide a novel identification strategy to estimate the welfare effects; and, compared to Jensen (2007), I show that information frictions are also relevant for the case of a storable good in the context of international trade. Instead of studying how technological innovations can overcome information frictions, Allen (2014) models the optimal behavior of agents when search is costly, and characterizes the resulting trade pattern.

[9] Similarly, Head and Ries (1998); Rauch (1999, 2001).

Another branch of the literature interprets information cost as fixed cost for entering an export market and shows how technology can reduce it (Freund and Weinhold 2004).

These interpretations of information frictions differ from the mechanism in this paper in which I interpret information frictions as a source for making forecast errors when predicting foreign market conditions. This view is related to the finance literature's focus on the effect of news on capital prices (Cutler et al. 1989; Koudijs 2013) and on how information technologies can increase the efficient functioning of capital markets (Portes and Rey 2005, Garbade and Silber 1978[10], Field 1998).

My paper focuses exclusively on the information effects of the telegraph. However, in the long run there might be other, additional effects: For example, Lew and Cater (2006) argue that the telegraph reduced transport costs by increasing the capacity utilization of shipping, which increased trade flows (however, using only data from after 1870). Clark and Feenstra (2003) argue that the telegraph enabled international transfer of other production technologies. These and other additional, long-run effects would increase the welfare gains brought about by the telegraph beyond the ones estimated in this paper.

The structure of the paper is as follows: Section 2 describes the historical setting, and Section 3 describes the collected data set. Section 4 provides reduced form evidence on the effect of the telegraph. Section 5 develops a theoretical model of information frictions and intermediaries in international trade that is consistent with the empirical findings. Section 6 estimates the welfare effects of information frictions. I conclude in Section 7.

2 Historical Setting

Transatlantic cotton trade was the world's most important trade linkage in mid 19th century. King Cotton accounted for more than one half of US exports[11]. One third of Great Britain's imports was in cotton (The Economist 1866).

In the mid 19th century, cotton was grown primarily in the South of the United States (over 55% of world production, Ellison 1886). The second largest producing country was India (29%), followed by Egypt (9%) and Brazil (5%). The dominance of the United States in cotton production is mainly explained by the superior quality of "American cotton", whose longer and stronger fibers were preferred by spinners (Irwin 2003; Henderson 1969). Other advantages of American cotton were lower production cost, lower transport costs, and faster shipping times. Cotton millers needed different machinery for spinning American cotton as compared to Indian cotton, therefore in the short run (e.g. within a year) there was no substitution across different types of cotton.[12]

Cotton millers spun the raw cotton into yarn, which was then woven into fabrics, and sewn into a wide variety of apparel and accessories. The industrial revolution in Great Britain had led to several

[10] Garbade and Silber (1978) show that the transatlantic telegraph connection reduced average spatial price difference and volatility of stock prices.

[11] Bruchey (1967). The term "King Cotton" was coined before the American Civil War and reflected its tremendous importance for 19th century economies (Surdam 1998). This dominance did not stop after the war: American cotton "was not toppled from his throne" and "resumed his former position of power", as Woodman (1968) phrases it.

[12] The sharp reduction of the supply of American cotton during the American Civil War (April 1861 to May 1865) led to increased patenting of machinery suitable for spinning Indian cotton (Hanlon forthcoming). While there was some replacement of American with Indian cotton over the course of the war years, the supply of American cotton during the war remained significant.

inventions in cotton manufacturing such as spinning machines, the spinning jenny, or the spinning frame, making the country the world's leading textile manufacturer: Great Britain produced 85% of worldwide cotton manufactures, and consumed half of the world's cotton production (Ellison 1886). Textile manufacturing was geographically highly concentrated and took mainly place in Lancashire, the hinterland of "Cottonopolis" Manchester.

Virtually all the cotton destined for Great Britain arrived at Liverpool, Lancashire's closest port. On the other side of the Atlantic, New York was the major port exporting to Great Britain: In 1866, 33% of cotton exported to Great Britain arrived from New York, followed by New Orleans (28%) and Mobile (18%).[13]

A thriving mercantile community was responsible for bringing cotton from source to destination.[14] Most merchants were generalists: In the 1860s, only 11-13% specialized in a specific commodity, and 13-14% specialized in certain trade routes (Milne 2000). Merchants were early multinationals. They usually set up a subsidiary in important foreign port cities, mostly run by family members (Ellison 1886; Milne 2000; Chapman 1984). Merchant trade was associated with relatively low entry cost, leading to fierce competition.[15] In fact, historical trade directories reveal that around 100–200 merchants were active in cotton trade between New York and Liverpool in 1866.[16] Merchants were usually not credit constrained, as there was a well developed and functioning banking sector that provided trade financing (Chapman 1984; Brown 1909).

Organized exchanges for cotton existed in both New York and Liverpool. Merchants bought cotton at the New York exchange from cotton farmers, shipped it to Liverpool, and sold it at the Liverpool exchange to cotton millers. Due to the dominance of Great Britain in textile manufacturing, Liverpool essentially constituted the world price for cotton. Cotton futures trading had not yet been established.[17] At each exchange there were also so called "speculators", who bought cotton when they thought prices would go up, stored it, and sold it at a later time. About 80% of the cotton stock was stored in warehouses near the ports by speculators, while spinners held only some widely scattered stocks and stored only as much cotton as they needed to supply their mills in the short run (Milne 2000). Average stock equaled around 70 days of cotton consumption in my data.

When merchants bought their cotton at the New York exchange, they had to forecast demand conditions in Liverpool upon arrival of their shipment. Demand for cotton at the exchange in Liverpool originated from cotton millers, whose customers were domestic but also foreign; mainly from Continental

[13] *Shipping and Commercial List*, printed on 11 October 1866 in *The New York Times*

[14] Direct exporting by cotton farmers consisted of <1% of imports (own estimation based on a sample of the Bills of Entry generously provided by Graeme Milne and data from historical trade directories).

[15] Milne (2000) notes that in the 1850's and 1860's many people entered the trading profession and competition was so large that some traders were willing to work on a no-profit, no-commission basis.

[16] Own calculations based on the Bills of Entry.

[17] There are two requirements to make futures trading across the Atlantic possible: First, transatlantic communication (in order to agree on the futures contract) needs to be faster than the shipment of cotton. This became possible after the telegraph (note that this is not an issue for futures trading within a market, and wheat futures trading within markets had been established by the middle of the 19th century). Second, futures are highly standardized contracts that are based on a clearly defined quality of the underlying good which can be enforced and makes short selling possible. Institutions are needed for objective assessment of the quality of the commodity, for drawing up standardized contracts, and for legal enforcement of the contract. These institutions for cotton were set in place only by the 1870s (Ellison 1886, Hammond 1897). There is some limited evidence of forward trading ("on arrival" business, the selling of a specific cotton lot that the seller possesses for delivery at a later date), but this was done only when a sample of the cotton in question could be inspected (again, because there was not yet a procedure for enforcement of a promised quality of cotton), hence there was no short selling of cotton during this period.

Europe. Market reports in historical newspapers describe how export demand for cotton textiles fluctuated frequently depending on the course of wars and peace negotiations on the continent, which could take quick surprising and unexpected turns. When a country on the continent was in war or in threat of war, its demand for cotton textiles dropped considerably, as the country shifted its funds towards war expenditures such as arms and munition. The Austro-Prussian war and the threat of a Franco-Prussian war fall within my sample period, and historical newspapers frequently identified a change in the war conditions as source for increasing or falling demand from cotton millers. These outlooks often changed within days, e.g. when ceasefire negotiations were started or abandoned.

Information was therefore important at the cotton exchanges. The 19th-century-equivalent to computer screens with price tickers was a large billboard with the latest price information and news, together with circulars that summarized market developments, provided in the *Exchange Newsroom*. The news agency Reuters provided a subscription service with the most important news from all over the world. The compilation of news included the cotton prices from New York and Liverpool and was called *Reuter's Telegram* – even before the transatlantic cable was established, because the news traveled the overland part of the way via telegraph. Contemporaneous newspapers as well as the cotton exchanges were subscribers. Since these news were posted publicly at the exchange, individual merchants could get them at zero cost.

The first successful transatlantic telegraph connection between Great Britain and United States was established on 28 July 1866 and caused a dramatic reduction in the delay in information transmission across the Atlantic. Before the telegraph connection, the only means of communication across the Atlantic was by sending letters and messages (including a print of *Reuter's Telegram*) via steam ships. The so called "mail steam ships" were the fastest ships of those times, specialized in speedy transmission of information items such as letters, newspapers and other documents. There was fierce competition among mail steam ships to win the unofficial "Blue Riband" for record speeds, and by 1866 the fastest ship had crossed the Atlantic in little over eight days (Gibbs 1957). However, these speed records could only be achieved under the best possible weather conditions, which resulted in daily variation in communication times. If conditions were very bad, ships could take as long as three weeks to cross the Atlantic. Important commercial information was transmitted between the commercial hubs in the United States and Great Britain using a combination of existing land based telegraph cables and mail steam ships.[18]

The transatlantic telegraph connection changed communication flows dramatically and immediately. For the first time in history, information traveled faster than goods across the Atlantic (Lew and Cater 2006). From one day to the next, communication between the United States and Great Britain was possible within only one day.[19] There were occasional technical break downs of the telegraph connection, but these were usually repaired within a couple of days and communication was restored.

The timing of the successful telegraph connection was unforeseen and exogenous to economic conditions, because the process of establishing a telegraph connection was characterized by a series of failures and setbacks over the course of around ten years, resulting in little confidence in the feasibility of a

[18]For example, the Liverpool price of cotton was telegraphed from Liverpool via the submarine Ireland/Great Britain connection on to a steam ship passing the coast of Ireland on its way to the United States. As soon as this ship reached the first telegraph post on the US coast, this information was further telegraphed to New York by land line, arriving faster at its destination than the steam ship.

[19]Messages sent from Great Britain to New York passed several telegraph posts along the route, and had to be retransmitted at each of the posts (Lew and Cater 2006). Therefore effective communication time between Liverpool and New York was around one day.

transatlantic telegraph connection. These technical difficulties arose because the transatlantic cable was the first undersea cable connecting two continents, which required it to traverse a greater distance (3,000 km) at a larger submarine depth (3,000 m) than any previous telegraph connection.[20] Consequently, it took five attempts over the course of almost ten years until a lasting connection was established on 28 July 1866.[21] The first attempt in 1857 had resulted in a snapped cable, whose ends were lost in the deep sea. The second attempt in 1858 produced a working connection, however with an extremely slow transmission speed that could not be used for commercial purposes,[22] and the connection lasted only briefly. After three weeks, the insulation of the cable was damaged, and the connection broke down permanently. After this failure, the public lost faith in the telegraph project, and another attempt in the same year was delayed indefinitely. In fact, the faith in the technology had become so poor that the media suspected the working connection had been a "hoax" altogether. The Boston Courier asked: "Was the Atlantic Cable a Humbug?"

Although technical understanding of undersea electrical signal transmission had progressed, the fourth attempt in 1865 resulted again in a broken cable with ends that got lost in the ocean. By 1866 there was little confidence left. Even if the public had expected this fifth attempt to work, the precise timing could not have been foreseen, as weather conditions determined the progress of the cable laying steam ship. Nonetheless, to everybody's surprise and excitement, on 28 July 1866 the first telegraph message, a congratulation message from the Queen of England to the President of the United States, was transmitted. From then on, the telegraph worked surprisingly reliably and fast. The newspapers of the next working day already reported cotton prices from the other side of the Atlantic in their commercial sections. By early September the 1865 cable was fished out of the sea and repaired. The two working transatlantic connections provided reliable and fast transatlantic communication. The transatlantic cable was subsequently referred to as the "Eighth Wonder of the World", reflecting people's amazement about this technological milestone.

Once completed, the contemporary press had high hopes for the impact of the transatlantic telegraph: "The Atlantic Cable will tend to equalize prices and will eliminate from the transactions in bonds, in merchandise and in commodities, an element of uncertainty which has had the effect of [...] seriously damaging the commercial relations between this country and Europe."[23] This paper uses empirical and theoretical evidence to assess whether this prediction came true.

3 Description of Data

For establishing a causal relationship between delayed information, market integration and trade flows data requirements are substantial. First of all, I need price and export data on an *identical* good from at least two different market places. Many observed "violations" of the Law of One Price can be blamed on a lax interpretation of this requirement (Pippenger and Phillips 2008). For example, wheat grown

[20]The previous submarine cables connected Great Britain to Ireland and France; they were much shorter and at a much shallower depth.

[21]Clarke (1992) provides a detailed and entertaining history of the cumbersome way towards a transatlantic connection.

[22]The first message took 17 hours to transmit. Overall, the average transmission speed was 0.1 words per minute. The messages being sent were concerned with how to increase speed and trying to resolve misunderstandings (Clarke 1992).

[23]*New York Evening Post*, 30 July 1866, as cited in Garbade and Silber (1978).

in the United States and wheat grown in Great Britain are not identical, and even different varieties of wheat grown in the United States are not identical. This is a severe restriction on the data, as many local newspapers – the primary source of historical market information – report prices of the local variety and not foreign varieties. Sometimes, for example for wheat, they report prices on foreign varieties, but then not for the same variety over a consistent period of time.[24] Another pitfall when studying the Law of One Price is using retail instead of wholesale prices (Pippenger and Phillips 2008), so it would be ideal to have data on a good that is traded on organized exchanges rather than local farmers' markets.

Second, these prices and export flows should be reported at a daily frequency, to correspond to the actual adjustment horizon of prices to information in the real world. I can then relate price changes on a certain day to news arriving on that day. Using weekly data decreases the power of tests relating prices to news, and observed time periods for consistent varieties (e.g. of wheat) are not long enough to compensate for that (usually after 2–3 years the reported varieties change).

Third, I need data on information flows across the Atlantic. Newspapers report the arrival of some type of news, but often these reports consist of political news and information about stock prices and exchange rates rather than specific commodity markets.

The importance of "King Cotton" in mid-19th-century allowed me to locate newspapers at important ports on either side of the Atlantic that provided detailed, daily information on cotton markets and trade flows. Furthermore, newspapers also reported news about foreign cotton prices, which makes it possible to reconstruct information flows. The richness of cotton data is extraordinary. No other good is consistently reported at such a high frequency in two different countries for the same variety around the mid 19th century.[25]

The resulting data set combines four types of data: market information from the Liverpool exchange, market information from the New York exchange, trade flows between New York and Liverpool, and information flows between New York and Liverpool (and vice versa).

Market information from the Liverpool exchange was reported in the *Liverpool Mercury*, which had a daily section called "Commercial" that provided a detailed market report on cotton. The *Liverpool Mercury* published the daily price for "Middling American", where "middling" indicates a specific quality of American cotton (other qualities that existed, but were not reported consistently, were "fair", "middling fair", "ordinary"). In addition, the *Liverpool Mercury* provided weekly estimates of the stock of American cotton in the warehouses of Liverpool.

Market information from the New York was reported in *The New York Times*, which also published a daily commercial section with detailed information on cotton. Again, the prices reported there are for "middling" American cotton.[26] *The New York Times* reported also a weekly and later bi-weekly estimate of

[24]For example, the Aberdeen Journal reported weekly American winter and American spring prices for the London market, but stopped in July 1866 for no apparent reason, similarly the Economist and The Daily Courier for American and Canadian Red Wheat. In contrast, the Daily Courier started to report Chicago wheat prices only in August 1866. Some newspapers report weekly wheat prices for some American varieties over longer time series, but the prices do not have any variation, which means there was no underlying trade based on the commodity, and prices were just copied forward at the same level for months. Ejrnaes and Persson (2010), who also fail to find grain price data that cover the years around 1866, explain that these years were a period when the export of US grain ceased temporarily.

[25]Wheat data are often used for market integration studies. However, these are available at most at weekly frequency, and qualities of wheat are often not comparable as there exist so many local varieties. Furthermore wheat exports from the United States to Great Britain ceased for several years around 1866 (Ejrnaes and Persson 2010).

[26]Several market reports pointed out that New York used the same classification scheme as Liverpool, as this was the most

the stock of cotton in the warehouses, as well as the daily "receipts" of cotton from the hinterland that arrived at the exchange on that day. I convert the prices at the New York exchange from US dollars to Pound Sterling using daily exchange rates from the historical time series provided by *Global Financial Data*. Since Great Britain had adopted the gold standard in those times. Overall, the fluctuations in exchange rates were very small.[27] Figure 1 illustrates the resulting time series of daily New York and Liverpool cotton prices. The Liverpool price for cotton exceeded the New York price almost always, except for a short period in May 1866. The price series seem to follow each other by and large.

The New York Times also had a separate "Freights" section, which reported daily the bales of cotton that were shipped to Liverpool, as well as the freight cost paid for that shipment.[28]

I can also reconstruct the data on information flows from the historical newspapers, as both newspapers reported the latest mail ship and telegraph arrivals on any given day and printed the main commercial indicators from the other country that these shipped or telegraphed messages included. The relevant sections were headed "Latest and Telegraphic News" and "News from Europe", respectively. These indicators included certain bond and stock prices and the price of cotton. The newspapers also reported the origination date of these business indicators in the other market and the arrival date of the information. The difference in these dates yields the information transmission time across the Atlantic for any given day, which I call "information delay l". The measure of transmission times in my data corresponds to the fastest possible way of communicating between Liverpool and New York, and not to the corresponding steam ship travel times.[29] Sometimes steam ships were overtaken by other, faster steam ships, and its news were "old". In that case the newspapers reported "news were anticipated".

My final database comprises 605 observations, one for every work day between 29 July 1865 and 27 July 1867. The cotton exchange was open every week Monday through Saturday, except on holidays and a few other special occasions (for example, during a "visit of the Prince and Princess of Wales"). I discarded days which were holidays only in the UK or only in the US. The resulting time period comprises one calendar year before (301 work days) and one calendar year after the telegraph connection (304 work days).

The American Civil War between April 1861 and April 1865 severely disrupted cotton exports from the United States, restricting the period of analysis.[30] In addition, historical newspapers did not report cotton prices before that. While it is possible to extend the period of analysis to years after 1867, I kept symmetry between the before and after telegraph periods.

4 Reduced Form Findings

The telegraph changed information frictions dramatically and suddenly: Figure 3 plots the time delay for information from Liverpool reaching New York for each day in the data set. This series shows a sharp

important destination for cotton.

[27] Using the average exchange rate for the whole period as opposed to the daily exchange rates does not affect the results in this paper.

[28] Very few shipments are reported to go to other ports in Europe.

[29] The difference arises because steam ships often got the latest commercial news from England via telegraph while passing the last part of the Irish Coast, and upon arrival on the Newfoundland Coast the news were again transmitted via telegraph to New York, arriving faster than the steam ship.

[30] I discuss potential implications of the American Civil War for my analysis in the empirical section.

drop on 28 July 1866, when the transatlantic telegraph was established. Before that, information from New York was around 10 days old when it reached Liverpool. After the telegraph, information from New York was usually from just the day before. Figure 4 shows the distribution of information lags before and after the telegraph: Before the telegraph, information lags varied between 7 and 15 days, caused by wind conditions that affected the speed of mail steam ships. After the telegraph information lags varied between 1 and 6 days, with lags over 1 day due to temporary technical breakdowns of the connection in the first few months of operation. However, these failures were usually quickly resolved. Table 1 confirms that the drop in average information transmission speed after the establishment of the telegraph connection was statistically significant.

How did this drop in information frictions affect the integration of the Liverpool and New York cotton markets? In this section I carefully develop six Reduced Form Findings that describe what happened to cotton prices and trade.

(1) The telegraph caused a better adherence to the Law of One Price, as the mean and volatility of the price difference fell.

Following the literature on the Law of One Price (LOP), I use the price difference between the two markets as a measure of market integration (Dybvig and Ross 1987; Froot and Rogoff 1995). When markets are perfectly integrated, the price difference should be zero, as any positive price difference has been arbitraged away. The telegraph reduced information frictions which are likely to have constituted a barrier to arbitrage, so we should expect to see the price difference go to zero.[31]

Figure 5 plots the difference between Liverpool and New York cotton prices. The vertical line indicates 28 July 1866, the date when the telegraph connection was established. The change in the behavior of the price difference due to the telegraph is striking: The volatility of the price difference falls sharply, and there are fewer very large and very small values. The average price difference falls as well. Table 1 shows that the average price difference was 2.56 pence/pound in the pre-telegraph period (16% of New York price), and fell to 1.65 pence/pound. This reduction is statistically significant, and corresponds to a fall of 35%. The variance of the price difference falls by even more, by 93%, and the coefficient of variation falls by more than half.[32]

Are these drops causally related to the transatlantic telegraph? The troublesome history of the transatlantic telegraph connection is in favor of this interpretation: The timing of the successful establishment was driven by technical "luck" and the weather, and therefore exogenous to market conditions.[33] The date of the connection could not have been deliberately timed by market participants to coincide with other market events or developments, and anticipation effects can also safely be excluded.[34]

In Table 2 I show that the observed deviations from the LOP are robust to a number of alternative explanations. For example, one alternative hypothesis is that the observed pattern in the price difference

[31] Garbade and Silber (1978) perform this check for stock prices and find that the mean and standard deviation of the price difference falls after the telegraph.

[32] Note that usual explanations for a fall in volatility like exchange rates or sticky prices are not relevant in this setting (Froot et al. 1995).

[33] Weather conditions affected the advancement of the cable laying steam ship, and its ability to locate and repair problems in the cable.

[34] For example, by withholding cotton trade in the weeks before the telegraph until the telegraph gets established.

is caused by variation in transport costs rather than information frictions. In fact, the Law of One Price can only be expected to hold after taking into account transport costs. In empirical trade papers, transport cost is rarely observed and often derived from the price difference. However, in my case *The New York Times* listed the daily freight cost of cotton for shipment from New York to Liverpool. Cotton could be shipped either using the slow sailing ships (taking 1–2 months) or the faster steam ships (taking 2–4 weeks). Figure 5 plots the freight rates for both transport types. Freight costs are lower in the post-telegraph period (see Table 1), but the reduction is very small compared to the drop in the price difference. In columns (2) to (4) of Table 2 I subtract the freight cost – by sail ship, steam ship, or an average of both – from the price difference. However, the fall in freight cost is too small to explain the drop in the price difference after the telegraph connection.[35]

While freight cost accounted for the major part of total transport costs, there were other transport costs such as fire and marine insurance, wharfage, handling at the port etc. Boyle (1934) provides a detailed account of all other transport costs, using historical bookkeeping figures of merchants.[36] The majority of transport costs, 83.1%, are charged based on weight, so they were unit cost.[37] Freight cost are the most important component of unit transport costs, comprising 65% of total transport costs. The remaining unit transport costs are paid for handling at the ports (including bagging, marking, wharfage, cartage, dock dues, weighing, storage at the port). Ad valorem transport costs constitute 16.9% of total transport costs and include fire and marine insurance, Liverpool town dues, and brokerage.[38] Based on these numbers I plot total transport costs in Figure 5. Column (5) in Table 2 shows that even after accounting for total transport costs we observe a large drop in the average price difference.

The Law of One Price does not hold in periods when there is no trade between two markets. In these periods, transport costs are too high, and the price difference will fluctuate freely between the bounds given by the transport costs (called commodity points): $|p_t^{LIV} - p_t^{NY}| < \tau$. If there were some periods before the telegraph when the price difference was not large enough to induce trade, this might explain why I observe high volatility before the telegraph. In fact, in my data exports occurred in every week in the sample except for a period of about four weeks during May 1866 (before the telegraph), when the threat of a war between Austria and Prussia depressed demand for cotton in Liverpool and lowered prices so much that exporting became unprofitable.[39] Column (6) of Table 2 excludes this period, but the results are again robust to this check.

Another concern might be that my observations begin in July 1865, three months after the end of the American Civil War. During the Civil War, the Northern states (the "Union") established a blockade of Southern ports ("Confederates") that stopped cotton exports almost completely. After the war, cotton production and trade were immediately taken up again: Woodman (1968) describes how the reopening of trade with the South immediately induced a "scramble among cotton merchants". However, it took

[35] Lew and Cater (2006) argue that the telegraph reduced freight rates, so the observed drop in freight cost could also be attributed to the telegraph. However, at least in the short run this is not the major contribution of the telegraph.

[36] See online appendix for a detailed breakdown of total transport costs.

[37] This is also why I do not use a log specification of the Law of One Price, this is only helpful with multiplicative transport costs.

[38] No export tariff or import tariff was imposed during the period under consideration.

[39] Only if the price difference becomes "negative enough" to cover transport costs, should we expect cotton re-exports to New York (and for those periods the LOP should hold again in absolute values). However, the price difference was not large enough to cover transport cost of re-export. Also, there is no evidence in historical newspapers that cotton was re-exported during this period.

five to 10 years before the pre-war levels of cotton production were restored. Reasons for the slow recovery included the destruction of cotton during the war, the substitution of cotton production for food production, bankruptcy of many cotton planters, and the abolishment of slavery (Woodman 1968). Cotton production fell by three quarters from four to one million bales during the years of the Civil War, and reached 2 million bales, half of the pre-war production, again in the first harvest after the Civil War (cotton year 1865/1866).[40] The return to pre-war levels took until 1870.[41] The first year of observations in my data coincides with the first year of cotton production after the Civil War. It is possible that cotton supply is still disrupted during that year. If there are no barriers to arbitrage, a larger volatility of production affects only price levels and not the price difference, as shocks are transmitted to the other country. To account for the possibility that there were some barriers to arbitrage, and to investigate whether supply irregularities therefore had an effect on the adherence to the LOP I use data on the quantity of cotton that arrived at the New York cotton exchange from the cotton farms on any given day, the so called "cotton receipts". Figure 6 illustrates the time pattern of cotton supply over the course of a harvest year. The cotton year starts in September, when the new harvest starts to come in. The winter months October to February are the months with the largest receipts of cotton, whereas the summer months June to August are the months with the smallest receipts. However, due to the time consuming cotton picking process and the long distances from the cotton fields in the interior to New York, the supply of cotton is positive on every single day in the sample. The visual evidence in Figure 6 does not suggest that the variation in cotton supplies differs very much before and after the telegraph.[42] Column (7) of Table 2 controls for cotton supply, but again this is unable to explain the fall in the price difference after the telegraph.

Column (8) of Table 2 controls for shipping time by using the price in Liverpool at the time of the arrival of the shipment instead of the contemporaneous Liverpool price to construct the time difference. I use the steam ship travel times (around 10 days) for all shipments, because even if the cotton shipment was transported by the slower sail ship, samples of the cotton lot were usually shipped by a faster mail steam ship. The lot was then sold on the spot market in Liverpool upon inspection of the sample, while still on sea, which is called "forward trading" (Milne 2000). Again, correction for shipping time does not affect the results. Finally, column (9) shows the difference in log prices instead of price levels. Again, this does not affect the findings.

Contemporary observers describe that the transatlantic telegraph contributed to the development of futures trading in cotton across the Atlantic, as for the first time information traveled faster than goods (Hammond 1897; Ellison 1886). If the change in the pattern of the price difference is due to the introduction of futures trading, it is indirectly caused by the telegraph (rather than directly by changing information frictions). However, the development of futures trading was not immediate. The necessary institutions for futures trading were set in place only by the 1870s. Forward trading, as described earlier, was still limited and based on a sample of cotton made available for inspection. The telegraph did not change the speed at which cotton samples could be shipped, as they had to be transported physically, it

[40]The detailed time series is provided in the online appendix.

[41]During the Civil War American cotton was only partly substituted with Indian and Egyptian cotton. Irwin (2003) argues that the low supply elasticity of other countries was due to the fact that planters expected the war to be temporary and were therefore unwilling to make long-term investments in cotton cultivation. The advantages of American cotton (longer fibers, lower production and transport costs) still prevailed after the Civil War, explaining the return of American cotton after the war.

[42]There is just one outlier in the pre telegraph area that is due to the closure of the New York cotton exchange over two Christmas holidays, when arrivals had piled up.

only changed the speed of the transmission of *information*. An introduction of futures or forward trading due to the telegraph can therefore not explain the observed findings.

Finally, it is interesting to check whether the observed change in the price difference is the result of a change in the markups of merchants, maybe because of increased competition among merchants. The Bills of Trade record the shipment of every merchant arriving in Liverpool and allow for the computation of a Herfindahl Index. The Bills of Trade have been digitized for 3 months (February, June, October) of four years around the time of the introduction of the telegraph (1855, 1863, 1866, and 1870).[43] Figure 2 shows the development of the Herfindahl Index for cotton merchants, separately for shipments from the US and shipments from Egypt and the East Indies. In 1863 the American Civil War disrupted cotton trade, only few cotton shipments came from the US to Great Britain, and the Herfindahl Index shows high concentration. However, after the Civil War the Herfindahl Index immediately returned to a very small number (around 0.05), indicating a very competitive market structure, and stayed like this until the 1870s. The market structure of merchants shipping from the East has a similar Herfindahl Index, though without the disruption of the Civil War. Overall, the analysis shows that merchants were very competitive, and this was unchanged by the telegraph. Therefore it does not seem plausible that a change in markups could be responsible for the observed change in the price difference after the telegraph.

In Table 3 I conduct the same robustness checks for the variance of the price difference. I use the squared deviation of the price difference from the mean before and after the telegraph, respectively, as dependent variable and regress them on a dummy that indicates the period after the telegraph.[44] Column (1) shows that the variance of the price difference falls significantly after the telegraph; the drop is around 90%. Excluding no trade periods explains one third of the drop, but the remaining fall is large and robust to all other robustness checks.

(2) Faster steam ships had a similar effect to that of the telegraph in the pre-telegraph period: They also reduced deviations from the Law of One Price. Similarly, in the post-telegraph period, temporary technical failures of the connection led to deviations from the Law of One Price.

The analysis so far has only used the one-time change in information frictions brought about by the telegraph to explain the deviations from the Law of One Price. However, the data provide much richer exogenous daily variation in information delays. In the pre-telegraph period, weather and wind accelerated or delayed mail steam ships, and in the post-telegraph period a few occasional technical breakdowns stopped the transatlantic communication temporarily. Figure 3 illustrates this variation. It shows how old the latest information from Liverpool is on a given day in New York (or in other words, how many days the last passage across the Atlantic took). Table 4 relates this variation in information delay to the variance of the price difference. Column (1) shows that deviations from the Law of One Price dropped significantly after the telegraph was established. Column (2) uses the exogenous variation in information delays. For each additional day that information takes to get from Liverpool to New York, the deviation from the Law of One Price increases by 24%. Column (3) only uses the within period variation by conditioning on the telegraph dummy, with similar results.

[43] The digitized sample of the Bills of Trade has been generously provided by Graeme Milne for the years 1855, 1863 and 1870. I digitized the three months for 1866 to check for any change around the introduction of the telegraph.

[44] In the online appendix I normalize the dependent variable by the average price difference before and after the telegraph connection. The findings are unchanged.

(3) New York prices respond to news from Liverpool.

The response of New York to news from Liverpool is best illustrated by an example that explains the large upwards spike in the price difference in Figure 5. Figure 7 zooms into this period and explains what happened in detail: On 29 and 30 September 1865 the market in Liverpool experienced increased demand for cotton from cotton spinners and millers. The *Liverpool Mercury* of that day writes that the market was "stimulated by the increasing firmness of the Manchester [yarn] market". At the same time a mistake in the estimation of cotton stock in Lancashire was detected, leading to a downwards correction. As a result, the Liverpool cotton price jumped up by 20% within two days, from 20 to 24 pence/pound. However, due to the delayed information transmission by mail ships, market participants in New York were not aware of this demand shock. The next steam ship, arriving in New York on 2 October, still carried the outdated price information from 23 September, a week before the demand shock. Only on 9 October the news of the demand shock arrived, causing a jump in the New York cotton price, as export demand increased. *The New York Times* reports an "unusually large quantity" of exports "under the favorable advices from England" on that day. This example also illustrates that information has real effects on export flows, and is not just a redistribution of profits across market participants.

To study more systematically whether news from Liverpool drive New York prices, column (1) in Table 5 starts with a parsimonious specification and regresses the New York price on a given day on the latest known price from Liverpool using only data from the pre-telegraph period. This latest known Liverpool price was transmitted by steam ship, on average 10 days old and is denoted as "steam shipped" Liverpool price in the table. In order to account for autocorrelation in prices, I implement maximum likelihood estimation including three lags of the dependent variable.

The coefficient on this latest known Liverpool price is positive, indicating a systematic reaction of the New York price to news from Liverpool. Since prices are serially correlated, it is possible that this coefficient picks up something other than the "news" about Liverpool. Therefore column (2) includes a "counterfactual" price, the Liverpool price from the previous day that was unknown to New Yorkers before the telegraph connection was established. Reassuringly, this unknown price has no impact on New York prices, while the coefficient on the steam-shipped price remains the same. Columns (3) and (4) perform the corresponding analysis for the period after the telegraph was established. The "telegraphed" Liverpool price, on average one day old, now is the major driving force of the New York price, and the outdated price information that the steam ship would have brought, had the telegraph not been in place, does not matter anymore.

This parsimonious specification is the most efficient regression to demonstrate the changing relevance of Liverpool's prices on the New York market, as it uses the timing of information arrivals explicitly. As an alternative specification I run a vector autoregression using both prices, separately before and after the telegraph. Figure 8 shows that before the telegraph, only lags on the Liverpool price larger than 10 days are relevant for the New York price. After the telegraph, lags between 1-5 days are most relevant, in line with the distribution of information lags in Figure 4. Interestingly, the lags around 14 days are significant after the telegraph, because steam ships were used to ship longer market reports such as circulars.[45]

[45]Full VAR estimation results are available in the online appendix.

(4) Market participants base their search for arbitrage opportunities on the latest news from Liverpool.

Figure 9 plots the difference of the New York price and the latest known Liverpool price (with the light gray line repeating the contemporaneous price difference from Figure 5). Interestingly, most of the largest price deviations disappear (except for the period of no trade in July 1865, which is shaded in the figure). Column (10) of Table 2 shows that the average price difference to the latest known Liverpool price falls after the telegraph connection were established. In contrast, column (10) of Table 3 shows that the variance of the price difference using the latest known Liverpool price shows only a small drop. This evidence indicates that market participants seem to arbitrage away the price difference between the current New York and the latest known, delayed Liverpool price, probably using it as a proxy for the price they expect for their exports.

(5) Exports respond to news about Liverpool prices.

The analysis so far has only considered prices as outcomes. But does information have real effects? In order for prices to equalize across marketplaces, goods must be moved. The detailed daily data on export flows can be used to understand whether the observed changes in the price difference are driven by equivalent changes in exports.

Table 6 uses a similar specification as Table 5 with exports as outcome and tests whether news about Liverpool prices affects exports. Column (1) uses only data from the year before the telegraph was in place and shows that news about an increase in the Liverpool price leads to increased exports in the pre-telegraph period. This news was brought by steam ship and was on average 10 days old. Column (2) conducts a placebo test and includes the unknown Liverpool price from the previous day, called "telegraphed" price. This counterfactual "news" does not have a significant impact on exports, as we would expect. Column (3) adds a linear time trend to control for a potential build up of supply after the American Civil War. Columns (4) to (6) conduct a similar analysis for the period after the telegraph. The news via telegraph about the Liverpool market again has a positive effect on exports, but the coefficient is not significant due to large standard errors. Column (5) includes the Liverpool price that market participants would have known had there been no telegraph. The news from the steam ship does not have a positive impact on exports, but the results are only suggestive as standard errors are large.[46] Column (6) allows for a linear time trend; the results remain unchanged. While the coefficient on the known Liverpool price is smaller, equality of the coefficients before and after the telegraph cannot be rejected.

[46]One might be concerned that the regression in Table 6 is invalid because prices are endogenously determined. However, the regression uses lagged Liverpool prices which are predetermined as far as current exports are concerned. However, if the underlying supply shocks are autocorrelated, the coefficients on Liverpool prices might be biased downwards because current supply shocks – which both increase current exports and are negatively correlated (via lagged supply shocks) with past Liverpool prices – are omitted. This downward bias might be stronger for the more recent "telegraphed" Liverpool price, explaining why the coefficient on the "telegraphed" Liverpool price in column (2) is smaller than the coefficient on the "steam shipped" Liverpool price. In columns (3) and (6) I include a linear time trend to control for buildup of cotton supply after the American Civil War. Coefficients in column (3) are larger than in column (2), indicating that a small downward bias was corrected. In any case, a larger downward bias for the telegraphed Liverpool price cannot explain why the relationship between the coefficients after the telegraph switches around, as the downward bias should still be stronger for the telegraphed than for the steam shipped Liverpool price.

(6) After the telegraph, exports are on average higher, and more volatile.

Row (1) in Table 7 shows that average daily exports from New York to Liverpool increased substantially after the telegraph cable was established: Average daily exports amount to 460 bales before the telegraph and increase by 170 bales after the telegraph, which is an increase of 37%. Row (1) in Table 8 shows that the variance of exports increases by even more. The increase in the variance after the telegraph of 0.33 represents an increase of 114% compared to the variance of 0.29 before the telegraph.

The remaining columns in Table 7 perform similar robustness checks for average exports to the ones implemented for the price difference. The increase in average exports after the telegraph connection cannot be explained by a fall in transport costs or fewer no trade periods. Can it be explained by an expanding cotton production after the American Civil War? Column (7) includes the cotton receipts at the New York exchange from the fields as a control, which does not affect the result.[47] In case this variable is not picking up the full increase in production column (8) adds harvest year dummies to control for a potential gradual increase in cotton production across years. Again, the increase in exports after the telegraph connection remains significant.

The remaining columns in Table 8 conduct the same robustness checks for the variance of exports. Again, the increase in variance after the successful telegraph connection cannot be explained by these alternative hypotheses.

The following section provides an intuitive model about how information influences the behavior of exporters which yields predictions that are consistent with the presented Reduced Form Findings.

5 Model of Information Frictions in International Trade

I add information frictions to a basic two-country trade partial equilibrium model with storage (based on Coleman 2009; Williams and Wright 1991) by changing the information set of market participants. The model mimics cotton trade in the 19th century. Cotton is elastically supplied by producers in country *NY* as given by the linear aggregate inverse (net) supply function $p^S(q_t) = \bar{a}_S + b_S q_t$.[48] Intermediaries buy cotton in *NY* and ship it to another country *LIV*, where they sell it to consumers. Shipping takes one period and costs τ per unit shipped.[49] Merchants are perfectly competitive and risk neutral.[50] Aggregate consumer demand in *LIV* is stochastic and given by a linear inverse demand function with stochastic, autocorrelated intercept: $p_t^D(q_t) = a_{Dt} - b_D q_t$.[51] In *LIV* there are storers who can buy cotton, store it for

[47]Cotton production can only be adjusted with a time lag, that is when a new harvest cycle starts. The increase in cotton exports is instead reflected in a reduction of New York stock levels. Only in the following harvest season can production adjust to increased exports, and this is what can be observed in the data.

[48]Later I allow for stochastic supply. This adds another layer of information frictions that affect the information storers in *LIV* have about supply shocks in *NY*, and another source of welfare gain from the telegraph. Furthermore, supply is elastic because it is net of domestic demand, not because cotton suppliers can adjust their supply at such a short (daily or weekly) time horizon.

[49]Transport costs of cotton consisted predominantly of unit cost (based on weight not value), as mentioned earlier. The numerical predictions are robust to allowing for ad valorem instead of unit trade cost. The predictions of the model are also true with immediate shipment, $k = 0$. However, it is not very realistic to add information frictions to such a model, as it would assume that goods can be shipped instantaneously, while information cannot.

[50]Assuming risk averse instead of risk neutral merchants would only reinforce the predictions of the model. With better information, the "risk" of exporting is reduced as the variance of expected profits falls, which will lead to an increase in average exports.

[51]The demand function is similar to Evans and Harrigan (2005), however, with an autocorrelated demand process. For welfare estimation it is not necessary to assume a specific time process for the demand shocks. In the numerical solution I assume

one period, and sell it in the next period.[52] Storage costs θ per unit stored for one time period.[53] Storers are perfectly competitive and risk neutral.

Maximization problem of merchants

The representative merchant i chooses exports x_{it} that maximize expected profits conditional on his information set I_t^M:

$$\max_{x_{it}\geqslant 0} E\left[\left(p_{t+1}^{LIV} - p_t^{NY} - \tau\right) x_{it}\middle| I_t^M\right]$$

As merchants are price takers, this maximization problem is linear with first order conditions $E\left[p_{t+1}^{LIV} \mid I_t^M\right] - p_t^{NY} - \tau = 0$ if $x_{it} > 0$ and $E\left[p_{t+1}^{LIV} \mid I_t^M\right] - p_t^{NY} - \tau < 0$ if $x_{it} = 0$. Total exports are $x_t = \sum_i x_{it}$. The no arbitrage condition at the industry level is[54]

$$E\left[p_{t+1}^{LIV} \mid I_t^M\right] \leqslant p_t^{NY} + \tau \quad \perp \quad x_t \geqslant 0 \tag{5.1}$$

Merchants choose exports that equalize the difference between expected prices in *LIV* in the next period and current prices in *NY*, subject to transport cost, except if expected prices in *LIV* are too low and it is not optimal to export at all. In either case, expected profits of merchants are zero, but realized profits may be positive or negative.

Maximization problem of storers

The maximization problem of the representative storer j is similar, but now arbitrage is across time instead of space. Each storer chooses stock s_{jt} in order to maximize expected profits conditional on his information set I_t^S:

$$\max_{s_{jt}\geqslant 0} E\left[\left(p_{t+1}^{LIV} - p_t^{LIV} - \theta\right) s_{jt}\middle| I_t^S\right]$$

Storers are also price takers, and first order conditions are:[55] $E\left[p_{t+1}^{LIV} \mid I_t^S\right] - p_t^{LIV} - \theta = 0$ if $s_{jt} > 0$ and $E\left[p_{t+1}^{LIV} \mid I_t^S\right] - p_t^{LIV} - \theta < 0$ if $s_{jt} = 0$. Total storage is $s_t = \sum_j s_{jt}$. The no arbitrage condition at the storage

demand shocks follow a AR(1) process around mean $\bar{a}_D$.

[52] Holding the good for more than one period is equivalent to storers selling their stored quantity and buying it immediately back, to store it for another period and so on. In the estimation of the welfare effect I will also allow for a storage industry in *NY*.

[53] Storage cost of cotton was also based on weight rather than value. However, the behavior of storage does not depend on whether one assumes additive or proportional storage cost (Williams and Wright 1991).

[54] The sign $\perp$ denotes a mixed complementarity problem which is equivalent to two conditions: either $E\left[p_{t+1}^{LIV} \mid I_t^M\right] - p_t^{NY} = \tau$ and $x_t \geqslant 0$; or $E\left[p_{t+1}^{LIV} \mid I_t^M\right] - p_t^{NY} \leqslant \tau$ and $x_t = 0$. If $E\left[p_{t+1}^{LIV} \mid I_t^M\right] - p_t^{NY} > \tau$ merchants would like to export an infinite amount which is not an equilibrium. If $E\left[p_{t+1}^{LIV} \mid I_t^M\right] - p_t^{NY} = \tau$, individual merchants are indifferent about how much to export and in equilibrium aggregate exports are determined by market clearing conditions.

[55] A detailed discussion of the storer's maximization problem and solution is provided by Williams and Wright (1991).

industry level is[56]

$$E\left[p_{t+1}^{LIV} \mid I_t^S\right] \leqslant p_t^{LIV} + \theta \quad \perp \quad s_t \geqslant 0 \tag{5.2}$$

Storers increase storage until expected prices in *LIV* in the next period are equal to today's prices in *LIV* plus storage cost, except if expected prices are too low to make profits from storage. The expected profits of storers is zero.

Information frictions

Decisions about storage and exports are based on expected prices in *LIV* conditional on the information set of agents.[57] I consider three different information regimes:

- *Delayed information (DI).* Assume merchants are based in *NY* where they make their exporting decision by buying from suppliers.[58] In the delayed information regime they possess information about all shocks in *LIV* up to period *t-1* and have to forecast *LIV* prices in period *t+1* when their exports can be sold in *LIV*. Similarly, storers are based in *LIV* where they make their storage decision. They have information about demand shocks in *LIV* up to period *t* when forecasting *LIV* prices for period *t+1* (and information about *NY* up to the previous period *t-1,* but this is only relevant with supply shocks).

- *Instantaneous information (II).* All market participants are informed about demand shocks in *LIV* up to period *t* when forecasting expected prices in period *t+1*.

- *Perfect foresight (PF).* Merchants and storers can foresee demand shocks in future periods.

The *delayed information regime* mimics the information frictions that were in place before the telegraph was established. One period can be interpreted as around 10 days, the time it takes for a steam ship to ship cotton (or at least samples of a cotton bale) and information. Merchants have only delayed information from Liverpool which is on average 10 days old at the time when they make their exporting decision. At the time of exporting they need to forecast Liverpool prices 10 days into the future, which is when their shipment can be sold in Liverpool. On the other hand, storers in Liverpool know current market conditions in Liverpool when they make their storage decision. How much they know about New York is only relevant if supply is stochastic, a case which will be addressed later.

The *instantaneous information regime* mimics the situation after the transatlantic telegraph was established. Merchants have roughly real-time information from Liverpool when making their exporting

[56] A particular feature of commodity storage models is that it is not possible for the market as a whole to store negative quantities. While each individual stock holder can in principle store a "negative amount" (that is, selling "short") by borrowing the commodity from other storers, selling it on the spot market, buying the same amount of stock in the next period and returning it to the lender, this is not true for the market as a whole (Williams and Wright 1991).

[57] Ex-ante decisions of exporters are also modeled in Hummels and Schaur (2010, 2013). A reduction of shipping time in these papers is equivalent to a reduction in the forecast horizon. A reduction of shipping time is complementary to a reduction in information frictions as modeled in this paper in the case with supply shocks, and equivalent to a reduction in information delay without supply shocks.

[58] In practice, merchants had representatives (usually family members) in both New York and Liverpool. If a merchant would have been based in Liverpool, he would have had to travel to New York (or communicate with New York) in order to export cotton from Liverpool to New York, and therefore have the same information as a merchant already based in New York. Therefore we can assume that merchants are based in New York only.

decision. Due to the time delay in shipping, they still have to forecast Liverpool prices 10 days into the future.

The *perfect foresight regime* is unrealistic, but serves as a useful benchmark for the welfare analysis, as it maximizes aggregate welfare. In the following I refer to the *DI* regime as having "information frictions". The introduction of the telegraph can be interpreted as a reduction in (or almost elimination of) information frictions.

Equilibrium conditions

Equilibrium is given by the FOC of merchants (5.1) and storers (5.2) and market clearing conditions in both countries. In *NY* elastic supply meets the export demand of merchants:

$$p_t^{NY} = \bar{a}_S + b_S x_t \tag{5.3}$$

In *LIV* supply is given by imports (equal to the amount of goods exported from *NY* in the previous period) plus storage from the previous period s_{t-1}, while demand is by consumers and storers:

$$p_t^{LIV} = a_{Dt} - b_D \left(x_{t-1} + s_{t-1} - s_t\right) \tag{5.4}$$

Analytical expressions

The first order condition for merchants (5.1) together with market clearing conditions (5.3) and (5.4) yields the following analytical expression for exports:

$$x_t \quad = \quad \max\left\{\frac{E\left[a_{D,t+1} + b_D s_{t+1} - b_D s_t \middle| I_t^M\right] - \bar{a}_S - \tau}{b_S + b_D}, 0\right\} \tag{5.5}$$

Exports depend on expected demand shocks and expected change of stock in period *t+1*, when the shipment arrives in *LIV*, conditional on the information of merchants. Storage is endogenous and different in each information regime. We need to solve for the storage functions under each information regime in order to see how a change in information regime affects trade. Since the no arbitrage conditions of merchants and storers are mixed complementarity problems and therefore non-linear, it is not possible to derive an analytical solution for the storage function (Deaton and Laroque 1996; Williams and Wright 1991), instead we need numerical solutions.

The price difference adjusted for shipping time is given by

$$\text{pdiff}_{t+1} := p_{t+1}^{LIV} - p_t^{NY} - \tau = \begin{cases} a_{D,t+1} - E\left[a_{D,t+1} \middle| I_t^M\right] + b_D\left(\triangle s_{t+1} - E\left[\triangle s_{t+1} \middle| I_t^M\right]\right) & \text{if } x_t > 0 \\ a_{D,t+1} + b_D\left(s_{t+1} - s_t\right) - a_S - \tau & \text{if } x_t = 0 \end{cases} \tag{5.6}$$

Whenever exports are positive, the price difference is equal to the forecast error made by forecasting demand and change in storage. On average, this is zero independent of the information regime. However, if exports are zero, prices are determined by supply and demand in each market, which (because of storage) depends on the information regime. Also the incidence of zero exports depends on the information regime.

No storage

The special case without storage (for example, when storage is prohibitively costly, or when the good is highly perishable) can be analytically solved and provides some intuition about the impact of information frictions.

Lemma. *Suppose storage is not possible and demand follows a stationary AR(1) process around mean $\bar{a}_D$ with innovations $\epsilon_t \sim N\left(0, \sigma_D^2\right)$. Suppose $\frac{\bar{a}_D - \bar{a}_S - \tau}{b_S + b_D} > 0$, which means that there are positive exports at the average demand shock. Then, when switching from delayed to instantaneous information:*[59]

1. *Average exports increase:*
$$E\left[x_t^{DI}\right] \leqslant E\left[x_t^{II}\right]$$

2. *Assume exports are always positive.*[60] *Then, the variance of exports increases:*
$$Var\left[x_t^{DI}\right] \leqslant Var\left[x_t^{II}\right]$$

3. *The average price difference falls:*
$$E\left[\text{pdiff}_t^{DI}\right] \geqslant E\left[\text{pdiff}_t^{II}\right]$$

4. *The variance of the price difference falls:*
$$Var\left[\text{pdiff}_t^{DI}\right] \geqslant Var\left[\text{pdiff}_t^{II}\right]$$

Proof. In appendix. □

For the intuition of this result consider equation 5.5 (ignoring storage). Exports are a function of expected demand shocks. The distribution of expected demand depends on the information regime, as illustrated in Figure 10. With more information, the variance of expected demand is higher. Consider two extremes: Without any information, expected demand is a constant with zero variance. With perfect foresight, expected demand is actual demand and has the variance of the demand shock. In between, more information leads to a higher variance in expected demand, and therefore exports (point 2 of the Lemma).

Since exports cannot be negative an asymmetry arises which affects average exports. With less information merchants underestimate high demand shocks and overestimate low demand shocks. When they underestimate states of high demand, they export less in the *DI* compared to the *II* regime. When they overestimate low demand there is no difference across information regimes as with low demand it is not profitable to export at all. Average exports are higher in the *II* regime, because periods of high demand lead to appropriately high exports (point 1 of the Lemma).

[59] In case of a white noise process, information is irrelevant, and the predictions hold with equality.

[60] Numerically I can show that this prediction also holds without assuming positive exports.

Merchants equalize expected prices across countries, and the resulting price difference equals the forecast error of merchants. If merchants were not making any forecast error, which would happen under the *PF* regime, the lagged spatial price difference pdiff_{t+1} would be zero, and the no arbitrage condition would hold ex post. With information frictions the no arbitrage condition holds only in conditional expectations, and merchants make a forecast error depending on the information they have. The volatility of forecast errors falls when more information becomes available (a result well established in the finance literature), which explains why the price difference falls when switching from the *DI* to the *II* regime (point 4 of the Lemma).[61]

Point 3 of the Lemma states that the average price difference falls after switching to the *II* regime. This holds for the same reason that average exports increase: Under the *DI* regime positive demand shocks are systematically underestimated, leading to high prices in Liverpool and a large price difference as exports are restricted. These positive price differences are eliminated under the *II* regime as exports are high enough. Note that this does not mean that merchants were making profits under the *DI* regime, as high ex-post profits in cases when demand was higher than expected were offset by equivalently high losses in cases when demand was smaller than expected. Neither does this mean that merchants make losses under the *II* regime, as they avoid negative price differences by not exporting at all (when they would have exported under the *DI* regime).

Storage

Storage reduces the effect of information frictions on prices: When merchants overestimate demand and ship too much, part of the imports can be stored for the future and consumed in cases when merchants underestimate demand and ship too little. As a result, in a model with storage, prices will fluctuate less than in a model without storage. If the storage technology was "perfect", information would not matter. However, "perfect" storage requires an infinite amount of stock, because it needs to be able to insure against the small but positive probability that long periods of particularly high demand will run down inventories (Townsend 1977). As Williams and Wright (1991, p. 159) state: "Storage is asymmetric - able to support a glut but not alleviate every shortage".[62] With finite stocks, information frictions still matter, but the quantitative impact of information frictions will be smaller compared to the no storage case. How much information matters depends on storage cost and inventory limitations, and is an empirical question which I will address for the case of cotton further below.

The commodity storage literature has provided numerical solution approaches for instantaneous information regimes (Coleman 2009; Williams and Wright 1991; Deaton and Laroque 1996). This paper adds information frictions in the form of delayed information to the model to obtain predictions for the effect of the telegraph. The central task of the problem is the numerical solution of the control functions for storage and exports as a function of state variables.

[61] Point 4 of the Lemma also holds if the demand shock is a random walk.

[62] It is interesting to note that a problem with speculators engaging in futures trading leads to the same market-level equilibrium conditions as a model with explicit modeling of storage, as long as at least some speculators have rational expectations and are risk neutral. If there were a mix of stock holders and speculators, and stock holders were not risk neutral, as long as some speculators are risk neutral and have rational expectations, these equilibrium conditions for the market still hold. Expected prices in the equilibrium conditions 5.1 and 5.2 are equivalent to the prices of futures. While futures trading might lead to a different allocation of risk across market participants (from risk averse to less risk averse or risk neutral), the aggregate properties of a model with storage and one with futures trading are the same.

In the instantaneous information case there are two state variables: "Stock on hand" m_t is the stock available at the beginning of each period, which consists of the sum of quantities stored in the previous period and arriving imports (equal to *NY*'s exports from the previous period), $m_t = s_{t-1} + x_{t-1}$; and the current realization of the demand shock, a_{Dt}. I approximate $x_t(a_{Dt}, m_t)$ and $s_t(a_{Dt}, m_t)$ simultaneously over a grid of state variables by checking the first order condition of merchants and storers for a guess for the control functions, and by updating the guess in every step. The approximation algorithm has converged when all the first order conditions in all grid points are satisfied up to a certain precision.

The delayed information regime requires a different set up of the problem, as storage and exports depend on different state variables because expectations are formed differently. In the delayed information regime merchants know only lagged demand shocks, so exports are a function of lagged demand and contemporaneous stock on hand (because this itself is a function of lagged storage and exports): $x_t(a_{D,t-1}, m_t)$. On the other hand, storage in Liverpool continues to be a function of contemporaneous demand, $s_t(a_{Dt}, m_t)$.

In the instantaneous information regime I approximate two control functions as a function of two state vectors: a_{Dt} and m_t. In the delayed information regime the number of state variables increases to three: a_{Dt}, $a_{D,t-1}$ and m_t. For a more realistic model that matches *NY* prices more closely, I extend the model to allow for stochastic supply shocks. Then the export decision also depends on the supply shocks: $x_t(a_{St}, a_{Dt}, m_t)$ in the *II* regime, and $x_t(a_{St}, a_{D,t-1}, m_t)$ in the *DI* regime. Storage in *LIV* depends on the information about supply shocks: $s_t(a_{St}, a_{Dt}, m_t)$ in the *II* regime, and $s_t(a_{S,t-1}, a_{Dt}, m_t)$ in the *DI* regime. In total the number of state variables in the *DI* regime increases to five: a_{Dt}, $a_{D,t-1}$, a_{St}, $a_{S,t-1}$ and m_t.[63]

Characterization of the solution with storage

Because of the non-negativity constraint, the storage function is zero until a "kink line" given by a combination of critical values for demand shocks and stock on hand. Beyond the kink line storage is increasing in stock on hand and decreasing in demand shocks. The slope of the storage function (the propensity to store) is everywhere less than one, and the behavior is non-linear.[64] The export function has a similar non-linear behavior because it depends on storage: It is also zero up to a certain "kink line", beyond which it is increasing in demand shocks and decreasing in stock on hand. With supply shocks, the non-linear behavior extends to a third dimension: Exports and storage increase in the supply shock, again after a certain "kink plane". The behavior of the control functions with delayed information is qualitatively similar as a function of lagged instead of contemporaneous shocks. However, the slopes are different as they reflect different expectation forming about the future.

To understand how storage changes the model, consider impulse response functions for a demand shock. Figure 11 starts out with the no storage case. Under delayed information (before the telegraph, green line), exporters in *NY* don't know about the demand shock and therefore there is no immediate response in exports. Prices in *LIV* increase while prices in *NY* stay the same, increasing the contemporaneous price difference. The difference between current price in *LIV* and lagged price in *NY* also increases

[63]As the number of calculations needed increase exponentially with the number of state variables (Williams and Wright 1991, p. 57), it is not possible to numerically solve a daily representation of the model. In this case the information lag would be around 10 days and I would need to keep track of 20 state variables (for a two-way trip; per market), which is computationally not feasible.

[64]Further discussion is provided in Williams and Wright (1991).

as prices in *LIV* go up. In the next period exporters learn about the demand shocks and adjust exports upwards which increases prices in *NY*, but it takes another period for exports to arrive in *LIV*. Only 2 periods after the shock the difference between the *LIV* price and the lagged *NY* price is driven down to transport cost.

Under instantaneous information (after the telegraph, blue line), adjustment is faster: Exports increase immediately, driving up the price in *NY*. There is still a spike in the contemporaneous price difference because of the shipping delay. The difference between the *LIV* price and the lagged *NY* price increases for one period, as exporters make unexpected profits, but adjusts in the next period as exporters arbitrage away these profits.

Figure 12 shows the impulse response functions allowing for almost costless storage. With instantaneous information, as the demand shock hits, stock is released from storage to satisfy the demand as exports cannot adjust immediately because of the shipping delay. This reduces the impact of the demand shock quantitatively, but with finite storage it is not optimal to release enough stock to smooth prices in LIV perfectly. Why is it not an equilibrium to run down stock today when a positive demand shock hits, as exports could replenish the stock the following period? To see this, assume a positive demand shock (for simplicity, assume it is uncorrelated across time) hits Liverpool. Because of the shipping lag, exports cannot adjust immediately to satisfy the demand shock. Assume that storage is run down instead in order to satisfy the additional demand and there is no price increase in Liverpool. If exports increase (in order to replenish the stock next period), prices in New York will go up because the supply curve is upwards sloping. Exporting more will only be optimal for merchants if expected prices in Liverpool next period increase. But in this case, the no arbitrage condition for storers is violated. Storers will find it optimal to store more, so they will not smooth prices in Liverpool perfectly. Only with an infinite stock in Liverpool exports are not needed in order to replenish the stock, and prices in Liverpool can be fully smoothed. With a finite stock, stock will be released to reduce the demand shock such that there is still an incentive for exports in this and the following periods to slowly replenish stock over time.

Because storage does not fully smooth prices, the difference between the delayed and instantaneous information regime in terms of trade and price differences is qualitatively similar to the case without storage, although magnitudes are smaller. For example, exports follow expected demand plus expected change in storage. With better information, the variance of expected demand is larger. If the storage function would not change with better information, the variance of expected change in storage would be larger for the same reason. With better information the storage function becomes more volatile, reinforcing the effect. Expected demand and expected change in storage are negatively correlated, and more so with better information. However, this effect is dominated by the increase in the variance of expected demand and expected change in storage, leading to a higher variance in exports.

Estimation of parameters

The model depends on ten parameters that need to be estimated: mean $\bar{a}_D$, variance σ_D^2 and autocorrelation ρ_D of the stochastic demand process; mean $\bar{a}_S$, variance σ_S^2 and autocorrelation ρ_S of the stochastic supply process; the slope of the demand function b_D, the slope of the supply function b_S; transport cost τ and storage cost θ.

First I focus on estimating the slopes of the demand and supply curves. These parameters will also be used for the estimation of welfare further below. Given these slopes, the underlying demand and supply shock processes can be backed out using data on prices, trade and storage. The mean, variance and autocorrelation coefficient of the shock processes are then estimates of the corresponding parameters. The remaining parameters of the model are transport cost, which is based on the data on freight cost as described earlier, and storage cost of cotton, which are obtained from the historical accounting statements of a merchant in Boyle (1934).

Estimation of the demand curve

Estimating the supply and demand functions is usually tricky, as quantities and prices are determined contemporaneously and finding a valid instrument is difficult. I propose a new identification strategy: Since shipping takes time, exports are predetermined once they arrive in Liverpool, breaking the simultaneity problem for the case of i.i.d. shocks. For the case of autocorrelated shocks and positive storage I use the model to control appropriately for the endogenous part of the shocks, yielding identified regression equations.

The demand curve in Liverpool on a specific day $t+k$, where k indicates the time (in days) a shipment takes to get from New York to Liverpool, is determined by the realization of the demand shock on that day, $a_{D,t+k}$, the imports arriving in Liverpool on that day which are equivalent to exports from New York k days earlier, x_t, and net take-up or release of stock from storage on that day, $\triangle s_{t+k}$:

$$p_{t+k}^{LIV} = a_{D,t+k} - b_D \left(x_t - \triangle s_{t+k} \right)$$

Daily prices in Liverpool as well as daily imports can be observed. The main identification problem is the unobserved demand shock that is positively correlated with change in stock and exports. Note that exports are actually a function of lagged demand shocks, which are correlated with demand shocks at t+k only via the autocorrelation of the demand shock. My identification strategy will exploit this fact by modeling this dependence explicitly.

Assuming demand follows an AR(1) process around mean $\bar{a}_D$, $a_{Dt} - \bar{a}_D = \rho(a_{D,t-1} - \bar{a}_D) + \epsilon_t$ with $\epsilon_t \sim N\left(0, \sigma^2\right)$, we can express the demand shock in period $t+k$ in terms of the demand shock in period $t-l$, where l denotes the information delay between Liverpool and New York, and the sum of demand innovations between $t-l$ and $t+k$:

$$a_{D,t+k} = (1-\rho^{k+l})\bar{a}_D + \rho^{k+k} a_{D,t-l} + \sum_{i=0}^{k+l-1} \rho^i \epsilon_{D,t+k-i}$$

We can use the lagged demand function to control for the lagged demand shock, as $p_{t-l}^{LIV} = a_{D,t-l} - b_D \left(x_{t-k-l} - \triangle s_{t-l}^{LIV} \right)$. This results in an equation where all of the regressors except change in stock $\triangle s_{t+k}^{LIV}$ are uncorrelated with the unobserved demand shocks. However, current imports x_t can be used as an instrument for $x_t - \triangle s_{t+k}^{LIV}$. Data on stock in Liverpool is available only at weekly intervals, so I distribute the the weekly change equally across the day of the week, which introduces a measurement error, which is also addressed by the instrumental variables strategy. Table 9 shows the results of estimating the following equation:

$$p_{t+k}^{LIV} = \beta_0 + \beta_1 \left(x_t - \triangle s_{t+k}^{LIV} \right) + \beta_2 p_{t-l}^{LIV} + \beta_3 \left(x_{t-k-l} - \triangle s_{t-l}^{LIV} \right) + \sum_{i=0}^{k+l-1} \rho^i \epsilon_{D,t+k-i}$$

Column (1) shows the OLS results and column (2) shows the IV results. The first stage is strong, as indicated by the F-statistics of 125. The instrument addresses both the correlation of stock changes and demand shocks in the error as well as measurement error in the stock changes. The latter seems to dominate as the OLS estimate is biased towards zero. The sign of the lagged Liverpool price is positive and less than 1 as expected. According to the model $\beta_1\beta_2 - \beta_3 = 0$, which cannot be rejected. Column (3) uses a more efficient estimation method by imposing this restriction, applying nonlinear least squares estimation. Column (4) implements the instrumental variable estimation using a control function approach, which again corrects for the measurement error in stock changes. In column (5) and (6) the non-linear IV specification are estimated separately for the period before and after telegraph, but this makes little difference to the estimates.

The last row in Table 9 computes the demand elasticity at mean values of prices and quantities. The resulting demand elasticities seem rather high when comparing them to estimates of demand elasticity of cotton in 19th century in the literature (Irwin 2003), which range between 1.7 and 2.3. Note however, that the estimates in the literature are based on yearly instead of daily data. Daily demand elasticities are much higher because they take into account the willingness of consumers (or cotton millers) to substitute consumption across time, which is easier across short periods compared to long periods. To empirically validate this argument, I run the demand estimation on different aggregation periods of my data. Aggregating the data reduces the demand elasticity strongly. For example, for 3-monthly data the demand elasticity is as low as -6 (see online appendix for details on aggregation patterns).

Estimation of the supply curve

The slope of the supply function is estimated in a similar way. In order to better match the data, the supply function given by equation 5.3 is extended by allowing both for supply shocks and for storage in New York:

$$p_t^{NY} = b_S \left(\triangle s_t^{NY} + x_t \right) + a_{St}$$

Again, the problems in estimating this equation are two-fold: First, New York stock data is only available at weekly intervals, so I distribute the weekly change equally across days, introducing measurement error. Second, exports and stock changes are correlated with current supply shocks. I add a dummy for the harvest year and include a quadratic in the day of the harvest year to model supply fluctuations, but as this cannot fully address endogeneity concerns, I pursue an instrumental variables approach for the estimation. In column (2) of Table 10 I use known prices from Liverpool p_{t-l}^{LIV} as instrument for the sum of export and stock changes, $\triangle s_t^{NY} + x_t$. The first stage is strong, as information about the latest prices from Liverpool influence exports and stock changes positively. If supply shocks are correlated, however, lagged Liverpool prices might reflect lagged supply shocks, and not be exogenous. Therefore I use implied demand shocks $a_{D,t-l} = p_{t-l}^{LIV} + b_D \left(x_{t-k-l} - \triangle s_{t-l}^{LIV} \right)$ using the estimated slope of the demand function from the previous section as instrument for exports and stock changes in column (3). In column (4) lagged Liverpool prices are again used as instrument, but here $x_{t-k-l} - \triangle s_{t-l}^{LIV}$ is added as a control, leaving only demand variations in the instrument.

The estimates yield a estimate of around 1.7 in all specifications after eliminating measurement error in the OLS estimation, also when I estimate the equation separately for the periods before and after the telegraph. Again, the equivalent supply elasticities are larger than the estimates based on yearly data mentioned in the literature which are between 1 and 2 (see Irwin 2003 for a review), as is expected when considering the substitution of supply across short time periods. When repeating the analysis of the supply estimation across data with an increasing aggregation horizon, the supply elasticity falls considerably and converges towards the estimates in the literature (see online appendix for details).

Delayed information as counterfactual

With the estimates of the slopes of the demand and supply functions I reconstruct the demand and supply processes from the data of the post-telegraph period and estimate the remaining supply and demand parameters. Table 11 gives an overview of all estimated parameters. The estimated AR(1) processes fit the data quite well, as it is not possible to reject white noise of the innovations in the supply and demand process (using a Portmanteau white noise test). The demand shocks are more autocorrelated than the supply shocks, while the supply shocks have a higher volatility than the demand shocks.

Together with an estimate for transport and storage cost I numerically solve for both the instantaneous (to which the parameters are calibrated) and delayed information regime (counterfactual analysis).

I use the counterfactual delayed information regime on the calibrated model to predict the effect of the telegraph on the data. Table 12 shows that the qualitative predictions of the model match the empirical section: The model predicts a fall in the average price difference between Liverpool and New York, and an increase in average exports. Similarly, the model predicts a fall in the variance of the price difference, and an increase in the variance of exports. This finding is robust to wide ranges of the parameter space. For example, the different columns vary storage cost from zero to prohibitively high storage cost. The panels below use the lower and upper 95% confidence interval for estimates of the slope of the supply and the demand functions.

Quantitatively, the model predicts the largest change for the fall in the standard deviation of the price difference, which is also the largest drop in the data. My preferred estimates with storage cost as given by Boyle (1934) are shaded in gray and predict a drop in the standard deviation of the price difference of around 40-60%, which is close to the drop in the data of 70%. The second largest change in the model is the increase in the standard deviation of exports, which again is also the second largest change in the data. Here, however, the model cannot fully predict the change. A possible explanation could be that storage cost are underestimated. Since storage and exports are complements in balancing out information frictions, higher storage costs imply that exports react more strongly. However, even with prohibitively high storage cost the model can only predict a increase in the standard deviation of exports of 6%.

The changes in the average price difference and in average exports are also larger in the data than in the model. A potential reason for this could be that in reality merchants were risk averse rather than risk neutral. An extension of the model with risk averse merchants is likely to predict larger changes in average exports and price difference, because the higher uncertainty in the delayed information regime should lead risk averse merchants to export less due to higher uncertainty.

6 Welfare Gains from the Telegraph

What are the welfare gains from reduced information frictions? This section shows that a lower bound of the deadweight loss (DWL) from information frictions is a function of only three parameters: the squared observed price difference across markets, and the slopes of the supply and demand functions presented in Section 5. This is an analytical result and does not rely on the numerical solutions obtained in the previous section, nor on assuming a specific time series process for the demand and supply shocks.

For intuition, consider a specific export transaction. The welfare arising from this transaction is the sum of immediate producer surplus, immediate consumer surplus, immediate merchant surplus, as well as the present value of future social surplus from the part of exports that is stored and not immediately consumed.[65] The red area in Figure 13 corresponds to the immediate producer surplus of exports. If a part of exports is stored, immediate consumer surplus corresponds to the blue area. The net present value of the social surplus from the quantity stored is given by the green area between the market demand curve and the price. The social surplus from storage is the sum of positive future consumer and negative future producer surplus, the expected surplus of storers is zero.

Note that Figure 13 ignores stock stored from the previous period (current stock on hand is equal to current imports only). This is because I measure welfare for each specific export transaction at the time when exporting occurs with the net present value (NPV) of social surplus. The stock in storage has been exported in previous periods and its welfare has already been accounted for by the net social surplus from storage then.

Figure 13 shows the perfect foresight equilibrium (*PF*), which I use as reference case to measure deadweight loss. In *PF*, merchants choose exports at the intersection of the lagged supply curve and the market demand curve, the price in Liverpool is equal to the lagged price in New York, and merchants make no profits.

In contrast, Figure 14 illustrates the case when there are information frictions[66] and merchants overestimate demand in Liverpool. In this case, exports are larger than *PF* exports, and prices are not equalized across markets. Merchants make a loss, and some of the inefficiently high export is stored for the future. However, optimal storage is not large enough to raise the Liverpool price to the level of the undistorted price in Figure 13. The size of the deadweight loss is given by the orange area. An equivalent deadweight loss triangle arises from an underestimation of demand.

Theorem. *The deadweight loss from information frictions for a specific export transaction $x_{t-1} > 0$ is bounded from below by $\underline{DWL}$:*

$$DWL\,(x_{t-1}) \geqslant \frac{\left(p_t^{LIV} - p_{t-1}^{NY}\right)^2}{2(b_D + b_S)} =: \underline{DWL}$$

[65]This discussion of welfare follows Williams and Wright (1991, p. 350). The current consumer surplus understates total consumer surplus, because positive stock raises current prices for consumers and reduces current consumption. However, eventually the stock is going to be consumed, and in that period prices for consumers will fall and consumption will increase. Similarly, current producer surplus overstates total producer surplus, because positive stock increases the current selling prices for producers and increases current production, whereas upon consumption it reduces prices and production.

[66]The term "information frictions" in this paper is used both for delayed information (equivalent to before the telegraph) and instantaneous information (equivalent to after the telegraph), but in the former case information frictions are larger. In order to measure deadweight loss from reduced information frictions, I compare the deadweight loss of having delayed information (as opposed to having perfect foresight) to the deadweight loss of having instantaneous information (as opposed to having perfect foresight).

That is, the spatial price difference $p_t^{LIV} - p_{t-1}^{NY}$, the slope of the demand curve b_D and the slope of the supply curve b_S are sufficient statistics for the lower bound of the deadweight loss from information frictions.

Proof. In appendix. □

It is not surprising that the welfare loss from information frictions is a function of the price difference. The Law of One Price states that any spatial price difference gets arbitraged away if agents are fully informed (due to the shipping lag, full information in this case would require foresight of market conditions upon arrival of shipments). The literature on the LOP therefore interprets observed price difference as a measure of the underlying market frictions and its associated deadweight loss. The theorem makes the relationship between deviations from the Law of One Price and welfare explicit.

I estimate the daily deadweight loss from information frictions by extending the formula above to a daily setting, while allowing for transport cost, $\frac{\left(p_t^{LIV} - p_{t-k}^{NY} - \tau_{t-k}\right)^2}{2(b_D + b_S)}$, where k denotes the actual shipping time in days, and the demand and supply elasticities are estimated based on daily data.

Figure 15 illustrates the observed price distortion $p_t^{LIV} - p_{t-k}^{NY} - \tau_{t-k}$. The spatial price difference falls dramatically after the telegraph gets introduced. The fall in the price distortion after the telegraph is equivalent on average to a roughly 6% ad valorem tariff.[67] The largest price distortions during the pre-telegraph period were equivalent up to a 50% ad valorem tariff. For comparison, note that the average US tariff that was abolished during NAFTA in 1994 was 3%, while the highest abolished tariff was 12%, for textile trading with Mexico (Caliendo and Parro 2012).

In order to translate these price distortions into welfare effects, I use estimates of the slope of the supply and demand curves as described previously. Combining the estimates for the slope of the supply and the demand function with the observed price difference, Table 13 reports the welfare loss due to delayed or instantaneous information as compared to perfect foresight. The difference in welfare loss can be attributed to the telegraph, and corresponds to 8% of the annual export value of American cotton from New York to Great Britain in the data which is around 10 million pounds in 1866.[68] I construct a confidence interval for the welfare loss based on the confidence intervals for the estimates of the slopes of the supply and demand functions. The confidence interval of the welfare gains from the telegraph ranges from 5% to 22%.

The 8% welfare gain can be divided into a 6.7% efficiency gain from reducing the variance of the price difference (due to within year reallocation), and 1.7% of efficiency gain from reducing the average price difference (due to increased average trade). If I exclude the anecdotal episode with the especially large demand shock described earlier from the welfare calculation, the efficiency gain is 6.6%.

This is somewhat larger than previous estimates in Ejrnaes and Persson (2010) who estimate the welfare gains from the transatlantic telegraph to be around 0.5-3% of trade value. Their estimate is based on weekly data which averages out some of the variation in the data. Furthermore, they rely on demand and supply elasticities from the literature which are estimated over yearly and not weekly time horizons because they do not observe trade flows to estimate the reaction of exports directly.

[67] The equivalent ad valorem tariff of the distortion is calculated for each day as the absolute price difference minus transport cost in percent of the lagged New York price p_{t-k}^{NY}. The average tariff equivalent of 6% is equal to the difference in the average of this measure between the pre- and post-telegraph period. Days with no trade are excluded from this calculation.

[68] Note that the total exports from the United States to Europe is around three times as much. In reality, the welfare benefit of the transatlantic telegraph applies to all of transatlantic cotton trade (and potentially other goods as well).

How is the welfare gain distributed across producers, consumers and merchants? The surplus of merchants is zero under all information regimes, as unexpected gains and losses average out. The distribution of the additional surplus across consumers and producers depends on the slopes of the supply and demand functions. Since the estimated slope of the supply function is larger than the estimated slope of the demand function, producers gain more from the telegraph than consumers.

7 Conclusions

This paper exploits a clean historical experiment to understand the impact of information frictions on the Law Of Once Price and trade: the establishment of the transatlantic telegraph cable, connecting the United States and Great Britain in 1866. This episode provides a unique setting for studying information frictions. On one hand, it provides a dramatic and exogenous reduction in information frictions, as the information transmission times between these two countries fell unexpectedly from around ten days to only one day. On the other hand, a rich data set based on historical newspapers includes high-frequency data not only on prices, but also on trade and information flows.

This setting allows me to contribute to the literature in several ways. First of all, it is possible to *identify* and *measure* the impact of information, which is usually endogenous, complex and unobserved. This paper shows that a fall in information frictions causes better adherence to the Law of One Price. The average price difference between New York and Liverpool falls by 35%, and its standard deviation falls by 73%. This reduction in price distortions is equivalent to abolishing a roughly 6% ad valorem trade tariff.

Second, this paper shows that information frictions have real effects and are not just a reallocation of profits across market participants, because exports *respond* to information. After the telegraph, average trade flows increase and become more volatile. The model explains that this is the case because exports follow expected demand, conditional on information. More information makes expected demand more volatile, which explains why we observe more volatile exports after the telegraph. However, this effect is asymmetric, as there is a cutoff when it is not profitable to export at all. More information increases average exports because there are more incidents with high expected demand and therefore large exports.

The third contribution of the paper lies in estimating the welfare gains from reducing information frictions. Better information helps merchants to better forecast future demand, resulting in a more efficient alignment of supply and demand across countries. This is reflected in the better adherence to the Law of One Price. In order to translate the reduced price distortions into welfare, one needs to estimate supply and demand elasticities, which is usually difficult due to simultaneously determined prices and quantities. This paper uses a novel identification strategy that exploits the fact that exports are predetermined once they arrive in Liverpool (since shipping takes time) and controls adequately for the possibility of storage. Overall, the welfare gains from the telegraph are estimated to be around 8% of the annual export value.

The historical example of the transatlantic telegraph can be generalized to any setting in which exporters or producers have to make ex-ante decisions about production and/or exporting and face uncertainty about demand. In this setting, information technologies can improve the ability of firms to forecast demand. The forecast error of exporters becomes smaller and less volatile the better the available information is. This leads firms to decide on production or export quantities that are better matched with consumer demand, and therefore reduces deadweight loss. The model also points out that the benefits from information technology are larger, the larger the underlying volatility of demand, and the larger storage cost.

Identifying and reacting to demand changes is still critical in today's world. Demand fluctuates more rapidly and widely than it used to as new trends appear and disseminate via social media networks. Global supply chains and outsourced stages of production make it more difficult to communicate demand changes across the different firms involved in the production process. Newly emerging information technologies such as the real-time analysis of "Big Data" have the potential to impact trade in a similar, but probably even more drastic, way as the telegraph. The smart phone era has generated an enormous amount of real-time data on consumer behavior. The technologies for analyzing these large amounts of data are still being developed, but they have the potential to provide firms with much more accurate demand forecasts. The model in this paper can be used in this context. For example, it would predict that industries with a more volatile demand or higher storage cost should adopt and develop these technologies earlier than other industries. The model can also be used to assess the welfare effects of these technologies, and compare them with their cost.

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Appendix

A Proofs

Proof of Lemma

Exports are given by equation 5.5. Assume first that exports are always positive, so exports x_t are equal to uncensored exports $\tilde{x}_t = \frac{E[a_{D,t+1}]-\bar{a}_S-\tau}{b_S+b_D}$ (the assumption of point 2 of the Lemma). Exports in both regimes differ only in the way how expectations about future demand shocks are formed. In the instantaneous information regime the information set I_{II} includes everything up to period t, while the information set in the delayed information regime I_{DI} includes only information up to period $t-1$: $I_{DI} \subset I_{II}$. By the Law of Iterated Expectations, average exports are the same in both information regimes:

$$
\begin{aligned}
E\left[x_t^{DI}\right] &= E\left[\frac{E_{t-1}\left[a_{D,t+1}\right]-\bar{a}_S-\tau}{b_S+b_D}\right] = \frac{\bar{a}_D-\bar{a}_S-\tau}{b_S+b_D} \\
&= E\left[\frac{E_t\left[a_{D,t+1}\right]-\bar{a}_S-\tau}{b_S+b_D}\right] = E\left[x_t^{II}\right]
\end{aligned}
$$

The variance of exports is a function of the variance of expected demand shocks, conditional on the respective information set:

$$
Var\left[x_t^{DI}\right] = \frac{Var\left[E_{t-1}\left[a_{D,t+1}\right]\right]}{\left(b_S+b_D\right)^2}
$$

$$
Var\left[x_t^{II}\right] = \frac{Var\left[E_t\left[a_{D,t+1}\right]\right]}{\left(b_S+b_D\right)^2}
$$

Applying Jensen's inequality to the function $E_t\left[a_{D,t+1}\right]$, conditional on information in *t-1*:

$$
\left(E_{t-1}\left[E_t\left[a_{D,t+1}\right]\right]\right)^2 \leqslant E_{t-1}\left[\left(E_t\left[a_{D,t+1}\right]\right)^2\right]
$$

Taking the unconditional expectation:

$$
E\left[\left(E_{t-1}\left[a_{D,t+1}\right]\right)^2\right] \leqslant E\left[\left(E_t\left[a_{D,t+1}\right]\right)^2\right]
$$

The variance of the conditional expectations are:

$$
\begin{aligned}
Var\left[E_{t-1}\left[a_{D,t+1}\right]\right] &= E\left[\left(E_{t-1}\left[a_{D,t+1}\right]\right)^2\right] - \left(E\left[E_{t-1}\left[a_{D,t+1}\right]\right]\right)^2 \\
&= E\left[\left(E_{t-1}\left[a_{D,t+1}\right]\right)^2\right] - \left(E\left[a_{D,t+1}\right]\right)^2
\end{aligned}
$$

$$
\begin{aligned}
Var\left[E_t\left[a_{D,t+1}\right]\right] &= E\left[\left(E_t\left[a_{D,t+1}\right]\right)^2\right] - \left(E\left[E_t\left[a_{D,t+1}\right]\right]\right)^2 \\
&= E\left[\left(E_t\left[a_{D,t+1}\right]\right)^2\right] - \left(E\left[a_{D,t+1}\right]\right)^2
\end{aligned}
$$

Combining the last three equations shows that the variance of a conditional expected value increases if the information set increases: $Var\left[E_{t-1}\left[a_{D,t+1}\right]\right] \leqslant Var\left[E_t\left[a_{D,t+1}\right]\right]$. It follows directly that $Var\left[x_t^{DI}\right] \leqslant Var\left[x_t^{II}\right]$, which proves the second point of the Lemma. Note that this part of the proof is more general as it does not assume any specific process or distributional assumptions about the demand shocks.

Now assume that exports have to be positive. From the above analysis we know that uncensored exports have the same mean in both information regimes, but the variance of uncensored exports is smaller in the delayed information regime: $\tilde{x}_t^{II} \sim N\left(\frac{\bar{a}_D-\bar{a}_S-\tau}{b_S+b_D}, \frac{Var(E_t[a_{Dt}])}{(b_S+b_D)^2}\right)$ and $\tilde{x}_t^{DI} \sim N\left(\frac{\bar{a}_D-\bar{a}_S-\tau}{b_S+b_D}, \frac{Var(E_{t-1}[a_{Dt}])}{(b_S+b_D)^2}\right)$. Denoting $\tilde{\mu} := E\left[\tilde{x}_t\right]$ and $\tilde{\sigma}^2 := Var\left[\tilde{x}_t\right]$, average exports are given by $E\left[x_t\right] = \Phi\left(\frac{\tilde{\mu}}{\tilde{\sigma}}\right)\tilde{\mu} + \tilde{\sigma}\phi\left(\frac{\tilde{\mu}}{\tilde{\sigma}}\right)$ (Greene 2003). A change from DI to II increases the variance of censored exports $\tilde{\sigma}^2$, and this increases average exports, which proves the first point of the Lemma:

$$
\begin{aligned}
\frac{\partial E\left[x_t\right]}{\partial \tilde{\sigma}} &= \phi\left(\frac{\tilde{\mu}}{\tilde{\sigma}}\right) \cdot \left(-\frac{\tilde{\mu}}{\tilde{\sigma}^2}\right) \cdot \tilde{\mu} + \phi\left(\frac{\tilde{\mu}}{\tilde{\sigma}}\right) + \tilde{\sigma}\phi'\left(\frac{\tilde{\mu}}{\tilde{\sigma}}\right)\left(-\frac{\tilde{\mu}}{\tilde{\sigma}^2}\right) \\
&= \phi\left(\frac{\tilde{\mu}}{\tilde{\sigma}}\right) > 0
\end{aligned}
$$

The average price difference $\text{pdiff}_{t+1} = p_{t+1}^{LIV} - p_t^{NY} - \tau$ is (plugging in the solution for exports):

$$
\begin{aligned}
E\left[\text{pdiff}_{t+1}\right] &= E\left[a_{D,t+1} - E_{t-1}\left[a_{D,t+1}\right] \middle| x_t > 0\right] Prob\left[x_t > 0\right] \\
&\quad + E\left[a_{D,t+1} - \bar{a}_S - \tau \middle| x_t = 0\right] Prob\left[x_t = 0\right]
\end{aligned}
$$

The first term is zero under both information regimes. For the second term consider that

$$
\begin{aligned}
E\left[a_{D,t+1} - \bar{a}_S - \tau \middle| x_t^{II} = 0\right] &= \bar{a}_D + \rho\sigma\frac{\phi\left(\frac{\bar{a}_S+\tau-\bar{a}_D}{\rho\sigma}\right)}{1-\Phi\left(\frac{\bar{a}_S+\tau-\bar{a}_D}{\rho\sigma}\right)} - \bar{a}_S - \tau > \\
\bar{a}_D + \rho^2\sigma\frac{\phi\left(\frac{\bar{a}_S+\tau-\bar{a}_D}{\rho^2\sigma}\right)}{1-\Phi\left(\frac{\bar{a}_S+\tau-\bar{a}_D}{\rho^2\sigma}\right)} - \bar{a}_S - \tau &= E\left[a_{D,t+1} - \bar{a}_S - \tau \middle| x_t^{DI} = 0\right]
\end{aligned}
$$

and

$$
\begin{aligned}
Prob\left[x_t^{II} = 0\right] &= Prob\left[a_{Dt} < \frac{\bar{a}_S + \tau - \bar{a}_D}{\rho} + \bar{a}_D\right] > \\
Prob\left[a_{D,t-1} < \frac{\bar{a}_S + \tau - \bar{a}_D}{\rho^2} + \bar{a}_D\right] &= Prob\left[x_t^{DI} = 0\right]
\end{aligned}
$$

From this, the third part of the proof follows:

$$
E\left[\text{pdiff}_{t+1}^{DI}\right] \geqslant E\left[\text{pdiff}_{t+1}^{II}\right]
$$

From the variance decomposition property it follows that the variance of the price difference is equal to the variance of the forecast error when making predictions about the demand shock:

$$\begin{aligned} Var\left[\text{pdiff}_{t+1}\right] &= E\left[V\left[a_{D,t+1} - E\left[a_{D,t+1}\right] \mid x_t > 0\right]\right] \\ &\quad + Var\left[E\left[a_{D,t+1} - E\left[a_{D,t+1}\right] \mid x_t > 0\right]\right] \\ &= V\left[a_{D,t+1} - E\left[a_{D,t+1}\right] \mid x_t > 0\right] \end{aligned}$$

Under the *II* regime,

$$\begin{aligned} V\left[a_{D,t+1} - E_t\left[a_{D,t+1}\right] \mid x_t^{II} > 0\right] &= \\ Var\left[\epsilon_{D,t+1} \mid a_{Dt} > \frac{\bar{a}_S + \tau - (1-\rho)\,\bar{a}_D}{\rho}\right] &= \\ Var\left[\epsilon_{D,t+1}\right] &= \sigma_D^2 \end{aligned}$$

while under the *DI* regime,

$$\begin{aligned} V\left[a_{D,t+1} - E_{t-1}\left[a_{D,t+1}\right] \mid x_t^{DI} > 0\right] &= \\ Var\left[\epsilon_{D,t+1} + \rho_D \epsilon_{Dt} \mid a_{D,t-1} > \frac{\bar{a}_S + \tau - \left(1-\rho^2\right)\bar{a}_D}{\rho^2}\right] &= \\ Var\left[\epsilon_{D,t+1} + \rho_D \epsilon_{Dt}\right] &= \left(1+\rho_D^2\right)\sigma_D^2 \end{aligned}$$

which is larger than the variance under the *II* regime. This proves the last part of the Lemma:

$$Var\left[\text{pdiff}_{t+1}^{II} \middle| x_t^{II} > 0\right] < Var\left[\text{pdiff}_{t+1}^{DI} \middle| x_t^{DI} > 0\right]$$

□

Proof of Theorem

Current welfare is composed of immediate consumer surplus CS_t, social surplus from storage SS_t, immediate producer surplus PS_{t-1} (lagged because shipping takes one period time), and immediate merchant surplus MS_t.

The market demand curve p_t^M as a function of exports x_{t-1} is given by

$$p_t^M = a_{Dt} - b_D\left(x_{t-1} - s_t\left(a_{Dt}, x_{t-1}\right)\right)$$

Immediate consumer surplus and net future social surplus of storage is the area underneath the market demand curve, minus the price paid by consumers and storers (Williams and Wright 1991):

$$CS_t + SS_t = \int_0^{x_{t-1}} p_t^M(q)\,\mathrm{d}q - p_t^{LIV} x_{t-1}$$

Immediate producer surplus is the area between the price received by producers and the supply curve p_t^S :

$$PS_{t-1} = p_t^{NY} x_{t-1} - \int_0^{x_{t-1}} p_t^S(q)\, \mathrm{d}q$$

The surplus of merchants is given by their profits[69]:

$$MS_t = \left(p_t^{LIV} - p_{t-1}^{NY}\right) x_{t-1}$$

Welfare of a specific export quantity is therefore

$$W_t\left(x_{t-1}\right) = \int_0^{x_{t-1}} p_t^M(q)\, \mathrm{d}q - \int_0^{x_{t-1}} p_t^S(q)\, \mathrm{d}q$$

In the perfect foresight equilibrium (PFE) export and storage are chosen such that prices are constant across markets and across time, denoting PFE outcomes with stars:

$$p_t^* := p_t^{LIV} = p_{t-1}^{LIV} = p_{t-1}^{NY} = p_t^{NY}$$

I define deadweight loss due to information frictions as the difference of welfare between a case with information frictions and the perfect foresight model.

$$\begin{aligned} DWL &= W_t^* - W_t \\ &= \int_{x_{t-1}}^{x_{t-1}^*} \left[p_t^M(q) - p_t^S(q)\right] \mathrm{d}q \end{aligned}$$

The storage function has a time-dependent slope (dependent on a_{Dt}) and can therefore not be estimated empirically, which precludes direct estimation of the deadweight loss (except in the numerical exercises). But I can estimate a lower bound for the deadweight loss as follows: Note that the value of the integrand equals $p_t^{LIV} - p_t^{NY}$ at the lower bound x_{t-1}, and 0 at the upper bound x_{t-1}^*. The integrand is monotonically decreasing, and its slope is smaller than $b_D + b_S$ in absolute values. To see this, note that the slope of the market demand function is in absolute value less than or equal to the slope of the consumption demand function, as the storage function is non-decreasing in exports (with slope between 0 and 1, Williams and Wright 1991, p. 101):

$$\frac{\partial p_t^M}{\partial x_{t-1}} = -b_D \left(1 - \frac{\partial s_t^B}{\partial x_{t-1}}\right) \geqslant -b_D$$

I denote $\tilde{q}$ where $p_t^{LIV} - b_D\left(\tilde{q} - x_{t-1}\right) = p_t^S(\tilde{q})$ and define $l(q)$ for $q \in \left[x_{t-1}, x_{t-1}^*\right]$ such that $l(q) \leqslant p_t^M(q) - p_t^S(q)$ in that interval:

[69] I ignore transport cost in this proof to avoid cluttered notation, but account for it in the empirical part.

$$l(q) \quad := \quad \begin{cases} p_t^{LIV} - b_D(q - x_{t-1}) - p_t^S(q) & \text{for } x_{t-1} \leqslant q \leqslant \tilde{q} \\ 0 & \text{for } \tilde{q} \leqslant q < x_{t-1}^* \end{cases}$$

Using integrand $l(q)$ yields a lower bound for the deadweight loss from information frictions:

$$DWL = \int_{x_{t-1}}^{x_{t-1}^*} \left[p_t^M(q) - p_t^S(q)\right] \mathrm{d}q \geqslant \int_{x_{t-1}}^{\tilde{q}} l(q)\,\mathrm{d}q = \frac{\left(p_t^{LIV} - p_{t-1}^{NY}\right)^2}{2(b_D + b_S)}$$

□

B Figures

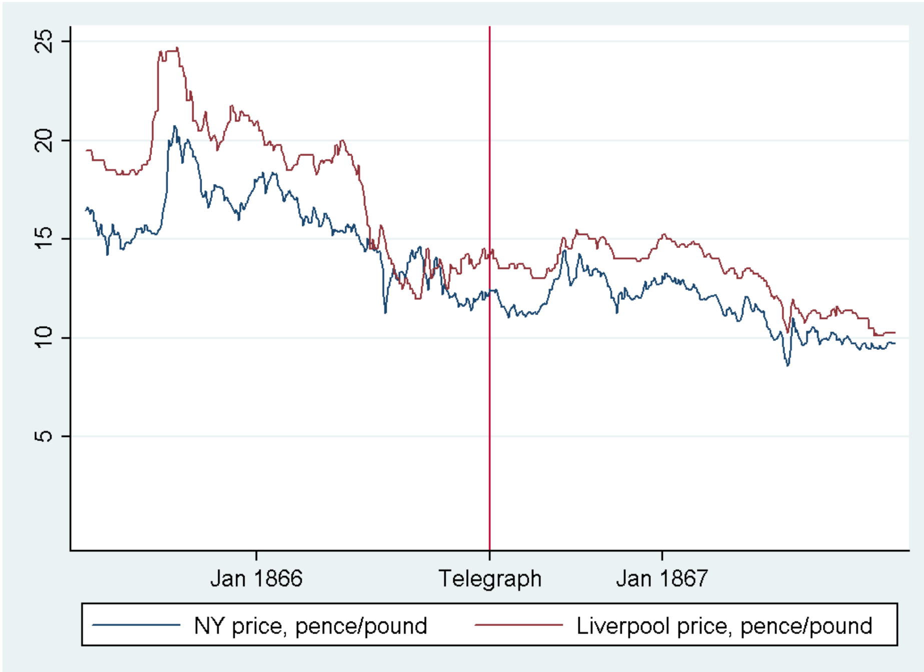


Figure 1: Price series

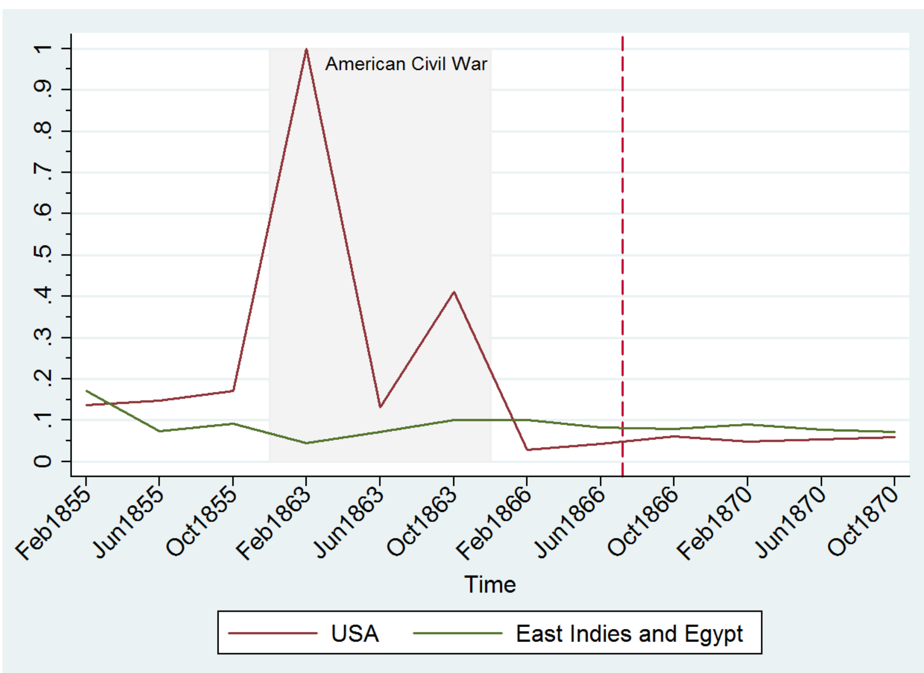


Figure 2: Herfindahl index of market structure of cotton merchants (monthly)

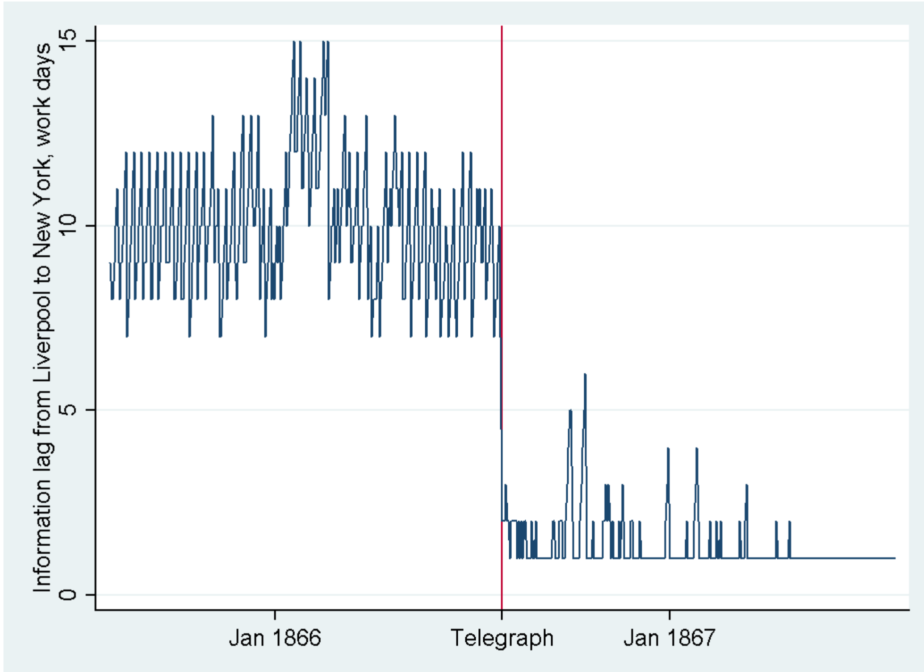


Figure 3: Information delay between New York and Liverpool over time

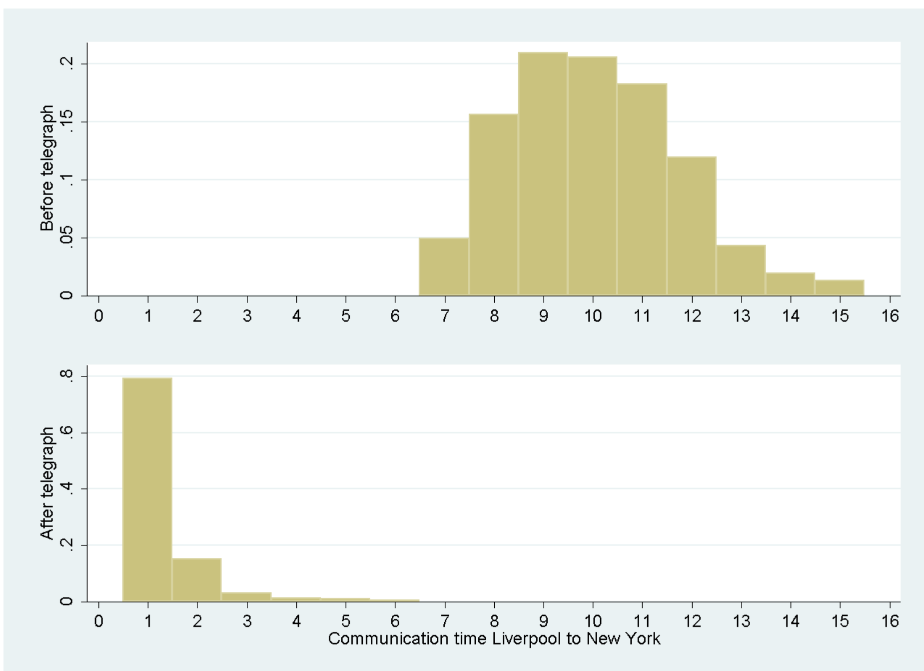


Figure 4: Distribution of information lags between New York and Liverpool (work days), before and after the telegraph

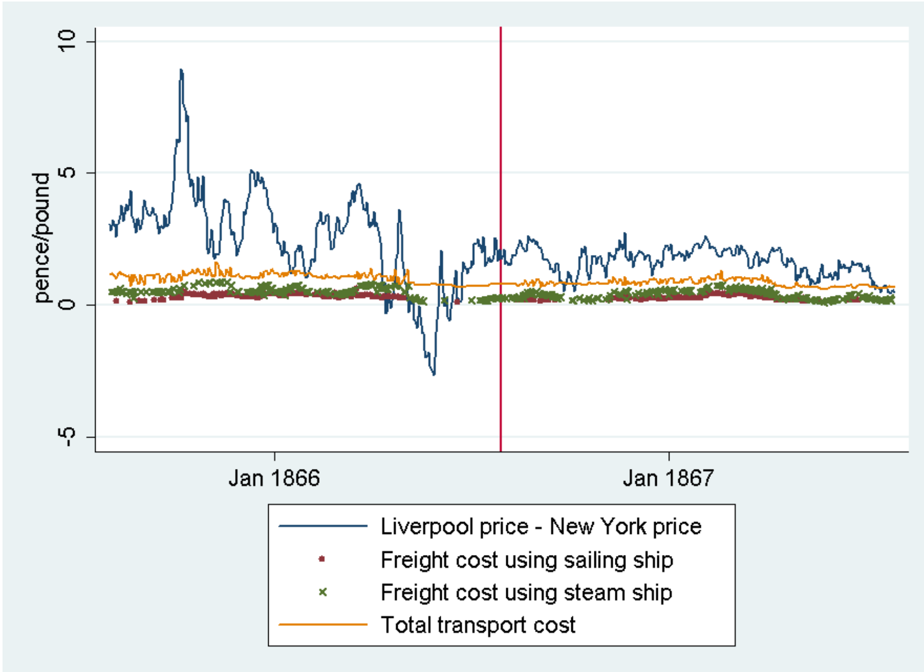


Figure 5: Price difference and freight cost

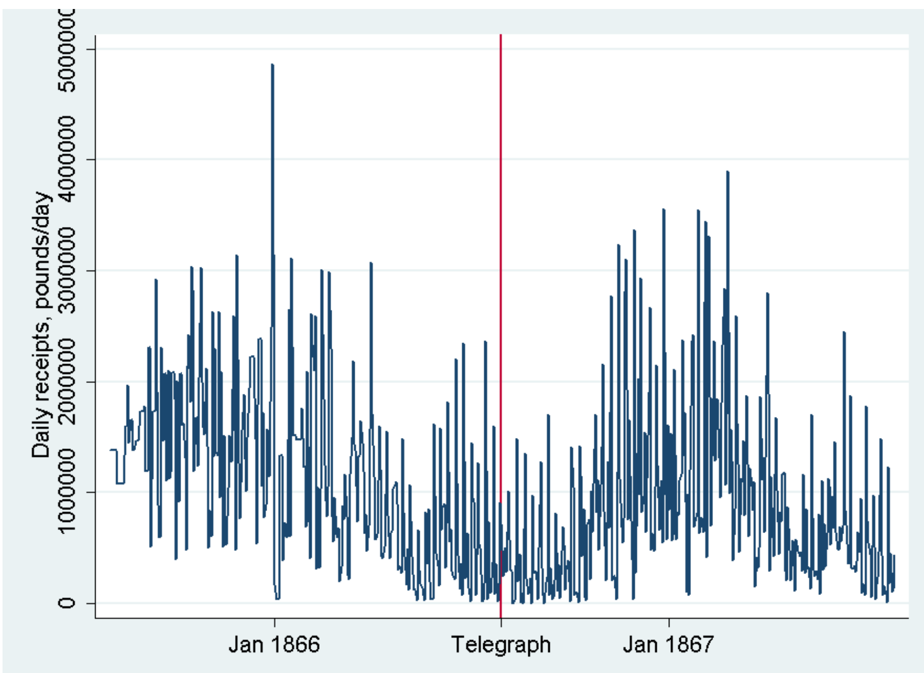


Figure 6: Cotton receipts at the New York exchange

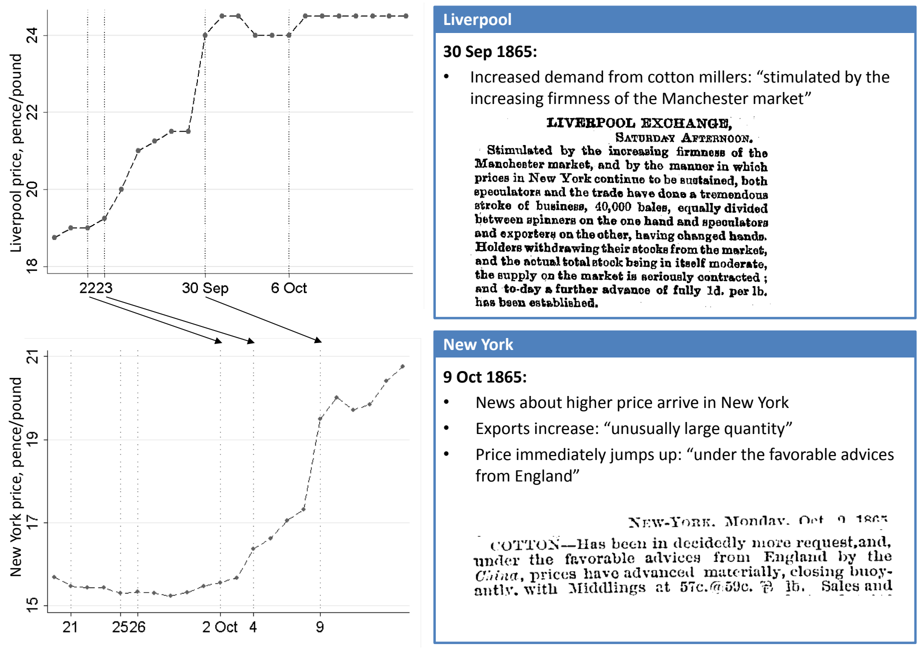


Figure 7: Reaction of New York prices to news from Liverpool

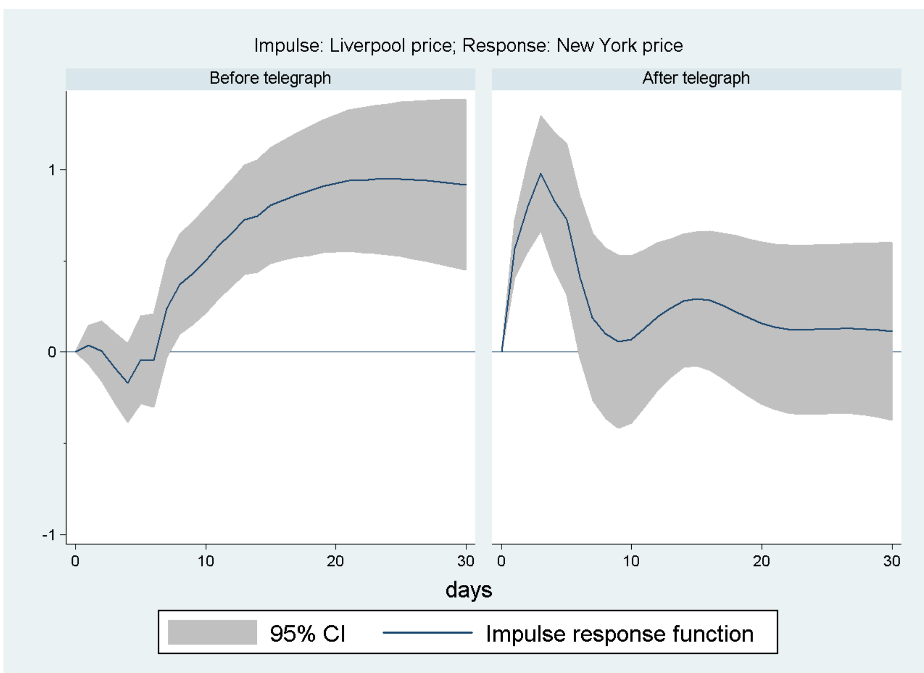


Figure 8: Impact of Liverpool price on New York price

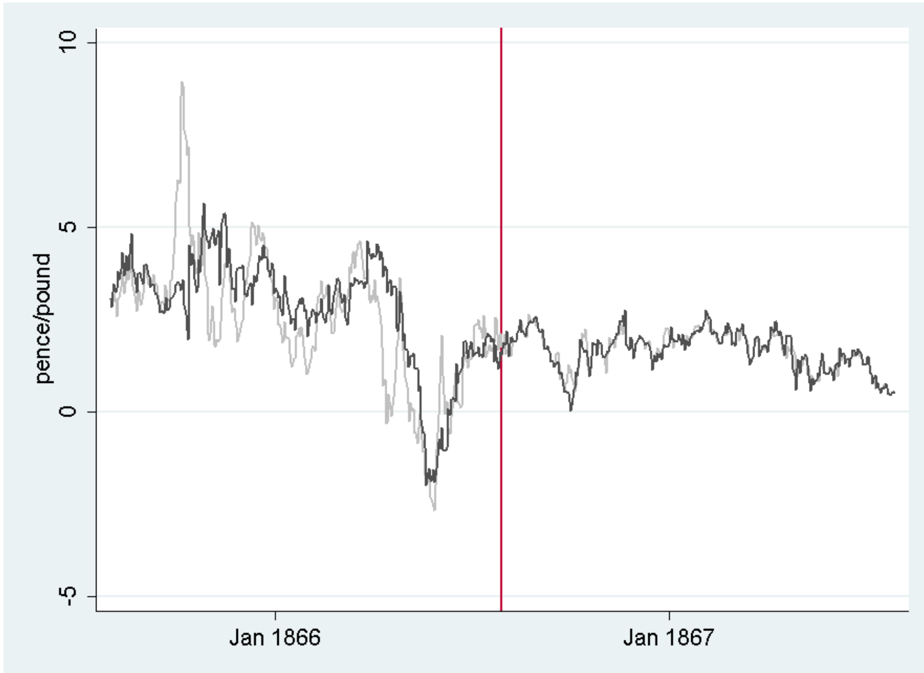


Figure 9: Contemporaneous price difference and price difference to the known, delayed Liverpool price

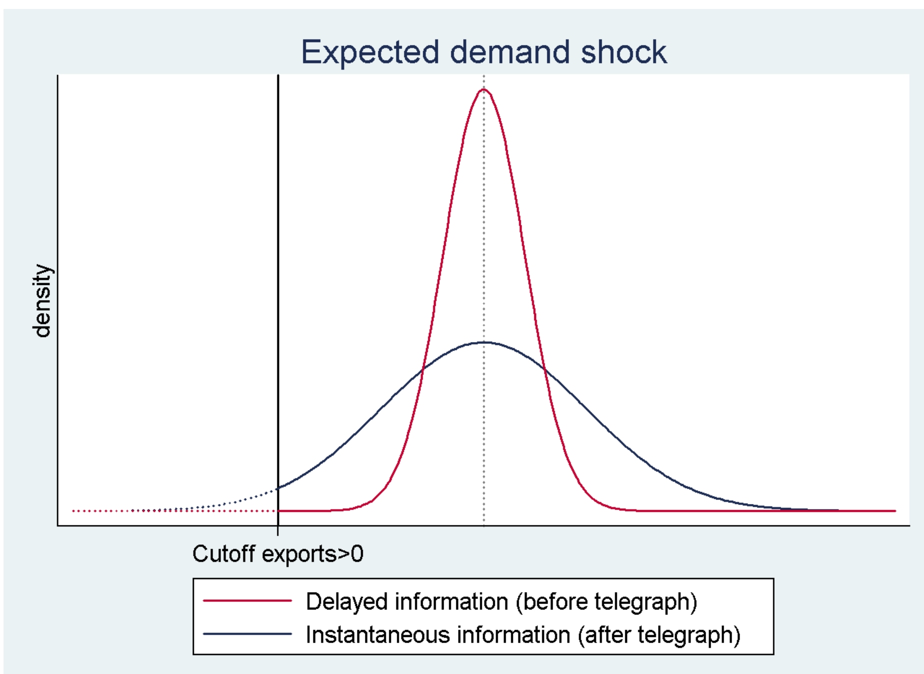
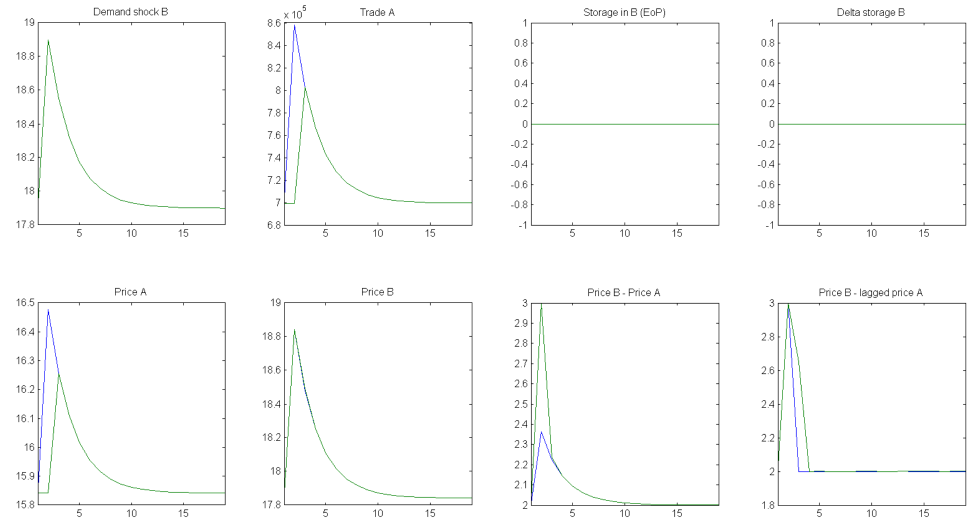
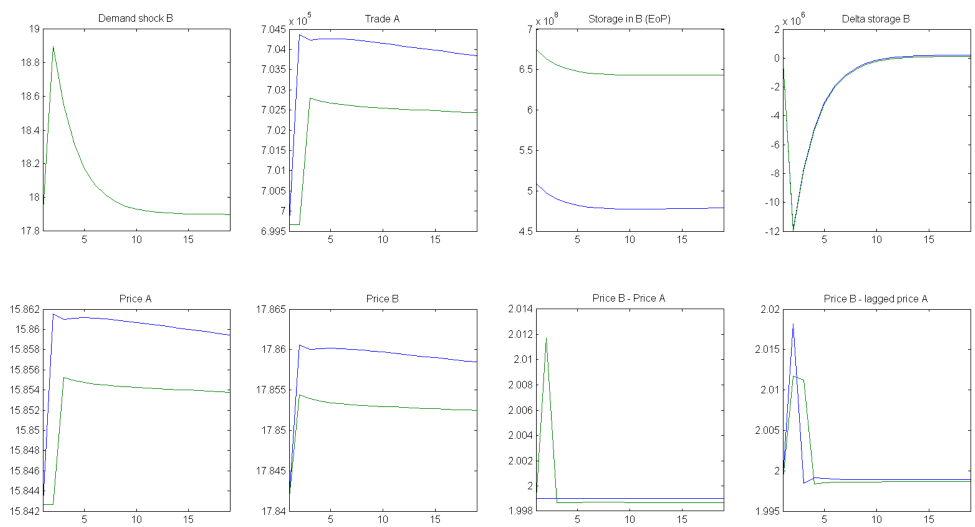


Figure 10: Exports follow expected demand



- delayed information (green line)
- instantaneous information (blue line)

Figure 11: Impulse response function; no storage



- delayed information (green line)
- instantaneous information (blue line)

Figure 12: Impulse response function; storage

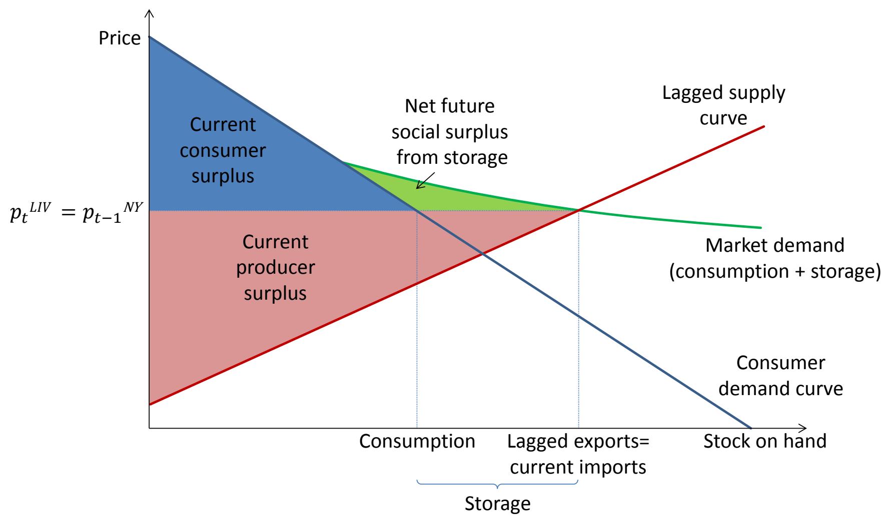


Figure 13: Surplus from export transaction, perfect foresight equilibrium

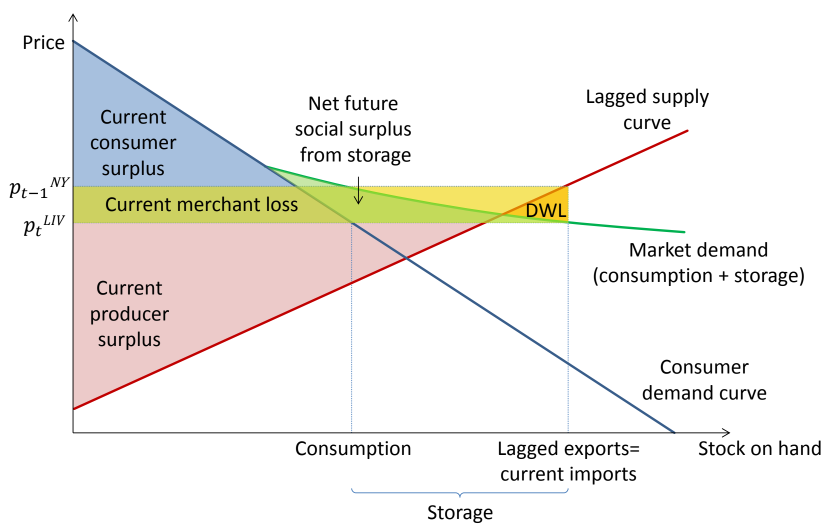


Figure 14: Surplus from export transaction when demand is overestimated

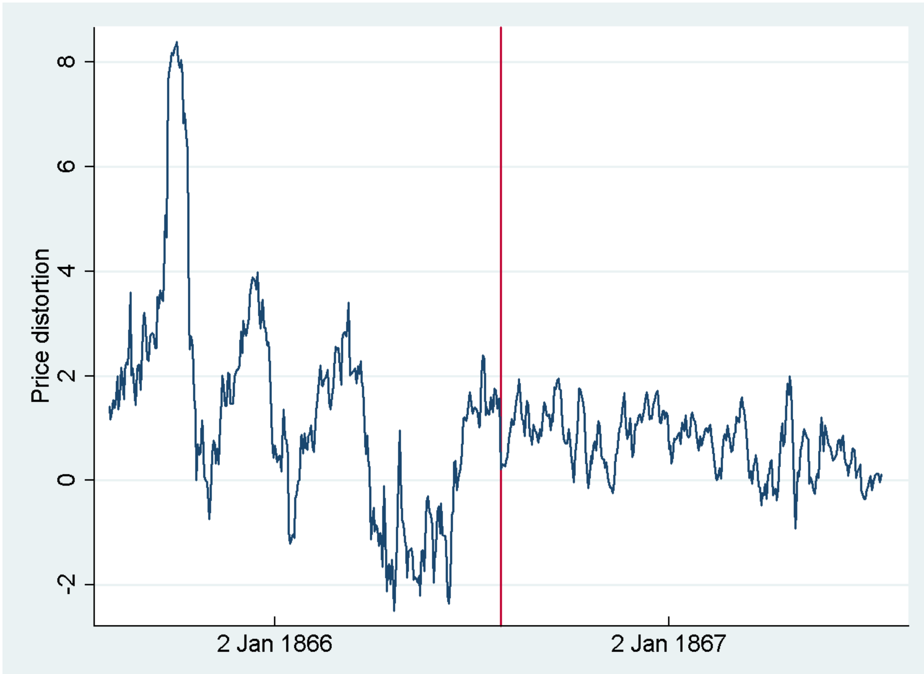


Figure 15: Price distortions: Difference between Liverpool price and lagged New York price plus transport costs

C Tables

Table 1: Summary statistics

	Before telegraph	**After telegraph**	**Difference**
Information lag	10.03	1.31	-8.72***
	(0.13)	(0.06)	(0.15)
Liverpool price	18.11	13.16	-4.95***
	(0.33)	(0.15)	(0.36)
New York price	15.55	11.51	-4.04***
	(0.21)	(0.13)	(0.25)
Price difference $\left(p_t^{LIV} - p_t^{NY}\right)$	2.56	1.65	-0.91***
	(0.18)	(0.05)	(0.19)
Sail ship freight cost	0.28	0.24	-0.04***
	(0.01)	(0.01)	(0.01)
Steam ship freight cost	0.51	0.39	-0.12***
	(0.02)	(0.02)	(0.03)
Exports	459.88	631.80	171.90**
	(37.64)	(61.80)	(72.37)

Notes: Information lag is in work days. Prices and freight cost are in pence per pound of cotton. Exports from New York to Liverpool are given in bales. Newey West standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 2: Average price difference

Dependent variable: $p^{LIV} - p^{NY} - \tau$	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	2.56***	2.27***	2.05***	2.17***	1.52***	1.84***	1.43***	1.26***	0.00	1.67***
	(0.18)	(0.18)	(0.17)	(0.17)	(0.17)	(0.15)	(0.16)	(0.21)	(0.04)	(0.13)
Telegraph dummy	-0.91***	-0.86***	-0.78***	-0.83***	-0.71***	-1.03***	-0.90***	-0.73***	-0.02**	-0.71***
	(0.19)	(0.18)	(0.17)	(0.18)	(0.18)	(0.16)	(0.15)	(0.21)	(0.01)	(0.12)
Cotton supply							0.13***	0.13***	0.01**	0.06***
							(0.03)	(0.04)	(0.00)	(0.02)
Transport costs τ:										
Freight cost	none	sail	steam	avg	avg	avg	avg	avg	avg	avg
Other transport costs					yes	yes	yes	yes	yes	yes
Excluding no trade periods						yes	yes	yes	yes	yes
Accounting for shipping time								yes	yes	yes
Observations	604	604	604	604	604	575	575	575	575	575

Notes: Newey West standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1. As freight cost are not available for all the periods, they are interpolated when missing. The average freight cost is calculated as the average of sail and steam freight rate if both are available, or the freight rate that is available (assuming freight cost are not printed in newspapers if the freight type was not used). Total transport costs include the average freight cost, additional 0.17 pence/pound unit freight cost, and 3.1% ad valorem transport costs (on the New York price). In (6) the period of around four weeks during May 1866 (when exporters were inactive because the price in New York exceeded the price in Liverpool) is excluded. In (7) the price difference daily cotton supply (receipts, in thousand bales) is used to control for potential disruptions in cotton production after the American Civil War. In (8) the price in Liverpool at the time of the arrival of the shipment (around 10 days in the future) is used to control for transport time of shipment. In (9) I use the difference in log prices instead of levels, and log cotton supply. In (10) the last known Liverpool price is used to calculate the price difference.

Table 3: Variance of price difference

Dependent variable: $\widehat{Var}$ (pdiff)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	3.36***	3.26***	3.00***	3.17***	3.09***	2.19***	2.07***	3.79***	0.01	1.37***
	(0.59)	(0.57)	(0.53)	(0.56)	(0.56)	(0.46)	(0.37)	(0.76)	(0.00)	(0.22)
Telegraph dummy	-3.11***	-3.03***	-2.82***	-2.96***	-2.89***	-1.99***	-1.95***	-3.91***	-0.01***	-0.43**
	(0.59)	(0.57)	(0.53)	(0.56)	(0.56)	(0.46)	(0.42)	(0.85)	(0.00)	(0.20)
Cotton supply							0.04	0.15	0.00	-0.10***
							(0.08)	(0.13)	(0.00)	(0.04)
Transport costs τ:										
Freight cost	none	sail	steam	avg	avg	avg	avg	avg	avg	avg
Other transport costs					yes	yes	yes	yes	yes	yes
Excluding no trade periods						yes	yes	yes	yes	yes
Accounting for shipping time								yes	yes	yes
Observations	604	604	604	604	604	575	575	575	575	575

Notes: Newey West standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1. The dependent variable is given by $\frac{N_{before}}{N_{before}-1}\left(\text{pdiff}_t - \overline{\text{pdiff}}_{before}\right)^2$ and $\frac{N_{after}}{N_{after}-1}\left(\text{pdiff}_t - \overline{\text{pdiff}}_{after}\right)^2$, so that the coefficient on the constant yields the sample variance on the period before the telegraph, and the coefficient on the telegraph dummy yields the change in the sample variance before versus after the telegraph. The different columns repeat the different specifications from Table 2.

Table 4: Variance of price difference using within period variation

Dependent variable ln $\widehat{Var}$ (pdiff)	(1)	(2)	(3)
Telegraph dummy	-2.21***		-0.97
	(0.24)		(0.78)
Information lag l, work days		0.24***	0.14*
		(0.03)	(0.08)
Supply	-0.05	-0.04	-0.05
	(0.06)	(0.06)	(0.06)
Observations	585	585	585

Notes: Newey West standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1. The dependent variable is given by log of $\frac{N_{before}}{N_{before}-1}\left(\text{pdiff}_t - \overline{\text{pdiff}}_{before}\right)^2$ and $\frac{N_{after}}{N_{after}-1}\left(\text{pdiff}_t - \overline{\text{pdiff}}_{after}\right)^2$. No trade periods are excluded as in Table 3.

Table 5: Impact of telegraphed vs. steam shipped Liverpool price on New York price

Dependent variable: ln(New York price)	(1) Before telegraph	(2) Before telegraph	(3) After telegraph	(4) After telegraph
ln("telegraphed"		0.002	0.734***	0.710***
Liverpool price)		(0.066)	(0.061)	(0.065)
ln("steam shipped"	0.434***	0.433***		0.069
Liverpool price)	(0.032)	(0.032)		(0.064)
Observations	301	300	303	303

Notes: Counterfactual "telegraphed" price before telegraph is the Liverpool price in $t-1$. Counterfactual "steam shipped" price after telegraph is Liverpool price in $t-10$. Prices are measured in pence/pound. Estimation of an AR(3) model with maximum likelihood. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 6: Impact of known Liverpool price on exports

Dependent variable: ln(exports)	(1) Before telegraph	(2) Before telegraph	(3) Before telegraph	(4) After telegraph	(5) After telegraph	(6) After telegraph
ln("telegraphed"		-0.559	-0.313	1.497	1.608	2.285
Liverpool price)		(1.080)	(1.174)	(1.856)	(2.352)	(2.460)
ln("steam shipped"	2.482***	2.940***	3.137***		-0.164	0.827
Liverpool price)	(0.682)	(1.103)	(1.111)		(2.478)	(2.449)
Linear time trend			yes			yes
Observations	216	215	215	234	234	234

Notes: Columns (1) to (3) use data from the sample before the telegraph got established, columns (4) to (6) use data from the sample after the telegraph got established. Counterfactual "telegraphed" price before telegraph is the Liverpool price in $t-1$. Counterfactual "steam shipped" price after telegraph is the Liverpool price in $t-10$. Exports are measured in bales, Liverpool price is measured in pence/pound. Columns (3) and (6) include a linear time trend. Estimation of an AR(14) model with maximum likelihood. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 7: Average exports from New York to Liverpool

Dependent variable: Exports	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.46***	-0.39***	-0.26***	-0.34***	-1.10***	-1.08***	-1.06***	-1.25***
	(0.04)	(0.10)	(0.08)	(0.10)	(0.19)	(0.23)	(0.23)	(0.24)
Telegraph dummy	0.17**	0.30***	0.35***	0.33***	0.48***	0.47***	0.47***	0.27***
	(0.07)	(0.07)	(0.07)	(0.07)	(0.08)	(0.09)	(0.09)	(0.10)
Transport costs		3.02***	1.42***	2.10***	1.50***	1.49***	1.43***	1.43***
		(0.38)	(0.16)	(0.27)	(0.20)	(0.22)	(0.23)	(0.23)
Cotton supply							0.01	0.01
							(0.02)	(0.02)
Transport costs τ:								
Freight cost		sail	steam	avg	avg	avg	avg	avg
Other transport costs					yes	yes	yes	yes
Excluding no trade periods						yes	yes	yes
Harvest year dummy								yes
Observations	604	604	604	604	604	575	575	575

Notes: Newey West standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1. Exports are in thousand bales.

Table 8: Variance of exports from New York to Liverpool

Dependent variable: $\widehat{Var}$ (exports)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.29***	-0.51**	-0.20	-0.38*	-0.94**	-1.03**	-1.03**	-1.12**
	(0.04)	(0.24)	(0.18)	(0.22)	(0.39)	(0.47)	(0.47)	(0.47)
Telegraph dummy	0.33***	0.45***	0.45***	0.46***	0.57***	0.61***	0.61***	0.21*
	(0.12)	(0.14)	(0.15)	(0.14)	(0.17)	(0.19)	(0.20)	(0.12)
Transport costs		2.85***	0.96***	1.77***	1.18***	1.25***	1.24***	1.26***
		(0.87)	(0.35)	(0.58)	(0.39)	(0.44)	(0.48)	(0.48)
Cotton supply							0.00	-0.00
							(0.03)	(0.03)
Transport costs τ:								
Freight cost		sail	steam	avg	avg	avg	avg	avg
Other transport costs					yes	yes	yes	yes
Excluding no trade periods						yes	yes	yes
Harvest year dummy								yes
Observations	604	604	604	604	604	575	575	575

Notes: The dependent variable is given by $\frac{N_{before}}{N_{before}-1}\left(\exp_t - \overline{\exp}_{before}\right)^2$ and $\frac{N_{after}}{N_{after}-1}\left(\exp_t - \overline{\exp}_{after}\right)^2$, so that the coefficient on the constant yields the sample variance on the period before the telegraph, and the coefficient on the telegraph dummy yields the change in the sample variance before versus after the telegraph. Exports are in thousand bales. Newey West standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 9: Estimation of the slope of the demand function

Dependent variable: p^{LIV}_{t+k}	(1) OLS	(2) IV	(3) NL	(4) NL-IV	(5) NL-IV	(6) NL-IV
Constant	1.735*	2.043**	1.775***	2.010***	2.992**	1.415
	(0.903)	(0.794)	(0.642)	(0.537)	(1.256)	(1.134)
$x_t - \triangle s^{LIV}_{t+k}$	-0.045*	-0.073**	-0.036*	-0.049***	-0.050*	-0.033***
	(0.027)	(0.037)	(0.019)	(0.015)	(0.026)	(0.012)
p^{LIV}_{t-l}	0.884***	0.871***	0.881***	0.870***	0.822***	0.897***
	(0.056)	(0.051)	(0.032)	(0.027)	(0.049)	(0.070)
$x_{t-k-l} - \triangle s^{LIV}_{t-l}$	-0.020	-0.023	n/a	n/a	n/a	n/a
	(0.039)	(0.038)				
Observations	402	402	402	402	206	196
R squared	0.827	0.826	0.827	0.827	0.687	0.736
First stage F stat		125.8		125.8	65.3	171.3
First stage coefficient		0.647***		0.647***	0.676***	0.614***
		(0.058)		(0.058)	(0.084)	(0.047)
Test: $\beta_1\beta_2 - \beta_3 = 0$	-0.020	-0.041				
	(0.046)	(0.058)				
Demand elasticity	-104.7	-64.8	-130.9	-97.7	-149.5	-90.7
Sample					before telegraph	after telegraph

Notes: Prices are denoted in pence/pound. The quantities in the regressor are given in 1,000 bales (1 bale≈400 pounds). HAC standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 10: Estimation of the slope of the supply function

	(1) p^{NY}_t	(2) p^{NY}_t	(3) p^{NY}_t	(4) p^{NY}_t	(5) p^{NY}_t	(6) p^{NY}_t
$\triangle s^{NY}_t + x_t$	0.071***	1.862***	1.715***	1.715***	1.574***	1.608***
	(0.026)	(0.338)	(0.286)	(0.287)	(0.300)	(0.518)
Observations	554	554	469	469	227	242
Harvest year FE	yes	yes	yes	yes	yes	yes
Harvest cycle	yes	yes	yes	yes	yes	yes
Regression	OLS	IV	IV	IV	IV	IV
Instrument		known Liv price	known demand shock	known Liv price	known Liv price	known Liv price
First stage F-stat		46.95	57.81	57.54	46.85	10.49
First stage coefficient		0.27***	0.30***	0.30***	0.33***	0.49**
		(0.04)	(0.04)	(0.04)	(0.05)	(0.15)
Supply elasticity	368.4	14.1	15.3	15.3	24.9	11.5
Sample					before telegraph	after telegraph

Notes: Prices are denoted in pence/pound. The quantities in the regressor are given in 1,000 bales (1 bale≈400 pounds). Index k denotes shipping time from New York to Liverpool, and index l denotes information delay between Liverpool and New York. Harvest cycle controls for day of the harvest season, and the square of it. HAC standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 11: Parameters for calibration

Parameter	Value	Method
Supply side (New York):		
b_S	1.608	Instrumental variables estimation
$\bar{a}_S$	13.03	Constant from estimation of AR(1) process on $\bar{a}_S$
ρ_S	0.24	AR(1) coefficient from estimation of AR(1) process on $\bar{a}_S$
σ_S^2	2.25	From estimation of AR(1) process on $\bar{a}_S$
Demand side (Liverpool):		
b_D	-0.033	Instrumental variables estimation
$\bar{a}_D$	17.15	Constant from estimation of AR(1) process on $\bar{a}_D$
ρ_D	0.91	AR(1) coefficient from estimation of AR(1) process on $\bar{a}_D$
σ_D^2	0.40	From estimation of AR(1) process on $\bar{a}_D$
Other parameters:		
Transport cost τ	0.81	Total transport cost as estimated in empirical section
Storage cost θ	0.004-0.01	From Boyle (1934)

Table 12: Change from delayed to instantaneous information regime, in percent

	Data	Model				
Storage cost:		0	0.004	0.1	1	∞
Main estimates for b_D and b_S:						
Mean						
LIV price - NY price	-35.9***	-1.36	-1.32	-1.04	-2.82	-2.79
Exports	35.7	0.33	0.32	0.25	0.63	0.63
Standard deviation						
LIV price - NY price	-72.3***	-41.84	-42.15	-57.40	-51.86	-52.62
Exports	65.7***	2.87	2.92	4.82	6.25	6.37
Lower CI for b_D and b_S:						
Mean						
LIV price - NY price	-35.9***	-0.49	-0.48	-0.98	-1.14	-1.13
Exports	35.7	0.23	0.23	0.43	0.50	0.50
Standard deviation						
LIV price - NY price	-72.3***	-30.85	-31.31	-41.28	-42.02	-42.01
Exports	65.7***	1.50	1.58	3.07	3.36	3.35
Upper CI for b_D and b_S:						
Mean						
LIV price - NY price	-35.9***	0	0	-0.68	-0.76	-0.49
Exports	35.7	0	0	0.08	0.09	0.06
Standard deviation						
LIV price - NY price	-72.3***	-1.10	-1.20	-7.14	-9.00	-9.21
Exports	65.7***	0.04	0.04	0.32	0.48	0.26

Notes: Change is from delayed (=before telegraph) to instantaneous (=after telegraph) information regime, in percent of the underlying variables. Model predictions are based on a simulation of the model over 10,000 periods. Summary statistics are based on weekly data. Storage cost of infinity mean prohibitively high storage cost. Preferred estimates are shaded in light gray.

Table 13: Estimation of welfare gain from telegraph

	Annual welfare loss, thousand pounds	[95% Conf. Interval]	
Before telegraph	988	608	2,667
After telegraph	125	77	342
Change	-863	-531	-2,325
Change in percent	-87%	-87%	-87%
In % of annual export value	-8.4%	-5.2%	-22.7%

Notes: Confidence interval of welfare loss is based on confidence intervals for the slopes of the demand and supply functions. Annual export value in the data is 10.2 million pounds.