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

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Abstract

Observed violations of the "Law of One Price" (LOP) are one of the most controversially discussed puzzles in International Trade. Information frictions have been suggested as a potential explanation, but empirical evidence is hard to find because information flows are complex, usually unobserved and notoriously endogenous. This paper uses a historical experiment to circumvent these problems: the transatlantic telegraph cable, connecting Great Britain and the United States in 1866. The telegraph reduced information frictions dramatically and suddenly. Using detailed data on information flows and cotton prices from historical newspapers, I demonstrate how information frictions impede adherence to the LOP.

I then develop a model of international trade to explain the behavior of intermediaries when faced with information frictions. Intermediaries use available information to form an expectation about prices. This generates distortions in trade flows that are consistent with historical data. I use the model to estimate the welfare effects of information frictions. The welfare gains from the telegraph are equivalent to those from abolishing a ~10% ad valorem tariff.

*Slogan from a Citi Bank advertisement

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1 Introduction

Observed violations of the "Law of One Price" have puzzled generations of economists. Understanding the nature of the trade barriers that inhibit arbitrage across markets is a vital topic in international trade. The majority of papers in this literature focus on the analysis of direct barriers to trade such as transport cost and tariffs. These can be easily observed, but at the same time they have been found to be of minor importance (Anderson and van Wincoop 2004). Recent papers have suggested information frictions as potential explanation (e.g. Allen 2011), but empirical evidence is scarce as information flows are complex, usually unobserved and notoriously endogenous.

This paper contributes to this emerging literature using a historical experiment that provides exogenous variation in information frictions across countries and allows me to observe information flows[1]: the establishment of the transatlantic telegraph, connecting Great Britain and the United States in 1866. Suddenly and unexpectedly information flows changed dramatically. Before the telegraph connection, mail steam ships were used to exchange information between the two countries, leading to an average information delay of 10 days (ranging from 7 days to 15 days in my sample). After the telegraph cable was in operation, the information of US market participants about British market conditions (and vice versa) originated from the previous day.

Unlike previous papers using exogenous shocks to information frictions, I can observe actual information flows in my data, because every day historical newspapers reported the latest price information about the market at the other side of the Atlantic. From these records I can reconstruct the flow of price information across the Atlantic on any given day. In addition, my database includes high frequency (daily) data on cotton prices in New York and Liverpool, export flows from New York to Liverpool, freight cost from New York to Liverpool, and supply of cotton from producers to the New York stock exchange.

Using this detailed data, I am able to document a striking change in the adherence to the LOP when the telegraph gets established: The price difference across the two markets becomes less volatile and less autocorrelated, bearing a closer resemblance to white noise. I show that these observed violations of the LOP are caused by the information frictions that were in place before the telegraph connection was established. This finding is robust to a number of alternative explanations such as transport cost variations, supply irregularities in the aftermath of the American Civil War, fluctuations within "commodity points" in no trade periods[2], futures or forward trading, and anticipation effects.

If market participants base their trading decision on the wrong (because outdated) price information, their export decision will be distorted, leading to welfare losses. In order to estimate the impact of information frictions on welfare, I develop a simple model of international trade, where intermediaries assume the role of international arbitrageurs. Information frictions take the following form: Intermediaries don't have perfect information about market conditions in the foreign countries, instead they form an expectation about these conditions based on their information set. The LOP will not hold in this setting, as intermediaries will equalize expected rather than actual (unknown) prices[3].

This model can explain the distortions of the LOP observed in the data: Longer information lags lead to a higher volatility and autoregression of the price difference. The model also yields implications for trade

[1] Previous papers using exogenous variation in information frictions have studied price dispersion within a small region of a country or within a country (e.g. Jensen 2007 and Aker 2010 using mobile phone coverage, Goyal 2010 using internet kiosks).

[2] If the absolute price difference across two markets is less is less than trade cost, trade will not occur and the price difference will fluctuate freely between the bounds given by the trade cost (called commodity points). In this case I might observe high volatility and autocorrelation of the price difference within the boundaries of commodity points, which are not caused by information frictions.

[3] Note that in contrast to Allen (2011), the information set in this model is not an endogenous choice.

flows, which I can test with my data: First, the known price information will influence the export decision of merchants, because it is used to form an expectation of the future price. Second, the better the information of merchants, the more volatile are trade flows. This is because with better information, trade will follow actual rather than expected foreign demand shocks, which are more volatile than the latter.

I test these implications using historical data on cotton trade and find that cotton trade is in fact more volatile after the telegraph than before. One might be concerned that the changes in trade flows are not caused by the telegraph, but rather by other trends in market integration that coincide with the telegraph. However, I can show that these implications still hold if I focus my analysis on the within pre-telegraph period, using the daily variation in information delays that is exogenously driven by weather conditions affecting steam ship speed.

Distorted trade flows imply dead weight losses. I continue with the structural estimation of the parameters in the model in order to quantify the welfare gains of the transatlantic telegraph connection. Information frictions turn out to have a sizeable effect on welfare, as the frictions that were in place in the pre-telegraph era corresponded to an ad valorem tariff of $\sim$10%.

The information frictions that were eliminated by the transatlantic telegraph represent a very specific application of the presented model, but the model itself is more general and applicable to any kind of uncertainty about demand that forces intermediaries (or exporting firms) to form price expectations. The model predicts that any demand uncertainty will lead to more volatile price differences and less volatile trade flows, associated with welfare losses.

This means that even though the telegraph has long been replaced by more advanced information technologies such as the internet, the model in this paper is still relevant for today's world. For example, even in today's world, shipping of goods takes time, which means that exporters or importers need to form an expectation about a selling price in the future, causing frictions consistent with the framework used in my model. In addition, the adoption of modern information technology lags behind in developing countries (e.g. Jensen (2007)), and it is crucial to understand the impact of information frictions on welfare to develop policy recommendations guiding investments in IT infrastructure. What is more, the "curse" of the internet is the vastness of its available information, which makes it again costly to filter out relevant from irrelevant information.

My paper contributes to the literature in several ways. By using exogenous variation in information frictions I can identify the causal effect of information frictions on the adherence to the LOP and distortions of trade flows (unlike Portes and Rey 2005; Rauch and Trindade 2002; Allen 2011; Freund and Weinhold 2004). Compared to studies using exogenous variation in information technology (e.g. Jensen 2007; Aker 2010; Goyal 2010) I observe actual information flows and can therefore pin down the effect of information flows rather than estimating the "reduced form" effect of a technology change. Also, the latter studies focus on regional price differences within a developing country, while my paper is in the context of international trade. Papers in the finance literature (e.g. Koudijs 2012; Garbade and Silber 1978) have used similar exogenous variation to study the LOP in financial markets.

Previous papers in international trade have highlighted the role of information to reduce search cost across a variety of markets (e.g. Allen 2011; Jensen 2007; Aker 2010), while this paper focuses on the role of information to reduce uncertainty about a specific foreign market. The paper most closely related to mine is Ejrnæs and Persson (2010) who study the impact of the telegraph on the LOP using weekly wheat prices. Data on cotton is available in much more detail than data on wheat (e.g. daily instead of weekly frequency, information flows, trade flows). This allows me to draw a much more detailed and coherent picture of the effect of information frictions on the LOP, trade distortions and welfare. Ejrnæs and Persson (2010) assume that information frictions always depress trade levels, while I highlight an additional source of deadweight loss studying the effect of information frictions on the volatility of trade flows. Also, the "after telegraph" data of Ejrnæs and Persson (2010) starts in 1883, more than 15 years after the introduction of the telegraph. By this time several other market developments, e.g. trading of standardized futures contracts, have been widely introduced, implying that they might overestimate the effect of information frictions from other trends in market integration.

The structure of the paper is as follows: Section II describes my experiment and the collected data. Section III documents how the more up-to-date information transmitted by the transatlantic telegraph caused a closer adherence to the LOP. Section IV develops a theoretical model of information frictions in international trade and derives implications for trade flows, which are tested in Section V. Section VI estimates the welfare effects of information frictions. I conclude in Section VII.

2 Experiment and data

The first successful transatlantic telegraph connection between Great Britain and United States was established on 28 July 1866 and caused a dramatic reduction of information frictions[4]. Before the telegraph connection, the only way of communication across the Atlantic was sending letters 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 8 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[5].

The transatlantic telegraph connection changed communication flows dramatically and immediately: Suddenly communication between the United States and Great Britain was possible almost without delay. New Yorkers usually received news from Great Britain within a day[6]. 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 transatlantic telegraph connection.

These technical difficulties arose because the transatlantic cable was the first undersea cable connecting two continents, which required to cover a greater distance (3,000 km) at a larger submarine depth (3,000 m)

[4]In 1858 there had been a working connection, but the transmission speed was so poor that it could not be used for commercial purposes, and the connection lasted only for 3 weeks, when it broke down permanently.

[5]Important commercial information, such as stock and commodity prices, were 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. For example, London stock exchange information was telegraphed from London 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 landline, arriving faster at its destination than the steam ship. 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.

[6]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. So despite the fact that transmission using the telegraph between two posts was instantaneous, the retransmission took time, and therefore effective communication time between London and New York was around 1 day.

than any previous telegraph connection[7]. Consequently, it took 5 attempts over the course of 10 years until a lasting connection was established on 28 July 1866. 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[8], and the connection lasted only shortly: After 3 weeks excessive voltage damaged the insulation of the cable when operators were trying to achieve faster transmission speeds, 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.

By 1865 there was some technical progress in the understanding of undersea electrical signal transmission, but the fourth attempt in that year resulted again in a broken cable with ends that got lost in the ocean. By 1866 there was little confidence left. Even if people had expected this fifth attempt to work, the precise timing could not have been foreseen, as weather conditions determined the progress of cable laying. 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.

The troublesome history of the transatlantic telegraph is useful for my analysis, as I can exclude the possibility that any anticipation effects[9] or the endogenous timing of the establishment of the telegraph (e.g. to coincide with any other market events or developments) drive my findings.

I can reconstruct the impact of the telegraph on information flows using historical newspapers (Liverpool Mercury and The New York Times). 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[10]. These indicators included the gold price, the exchange rate, 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 lag l".

Table 1 shows how the telegraph impacted information lags between New York and Liverpool. Before 28 July 1866, the day of the successful telegraph connection, information from New York was on average 10 days old when it reached Liverpool. After the telegraph this was reduced significantly: Information from New York was now from just the day before. There was some variation in the information lag: Before the telegraph, information lags varied between 7 and 15 days, caused by wind and weather 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 technical failures of the telegraph cable, especially in the first few months.

Figure 1 shows the distribution of information lags, separately before and after the telegraph. After the telegraph, in 80% of the observations (each observation corresponds to one work day) the information about the other market was received within a day.

In several of my empirical analyses I will not only use the one time drop in information frictions due to the telegraph, but I will also use the variation of information lag l within the periods before and after the telegraph. This variation was also exogenous, because weather and wind accelerated or delayed mail steam ships before the telegraph, and technical breakdowns delayed telegraph messages after the telegraph. Figure

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

[8] The first message took 17 hours to transmit (it didn't include any commercial information). The average transmission speed was 0.1 words/minute.

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

[10] The relevant sections were headed "Latest and Telegraphic News" and "News from Europe", respectively.

2 shows the resulting variation in information lag l over the whole sample period.

I combine the data on information lags with data on cotton, one of the most important traded goods between Great Britain and the United States of those times. In the 19th century, cotton was grown primarily in the South of the United States and India, followed by Egypt and Brazil. The cotton was then exported to Great Britain to be manufactured into cotton textiles. The industrial revolution in Great Britain had led to several inventions in cotton manufacturing (e.g. spinning machines, spinning jenny, spinning frame), which made Great Britain the world's leading textile manufacturer. Textiles were mainly produced in Lancashire, the hinterland of Manchester and Liverpool. Virtually all the cotton destined at Great Britain arrived at the port of Liverpool.

I was able to find the following detailed cotton data in historical newspapers: daily cotton exports from New York[11] to Liverpool, the daily price of cotton in New York, the daily price of cotton in Liverpool, daily freight cost of cotton from New York to Liverpool, and daily "cotton receipts" of the New York exchange (arrivals of cotton at the New York market from the producers). I convert the prices at the New York exchange from US dollars to Pound Sterling using daily exchange rates from the historical times series provided by "Global Financial Data". Note that Great Britain had adopted the gold standard during that time, so exchange rate fluctuations were small and within gold points. The resulting variation in New York prices is not due to fluctuations in the exchange rate, but rather due to fluctuations in the original US dollar price.

It is crucial to use price data for identical goods in studies of the LOP (e.g. Anderson and van Wincoop 2004, Pippenger and Phillips 2008). While cotton might seem like a fairly homogenous product to the non-expert, cotton grown in different areas of the world are of different quality to the textile producer. In fact, Lancashire cotton textile producers considered cotton grown in the United States, "American cotton", as superior to cotton from India or Egypt because of its longer and stronger fibers (on top of lower production cost, transport cost and shipping time). But there were even quality differences within types of American cotton, characterized by a combination of origin area (e.g. "Uplands", "New Orleans", "Texas", "Florida", "Mobile", "Caribbean") and a quality statement (e.g. "middling", "fair", "middling fair", "ordinary"). In order to ensure comparability of American cotton between New York and Liverpool I used the main reference quality of American cotton, "Middling Uplands", in both markets.

Another common pitfall is to use retail instead of wholesale prices for LOP tests (Pippenger and Phillips 2008). I use the official daily reference prices at cotton exchanges, which are wholesale prices.

Figure 3 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, indicating some kind of relationship between them.

My final database comprises of 605 observations, one for every work day. The time period comprises one calendar year before (301 work days) and one calendar year after the telegraph connection (304 work days). It is not possible to collect data for a longer period before the establishment of the telegraph connection, because the American Civil War impeded cotton trade between April 1861 and April 1865. In the empirical analysis I will provide evidence that my findings are not driven by the Civil War.

[11] New York was the most important cotton export port in the United States besides New Orleans.

3 The Telegraph and the Law of One Price

If arbitrageurs are rational, they should take advantage of any arbitrage opportunity until no one is left. As a consequence, the Law of One Price (LOP) must hold, which means that two perfect substitutes trade at the same price. If the LOP does not hold, there must be some impediments to arbitrage (Dybvig and Ross 1987)[12]. Information frictions might be one potential impediment. If this is true, the transatlantic telegraph should have led to improvements in the adherence to the LOP, as it eliminated information frictions. This section documents the change in the adherence to the LOP due to the telegraph.

Denote p_t^{LIV} and p_t^{NY} as the prices of American cotton in Liverpool and New York, respectively, and τ as transatlantic transport cost. The LOP then implies $p_t^{LIV} = p_t^{NY} + \tau$ (assuming cotton is exported from New York to Liverpool). Figure 4 plots the price difference $p_t^{LIV} - p_t^{NY}$. The vertical line indicates 28 July 1866, the date when the telegraph was introduced. The change in the behaviour of the price difference due to the telegraph is striking: After the telegraph, the price difference is less autocorrelated, less volatile, there are fewer outliers and faster returns from outliers. Table 1 shows that the average price difference as well as the volatility of the price difference fell significantly.

Overall, the price difference looks much more like a white noise process after the telegraph got introduced. I test this more formally using two standard white noise tests, the Bartlett test and the Portmanteau Q-test (Ljung–Box test). The Portmanteau test computes a test statistics based on autocorrelations. The Bartlett test checks whether the cumulative periodogram of the time series is close to certain values. The first row in Table 2 computes both test statistics separately for the pre and post telegraph period. Both tests reject the Null Hypothesis of white noise in the price difference in both periods (critical values are given below the Table), but - more importantly - both test statistics fall after the telegraph, indicating closer adherence to the LOP[13].

The LOP across markets will only hold if transport cost are smaller than the price difference. Otherwise there will be no possibility for arbitrage, and the price difference will fluctuate freely between the bounds given by the transport cost (called commodity points): $|p_t^{LIV} - p_t^{NY}| < \tau$. Therefore most studies that infer transport cost from spatial price differences use only periods when trade actually occurred (Anderson and van Wincoop 2004). If there were some periods before the telegraph when the price difference was not large enough to induce trade, this might explain why I don't observe white noise. The cotton exports in my data indicate that exports occurred in every week in the sample except for a period of about 4 weeks during May 1866, when the price of cotton in New York exceeded the one in Liverpool[14]. The second row in Table 2 excludes this period. The test statistics before the telegraph are much smaller, but there is still a large difference between the pre and post telegraph periods.

One might worry that the pattern observed in the price difference is not due to information frictions, but rather due to variation in other factors such as transport cost or supply irregularities (due to the build-up of cotton production after the American Civil War).

[12] The alternative conclusion would be that there is not even one single rational agent in the economy. This seems implausible, which is why an observed violation on the law of one price is typically interpreted to imply impediments to arbitrage.

[13] Note that many papers in this literature use cointegration tests (using Dickey-Fuller tests) to test for market integration across markets (e.g. Pippenger and Phillips 2008, Shiue and Keller 2007). These tests try to detect a long run relationship between prices in different markets, but they lack micro foundation relative to the arbitrage process. Perfect arbitrage suggests that the price difference should be white noise. However, cointegration tests test only for non-stationarity of the residual of a regression of one price on the other price. For the purpose of this paper, cointegration tests are therefore less meaningful and not reported. In any case, they would lead to the same conclusion, i.e. increased market integration after the telegraph.

[14] Only if the price difference becomes "negative enough" to cover transport cost, we should expect cotton re-exports to New York (and for those periods the LOP should hold again in absolute values). I don't have any indication from the historical newspapers that this has happened.

In order to assess whether transport cost drive the closer adherence to the LOP, I substract the daily transport cost from the price difference, using four different measures. The major component of transport cost are freight cost, which are reported daily in The New York Times (with some missing days) and refer to shipment of cotton 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. The freight cost are remarkably stable across the period.

While freight cost accounted for the major part of total transport cost, there were other transport cost such as fire and marine insurance, wharfage, handling at the port etc. Boyle (1934) provides a detailed account of all other transport cost, using historical book keeping figures of merchants. Besides unit freight cost, which averages around 0.4 pence/pound in my sample, there were additional unit transport cost of 0.17 pence/pound for handling at the ports (including bagging, marking, wharfage, cartage, dock dues, weighing, storage at the port) and additional 3.1% ad valorem transport cost (for fire and marine insurance, Liverpool town dues, and brokerage), which amount to 0.4 pence/pound on average in my sample. Total transport cost is on roughly 2.5 times the freight cost. Figure 5 also plots the total transport cost, but the ad valorem part of the transport cost also fails to create the volatility we observe in the price difference. The white noise tests in Table 2 substract the different measures of transport cost from the price difference. However, they fail to explain the observed pattern in the LOP.

Another concern might be that my observations begin in July 1865, shortly after the end of the American Civil War on 9 April 1865 that disrupted cotton trade severely. During the Civil War, the Northern states ("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, but it took five to 10 years until the pre-war levels 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 (which were a major production input in the labour-intensive hand picking of the cotton harvest) (Woodman 1869). Figure 6 illustrates that 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). The return to pre-war levels took until 1870[15]. 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, causing the variations in the price difference I observe.

Notice that with perfectly integrated markets, even irregularities in cotton supply should not show up in the price difference (rather in price levels). However, if integration is imperfect (and even if this was unchanged due to the telegraph), the supply pattern might show up in the price difference. In order to investigate whether supply irregularities impacted the adherence to the LOP I collected 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 7 illustrates the time pattern of cotton supply over the course of a harvest year. The cotton year starts on 1 September, which is when the new harvest comes in[16]. The value of cotton brought to market on 31 August is equal to the total cotton output of a year. 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

[15]During the Civil War American cotton was substituted with Indian and Egyptian cotton. However, the advantages of American cotton (longer fibres, lower production and transport cost) still prevailed after the Civil War, which is why cotton millers returned to American cotton after the Civil War, as long as prices were not too high.

[16]In practice there is around one month of overlap between "new" and "old" cotton receipts"

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 7 doesn't suggest that the variation in cotton supplies differs very much before and after the telegraph[17]. Nevertheless, in row (4) of Table 2 I conduct the LOP tests controlling for daily cotton supply (in addition to transport cost). Again, this is unable to explain why we observe more adherence to the LOP after the telegraph.

Another worry might be that futures trading, made possible by the telegraph, might have caused a lower price volatility. However, futures trading (which involves the trading of a highly standardized contract based on a clearly defined quality of the underlying good, that can be enforced; and the possibility to short sell) was not possible until the 1870s (Ellison 1886). 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 (because there was not yet a procedure for enforcement of a promised quality of cotton). Typically samples of a cotton lot would be shipped by the fastest mail steam ship, while the lot was shipped by a slower steam ship or a sailing ship. The telegraph did not change the speed at which cotton samples could be shipped, as they had to be tranported physically. Therefore the telegraph did not change the (limited) extent of forward trading, but only the speed of the transmission of *information*, which is why the observed pattern in the LOP can't be explained by forward trading.

So far I have shown that the deviations from the LOP observed in the pre-telegraph period are caused by the telegraph rather than by alternative explanations. The telegraph changed the availability of up to date information across the Atlantic. In the following I show that the observed pattern in the LOP can be explained by the change in information frictions.

I illustrate this with anecdotal evidence, using the first spike in the price difference in Figure 4. Figure 8 zooms in 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. 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 from 20 to 24 pence/pound within two days. 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, 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 episode illustrates how information frictions caused the observed temporary deviations from the LOP, and distorted and delayed export flows.

To study this more systematically, Figure 9 illustrates the time lag between the actual contemporaneous Liverpool price and the Liverpool price that was known in New York on any day. Before the telegraph, there is a lag of one to two weeks, after the telegraph the known and actual price almost coincide. Figure 10 now plots both the contemporaneous price difference (the same as in Figure 4) together with the difference of the current New York price to the lagged, known Liverpool price. It turns out that this series seems to adhere to the LOP closer (except for the period of no trade in July 1865, which is shaded in the figure). In row (5) of Table 2 I conduct the white noise tests on this difference (in a specification comparable to row (4) which excludes the no trade period, and controls for transport cost and supply shocks). The difference in the test statistics before and after the telegraph now gets almost halved.

[17] 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, over which days arrivals piled up

This indicates that market participants seemed to arbitrage away the price difference between the current New York and the known, lagged Liverpool price. But there is still something left unexplained. In the following section I suggest a model to explain the behaviour of market participants under information frictions. Arbitrage will be based on the expected Liverpool price at the delivery time, conditional on the most recent information from Liverpool. The model also yields predictions for trade flows, which I use to test the model.

4 Model of Information Frictions in International Trade

Assume there are two countries, denoted by A and B. A homogeneous good is produced in country A and consumed in country B. Intermediaries (merchants) buy the good in country A, ship it to country B and sell it there. Merchants face aggregate supply in country A given by the (inverse) linear supply function:

$$p_t^S(q) = a_{St} + b_S q$$

For tractability and the welfare estimation I suppose that aggregate supply is stochastic with intercept a_{St} following a random walk[18]: $a_{St} = a_{S,t-1} + \nu_{St}$ with $E(\nu_{St}) = 0$ and $Var(\nu_{St}) = \sigma_S^2$. However, note that the qualitative predictions of the model hold for any time series process[19]. The slope of the supply function b_S determines the elasticity of aggregate supply: $\epsilon_S = \frac{1}{b_S}\frac{p}{q}$.

There are merchants which can buy some quantity x_t of the homogenous good in country A and export it to country B in each period t. There is perfect competition among merchants (i.e. they are price takers and take prices in both markets, p_t^A and p_t^B, as given).

Shipping from country A to country B takes k periods[20]. Therefore exports x from country A in time period t will equal imports m of country B in time period $t+k$: $x_t = m_{t+k}$. Merchants have to pay a transport cost of τ per unit shipped.

In country B, merchants face aggregate demand given by the (inverse) linear demand function:

$$p_t^D(q) = a_{Dt} - b_D q$$

Aggregate demand is also stochastic and intercept a_{Dt} follows a random walk[21]: $a_{Dt} = a_{D,t-1} + \nu_{Dt}$ with $E(\nu_{Dt}) = 0$ and $Var(\nu_{Dt}) = \sigma_D^2$. The slope of the demand function b_D determines the elasticity of aggregate demand: $\epsilon_D = \frac{1}{b_D}\frac{p}{q}$.

Merchants are based in country A and engage in trade whenever they expect to make profits[22]. This means that merchants are assuming the role of arbitrageurs across the two countries. The profit from trading quantity x_t is:

$$\pi(x_t) = \left(p_{t+k}^B - p_t^A - \tau\right) x_t$$

[18] The assumption of random walk demand and supply shocks for the welfare analysis is justified by the existence of efficient cotton storage. Storage will arbitrage away any difference between today's price and tomorrow's expected price in a given market, leading to prices following a random walk (Coleman 2009). This is consistent with the data, as both the Liverpool and the New York prices are non-stationary, using Augmented Dickey-Fuller tests. The effects of information frictions on stock levels will be investigated in future work.

[19] Proofs available on request.

[20] The predictions of the model are also true with immediate shipment, i.e. $k = 0$. However, it is not very realistic to assume that goods can be shipped faster than information.

[21] Again, the qualitative predictions of the model don't depend on the assumed time series of the demand process, see footnote on supply shocks.

[22] 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, which is equivalent to assuming merchants based in New York (country A) only.

Assume there are information frictions of the following type: Merchants know about market conditions in country B only with a time lag of l, because transmitting information takes time. At time t merchants therefore only know the lagged realization of the demand shock in country B, $a_{D,t-l}$. Since merchants are located in country A when making the purchasing decision, I assume they know the realization of the contemporaneous supply shock a_{St}.

Figure 11 provides a sketch of the model just described.

Ideally merchants would like to know the realization of the demand shock in the period when their shipment arrives, i.e. $a_{D,t+k}$. Since they don't know that, they will have to use the most recent information they have about the demand shocks, $a_{D,t-l}$, to form expectations about the future shock. This means that merchants will choose x_t in order to maximize expected profits conditional on all the available information at time t:

$$\max_{x_t} E\left[\pi(x_t)|a_{D,t-l}\right]$$

.

The first order condition of the merchant's optimization problem is

$$E\left[p^B_{t+k} \mid a_{D,t-l}\right] - p^A_t - \tau = 0$$

Using the demand and supply functions, in equilibrium trade will be:

$$\begin{aligned} x_t &= \frac{E\left(a_{D,t+k}\,|a_{D,t-l}\,\right) - a_{St} - \tau}{b_s + b_D} = \\ &= \frac{a_{D,t+k} - a_{St} - \tau}{b_S + b_D} - \underbrace{\frac{a_{D,t+k} - E\left[a_{D,t+k}|\,a_{D,t-l}\right]}{b_S + b_D}}_{\text{information frictions}} \end{aligned} \tag{1}$$

With perfect information (i.e. if the true demand shock $a_{D,t+k}$ was known) optimal trade would be equal $x^{PI}_t = \frac{a_{D,t+k} - a_{St} - \tau}{b_S + b_D}$. In this case the LOP would hold exactly subject to shipping time k, and trade cost τ:

$$p^B_{t+k} = p^A_t + \tau$$

With information frictions distortions arise, because of the forecast error of the demand shock: $a_{D,t+k} - E\left(a_{D,t+k}\,|a_{D,t-l}\,\right)$. I call this "distortion due to imperfect information". The larger the difference between predicted and actual demand shocks, the larger is the trade distortion. Note that the sign of the distortion from imperfect information is ambiguous: Sometimes actual demand in period $t+k$ might be underestimated, resulting in "too little" exports (compared to the world with perfect information). In other periods, actual demand might be overestimated, resulting in "too much" trade.

These distortions result in violations of the LOP. The price difference (adjusted by transport cost) will be equal to the forecast error, p_{II}. Again, the sign of the forecast error is ambiguous:

$$p^B_{t+k} - p^A_t + \tau = \underbrace{a_{D,t+k} - E\left(a_{D,t+k}\,|a_{D,t-l}\,\right)}_{p_{II}} \tag{2}$$

Since $a_{D,t+k}$ follows a random walk, $E\left[a_{D,t+k}|a_{D,t-l}\right] = a_{D,t-l}$, i.e. the best prediction of future demand shocks is the current demand.

Total trade flows in each period will therefore equal

$$x_t = \frac{a_{D,t-l} - a_{St} - \tau}{b_S + b_D} \tag{3}$$

The contemporaneous price difference will equal

$$\begin{aligned} p_t^B - p_t^A &= \frac{b_S\left(a_{Dt} - a_{D,t-l}\right) + b_D\left(a_{Dt} - a_{D,t-k-l}\right) + b_D\left(a_{S,t-k} - a_{St}\right)}{b_S + b_D} = \\ &= \frac{b_S \sum_{u=l-1}^{t} \epsilon_{D,t-u} + b_D \sum_{u=k+l-1}^{t} \epsilon_{D,t-u} + b_D \sum_{u=k-1}^{t} \epsilon_{S,t-u}}{b_S + b_D} \end{aligned}$$

The model creates violations in the LOP as we have observed in the data. More specifically: The variance and the autocorrelation of the price difference fall as information frictions fall[23].

In the following I show why these predictions hold:

1. *The variance of price differences falls as information frictions fall.* The variance of the (contemporaneous) price difference is given by:

$$Var(p_t^B - p_t^A) = \frac{\left((b_S + b_D)^2 l + b_D^2 k\right)\sigma_D^2 + b_D^2 k \sigma_S^2}{(b_S + b_D)^2}$$

   The variance depends positively on the information lag:

$$\frac{\partial Var(p_t^B - p_t^A)}{\partial l} = \sigma_D^2 > 0$$

   As the information lag l falls, the variance of the price difference will also fall. Without any information frictions (and immediate shipment), merchants would arbitrage away any price difference that exceeds transport cost. The variance of the price difference would then be zero. However, with information frictions, the merchants have imperfect information about the true demand shock, and will sometimes export more than is needed to equalize prices across markets, and sometimes less. The resulting variation in the price difference will depend positively on the degree of information frictions.

2. *The autocorrelation function of the price difference falls if the information frictions fall.* The autocorrelation function of the price difference (as a function of time lag κ) is the following piecewise linear function, that reaches a constant zero after lag $k + l - 1$:

$$\begin{aligned} Corr_{p^B - p^A}(\kappa) &= \frac{1}{l(b_S + b_D)^2\sigma_D^2 + kb_D^2(\sigma_D^2 + \sigma_S^2)} \\ &\quad \left[\mathbb{I}_{\kappa \le l}\left(l(b_S + b_D)^2\sigma_D^2 + kb_D^2(\sigma_D^2 + \sigma_S^2) - \kappa b_D^2(\sigma_D^2 + \sigma_S^2)\right) + \right. \\ &\quad + \mathbb{I}_{\mathrm{l} < \kappa \le \mathrm{k}}\left(lb_D(b_S + b_D)\sigma_D^2 + kb_D^2(\sigma_D^2 + \sigma_S^2) - \kappa b_D^2(\sigma_D^2 + \sigma_S^2)\right) + \\ &\quad + \mathbb{I}_{\mathrm{k} < \kappa \le \mathrm{k+l-1}}\left(lb_D(b_S + b_D)\sigma_D^2 + kb_D(b_S + b_D)\sigma_D^2 - \kappa b_D(b_S + b_D)\sigma_D^2\right) + \\ &\quad \left. + \mathbb{I}_{\mathrm{k+l-1} < \kappa \le \mathrm{k+l}}\left(lb_D^2\sigma_D^2 + kb_D^2\sigma_D^2 - \kappa b_D^2\sigma_D^2\right)\right] \end{aligned}$$

   If information lag l falls, the autocorrelation function falls as well (for every lag κ). Also, a fall in

[23] I am currently working on a dynamic version of the model that allows for storage of the good. The predictions for prices hold even when allowing for storage, the magnitude of the precdictions for trade is weaker, as storage and trade are to some degree substitutable actions.

information lag l will lead to the autocorrelation function reaching zero at an earlier lag.

In addition to being able to explain the observed pattern in price differences which motivated this paper, the model yields predictions about the trade distortions from information frictions: Exports will depend on the most recent price information from country B, and the variance of exports will increase as information frictions fall.

In the following I show why these predictions hold:

1. *Exports depend on the most recent price information from country B.* Optimal exports in equation (3) depend on the most recent demand shock in country B, $a_{D,t-l}$. This is equivalent to using the most recent price information from country B, p^B_{t-l} together with lagged exports x_{t-k-l}, because

$$p^B_{t-l} = a_{D,t-l} - b_D x_{t-k-l}$$

Plugging this into the expression for trade yields

$$x^*_t = \frac{p^B_{t-l} + b_D x_{t-k-l} + a_{St} - \tau}{b_S + b_D}$$

Exports depend positively on the most recent price information from country B (controlling for supply).

2. *The variance of exports increases as information frictions fall.* The variance of exports is given by:

$$Var\left(x^*_t\right) = \frac{(t-l)\sigma^2_D + t\sigma^2_S}{(b_S + b_D)^2}$$

As the information lag l falls, the variance of exports increases:

$$\frac{\partial Var\left(x^*_t\right)}{\partial l} = -\frac{\sigma^2_D}{(b_S + b_D)^2} < 0$$

The intuition of this result comes from the fact that exports follow the predicted demand shock. This predicted demand shock, being a conditional expectation, varies less than the true demand shock[24]. The longer the information lag l, the larger the effect.

5 Testing the Model

The model's implications for the price difference are consistent with the empirical evidence provided earlier: The variance and the autocorrelation of the price difference fall after the telegraph. However, the predictions of the model are more detailed, in terms of the actual information lag. Since I have exogenous variation of the information lag, because of weather delaying steam ships in the pre-telegraph period, and because of technical breakdowns in the post-telegraph period, I can use this variation to test the prediction in more detail. I will also present empirical evidence for the implications of the model on trade flows in this section.

1. *The variance of price differences falls as information frictions fall.* I have already shown in Table 2 that the variance of the price difference falls after the telegraph.

One might argue that the changing variance of the price difference in the year after the telegraph might

[24] This result does not depend on assuming that the demand shocks follow a random walk, but holds in general as an implication of the law of interated expectations.

be due to other reasons. Instead of just comparing the standard deviation of the price difference before and after the telegraph, I can use the actual information lag l on each day that I have in the data, which is exogenous.

Figure 12 plots the variance of the price difference by information lag l, and except for some outliers at rarely observed extreme values for the information lag, the positive relationship is clearly visible. In order to make sure outliers don't drive this relationship, Table 3 regresses the variance of the price difference on information lags, weighting each observation by the underlying number of observations. The regression confirms a positive and significant relationship, consistent with my theory.

Driving this even further, I compute an estimator for the daily variance of the price difference $pdiff_t = p_t^{LIV} - p_t^{NY} - \tau_t$ using

$$\widehat{Var(pdiff_t)} = \left(pdiff_t - \overline{pdiff}_{before/after}\right)^2$$

where $\overline{pdiff}_{before/after}$ are average price differences before/after the telegraph, respectively. In Table 4 I use this as dependent variable, regressing it on the daily information lag. An increase in the information lag is associated with an increase in the Variance of the price difference (even after controlling for the variance of the supply).

2. *The autocorrelation function of the price difference falls if the information frictions get smaller.* Figure 13 plots the autocorrelation function of the cotton price difference between Liverpool and New York, separately before and after the telegraph got introduced (the lines are dashed when the autocorrelation becomes insignificant). The theory predicts that I should observe two changes in the autocorrelation function as information frictions fall: First, the autocorrelation function should shift downwards (but not necessarily a parallel shift) and second, the autocorrelation function should reach zero at a smaller lag. Figure 13 is consistent with both predictions: Before the telegraph, autocorrelations became insignificant after lag 16. After the telegraph, autocorrelations became insignificant already at lag 9. Also, the autocorrelation function after the telegraph has lower magnitudes for all of the lags.

3. *Exports depend on the most recent price information from country B.* Table 5 confirms that merchants used the most recent information they had when making their export decision. In column (1) I regress exports on the known price from Liverpool, using the sample in the pre-telegraph period. The relationship is positive and significant: If merchants have information about rising cotton prices in Liverpool, they react by exporting more.

   Since prices are serially correlated over time, the coefficient in column (1) might pick up the effect from a differently lagged price. In order to test whether it's really the most recent known price that influences the exports, I test against a counterfactual price in column (2), the (unkown) price in Liverpool from the day before, which they knew only once the telegraph got introduced. The counterfactual price turns out to be insignificant as expected, in line with the proposed mechanism by which only the most recent price information matters for the export decision.

   In columns (3) and (4) I control for cotton supply, which are insignificant (as expected) and which doesn't affect the results.

4. *The variance of exports increases as information frictions fall.* Table 1 also shows the impact of the telegraph on the variance of exports. Consistent with the model, the variance of exports increases significantly after the telegraph, by 45%.

   One might worry that I am picking up a trend in the variance of exports that's driven by something else, not the information frictions reduced by the telegraph. In order to make sure that this is not true, I calculate the variance of exports separately by information lag l, and plot the result in Figure 14. Except for two outliers (at information lags 4 and 14, which are based on very few observations), the variance of export falls continually as the information lag increases.

A regression of the variance of exports on information lag l weighted by the number of observations underlying each variance calculation in order to reduce the impact of outliers confirms a negative and economically significant relationship in Table 3.

Alternatively, I use a daily estimator for the Variance of exports, $\widehat{Var(x_t)} = \left(x_t - \overline{x}_{A/B}\right)^2$where $\overline{x}_{A/B}$ are average exports before/after the telegraph, and regress it on the information lag of the corresponding day. Table 6 confirms that the negative relationship holds, even when controlling for supply shocks. When I use both a dummy variable for the telegraph as well as the information lag, the coefficients become insignificant, but the sign and magnitude of the coefficients remain.

This paper is the first to point out that information frictions also have an impact on the second moments of trade and prices. This is of first order importance for welfare, because distorted exports (whether too large or too small) in any period will always lead to deadweight losses. The impact of information frictions on average exports will therefore be smaller than the impact of information frictions on welfare. The impact of information frictions on the variance of exports and price differences suggests that the welfare effects of the telegraph will be larger than when one just considers the average change in trade (e.g. as in Ejrnæs and Persson 2010). Unless merchants are risk neutral, my model does not predict any changes in average trade and price differences as a result of a change in information frictions[25]. However, information frictions still have an impact on welfare, and this is reflected in the effect on the variance of exports and price differences.

In summary, the empirical section is consistent with the predictions of the model along several dimensions: Merchants took into account the most recent information they had about Liverpool when they made their export decision in New York. When information frictions are small, exports are more volatile because they can better track the fluctuation of actual demand shocks in the destination market. Consequently, smaller information frictions lead to more integrated markets in the sense that the price difference becomes less volatile, less autocorrelated, and more similar to white noise.

6 Structural Estimation and Welfare Effects of Information Frictions

Equations (2) and 3 illustrate that information frictions cause distortions in trade flows due to imperfect information, which might be positive or negative. These distortions in exports result in equivalent violations of the law of one price (adjusted by shipment time).

Figure 15 illustrates the welfare effects in the baseline case, without any information frictions. Total welfare consists of consumer surplus (CS) and producer surplus (PS). The surplus of merchants (MS) is zero, because the gross profit[26] from exporting is spent on transport cost.

Information frictions have an impact on welfare, as illustrated in Figure 16 (for the case $p_{II} > 0$). Distortions due to imperfect information reduce exports compared to the case without information frictions, and enlarge the price gap. Both the consumer surplus and the producer surplus is much reduced, while in the graphed

[25] Note that I tested the implications of an extended model with risk averse merchants, yielding insignificant estimates for the risk aversion parameters

[26] Gross profits are the difference between purchasing and selling price, times exported quantity.

case merchants also make a (unexpected) surplus, net of trade cost.

Comparing the two figures, it becomes clear that imperfect information causes a deadweight loss, as total welfare under information frictions are smaller than without information frictions (this is also true for $p_{II} < 0$). The deadweight loss from imperfect information is given by the triangle given by the price distortions, p_{II}, and the trade distortion, x_{II}. Since demand and supply are linear, $x_{II} = \frac{p_{II}}{b_S + b_D}$, and the deadweight loss is given by:

$$W = -\frac{p_{II} x_{II}}{2} = -\frac{p_{II}^2}{2(b_S + b_D)} < 0$$

Note that the welfare effect is negative, indicating a deadweight loss whenever there are any information frictions.

I can get estimates for b_D from equation (3), if I express the demand and supply shocks in terms of observables (i.e. using $a_{St} = b_S x_t - p_t^A$ and $a_{D,t-l} = p_{t-l}^B + b_D x_{t-k-l}$). I rearrange the equation into the following form:

$$x_t - x_{t-k-l} = \frac{1}{b_D} \left(p_{t-l}^B - p_t^A - \tau_t \right)$$

I can estimate this equation using ordinary least squares:

$$x_t - x_{t-k-l} = \beta_0 + \beta_1 \left(p_{t-l}^B - p_t^A - \tau_t \right) \tag{4}$$

A note on identification of equation 4 is required here, as usually there is a simultaneity bias when regressing quantities on prices in order to estimate a demand elasticity. However, due to the information frictions, Liverpool demand is effectively fixed at their past levels the moment when New York merchants make their trading decision. Hence, any current supply shocks provide variation along the demand curve and allow me to identify the demand elasticity as long as I can correctly control for these fixed demands. The model shows that past demand shocks can be derived from past Liverpool prices and imports.

I regain estimates for b_D from the estimated coefficients of this regression:

$$\hat{b}_D = \frac{1}{\hat{\beta}_1}$$

I derive an estimate for p_{II} by expressing the demand and supply shocks in terms of observables, using estimate $\hat{b}_D$ from before:

$$\hat{p}_{II} = a_{D,t+k} - a_{D,t-l} = p_{t+k}^B - p_{t-l}^B + \hat{b}_D \left(x_t - x_{t-k-l} \right)$$

Using these estimates for $\hat{b}_D$ and $\hat{p}_{II}$, I estimate an upper bound of the deadweight loss $\overline{DWL}$ (given by $b_S = 0$) caused by information frictions:

$$\overline{DWL} = \frac{\hat{\beta}_1}{2} \hat{p}_{II}^2$$

The first column of Table 7 implements regression 4. Column (1) ignores trade cost, yielding demand elasticity (evaluated at average prices and trade) of around 2 (see last row in the table). Column (2) includes transport cost, which doesn't affect the estimated demand elasticity. My estimates are a bit smaller than other estimates in the literature. For example, Johnson (1977) estimates the export demand elasticity of American cotton to be 5.5. This larger value might be explained to the fact that he uses data from the 1970s, which is more than one century later than the time.

As a next step, I calculate the estimate for the price distortions, $\hat{p}_{II}$, as explained above. Figure 17 illustrates the daily price distortion due to imperfect information. The price difference falls radically after the telegraph gets introduced. The average price distortion in the pre-telegraph period is equivalent to an average ∼10% ad valorem tariff. The largest price distortions during the pre-telegraph period were equivalent up to a 50% ad valorem tariff.

Finally I use all the estimates to compute the welfare effects of the telegraph. Figure 18 shows the welfare loss from information frictions over time. The telegraph almost eliminated the deadweight loss from information frictions: It fell from an average of 73,227 pounds/year by 82% to 13,211 pounds/year, equivalent to 2% of the value of total cotton exports. The deadweight loss might be higher in the case of risk aversion, but I didn't find significant evidence for that.

7 Conclusions

The objective of this paper was to understand the importance of information frictions in explaining deviations from the law of one price; an empirical phenomenon that is widely documented in the literature.

I provide empirical evidence on the impact of information frictions on the LOP using a clean historical experiment that reduced information frictions suddenly and unexpectedly: the transatlantic telegraph, connecting the United States and Great Britain in 1866. The telegraph led to a lower volatility of the difference of cotton prices across New York and Liverpool, and the autocorrelation of the price difference also fell. These findings are robust to a number of alternative explanations, such as transport cost variations, supply irregularities in the aftermath of the American Civil War, fluctuations within "commodity points" in no trade periods, futures or forward trading, and anticipation effects.

Instead, the pattern in the LOP can be explained considering the change in information flows induced by the telegraph. In the absence of up to date information, market participants seem to use the known, outdated, price information to form expectations of the true price.

The empirical evidence motivates the model developed in this paper. It is based on a simple model of international trade, where intermediaries assume the role of international arbitrageurs. Information frictions take the following form: Intermediaries don't have perfect information about market conditions in the foreign countries, instead they form an expectation about these conditions based on their information set. The LOP will not hold in this setting, as intermediaries will equalize expected rather than actual (unknown) prices. This model can explain the distortions of the LOP observed in the data: Longer information lags lead to a higher volatility and autoregression of the price difference.

The model also yields several testable implications for trade flows: First, the known price information will influence the export decision of merchants, because it is used to form an expectation of the future price. Second, the better the information of merchants, the more volatile are trade flows. This is because with better information, trade will follow actual rather than expected foreign demand shocks, which are more volatile than the latter.

The empirical evidence on cotton trade flows is consistent with the predictions of the model. I then use the model to empirically estimate an upper bound for the impact of information frictions on welfare: The information frictions during the pre-telegraph era were equivalent to a 10% ad valorem tariff.

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Appendix

A Figures

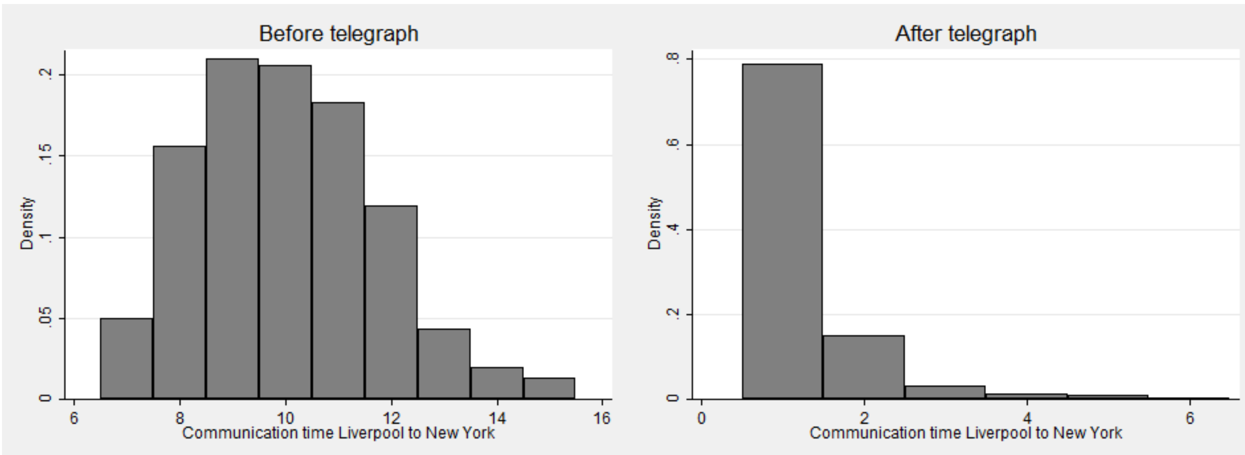


Figure 1: Distribution of information lags between New York and Liverpool (work days), before and after the telegraph

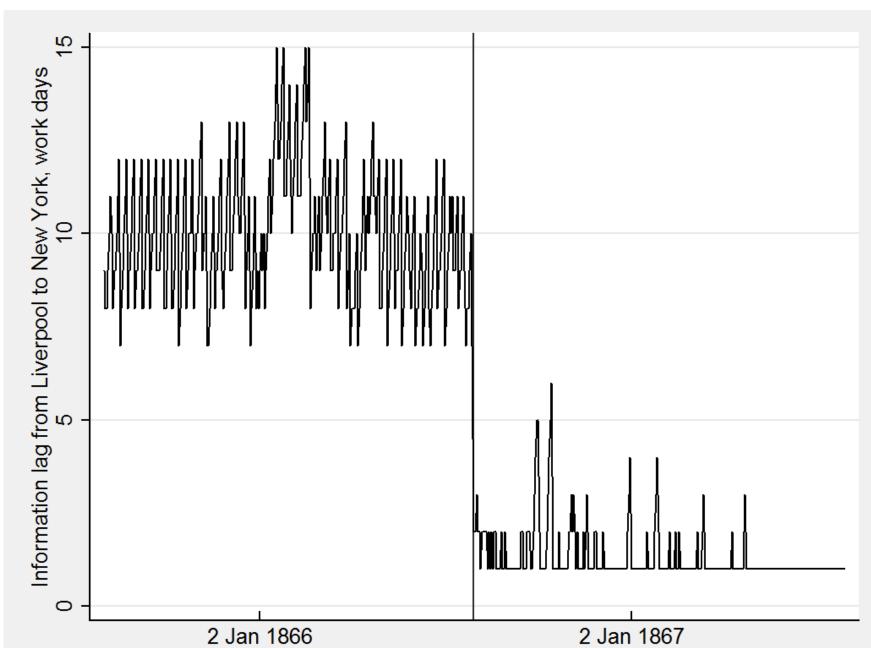


Figure 2: Information lag between New York and Liverpool over time

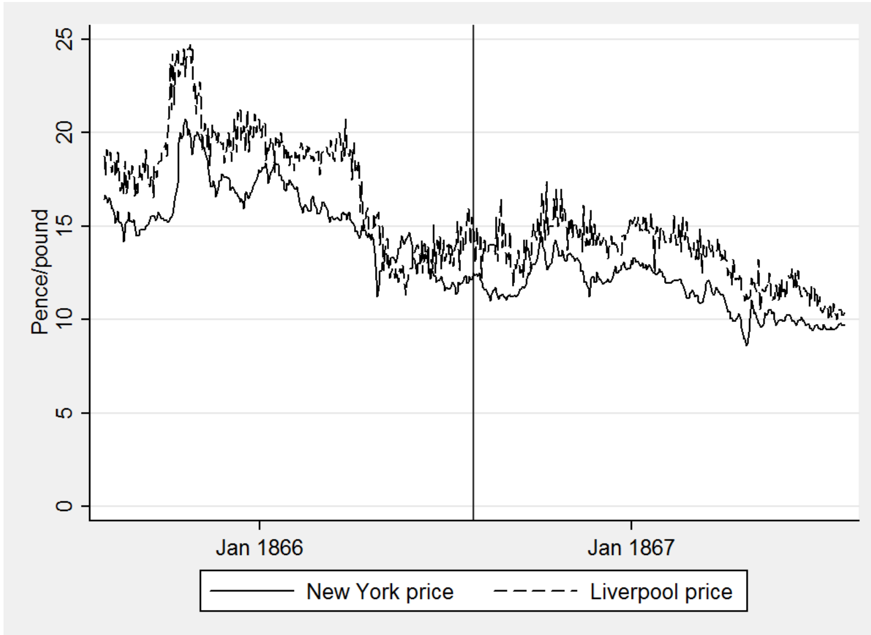


Figure 3: Price series

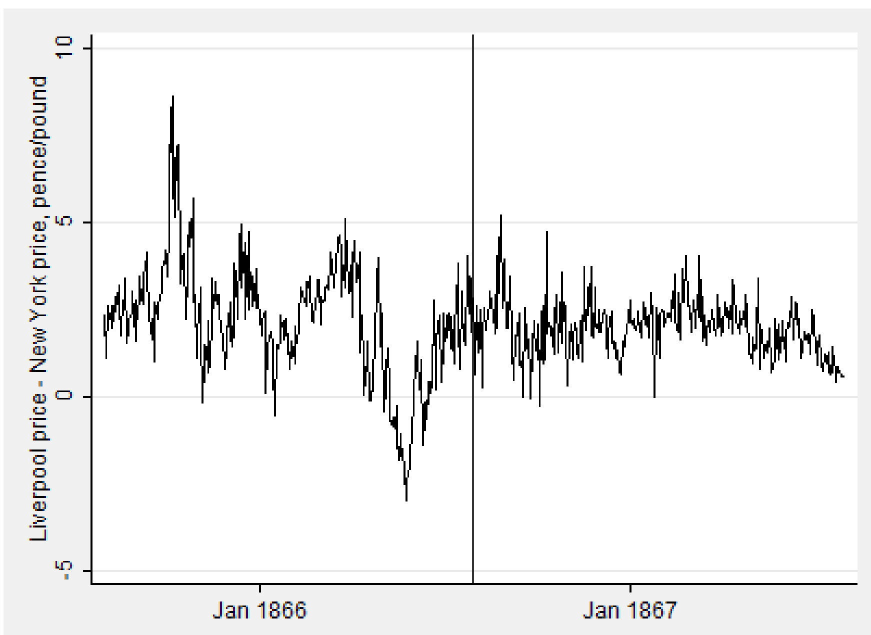


Figure 4: Price difference of American cotton in New York and Liverpool

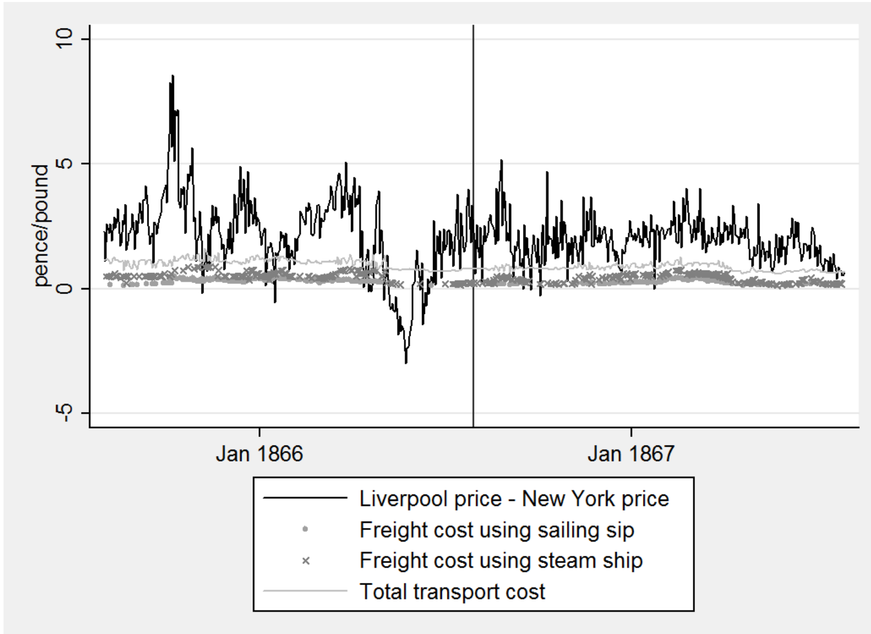
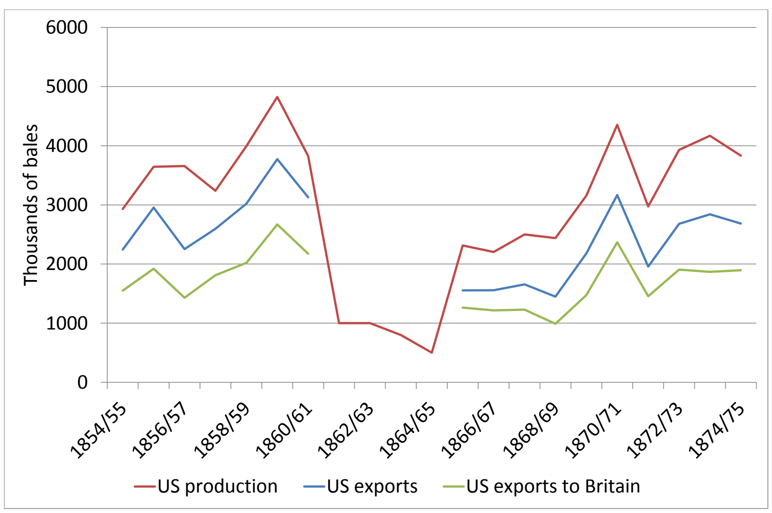


Figure 5: Price difference and freight cost



Source: Ellison (1886). Production numbers during the Civil War (cotton year 1861/62 to 1864/65) are estimates from New York Shipping and Commercial List as reproduced in Hammond (1897). Note that the cotton year starts on September 1 and ends on August 31.

Figure 6: Cotton production and exports of the United States

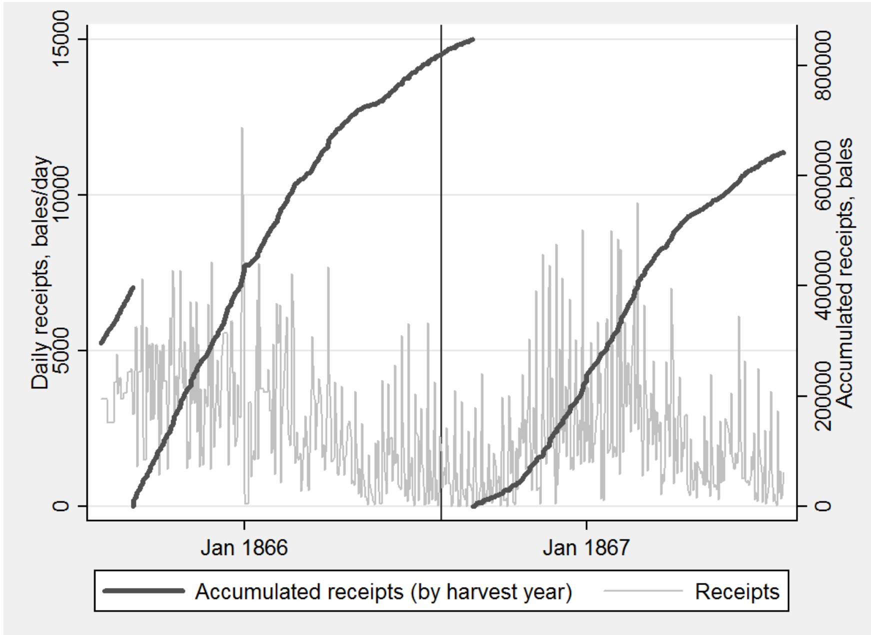


Figure 7: Cotton receipts at the New York exchange

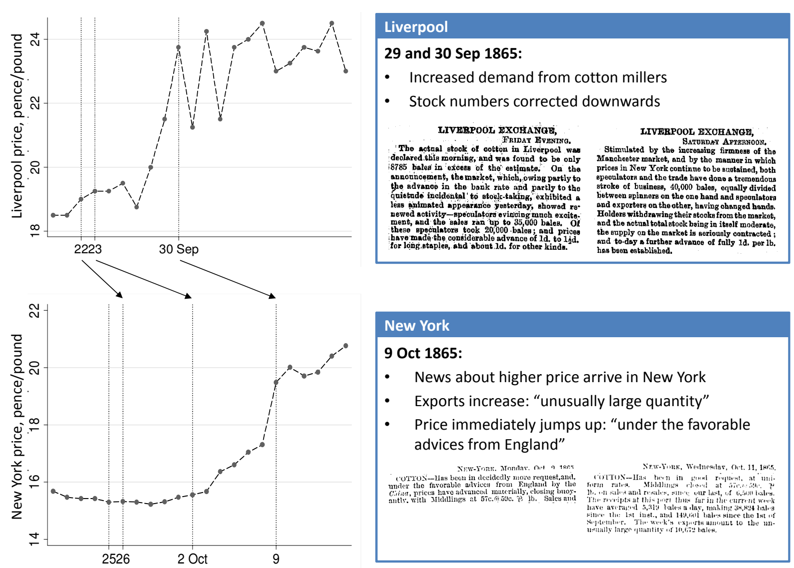


Figure 8: Lagged transmission of price shock from Liverpool to New York before telegraph

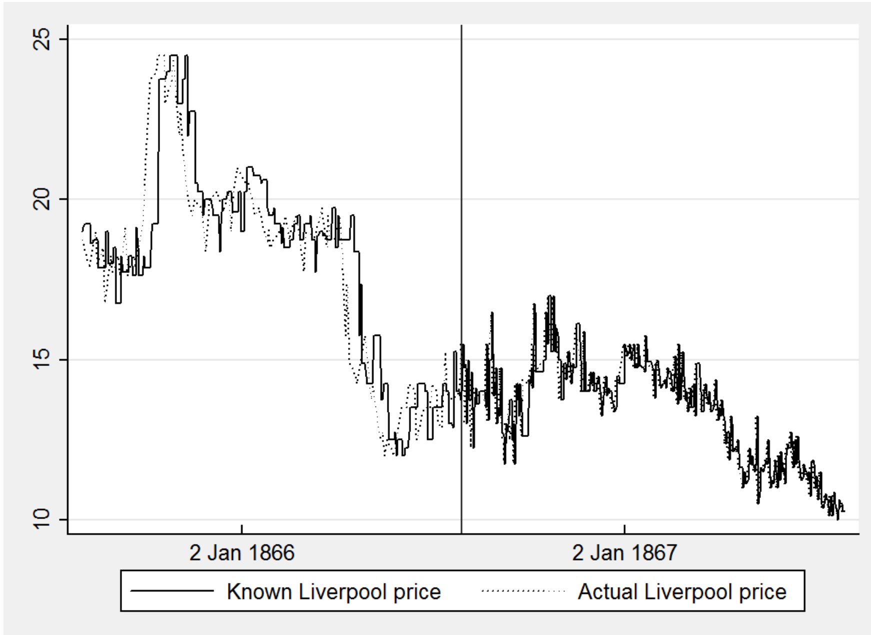


Figure 9: Most recent price information from Liverpool versus actual Liverpool price

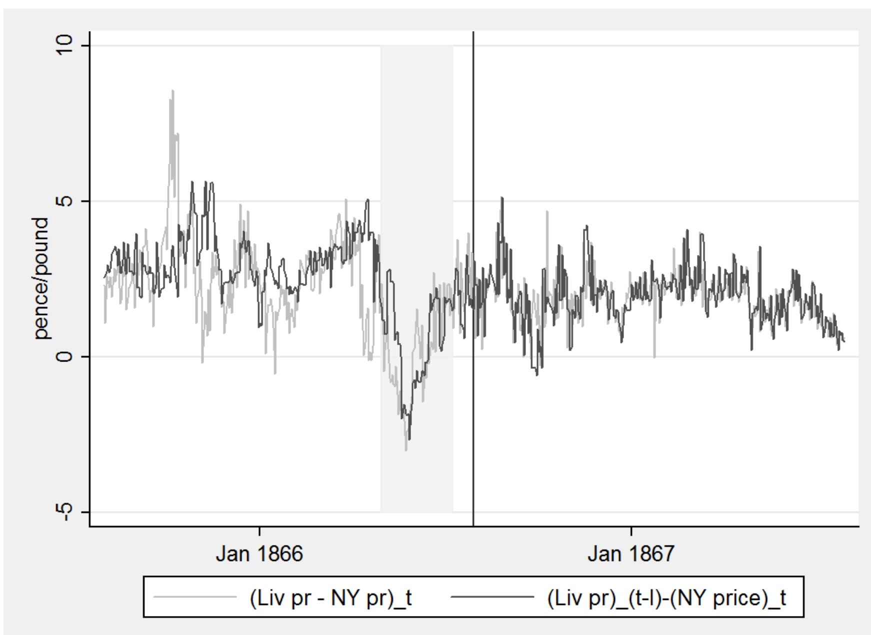


Figure 10: Contemporaneous price difference and price difference to the known, lagged, Liverpool price

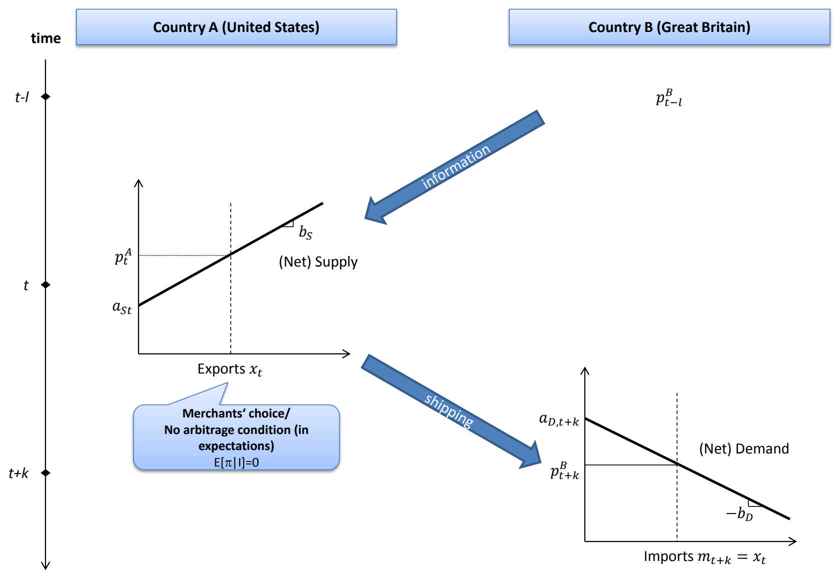
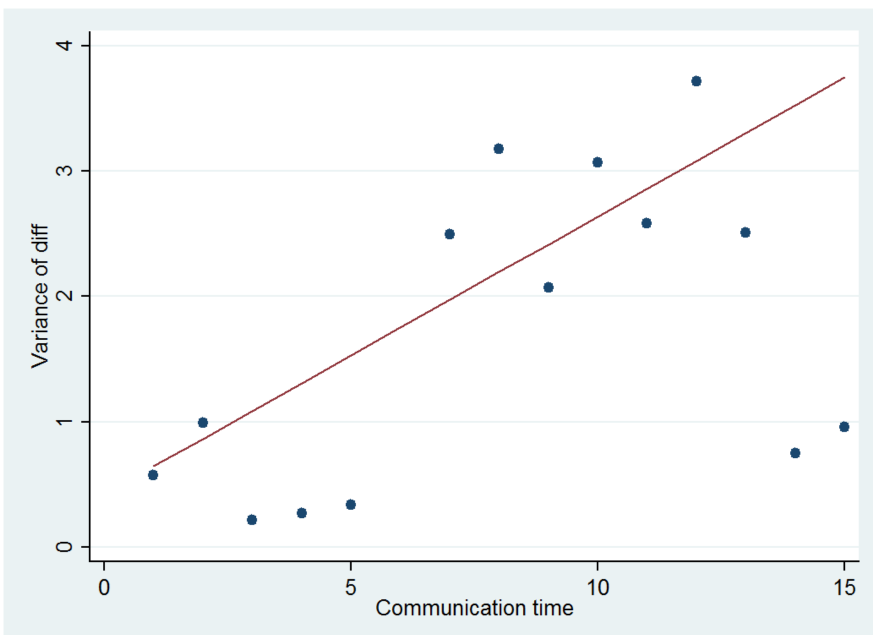


Figure 11: Sketch of the model



Note: The variance of the price difference is computed across all observations with the same information lag l.

Figure 12: Variance of price difference as a function of information lag l

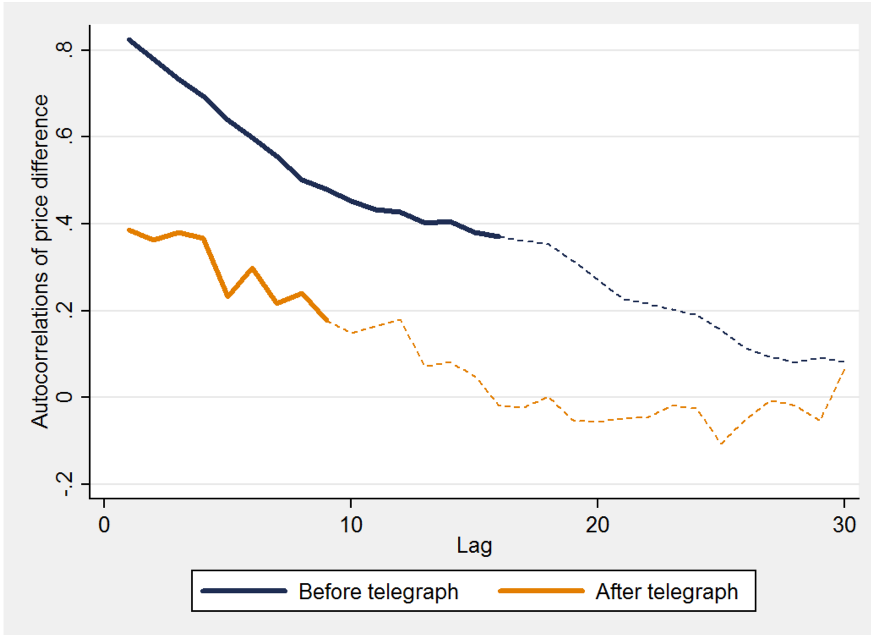
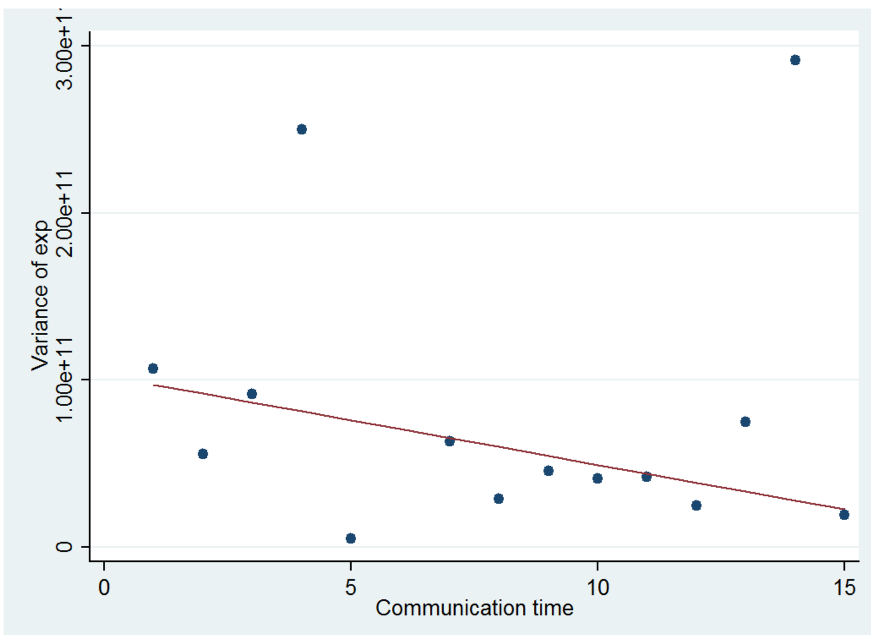


Figure 13: Autocorrelation of price difference, before and after the telegraph



Note: The variance of exports is computed across all observations with the same information lag l.

Figure 14: Variance of exports as a function of information lag l

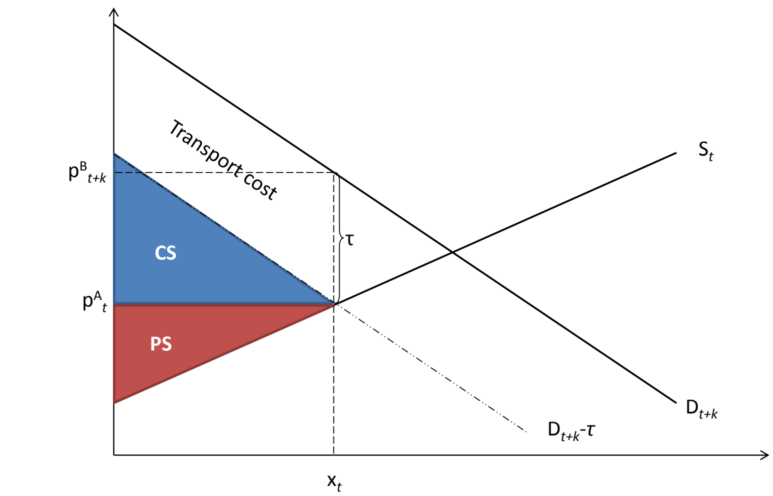


Figure 15: Welfare under perfect information

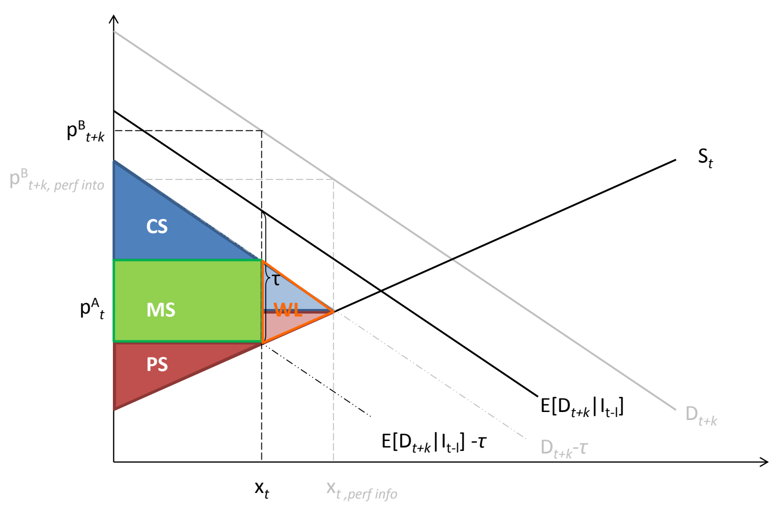


Figure 16: Welfare under information frictions

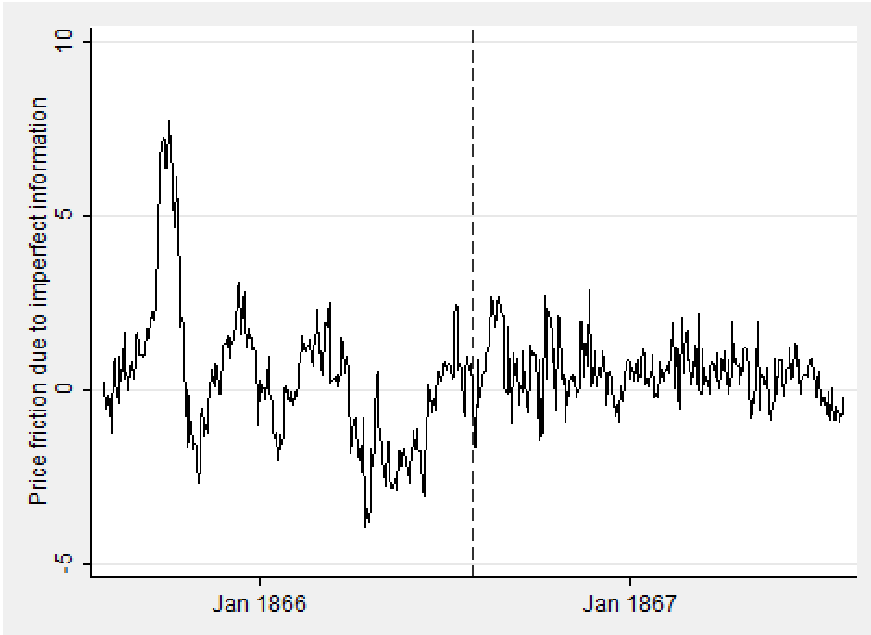


Figure 17: Estimated price distortions due to information frictions

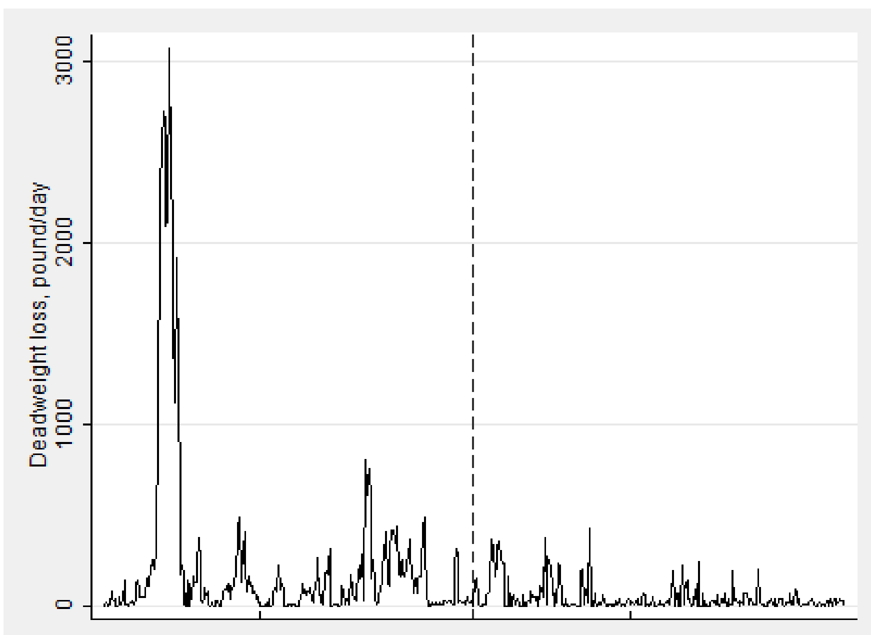


Figure 18: Estimated welfare loss due to information frictions

B Tables

Table 1: Summary statistics, before and after telegraph

	Before telegraph	**After telegraph**	**Difference**
Information lag between New York and Liverpool, work days			
Mean	10.03	1.31	-8.72***
	(0.10)	(0.04)	
Minimum	7	1	
Maximum	15	6	
Contemporaneous price difference $p_t^{LIV} - p_t^{NY}$, pence/pound			
Mean	2.23	1.93	-0.30***
	(0.10)	(0.05)	(-13.6%)
Standard deviation	1.71	0.81	-0.90***
			(-53.2%)
Trade x_t (exports from New York to Liverpool, pounds)			
Mean	184,614	255,072	+70,458***
	(12,497)	(18,123)	(38.2%)
Standard deviation	216,098	314,942	+98,844***
			(+45.7%)

Table 2: White noise tests of price difference

	Portmanteau test			**Bartlett test**		
	Before telegraph	**After telegraph**	**Change**	**Before telegraph**	**After telegraph**	**Change**
$p_t^{LIV} - p_t^{NY}$						
(1) Full sample	1792.38	313.59	-1478.79	8.64	4.31	-4.33
(2) Excl. no trade periods	688.86	313.59	-375.27	6.50	4.31	-2.19
(3) Transport cost						
Sailing ship freight cost	676.63	284.91	-391.72	6.52	4.11	-2.41
Steam ship freight cost	745.09	215.81	-529.28	6.51	3.47	-3.04
Average freight cost	701.30	246.08	-455.22	6.48	3.76	-2.72
Total transport cost	688.34	242.03	-446.31	6.46	3.69	-2.77
(4) Supply irregularities	596.24	202.64	-393.60	6.00	3.32	-2.68
$p_{t-l}^{LIV} - p_t^{NY} - \tau_t$						
(5) All of the above	556.73	304.02	-252.71	5.74	4.57	-1.17

Note: This table displays the test statistics of the Portmanteau (Ljung–Box test) and Bartlett tests, respectively. Under H0 (white noise), the Portmanteau test-statistics$\sim \chi^2_{40}$, the critical values for rejecting H0 are 51.81 (significance level 10%), 55.76 (5%) and 63.69 (1%). The critical values for rejecting H0 using the Bartlett test are 1.223 (significance level 10%), 1.358 (5%) and 1.627 (1%). As the white noise tests are only meaningful on time series without gaps, I interpolated the price difference for the 2 missing observations before the telegraph, and 9 observations after the telegraph. These observations are missing because Liverpool prices are sometimes not reported in the newspaper on Fridays (there is a weekly summary instead).
Each row adds restrictions to the row before (with the exception of transport cost, where I provide four alternative measures). In (2) the period of 4 weeks during May 1866 (when exporters were inactive because the price in New York exceeded the price in Liverpool) is excluded. In (3) transport cost are substracted from the price difference before conducting the white noise tests. As freight cost are not available for all the periods, they are interpolated when missing. The freight cost using a combination of sailing and steam freight rates uses the average if both are given, or the freight rate that is available (freight cost are not printed in newspapers if the freight type was not used). Total transport cost include the combined freight cost, additional 0.17 pence/pound unit freight cost, and 3.1% ad valorem transport cost (on the New York price). In (4) the white noise test is based on the residual from the regression of the price difference reduced by total transport cost on daily cotton supply (receipts). In (5) the same specification is used as in (4), but the contemporaneous Liverpool price is replaced by the known Liverpool price.

Table 3: Variance of price difference and exports, computed by groups of observations with the same information lag

	Var(price difference)	Var(exports)
Information lag l	0.222***	-5.327e+09***
	(0.028)	(1.660e+09)
Obs	14	14
Weights	# underlying observations	# underlying observations

Note: Var(exp)= $(x_t - \overline{x}_l)^2$where $\overline{x}_l$ are the average exports of all observations with information l. Same for the price difference. Robust standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 4: Variance of price difference, using daily observations

	(1) Var(price difference)	(2) Var(price difference)	(3) Var(price difference)	(4) Var(price difference)	(5) Var(price difference)	(6) Var(price difference)
Telegraph dummy	-1.380***		-0.516	-1.355***		-0.472
	(0.281)		(1.202)	(0.273)		(1.214)
Information lag l		0.150***	0.0967		0.146***	0.0983
		(0.0306)	(0.130)		(0.0296)	(0.131)
Var(supply)				2.00e-05	2.77e-05	2.31e-05
				(5.61e-05)	(5.58e-05)	(5.64e-05)
Observations	534	534	534	534	534	534

Note: Var(price difference)= $\widehat{Var(pdiff_t)} = \left(pdiff_t - \overline{pdiff}_{A/B}\right)^2$ where $\overline{pdiff}_{A/B}$ is the average price difference in the period before the telegraph, if the observation corresponds to the period before, and after the telegraph, if the observation lies within the period after the telegraph. Robust standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 5: Impact of known vs. counterfactual Liverpool price on exports

	(1) $ln\,(exports)_t$	(2) $ln\,(exports)_t$	(3) $ln\,(exports)_t$	(4) $ln\,(exports)_t$
Known Liverpool price: $ln\left(p_{t-l}^{LIV}\right)$	2.039***	1.840**	1.917***	1.798**
	(0.426)	(0.807)	(0.470)	(0.812)
Counterfactual "telegraphed"		0.234		0.151
Liverpool price: $ln\left(p_{t-1}^{LIV}\right)$		(0.827)		(0.848)
Cotton supply			0.0392	0.0360
			(0.0674)	(0.0688)
Observations	217	217	217	217
R-squared	0.104	0.105	0.10	0.106

Note: The regressions use only the sample before the telegraph was established. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 6: Variance of exports, using daily observations

	(1) Var(exports)	(2) Var(exports)	(3) Var(exports)	(4) Var(exports)	(5) Var(exports)	(6) Var(exports)
Telegraph dummy	408,751***		62,136	478,734***		210,430
	(110,212)		(220,550)	(131,702)		(258,855)
Information lag l		-50,908***	-43,467		-58,470***	-33,480
		(13,843)	(30,242)		(16,041)	(31,130)
Var(supply)				51.75	49.40	50.77
				(43.45)	(42.81)	(43.71)
Observations	337	337	337	337	337	337

Note: Var(exp)= $\widehat{Var(x_t)} = \left(x_t - \overline{x}_{A/B}\right)^2$where $\overline{x}_{A/B}$ is the average exports in the period before the telegraph, if the observation corresponds to the period before, and after the telegraph, if the observation lies within the period after the telegraph. Robust standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1.

Table 7: Structural estimation of parameters

	(1)	(2)
	$x_t - x_{t-k-l}$	$x_t - x_{t-k-l}$
$p^B_{t-l} - p^A_t$	25,834***	
	(8,531)	
$p^B_{t-l} - p^A_t - \tau_t$		24,945***
		(9,229)
Observations	601	601
Implied demand elasticity	1.995	1.926

Note: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.