Commodities, capacity, and convenience: what can be learned from high frequency price variability?

Andrew Coleman
University of Otago and New Zealand Treasury
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andrew.coleman@otago.ac.nz
Abstract
Two features of the industries producing and transporting commodities are (i) they are capital intensive and often capacity constrained; and (ii) they experience high frequency price volatility. Various theoreticians and observers have linked these features, arguing capacity constraints cause periods of high prices, and periods of high prices are needed to justify investment in capacity. It is well known that commodities are often stored when the spot price exceeds the future price in a central market. Wright and Williams conjectured that inventories are held in locations far from the central market on these occasions, and not immediately delivered to the central market because capacity constraints force temporary increases in transport prices. In the locations where inventories are held, spot prices are lower than forward prices even if they are higher than forward prices in the central market. Until now, this hypothesis has not been directly tested, because prices for forward delivery are not normally available at non-central locations. This article uses an example where these prices exist to test the hypothesis. The evidence, from the late nineteenth century corn markets in Chicago and New York, strongly supports the conjecture, and suggests time varying transport costs are a cause of high frequency fluctuations in commodity prices.
Introduction

A feature of the world economy in the last two and a half centuries has been the astonishing increase in the production and trade of industrial commodities. In broad terms, this phenomenon has reflected an enormous improvement in the efficiency of production, extraction, and transportation technologies, and an associated decline in the relevant prices. Over the course of this period traders, producers, economists, and economic historians have observed and analysed many aspects of these prices. Five of these features are salient for this paper.

1. Commodity prices are volatile, often experiencing sharp increases followed by declines.
2. In real terms, most commodities have fallen in price, or have little trend, over long periods of time.
3. Transport prices are volatile, often experiencing sharp increases followed by declines.
4. In real terms, transport prices have decreased significantly over time.
5. Most commodities have a “Supply of Storage” curve, linking the spot-forward price spread to the amount of the commodity in storage. In all cases the forward price exceeds the spot price when large quantities of inventories are held, but some inventories are held even when the spot price exceeds the price for forward delivery.

Economic historians, in particular, have focused upon and celebrated the long decline in transport costs and their role in integrating world markets (eg North 1958; Harley 1980; O’Rourke and Williamson 1999). Without these declines, the vast increase in trade would not have occurred. Yet here has been much less focus on the volatility of transport prices,
despite the contention of many industry participants and observers that it is central to understanding investment patterns and the overall capacity of the industry (Koopmans 1939; Zannetos 1966; Stopford 1988; Adland 2003). The capital intensive nature of the transport industry means that transport prices have volatile “peak load” pricing characteristics caused by occasional periods when capacity constraints bind (Williamson 1966). These price peaks enable owners of the capital to make a profit on their investment, and determine the timing of new investment or scrapping. A parallel literature suggests there may be a similar link between price volatility, investment patterns, and production capacity in mining industries (Adelman 1990).

Capacity constraints in the mining and transport industries have the potential to explain two separate puzzles. The first is why mineral prices have not increased at the rate of interest, given the incentive of a producer to increase output and invest the proceedings if prices do not increase at this rate (Hotelling 1931). When there are production capacity constraints, producers cannot increase production to take advantage of high prices without first increasing productive capacity. The incentive to increase capacity must balance the benefit of bringing production forward against the higher cost of expanding capacity within an existing mine, or developing a new mine. The fine balance of these costs and benefits means a rapid change in capacity rarely occurs unless there is a significant reduction in production technologies, or a significant increase in demand. Under these circumstances, the value of mineral resources in an individual mine increases at the rate of interest, even if neither the total value of the mine (including the value of invested capital) or global prices increase at this rate (Cairns 2001).
The second puzzle is why commodities are stored when the future price is lower than the spot price — that is, when prices are in backwardation. The standard explanation for this curve, dating back to Kaldor (1939), Working (1949), and Brennan (1958), is that some agents hold inventories when the future price is lower than the spot price because they gain a “convenience yield” from their stocks. In the last two decades, several authors have questioned the necessity of the “convenience yield” explanation for a supply of storage curve. Wright and Williams (1989) argued that the supply of storage curve might be an artifact of an inappropriate method of aggregating inventory levels when there is high frequency transport cost variation, most likely due to transport capacity constraints. In particular, they argued that inventories held at locations far from a central market where prices were in backwardation would not be sent to the central market if transport costs were temporarily high, as it would be more profitable to wait until they were lower. Indeed, in these circumstances, spot-future price spreads would vary over space. Even if the spot price exceeded the future price in the central city, in the locations where the inventories were actually held the future price would exceed the spot price.

A simple two centre example makes their argument clear. Suppose there is a central market C with a spot price $S_t^C$ and a future price $F_t^{C,1}$ that imports from a distant market D. If it costs $K_t^T$ to ship goods immediately, and $K_{t+1}^T$ to ship them at $t+1$, the spot and future prices in the distant market will be $S_t^D = S_t^C - K_t^T$ and $F_t^{D,1} = F_t^{C,1} - K_{t+1}^T$. The spot-future price spreads in the central and distant markets will be $S_t^C - F_t^{C,1}$ and $S_t^C - F_t^{C,1} + (K_{t+1}^T - K_t^T)$ respectively. Consequently, if transport costs are temporarily high, spot prices can be
lower than future prices in the distant centre (or lower than the expected future spot price, if a futures market does not exist) even if the reverse is true in the central market.

Coleman (2009a) formally developed their model, explicitly introducing transport capacity constraints and travel time into a model of commodity prices under uncertainty with two centres and storage. This model derived the distribution of transport costs and spot and forward commodity prices, and showed that transport prices should have peak-load pricing characteristics. As the profits earned when transport prices were above marginal cost paid for the transport capacity investments, transport price variability and across-space commodity price variability was needed to attract investment into the sector. This accords with more than a century of industry comment (eg United States Congress (1874); Snodgrass (1926); Stopford (1988)). Moreover, the model suggested that spot-future spreads would often vary across space. When transport capacity was fully utilized, the model predicts forward prices would exceed spot prices in an exporting centre, whereas spot prices would exceed forward prices in the importing centre.

In both cases, the most important long term issue concerns the extent that commodity price volatility is needed to attract investment into capital intensive industries. In each case, the theoretical models investigating the effects of capacity constraints on output also have implications for the time paths of the shadow prices of the resources (minerals in the ground, or stored commodities awaiting transport) and the shadow values of additional investment. Aldeman (1990) calculated the shadow value for oil reserves when extraction capacity constraints are binding and showed that they were reflected in the actual prices paid
for working oil wells\textsuperscript{1}. This provides some support for a theory of mineral prices in which capacity constraints have an important role. Up to now, however, there has been little empirical support for the Wright-Williams conjecture that transport capacity constraints are a major reason why inventories are held when the spot rate exceeds the forward price.

A central aspect of the Wright-Williams conjecture is that even if spot prices exceed forward prices in a central market, forward prices will exceed spot prices in the non-central locations where inventories are held. In general, the non-central locations where inventories are mainly held do not have futures markets, so this prediction has not been able to be tested as spot-future price spreads cannot be calculated in these locations. The best support is from Brennan, Williams and Wright (1997), who examined the rail transportation and storage networks used to transport wheat to the Australian port of Freemantle to provide empirical support for this argument. They demonstrated that wheat was stored alongside railroads far from the port even when port prices were in backwardation because it was more profitable to store the grain and wait for off-peak transportation than it was to ship it in the peak transport season. Yet they were unable to show that the future price was higher than the spot price in the areas where inventories were held, because future prices did not exist in these locations.

This paper directly tests this aspect of the Wright-Williams conjecture using an historic example where two futures markets existed in close proximity. The example is the New York and Chicago corn markets in the late nineteenth century - markets that were a part of the

\textsuperscript{1} These values were systematically lower than the values consistent with a metric based on the Hotelling rule. He noted that a valuation methodology consistent with capacity constraints is widespread in the oil industry.
huge trans-Atlantic grain trade. The data are ideally suited to test their hypothesis because transport costs varied seasonally and both cities had active futures markets with spot-future price spreads that were often different. In addition, high frequency (weekly) transport price and volume data are available that enable an exploration of the relationship between transport prices, transport volumes, and commodity price spreads.

The data support their hypothesis. Each year, transport costs from Chicago to New York were high during the winter because the lowest cost transportation method — by ship to Buffalo and then by canal to New York — was unavailable. During this season shipping agents stored large amounts of grain in Chicago, choosing to store grain and wait for the opening of the lakes in May rather than to ship by rail immediately. The May future price exceeded the spot price during this time by an amount similar to the cost of carrying inventories. In contrast, the May future price in New York was lower than the spot price in several of the years examined, normally when New York inventories were low, although not literally zero. This evidence provides direct evidence in favour of the Wright Williams conjecture, that the spot price is lower than the shadow forward price in locations where inventories are actually held. It also provides some evidence for their more general point, that convenience yield is not necessary to generate a supply of storage curve if a supply of storage curve compares inventories held in many locations with the spot-future price differential of a single location. On these occasions, a comparison of the New York spot-future price spread against total (New York plus Chicago) inventories would falsely suggest that large quantities of inventories were held when the spot price exceeded the future price, for most of these inventories were held in Chicago where future prices exceeded spot prices.
If transport prices are variable, the Wright-Williams model has a further implication: inventories can be profitably stored in a centre where local prices are in backwardation if prices are expected to increase before decreasing. For example, corn could have been stored in New York in January even though the January spot price exceeded the May future price if the price for delivery in February was higher than the January price. This possibility was tested to see if it explains why inventories were held in New York when the spot price exceeded the May future price. It does not. Even though May transport costs were lower than winter transport costs, there were almost no examples when the spot price in winter was lower than the price for delivery one month later.

The empirical focus of this paper is deliberately limited: it simply tests the Wright-Williams conjecture using data from a particular historic episode. It doesn’t provide evidence of the importance of capacity constraints or price volatility to explain investment in the mining or transport industries, even though this provides the broader context for why the question is of interest. It does, however, provide a little evidence suggesting that high frequency shipping prices and shipping volumes are positively correlated, and that transport price volatility is associated with the pattern of commodity prices over space.

The paper starts with a brief summary of arbitrage relationships in section 2. The operation of the late nineteenth New York and Chicago corn transport market is described in section 3. An analysis of the relationship between transport prices and transport volumes during the summer months is presented in section 4, while the test of the Wright-Williams conjecture is presented in section 5. Lastly, a discussion is offered in section 6.
2. Arbitrage Price Relations

This section provides a brief outline of the way storage and transport arbitrage affect commodity prices in different locations. It is deliberately simplified by assuming transport is instantaneous but costly. Coleman (2009a) solves the more complicated case where transport takes time and where there are transport sector capacity constraints.

Consider a model of trade and storage in a central market C and a “distant” market D that regularly exports to C. In each location i there is a spot price \( P_i^t \) for immediate delivery and a future price \( P_i^{t,n} \) for delivery in n periods. It is assumed that trade from D to C can take place instantaneously. Let \( T_i^D \) be the shipments from D to C, and \( K_i^T \) the cost of shipping goods at time t. Let \( S_i^C \) and \( S_i^D \) be the quantities stored in each centre at time t. There are two storage costs: a storage fee of \( K^S \) per period, and an interest rate opportunity cost \( r \). For ease of exposition, in the following derivation it is assumed the storage costs are the same in each centre and invariant through time.

Following Samuelson (1952) and Williams and Wright (1991), the conditions for profitable trade from D to C at time \( t \) and \( t+n \) are:

1. \[
    P_i^C \leq P_i^D + K_i^T; \quad \left[ P_i^C - (P_i^D + K_i^T) \right] T_i^D = 0
\]

2. \[
    F_i^{C,n} \leq F_i^{D,n} + K_{{t+n}}^T; \quad \left[ F_i^{C,n} - (F_i^{D,n} + K_{{t+n}}^T) \right] E[T_{i+n}^D] = 0
\]

where \( E[T_{i+n}^D] \) is the expected trade at time \( t+n \).
These equations state that the price in centre C will equal the price in centre D plus shipping costs when C imports from D; otherwise, the price in centre C will be less than the price in centre D plus shipping costs. Note that these equations hold in the case when there are binding capacity constraints. If there is a capacity constraint $T$ and $T_i = T$, equation 1 holds with equality because transport prices rise to make it hold.

The conditions for profitable storage at time $t$ when there is no convenience yield are:

$$\frac{1}{1 + r} F_{i,t}^{i,1} \leq P_t' + K^S \left[ \frac{1}{1 + r} F_{i,t}^{i,1} - \left( P_t' + K^S \right) \right] S_t' = 0$$

This pair of equations states that the future price in a centre will equal the spot price plus the costs of storage if inventories are positive; if inventories are zero, the future price will be less than the spot price adjusted for storage costs. Equation 3 has the implication that storage will be zero whenever spot prices are greater than the future price.

These equations can be used to analyse two different relationships between inventories and price spreads. The relationships are derived formally in Appendix 2. First, the conditions when the central market has no inventories and when prices are in backwardation even though there are inventories in the distant market are derived by analysing the arbitrage relationships described by equations 1 – 3 over two periods. The key conditions are that both transport costs and the prices in the importing centre must be temporarily high. In particular, if $S_t^C = 0; S_t^D > 0; K_t^T > K_{t+1}^T$, it is possible that $S_t^C - F_t^{C,1} > 0$ and $S_t^D - F_t^{D,1} = S_t^C - F_t^{C,1} + (K_{t+1}^T - K_t^T) < 0$. (The exact conditions depend on whether trade at $t= 0$ is positive or zero.) This, of course, is the argument made by Wright and Williams.
The second case concerns the conditions when a market can have inventories even though the spot price is greater than a distant future price. These are derived by analysing the arbitrage relationships described by equations 1 – 3 over three periods. It is shown that inventories may be profitably held in the central market when prices in that market are in “long-term” backwardation if prices in the central market are expected to first rise and then fall. This can occur if transport prices are expected to be temporarily high for some of the time between the present and the time that they are required for future delivery, that is if

\[ K_{t+1}^T > K_{t+2}^T \]

3. The New York and Chicago nineteenth century corn markets

This paper uses data from the New York and Chicago corn markets in the late nineteenth century to test the Wright-Williams conjecture. The period has been chosen because both cities had active futures markets in the same grade of corn and thus spot-future price spread can be calculated at the two locations. The relatively close proximity of these two futures markets is unusual, but provides an ideal setting to examine the hypothesis.\(^2\) The markets co-existed because seasonal transport fluctuations meant that a contract promising delivery in Chicago was not always a good substitute for a contract promising delivery in New York. In this section the major features of these markets including trade-flows, transport costs and storage patterns are described.

*Basic Production and Shipping Patterns.*

In the late nineteenth century, the Great Plains region west of Chicago was the main corn producing area in North America. Nebraska, Iowa, and Illinois typically produced a third of
the U.S. crop, which amounted to 2000 million bushels in 1891; in contrast, New York, New Jersey, and Pennsylvania only produced 75 million bushels per year. Chicago was the preeminent midwestern transportation centre as a result of its inward and outward transport networks. It shipped an average of 62 million bushels per year during the period 1875 – 1889, primarily to New York, Boston, Baltimore, and Philadelphia. Most of this corn was exported to Europe. New York was the most important of these ports and frequently accounted for more than half of East Coast corn exports. Both Chicago and New York developed elaborate infrastructure to handle large volumes of corn and other grains.

The transport links between Chicago and New York were central to the operation of this market. There were three ways that corn could be shipped from Chicago to New York:

(1) by ship over the Great Lakes to Buffalo, and thence by canal boat to New York, a trip taking 20 days on average;

(2) by ship over the Great Lakes to Buffalo, and thence by rail to New York, a trip taking 10 days on average; or

(3) by rail to New York, using various lines, a trip taking 3-4 days.

While the Great Lakes shipping route was the primary means of transporting corn from Chicago, it was not available between December and April as the harbours and canals froze. In contrast, the rail route operated all year round. However, since rail freight rates were significantly more expensive than lake and canal freight rates, most grain sold in Chicago and

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2 Carlton (1984) and Williams (1986) discuss why it is unusual to find futures markets for the same commodity in close proximity. The basic argument is that futures markets have high fixed costs so if the futures contracts are close substitutes for each other one market usually dominates.

3 A bushel of corn weighed 56 pounds.
shipped to New York was shipped via the lakes and canals during the open water season.\footnote{See Coleman (2009b) for a detailed analysis of the Chicago-New York freight patterns. The analysis is complicated because the Chicago freight statistics include shipments of grain that were sold in Chicago and shipped east and grain that passed through Chicago but which was never unloaded in the city. He uses regression analysis to demonstrate that the vast majority of grain that was sold in Chicago and shipped to New York was shipped via the Great Lakes during the open water season. Throughout the year, however, there were large through shipments by rail that started in the Great Plains region and passed through Chicago. Thus, even though a casual inspection of the data suggests that Chicago frequently shipped grain by rail to New York, this was not the case.}

From 1881 - 1891, when transport prices were relatively stable, the average cost of shipping a bushel of corn from Chicago to New York was 7.7 cents by Lake and canal, 10.3 cents by lake and rail, and 14.6 cents by rail (Chicago Board of Trade, 1892, p. 122).

Freight prices from Chicago to New York had a marked seasonal pattern. In part this reflects the unavailability of the lake-canal route during the winter months, and in part reflects seasonal fluctuation in lake-canal and rail freight prices. Figure 1 shows weekly transport costs by lake and canal, and by rail from 1879 - 1891.\footnote{Initially there was marked seasonality in both rail and lake and canal prices, as railroads competed aggressively with each other for the grain business in the summer season. This price competition is understated in the official price data, as much of the business was transacted at lower, unrecorded prices (See the discussion by Nimmo in his reports on the internal commerce of the United States: United States Bureau of Statistics, 1879, 1881, 1884.) The competition was sufficiently fierce to divert substantial quantities of the grain trade from the water route to rail (Tunell, 1897.) The seasonal pattern in rail prices persisted until the mid 1880s, but declined} Figure 2 shows the mean transport price by week calculated for each week in each of the years 1881 - 1891 for the lake and canal and all-rail transport modes. On average, lake and canal rates fell from the beginning of the season in May until July before increasing by 0.2 cents per week until the end of the shipping season. There is a similar, but much less marked pattern in the lake and rail rates, while the rail rates essential comprise high (winter) and low seasons.

Figure 2 also shows the average difference between the New York and Chicago spot prices. The average spot price difference was higher during the winter than the open water season.
Note, however, that while the average spot price difference exceeded the lake-canal freight rate during the open water season, making transport profitable, it was less than the average cost of rail transport during the winter. During the winter it was ordinarily not profitable to buy grain in Chicago and send it to New York by rail, and the rail shipments from Chicago to New York during these months were almost all through-shipments originating to the west of Chicago⁶.

The seasonal pattern in freight prices is the reason why this dataset can be used to test the Wright-Williams conjecture. Transport prices from Chicago to New York were high between December and April because low cost lake and canal transport was unavailable. The alternative transport technology, rail, was considerably more expensive than lake and canal shipping and in practice was little used in winter. Rather, shipping agents in Chicago stored grain, waiting for the opening of the open-water season some time in April or May.

**Basic storage patterns**

Chicago inventories were largely determined by shipping patterns. Inventories increased steadily over the winter as corn was brought to Chicago from the surrounding hinterland and stored until the opening of the Great Lakes shipping season. They declined after the shipping season opened in May, and reached a seasonal low at the end of the open water season in November. New York inventories followed a different seasonal pattern. Receipts were highest from May through July, corresponding to the opening of the Great Lakes shipping route, and again in September and October, corresponding to the first of the new

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⁶ I have been unable to assemble a consistent series on freight charges for these through shipments. It appears, however, that they were not noticeably higher in winter than during the open water season. Much larger
crop. For this reason, inventories reached a peak late in the year, and then declined through winter. Even at peak times, New York had surplus storage capacity, and it was extremely rare for more than 70 percent of the total capacity to be utilised7.

Storage charges were subject to regulation. In Chicago maximum storage charges for public warehouses were proscribed by a series of legislative acts and constitutional articles passed by the Illinois State Government, in part because the industry was heavily concentrated8. In 1888, it cost \( \frac{\frac{3}{8}}{\text{per bushel}} \) to deposit grain in an elevator, including the cost of 10 days storage; thereafter, storage costs (excluding the interest opportunity cost, and other costs such as insurance) were \( \frac{1}{4} \) of a cent per bushel per ten days with a maximum of 4 cents for storage between December and May. Storage charges in New York were similar. Insurance and interest costs were approximately 1.4 cents a bushel per month in 1913.

It is important to note that in both cities the grain elevators served two purposes. First, the elevators could be used to store grain for long periods. Secondly, they were used to transfer grain from inward bound shipping to outward bound shipping. When grain arrived in New York, either by rail or by canal boat, it was transferred to an elevator or a lighter and then either stored or shipped.9 The transfer charge included allowance for a few days storage while the grain was in transit. Since corn was always arriving in New York, the grain held in

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7 In 1890 there were 21 million bushels storage capacity in New York and Brooklyn, and a further 6 million in New Jersey. The elevators were mainly used for storing wheat, not corn. In 1887, for example, inventory levels in New York and Brooklyn peaked at 16 million bushels, of which 11 million bushels were wheat and 4 million bushels were corn.

8 In 1870, ninety percent of capacity was owned by five concerns, a pattern that continued for the whole period.

9 Grain from canal boats could be unloaded to an elevator or be sold "afloat", whereupon it could be transferred directly to a ship using a lighter.
transit meant that recorded storage quantities were never literally zero even when no grain was held for long term storage

4 The summer relationship between transport prices and volumes

The main empirical focus of the paper is the relationship between commodity prices and transport prices over the winter months (December – May) when transport across the Great Lakes and the canals was not possible. This relationship is reported in section 4. However, the relationships over the summer months are also of some interest, as it is possible to link shipping volumes to shipping prices during these months, and shipping prices to commodity prices.

Figure 3 shows a scatterplot of the relationship between lake and canal transport costs and the volume of grain shipped from Chicago, by month, for the period 1878 – 1891. The transport price is calculated as the simple average of the weekly transport price. Only data on dates between May and October are used, as November volumes depended on the exact date shipments ceased due to poor weather. The volume of grain shipped is the monthly total of corn, wheat, and oats shipped from Chicago by lake that month. While corn was the dominant grain shipped from Chicago, with an average of 45 million bushels shipped each year over the period, appreciable quantities of wheat (12 million bushels) and oats (8 million bushels) were transported by lake and presumably had some bearing on the transport price. The data indicate there was a positive relationship between the volume of grain shipped and

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10 Corn receipts exceeded 200,000 bushels per week on 90 percent of the weeks in the period. Median receipts were approximately 600,000 bushels per week.
11 If there are missing observations for a month, say three weeks rather than four weeks, the average is taken over the smaller number of observations.
12 Monthly data is used because the weekly data does shipment data does not describe which transport mode was used to move the grain.
the transport price, particularly between 1878 and 1887. The relationship is weaker from 1888 to 1891, possibly because of the increase in shipping tonnage on the Great Lakes\textsuperscript{13}.

Using a single reduced form equation to describe price and quantity data is always problematic, as prices and quantities are determined simultaneously by supply and demand considerations. The upward slope suggests it is more likely that the scatterplot is tracing out the effect of changing demand conditions on a supply schedule than changing supply conditions on a demand schedule. Without a suitable instrument for demand, it is impossible to do more than simply report the reduced form equation, estimated using feasible generalized least squares to take into account first order serial correlation in the errors\textsuperscript{14}. The best fitting lines for the two sub-periods are:

\textbf{1878-1887}

\begin{align*}
\text{Transport Cost}_t &= 2.39 + 0.53 \text{Transport volume}_t + u_t \\
&= + (0.63) (0.12) \\
\end{align*}

\begin{align*}
\text{Price of Grain}_t &= 0.39 \text{Price of Grain}_{t-1} + e_t \\
R^2 &= 0.55 \quad N = 56 \\
\end{align*}

\textbf{1888-1891}

\begin{align*}
\text{Shipping prices}_t &= 1.58 + 0.82 \text{Chicago shipments}_t + u_t \\
&= + (1.76) (0.21) \\
\end{align*}

\textsuperscript{13} The average shipping tonnage clearing Chicago from 1878 to 1887 was 4.1 million tons, compared to 5.1 million tons, 1888-1891. These figures include all ships, not just grain ships.

\textsuperscript{14} Needless to say, one tried to think up an instrument. One possibility is the volume of grain exports sent from New York to Liverpool, and this should be correlated with the demand to ship grain from Chicago to New York but not with the amount of shipping available on any particular day or week in Chicago. When this is used as an instrument for the quantity of shipments from Chicago to New York, the following relationships were estimated for the 1878-1887 period:

\begin{align*}
\text{Chicago shipments}_t &= 6.56 + 0.72 \text{New York shipments}_t + u_t \\
&= + (0.48) (0.25) \\
R^2 &= 0.27 \quad N = 56 \\
\end{align*}

While this equation is not awful, and provides some support for the contention that a supply curve is being estimated, the equation for 1888-1891 had no statistically significant coefficients.
Transport Cost, = 2.57 + 0.18Transport volume, + u, 
(0.55) (0.08)

\[ u_t = 0.40u_{t-1} + e_t \]

\[ R^2 = 0.26 \quad N = 23 \]

The regressions suggest that there was a statistically significant and sizeable positive relationship between shipping volume and transport price, particularly from 1878-1887 when the transport price increased by half a cent (or approximately 6-7 per cent of the average price) for every additional million tons shipped per month. From 1888-1889 the relationship was more muted, but still transport costs increased by 0.2 cents (or 2 – 3 percent) for every additional million tons shipped per month.

Although these data indicate that transport prices are correlated with transport volumes, the curve doesn’t look like a traditional “peak-load” price schedule that occurs when there is a fixed capacity constraint. Given that transport prices varied day-to-day, however, it is possible that the use of monthly data has induced an aggregation bias into the results. Even if there were a “peak-load” transport price-volume relationship at daily frequency, it would not be detected in a monthly average if transport volumes varied from day to day.

Unfortunately, higher frequency data are not easily obtained\textsuperscript{15}.

The interpretation that these data are tracing a positive relationship between shipping volumes and shipping prices is given some credence from contemporaneous accounts.

\textsuperscript{15} Weekly data on corn, wheat and other grain shipments from Chicago are available. The difficulty with the weekly data is that they do not state the destination port, and it includes all-rail grain shipments that started west of Chicago and passed through Chicago but which were not sold in Chicago. There is no way to strip these rail shipments from the data.
Various shipping agents and commodity merchants were interviewed by Congress in 1874 as part of an enquiry into transportation between the mid-west and the eastern seaboard. Several of these agents argued that transport costs fluctuated daily in response to the supply and demand of shipping, and that the high prices obtained when shipping capacity was sparse was necessary to generate a reasonable average return to shipping companies. For example, Mr Hayes, General Manager of Blue Line Fast Freight, Detroit, said

“the lake rates from Chicago to Buffalo depend on the fluctuating demand for transportation. They will sometimes not only vary day by day but hourly through the day. If there happens to be a large influx of vessels brought in by a favorable wind the rates will go down, and the reverse will take place when there is a reverse condition of things, and this action takes place instantaneously, and ordinarily without any combination on the part of the vessel owners. Last week there was a sudden call for much transportation, I suppose caused by some sudden foreign grain demand. It was in excess of the capacity of the lake to furnish, and vessel owners rapidly advanced their prices from 6 to 15 cents a bushel.” (US Congress (1874) Part II 33-34)\(^\text{16}\).

While such statements are anecdotal, in combination with the above statistical evidence it appears that a positive relationship between high frequency transport prices and transport volumes occurred.

The second link concerns the relationship between high frequency transport price variability and the distribution of price differences across space. Figure 4 shows corn prices in Chicago and New York while Figure 5 shows the weekly difference between New York and Chicago

\(^{16}\) It is also worth recording what Mr Hayes said about average transport prices, this time in the context of railways: “…at no time in any year in my knowledge, whether the crop was large or small, was there a regular demand for transportation up to the amount that the various lines could supply. Even when the crop was large cars laid idle at certain seasons, and because many laid idle the service was performed at a loss. If there is to be a fair average annual result to the transporter, then, when the demand again picks up, there must be a sufficient increase of charges to make a good average price.” p37.
prices plotted against the weekly transport cost. Not only does the graph show the extent of the weekly variation on transport prices, but the correlation coefficient is 0.86 and the slope of the graph is insignificantly different from one. The interpretation suggested by the “storage under backwardation” story is that temporary fluctuations in New York demand increased the incentive to ship corn from Chicago; but when shipping capacity was limited, competition to ship grain caused the price of shipping to be bid up until the transport cost equaled the difference between New York and Chicago prices. If Mr Hayes, or more recently Zannetos (1966) or Stopford (1988) were correct, it is this high frequency variability that makes the industry sufficiently profitable to attract investment.

5. Storage under Price Backwardation in Chicago and New York

The simultaneous existence of two future markets relatively close to each other means that it is straightforward to directly test the Wright-Williams conjecture. The future-spot spread in New York is calculated at various dates. At each date that prices are in backwardation, the future-spot spread in Chicago is calculated. The Wright-Williams conjecture implies (i) that the future price in Chicago will be greater than the spot price if Chicago has positive inventories and (ii) the transport cost on that date will be higher than the transport price in the future. Both propositions can be simply tested by calculating the average premiums and testing whether they are significantly greater than zero.

The test is applied to data from the period 1878 – 1891 that is described in Appendix 1 and used in Coleman (2009b). The data comprise weekly spot and forward prices from Chicago and New York, weekly storage quantities in both cities, and weekly transport costs. The test

17 The dependent variable is the New York price for delivery in three weeks minus the spot price in
is applied to price data from the second week of December, January, February, March, and April and in each case the forward-spot premium is calculated with respect to the May future. The mean future-spot premium in Chicago is calculated on the dates that the future-spot premium in New York is negative.

*Chicago and New York inventory and price patterns*

Tables 1 – 5 present the data for the five months, while table 6 and 7 present the summary statistics for the dates on which prices in New York were in backwardation. Consider the data for February, in table 3 and also displayed in figure 6. On seven of the thirteen years, the New York May future price was lower than the spot price, by an average of 2.1 cents. On these occasions, Chicago inventories averaged 2.65 million bushels (table 7) and the Chicago May future price was higher than the spot price by 3.7 cents. A test of the hypothesis that the difference between the Chicago May future price and the spot price was equal to zero has a t-statistic of 5.78 and can be rejected at the 1 percent significant level. In addition, on these seven occasions, the February transport cost exceeded May transport cost by an average of 7.7 cents, an amount that is statistically different from zero, with a t-statistic of 8.82.

Table 6 shows the results for January and March were similar to those in February. When prices were in backwardation in each of these months, future prices exceeded spot prices in Chicago by an average of approximately 3 cents. In each case, this amount is statistically significant at the one percent significance level. During these months, transport prices exceeded May transport prices by an average of 6 – 8 cents, and these differences were also statistically significant at the 1 percent level. This is clear evidence that inventories were held

Chicago, using midweek data. There are 358 observations.
in Chicago when the future price exceeded the spot price and when transport prices were temporarily high.

The results for April are similar, but the average difference between the May future and spot prices was not different from zero at a statistically significant level. In Chicago the May future prices exceeded the spot prices on 6 out of 7 occasions that New York prices were in backwardation, but the average excess was only 1.4 cents. Presumably the future-spot spread was so small in part because the inventory only needed to be held for a month so only a small carrying charge was warranted.

The results for December are most perplexing. In the second week of December, Chicago prices were in backwardation in three of the seven years that New York prices were in backwardation, that is 1882, 1884, and 1885. On average, the May future price exceeded the spot price by 1.3 cents, but the hypothesis they were equal cannot be rejected at the 5 percent level. Inventories on the three occasions that Chicago prices were in backwardation were below average, but in each case amounted to more than 600,000 bushels. It is not clear why inventories were held on these occasions, although on all of the occasions the spot price had declined substantially in the previous four weeks and the markets appeared to be unusually unsettled. In two of these years, the spot price had fallen sufficiently by the end of December that the future price exceeded the spot price by a considerable margin; indeed, price patterns in the fourth week of December were very similar to those in January, February, and March.\(^\text{18}\). Nonetheless, it would appear that just at the end of the open water

\(^{18}\)In the fourth week of December, Chicago future prices exceeding spot prices in six out of the seven years

The exception was 1882, a year of considerable irregularity in the Chicago and New York corn markets.
transport season the Chicago markets were sufficiently unsettled that normal price relationships did not always hold.

Despite the December patterns, the evidence presented is strongly supportive of the Wright-Williams conjecture. For most of the winter season, when transport prices were temporarily high, inventories were held in Chicago at a positive spread even when prices were in backwardation in New York. They were not shipped to New York because the premium that could be earned for immediate delivery was insufficient to pay the additional transport costs; it was more profitable to keep the grain in Chicago and wait for a cheaper shipping time.

New York price patterns

A second test is used to examine the reason why inventories were held in New York while prices were in backwardation. In section 2 it was shown that it would be profitable to hold inventories in a month like January even if the spot price exceeded the May future price if prices were expected to increase before subsequently falling. This hypothesis has superficial plausibility, for large volumes of corn were shipped to New York at the end of the open water season in anticipation of the high transport costs over the winter. As such, it is quite possible that price for delivery in one month exceeded the price for spot delivery for much of the winter, as inventories were run down, even though the spot price exceeded the price for May delivery. At least one piece of data is consistent with this story: on average, inventories declined in New York each month between January and April.

The hypothesis can be tested by examining the spread between the one-month future price and the spot price on the occasions that spot prices exceeded the May future price in New York, and testing to see whether the average spreads were positive. There is no support for
the hypothesis. On six out of seven occasions that prices were in “long-term” backwardation in December, February, and March, and seven out of eight cases in January, the one-month future price was also below the spot price. It follows that in each month the mean price spread was negative, not positive as hypothesised; in three out of the four months one can reject the hypothesis that the one month future price was equal to the spot price at the five percent significance level, in each case because the future price was less than the spot price.

The explanation for why New York had positive inventories while the spot price exceeded both the one month future and the May future must lie elsewhere. As suggested in section 3, it may be because the elevators were dual purpose and the grain in the elevators was being held in transit rather than held for long term storage.

6. Discussion

This paper directly contributes to the literature including Benirschka and Binkley (1995), Brennan, Williams, and Wright (1998), and Frechette and Fackler (1999) that examines the hypothesis that a supply of storage curve may be an artifact of an inappropriate method of aggregating inventory levels. Unlike the other literature, this article has directly tested whether inventories held in a distant location are held at positive carrying charges when prices in a central market are in backwardation. In the historic episode considered, the answer is an over-whelming “yes”: most of the time when corn prices in New York were in backwardation, inventories in Chicago were positive and future prices in Chicago exceeded spot prices. Moreover, the reason why corn was not shipped to New York to take advantage of the temporarily high spot prices is also clear. In accordance with the Wright-Williams conjecture, transport prices were temporarily high in Chicago and it was not worth paying a
very high transport price to immediately ship corn to New York to take advantage of the high spot prices in that city.

The article has been able to conduct a very simple test of the Wright-Williams conjecture because futures markets existed in Chicago and New York. It is unusual to find futures markets for the identical commodity in the same proximity for, as Williams (1986) pointed out, if the prices are highly correlated the market with the highest transactions costs will usually shut down. The fact that these two markets existed so close to each other is not a coincidence, however. The seasonality in the transport costs caused by the closure of the Great Lakes shipping lanes every winter meant that the spot-future price spreads in each city were not highly correlated with each other, so the New York futures markets could not be used as a substitute for the Chicago markets. In some sense, therefore, it would be surprising if it had not been found that Chicago prices were in contango while those in New York were in backwardation. The circumstances that meant the test could be carried out are the circumstances where one would expect the conjecture to be true.

The second result of the paper was less obvious. An implication of the Wright-Williams conjecture is that if transport costs are variable, inventories can be profitably held in a centre even if the price for forward delivery is below the spot price if prices are expected to increase before declining. In these circumstances inventories are expected to fall to zero sometime before the future contract expires, but they are not run down immediately as speculators realise it will be unusually expensive to import goods in the mean time. Since New York usually started the winter period with large inventories and ran them down over the winter, it is plausible that this theory could have explained why inventories were held in New York over the winter even though the spot price exceeded the price for May delivery.
The theory does not explain the data, however. Quite simply, almost all the time that spot prices exceeded May prices in New York, spot prices also exceeded the price for delivery in one month’s time. An alternative explanation for why inventories were held in New York despite prices being in backwardation is needed.

In this historic episode, transport prices varied because of seasonal weather related factors. As Stopford (1988) and Fackler and Goodwin (2001) make clear, however, transport prices vary for a variety of reasons. They could vary because of the price of fuel; they could vary because of capacity constraints in the shipping industry (Brennan, Williams and Wright 1998; Coleman 2009); or they could vary because the transport industry has a steeply rising short run marginal cost curve. A steep upwardly sloping supply curve is common because low cost transport systems (such as rail networks) are capital intensive, and operators minimise costs by limiting capacity but operating it throughout the year. If there is an increase in demand, less capital intensive transport systems (such as trucks) can be used to supplement the capacity; but these systems have higher costs, and so transport costs must rise to justify their employment. For this reason, a short term increase in demand in an importing centre can lead to a steep increase in the price of transport for immediate delivery without affecting the price of transport for future delivery. Even if the variation is not sufficiently regular to justify the existence of a separate futures market, it is plausible that transport cost variation makes it profitable to hold inventories in distant locations while prices in the central market are in backwardation, as in this case. If so, it is quite possible that supply of storage curves for many commodities reflect transport price variability rather than convenience yield.
The broader question remains: how important is, and what can be learned from, high frequency commodity price and transport price volatility? Some oil experts argue that the size of mining investment decisions depend on the tradeoff between the sunk costs of additional capacity and the option provided by this capacity to increase production to take advantage of price fluctuations. They also suggest that price volatility not only reflects capacity constraints in the industry that prevent immediate production increases in response to high frequency price changes, but constraints in the capacity building industry (exploration and mine development) that limit capacity expansion in response to medium term fluctuations. This suggests a possible role for high frequency commodity price fluctuations in determining the level of investment, without quantifying its importance.

A similar argument is forwarded by logistics experts. The quantity of transport and storage capital depends on the tradeoff between the sunk costs of additional capacity and the option provided by this capacity to take advantage of price fluctuations. In turn, additional capacity reduces price volatility. In the era studied in this paper, huge elevators dotted over the landscape provided a cheap alternative to additional transport equipment. In the modern era, elevators and warehouses still dot the landscape to ensure transport equipment is fully utilized. The evidence from the paper provides support for theories in which these capacity constraints are crucial for understanding fluctuations in short term spot-future price spreads. It remains to be determined whether more general evidence on the link between these price spreads and investment patterns can be established.
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Appendix 1: Data Sources

Corn Prices.

Prices were collected for Number 2 Yellow corn in Chicago and New York. Spot prices for both cities were collected in the Thursday edition of the New York Times, 1878-1892. The prices were for the preceding Wednesday, or Tuesday if the Wednesday were a public holiday. If the markets were closed on both Wednesday and Tuesday, the data was skipped for that week. New York futures prices were also collected from the Thursday edition of the New York Times. The Chicago future prices were collected from the Annual Report of the Chicago Board of Trade. In each case, the quotes are for seller delivery: the seller could choose any day to deliver within the said month. Wednesday quotes were collected.

Storage Data.

Storage data for Chicago was sourced from the Chicago Board of Trade Annual Reports. The New York data came from a variety of sources. Where possible, it came from the New York Produce Exchange Annual Reports, but data from 1882 and 1887 came from the weekly newspaper, the Commercial and Financial Chronicle. Information on the cost of storage come from the Chicago Board of Trade and New York Produce Exchange Annual Reports, and from Goldstein (1928).

Transport Data.

The transport cost data were published by the Chicago Board of Trade and New York Produce Exchange Annual Reports. They are similar not identical to the data published in the Aldrich Report, (United States 52nd Congress 2nd Session (1893) Senate Report 1394: Wholesale Prices, Wages, and Transportation. Report by Mr Aldrich from the Committee on Finance March 3 1893 Part 1. (Washington: Government Printing Office).
Appendix 2

Two period arbitrage relationships.

In this section, price relationships in the two centres are calculated under the assumptions:

A1: Inventories are held in centre D at time t; and

A2: D is expected to export to C at time t+1.

From equation 2 and equation 3 applied to D, \( F_t^{C,1} = F_t^{D,1} + K_{t+1}^T \) and \( \frac{1}{1+r} F_t^{D,1} = P_t^D + K_t^S \).

Let \( P_t^S \) be the centre C price at time t at which it is just profitable for inventories to be held, and let \( P_t^M \) be the centre C price at time t at which it is just profitable to import. At \( P_t^S \), equation 3 applied to C holds with equality and implies

\[
(4) \quad P_t^S = P_t^D + \frac{1}{1+r} K_{t+1}^T
\]

At \( P_t^M \), equation 1 holds with equality and implies

\[
(5) \quad P_t^M = P_t^D + K_t^T
\]

There are two different cases. Suppose transport prices in period t are low compared to prices in period t+1, that is \( K_t^T \leq \frac{1}{1+r} K_{t+1}^T \). Then \( P_t^M \leq P_t^S \) and

a. if \( P_t^C > P_t^S \) \( \Rightarrow S_t^C = 0; T_t^D > 0; \)

b. if \( P_t^M \leq P_t^C \leq P_t^S \) \( \Rightarrow S_t^C > 0; T_t^D > 0; \)

c. if \( P_t^C < P_t^M \) \( \Rightarrow S_t^C > 0; T_t^D = 0. \)

Alternately, suppose transport prices in period t are high compared to prices in period t+1, that is \( K_t^T > \frac{1}{1+r} K_{t+1}^T \). Then \( P_t^S \leq P_t^M \) and

d. if \( P_t^C > P_t^M \) \( \Rightarrow S_t^C = 0; T_t^D > 0; \)
e. if $P^S \leq P^C_t \leq P^M$  \quad S^C_t = 0; \quad T^D_t = 0$

f. if $P^C_t < P^S$  \quad S^C_t > 0; \quad T^D_t = 0$.

Case (e) is of particular interest. It says that when transport costs are sufficiently high in period $t$ compared to $t+1$, it is possible for centre C to neither import nor have inventories even though centre D has positive inventories. This, of course, is the argument made by Wright and Williams. In these circumstances, the following price relationships apply

1. $P^C_t > \frac{1}{1+r} F^C_{t+1} - K^S$ and $S^C_t = 0$

2. $P^D_t = \frac{1}{1+r} F^D_{t+1} - K^S$ and $S^D_t > 0$

3. $P^C_t < P^D_t + K^T_t$ and $T^D_t = 0$

4. $K^T_t > \frac{1}{1+r} K^T_{t+1}$

Note that the first of these conditions is less stringent than the requirement that prices in centre D be in backwardation.

Three period arbitrage relationships

If the above model is extended to three periods, a further implication of the Wright-Williams conjecture can be derived. In particular, inventories may be profitably held in the central market when prices in that market are in “long-term” backwardation if prices in the central market are expected to first rise and then fall. This can occur if transport prices are expected to be temporarily high for some of the time between the present and the time that they are required for future delivery. To show this, the initial assumptions are modified:

A3: Inventories are held in centre D at times $t$ and $t+1$; and

A4: D is expected to export to C at time $t+2$.  
These assumptions imply the following price relationships:

\[ F_{t}^{C,2} = F_{t}^{D,2} + K_{t+2}^{T}, \]

\[ \frac{1}{1+r} F_{t}^{D,1} = P_{t}^{D} + K_{t}^{S}, \] and

\[ \frac{1}{1+r} F_{t}^{D,2} = F_{t}^{D,1} + K_{t}^{S} = (1+r)P_{t}^{D} + (2+r)K_{t}^{S}. \]

Let \( P_{t}^{S} \) be the centre C price at time \( t+1 \) at which it is just profitable for inventories to be held, and let \( P_{t}^{M} \) be the centre C price at time \( t+1 \) at which it is just profitable to import. At \( P_{t}^{S} \), equation 3 applied to C holds with equality and implies

\[ (6) \quad P_{t}^{S} = F_{t}^{D,1} + \frac{1}{1+r} K_{t+2}^{T} \]

At \( P_{t}^{M} \), equation 2 holds with equality and implies

\[ (7) \quad P_{t}^{M} = F_{t}^{D,1} + K_{t+1}^{T} \]

Assume that transport prices are higher in period 1 than period 2, \( K_{t+1}^{T} \geq \frac{1}{1+r} K_{t+2}^{T} \), so that

\[ P_{t}^{S} \leq P_{t}^{M}. \] It is then possible to calculate centre C prices in period \( t \) as a function of centre C future prices at \( t+1 \). Let the price for future delivery in C at period \( t+1 \) be

\[ (8) \quad F_{t}^{C,1} = P_{t}^{M} + \varepsilon (1+r) = F_{t}^{D,1} + K_{t+1}^{T} + \varepsilon (1+r) \]

If \( \varepsilon \geq 0 \), \( S_{t+1}^{C} = 0 \) and \( T_{t+1}^{D} = 0 \); if \( \left( \frac{1}{1+r} K_{t+2}^{T} - K_{t+1}^{T} \right) < \varepsilon < 0 \), \( S_{t+1}^{C} = 0 \) and \( T_{t+1}^{D} = 0 \); and if

\[ \varepsilon \leq \left( \frac{1}{1+r} K_{t+2}^{T} - K_{t+1}^{T} \right), \quad S_{t+1}^{C} \geq 0 \] and \( T_{t+1}^{D} = 0 \). There are two critical thresholds for prices at time \( t \):

the price \( P_{0}^{S} \) at which storage occurs at \( t \), and the price \( P_{0}^{M} \) at which C imports. The equation for equation for \( P_{0}^{S} \) is

\[ P_{0}^{S} = \frac{1}{1+r} F_{t}^{C,1} - K^{S} \]
and the equation for $P^*_0$ is
\begin{equation}
P^*_0 = P^*_D + K^T.
\end{equation}

Suppose centre C prices are in “long-term” backwardation, that is $P^*_D > F^{C,2}_t$. This implies
\begin{align*}
P^*_D &= F^{D,2}_t + K^T_{t+2} \\
&= (1 + r)^2 P^D_t + (1 + r)(2 + r)K^S + K^T_{t+2}
\end{align*}
\begin{equation}
(11)
(2 + r)(rP^D_t + (1 + r)K^S) + K^T_{t+2} < 0
\end{equation}

If at the same time $P^S_t < P^*_0$ and $(\frac{1}{1 + r}K^T_{t+2} - K^T_{t+1}) < 0$, there will be storage in centre C at time $t$ even though prices are in long-term backwardation, and there will be no storage or imports at C at $t+1$. For this to occur,
\begin{equation}
(12)
P^*_D < P^*_D + \frac{1}{1 + r}K^T_{t+1} + \varepsilon; \quad \left(\frac{1}{1 + r}K^T_{t+2} - K^T_{t+1}\right) < 0
\end{equation}

Equations 11 and 12 can be satisfied simultaneously if
\begin{equation}
(13)
(2 + r)(rP^D_t + (1 + r)K^S) + K^T_{t+2} < \frac{1}{1 + r}K^T_{t+1} + \varepsilon
\end{equation}

which will be true if transport costs in period $t+1$ are sufficiently high compared to transport costs in period $t+2$ and $\varepsilon$ is sufficiently close to zero. In these conditions it is possible for storage to take place in C at time $t$ even though prices are in long term backwardation.
Table 1: April data, 1879-1991

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Spot: spot price in New York or Chicago
Stores: inventories in millions of bushels
F₁-S: one month future price minus the spot price
F₅-S: May future price minus the spot price
Spot transport prices for the second week of April (all rail) and the lake and canal price in the first week of May.
## Table 2: March data, 1879-1891

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Spot: spot price in New York or Chicago  
Stores: inventories in millions of bushels  
F1-S: one month future price minus the spot price  
F2-S: May future price minus the spot price  
Spot transport prices for the second week of March (all rail) and the lake and canal price in the first week of May.
Table 3: February data, 1879-1891

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Mean 54.9   1.7   -0.3   -0.2  41.3  3.9  0.21  3.96  15.5  7.7

Spot: spot price in New York or Chicago
Stores: inventories in millions of bushels
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F₃M-S: May future price minus the spot price
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Spot: spot price in New York or Chicago
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Spot transport prices for the second week of January (all rail) and the lake and canal price in the first week of May.
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Table 6: Test of mean spreads when New York May future-spot spread is negative

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t-test is a test of the hypothesis that the mean of the difference between the price for delivery in May and the spot price is zero.
* implies the test can be rejected at the 5% significance level.
** implies the test can be rejected at the 1% significance level.
Table 7: One month future-spot premium when New York May future-spot spread is negative

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<td>-1.47</td>
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<td>-3.43</td>
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</tbody>
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t-test is a test of the hypothesis that the mean of the difference between the price for delivery in one month and the spot price is zero.
* implies the test can be rejected at the 5% significance level.
** implies the test can be rejected at the 1% significance level.
Figure 1: Chicago – New York transport prices, 1879-1891

Figure 2: Average transport costs and NY-Chicago spot price difference, 1881-1891
Figure 3

Transport cost versus grain shipments, monthly 1878-1891
(total corn, wheat, and oats shipments)

Figure 4

New York and Chicago Corn Prices, 1878-1891
Figure 5

NY future minus Chicago spot price versus transport cost 1878-1891

New York future is "delivery this month" if date is before the 10th; otherwise "delivery next month"
Figure 6: Storage and May future premium, Chicago and New York, February 1879-1891