# Have we misunderstood the law of one price? A reinterpretation based on a trade model with transport capacity constraints.

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**Abstract**
This paper solves a rational expectations model of price arbitrage incorporating storage and trade when there are capacity constraints limiting the amount that can be exported in any period. It shows that the law of one price will hold, but do so because transport costs rise to make it hold when the demand to ship goods exceeds the capacity limit. Such increases in transport costs are necessary to attract shipping capacity into the industry. In equilibrium this means that the law of one price is consistent with considerable spatial price dispersion, and that price dispersion and transport cost volatility increase as the variance of output increases. An analysis of extremely detailed data from Chicago and New York corn markets in the late nineteenth century provides empirical support for the model.

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## 1. Introduction

According to the traditional approach to the law of one price, the prices of an identical good in two different locations should never differ by more than the cost of transporting the good from the low priced place to the high price place. The story associated with this paradigm is quite simple: if, for instance, it costs ten cents to ship a good from Chicago to New York and the price of the good in Chicago is forty cents, then the New York price should not exceed 50 cents, or else abnormally high profits will be made by arbitrageurs. Despite the compelling logic of this theory, however, there is considerable empirical evidence that prices in different places are very different, and the difference between any two prices varies significantly over time.

This paper offers a new interpretation of the law of one price that explains why the difference between two spatially separated prices varies so much through time. It is predicated on the observation that transportation and distribution systems have finite capacity because they are capital intensive. In order to minimize shipping costs, owners restrict their purchases of transport machinery and engage in a variety of logistics management practices that ensure their machinery is utilized as much as possible. This means there are capacity constraints in the transport and distribution systems and, if transport services are sold, that transport prices are high when demand to shift goods is high, and are low when the demand to ship goods is low. Put differently, the transport price is endogenous to the quantity of goods being shipped. Since one should not condition upon an endogenous variable, the traditional interpretation of the law of one price proves to be misleading. Rather than the import price adjusting to equal the export price plus the transport cost, as usually understood, the transport cost often adjusts to equal the difference between the import and export prices.

This reinterpretation can also be told as a simple story. Suppose that the marginal cost of shipping goods from Chicago to New York is four cents, and the capital costs associated with providing a ship are six cents. Suppose further that Chicago is the dominant supply region, New York is the importing region, and the price in Chicago is forty cents. If demand in New York is weak, there will be little demand for shipping capacity, shipping will cost four cents and the New York price will be forty-four cents. Alternatively, if demand in New York is extraordinarily high and the price there is sixty cents, shippers will clamber for shipping capacity, bidding the price of shipping up to twenty cents. In each case the law of one price holds, but it holds because shipping prices adjust to make it hold. If shipping markets are competitive, the shipping capacity available will be just sufficient to ensure that the profits expected to be made in the periods of high prices will offset the losses expected to be made in the periods of low prices. Indeed, this story was told a century ago, by shipping agents and shipping companies in testimony to the U.S. Senate Select Committee on Transportation Routes to the Seaboard[1].

This paper develops a formal model that examines how the law of one price holds when there are transport capacity constraints. The model is an extension of the rational expectations model of storage and trade developed by Coleman (2004). There are two centres with independent stochastic supply and demand functions, and forward looking, risk neutral agents either store goods or ship goods between centres to take advantage of arbitrage possibilities. In the model shipping is assumed to take time and the shipping capacity is fixed, but the price of this shipping is allowed to vary in response to the demand to ship between centres. In particular, the shipping price is assumed to equal the marginal cost if the amount shipped is less than full capacity, but to equal the difference between the spot price in the exporting city and the expected future price in

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[1] See for example the testimony of Mr Hayes, to the committee, pp33-39 (Part II) of the report. (United States Congress (1874)) This report is discussed in more detail in Section 4. A very similar set of explanations for why cattle prices in New York and Liverpool varied so much were given to the 1890 United States Congress Select Committee on the Transportation and Sale of Meat Products. (United States Congress (1890).) See the testimony by T.C. Eastman pp 513 – 527, and Mr F. W. J. Hurst pp 555-557.

the importing city appropriately discounted to allow for transit times if the amount shipped is equal to full capacity.

Storage is an essential component of the model. The possibility of storage ensures that prices in each centre are dynamically consistent, and it ensures shippers facing high transport prices in one period recognize the opportunity cost of not shipping, namely storing and waiting to ship next period. Because inventories must be non-negative, an analytic solution to the model cannot be found, but by using the techniques developed by Deaton and Laroque (1992, 1996) and Williams and Wright (1991) it is possible to find a numerical solution to the model. This solution comprises the equilibrium distributions of quantities shipped, consumed and stored, along with the equilibrium distributions of commodity and shipping prices. These distributions depend on the primitives of the model, such as the demand curve in each centre, and the distribution of output or demand shocks.

The model solution indicates how commodity prices and shipping prices behave when there are transport capacity constraints. Ordinarily, both centres have some inventories of the commodity that are used to smooth fluctuations in the local supply of the good, and prices are expected to rise slowly through time to provide a return to those holding the inventories. If there are small fluctuations in output, there is little effect on prices as inventories are adjusted, and the difference between prices in the two cities is less than or equal to the marginal cost of shipping, adjusted for storage costs. If a city has a large negative supply shock, however, local inventories are exhausted, and new supplies are ordered from the other city. Since it takes a period for the imported goods to arrive, the spot price in the importing centre temporarily exceeds the spot price in the exporting centre plus the transport cost. If transport capacity is unlimited, enough goods are imported to ensure that the following period's price in the importing centre is expected to equal the current price in the exporting centre plus the marginal transport cost. If there are binding transport capacity constraints, however, insufficient quantities will be shipped and the following period's price in the importing centre is expected to exceed the current price in the exporting centre plus the marginal transport cost. As shippers clamber for the available shipping capacity to take advantage of the expected high prices in the importing city, they drive up the shipping price until it just equals the difference between the current price in the export centre and the expected future price in the importing centre.

The model is initially solved for a fixed shipping capacity constraint, and is used to calculate the equilibrium distribution of prices in each centre, and the equilibrium distribution of shipping prices. In turn, the distribution of prices can be used to calculate the average earnings of the transport sector. As the shipping capacity increases, shipping constraints bind less often, so the shipping price exceeds the marginal shipping cost less often and average earnings decrease. Likewise, as shipping capacity increases, the fraction of times that commodity prices in one centre exceed commodity prices in the other by more than the marginal shipping costs decreases, and the variance of the spatial price difference decreases.

Because entry into the shipping industry is assumed to be competitive, the model is iterated to find the shipping capacity that generates a competitive rate of return. This means the effect of endogenously determined shipping constraints can be examined. For example, the paper examines how an increase in the variance of the underlying output shocks affects prices. As the underlying output shocks in the model are increased, the variance of shipping prices, the profitability of the shipping industry, and the variance of the spatial price difference increases for any level of shipping capacity. The additional profitability of shipping attracts more shipping capacity, which lowers the variance of shipping prices. Nonetheless, if additional shipping capacity increases until the returns to shipping again equal the competitive rate of return, the variance of shipping prices and the variance of the spatial price difference will both have increased when compared to their initial levels. Shipping companies increase their capacity in response to more volatile output, as their peak demands are higher; but this means they operate below capacity for a greater fraction of the time, so their earnings are more volatile.

It should be stressed that according to this model, evidence that spatially separate prices differ by time varying amounts is not evidence against the law of one price. Rather, such price differences are necessary to generate the profits that enable transport operators to cover their cost of capital. Without these price differences — these deviations from the law of one price as traditionally interpreted — goods would not be transported from one place to another.

In the last decade, several papers have shown empirically that there is considerable high frequency variation in transport costs, and that this variation explains some of the high frequency variation in spatial price differences (see for example Goodwin, Grennes, and Wohlgenant (1990) or Persson (2004)). Most of these papers describe the pricing and transport of agriculture commodities, as high frequency transport data have been more easily obtained for agricultural commodities than other commodities. This paper uses the dataset assembled by Coleman (2004) describing the late nineteenth century corn markets in New York and Chicago to provide empirical support for the model. The dataset was chosen because it is more detailed than any other comparable dataset, containing transport cost and trade volume data, inventory data, and spot and future price data for both cities, all collected at weekly frequencies. The data describe the corn markets during the summer months from 1878 to 1891, a time when grain was shipped from Chicago to New York via the Great Lakes and the Erie Canal, a trip that took three weeks.

The data show that transport costs varied considerably from week to week and that this variation was positively correlated with variation in the quantity of grain shipped between Chicago and New York. Shipping prices ranged from 4 cents per bushel to 18 cents per bushel, compared to an average Chicago price of 45 cents per bushel, and typically peaked at the beginning and end of each shipping season when volumes were highest. Furthermore, it is shown that over two thirds of the variation between the New York and Chicago corn prices costs can be explained by high frequency variation in the transport cost. The clearest demonstration comes from a regression of the difference between the New York corn price for delivery in three weeks and the Chicago spot price against the transport cost. The simple correlation between these two series is 0.86, and the coefficient on the transport cost variable is extremely close to (and statistically indistinguishable from) one, indicating a one to one relationship between high frequency transport costs and spatial price differences. The relationship between transport costs and the difference between the New York spot price and the Chicago spot price is more complicated because one has to take into account the occasions when New York has very low inventories and when (according to the theory) the New York spot price should exceed the Chicago spot price plus the transport cost. The data shows that the New York price did exceed the Chicago price plus the transport cost on these occasions; when these occasions are taken into account, over two thirds of the variation in the spatial price difference can be explained by variation in the transport cost and inventory levels.

The paper begins in section 2 with a short review of the relevant literature, which is followed with the details of the model. In section 3 various aspects of the solution to the model are presented. Section 4 briefly describes the late nineteenth century corn market and presents the empirical results. Lastly, a conclusion is offered in section 5.

## 2. A Structural Model of Storage and Commodity Arbitrage

**Previous Literature.**

Almost all of the theoretical literature that analyses how transport costs affect prices has assumed that the transport cost between any two locations is fixed. This is somewhat surprising, because the idea that transport systems have capacity constraints that cause transport costs to vary is rather standard among transport economists. For example, it is discussed as a foundational principle of bulk-commodity shipping by Stopford (1988) in his text on maritime shipping economics. In this book he argues that the elasticity of transport costs to the quantity of goods shipped is near zero when the quantity shipped is substantially less than capacity, but that it approaches infinity as the capacity constraint is approached.

Spiller and Wood (1988) were amongst the first authors to incorporate variable transport costs into a model of price arbitrage. They assumed that arbitrage was instantaneous, that storage could be ignored, and that transport costs followed a parametric distribution (either a truncated normal or a gamma distribution) and developed a switching regression model to estimate the distribution of transport costs from spatial price differences. While this methodology has often been used in empirical work, they did not explain why transport costs should have such a distribution. Furthermore, by ignoring shipping times and the manner by which inventory management affects prices, their estimates are biased as they mistake localized price spikes resulting from occasions when inventories are zero for times when transport prices are particularly high.

The approach most closely related to that adopted in this paper is that of Wright and Williams (1989.) They argued that transport costs vary and this explains why futures prices are often in backwardation —that is, the future price is less than the spot price — when aggregate inventories are positive. Their argument has two components. First, they argue that even though spot and futures prices are quoted for delivery in a primary market, most inventories are held in locations distant from this market. Secondly, they argue that when the spot price is higher than the future price, inventories in the primary market are depleted, and an attempt is made to move inventories held elsewhere to the primary market. Some inventories are moved, but because there are only limited transport facilities, most are not; indeed, transport costs are bid up to unusually high levels, which makes it unprofitable for most of the inventories held in remote locations to be shipped to the central market to take advantage of the unusually high spot prices. The model in this paper, which is based upon the same basic idea, can be considered a formalization of their approach in which equilibrium prices, storage quantities, shipping volumes and transport capacity are all determined endogenously.

**The Model**[2]

The model is an extension of the rational expectations model of storage and trade developed by Coleman (2004), which in turn is based on the model of Williams and Wright (1991) and more distantly on Samuelson (1952). The basic approach is to link a set of equations representing supply and demand curves in different locations with a set of no-arbitrage conditions that preclude excess profits from either the storage of goods at a location or the shipment of goods between locations.

There are two centres, A and B, each with a separate inverse demand function for a commodity:

$$P_t^i = D_i^{-1}(Q_t^i) : \qquad D_i^{-1}(0) < \infty, \quad \lim_{Q\to\infty} D_i^{-1}(Q) = 0 \tag{1}$$

where $Q_t^i$ is the amount purchased for final use at time $t$ and i = A, B. The output produced each period is assumed to be price inelastic but stochastic, because it has a long gestation period. There are two ways that output is usually modeled in the literature: either it is serially autocorrelated or it varies seasonally. Since the analytical structure of the model does not depend on how output is modeled, in this paper I follow Deaton and Laroque (1996) and assume that output in each centre follows an independent first order autoregressive process around a constant mean:

$$(X_t^i - \bar{X}^i) = \rho^i (X_{t-1}^i - \bar{X}^i) + e_t^i \qquad i = A, B \tag{2}$$

[2] The following paragraphs are adapted from Coleman (2004).

where $e_t^i$ is a white noise process and $|\rho^i|<1$.

All production, consumption, storage and trade activity takes place at the beginning of the period, and the length of a period is the time that it takes to ship goods from one centre to another. It is assumed that unlimited quantities of the good can be stored in either centre, and that goods produced at different times are indistinguishable and have the same price. Risk neutral arbitrageurs are assumed to predict future prices and purchase and hold inventories until the expected price increase just offsets the cost of storage; conversely, if the expected appreciation is less than the cost of storage, inventories will be zero. There are three possible storage costs. First, there can be an elevator charge $K^S$ per unit to store goods each period; this charge is assumed to be smaller than the marginal cost of transporting goods from one centre to the other, $K^T$. Secondly, the commodity depreciates at rate $\delta$ so if $S_t$ is stored in period *t*, $(1-\delta)S_t$ will be available in period $t+1$. Thirdly, there is an interest cost *r* foregone when storage is undertaken. A key determinant of prices is product availability, $M_t^i$, the total quantity of stored and imported goods in a centre at the beginning of the period,

$$M_t^i = (1-\delta)\left(S_{t-1}^i + T_{t-1}^j\right) \tag{3}$$

where $S_{t-1}^i$ is the non-negative quantity stored in centre i and $T_{t-1}^j$ is the non-negative quantity exported from centre j. $M_t^A$ and $M_t^B$ are two of the state variables of the model. The quantities stored and exported are such that $S_t^i + T_t^i \leq X_t^i + M_t^i$.

There is an innate difficulty modeling transport when it is capacity constrained and when shipping takes time, because one needs to keep track of the amount of transport equipment in each centre at the beginning of each period. To simplify the analysis, it is assumed all transport operators own two pieces of transport equipment, one in each centre, and that whenever one is dispatched full the other one is shipped back empty in the opposite direction. In this way, there is always the same amount of transport equipment in each centre at the beginning of each period. Since there is only one good in the model, it is never profitable to simultaneously ship the good in both directions; hence one ship is always empty. While this modeling assumption is unrealistic, it substantially simplifies the analysis as it means the shipping capacity is the same every period[3].

The amount of shipping capacity is $\overline{T}$ . If an amount less than $\overline{T}$ is shipped, the price charged to shippers is assumed to be the marginal cost of shipping, $K^T$[4]. If an amount equal to $\overline{T}$ is shipped, shippers are assumed to bid competitively for the shipping capacity, and the price is assumed to be the difference between the spot price in the originating city and the appropriately discounted expected future price in the other city. (See equations 4e, 4f, and 4g, or 4h, 4i and 4j, for a formal definition.) When goods are transported they are assumed to depreciate at rate δ, the same rate at which they depreciate while in storage.

It is assumed that risk neutral, profit maximising, and rational speculators in both cities undertake a mixture of trade and storage to take advantage of expected price differences. The speculators have rationally determined expectations about future prices that incorporate all information about output, storage, and trade in both centres. The behavior of risk neutral speculators can be represented by four inequalities. Let $y_t = \left[M_t^A, M_t^B, X_t^A, X_t^B\right]$ be the vector of state variables, and $K_t^A$ and $K_t^B$ the variable transport costs of shipping from A and B respectively. Then, at each point $y_t$:

[3] Moreover, the assumption is not entirely unrealistic, as many shipping lines organise their services to ensure a regular service with half the fleet going one way and the other half returning.
[4] Note that the cost $K^T$ is the total cost of sending goods from one city to the other and simultaneously sending the same amount of shipping capacity in the other direction empty .

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{A}\mid y_t]-P^{A}(y_t)\le K^{S};\ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{A}\mid y_t]-P^{A}(y_t)-K^{S}\right].S^{A}(y_t)\ =0\quad 4a,b$$

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{B}\mid y_t]-P^{B}(y_t)\le K^{S};\ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{B}\mid y_t]-P^{B}(y_t)-K^{S}\right].S^{B}(y_t)\ =0\quad 4c,d$$

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{B}\mid y_t]-P^{A}(y_t)\le K_t^{A};\ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{B}\mid y_t]-P^{A}(y_t)-K_t^{A}\right].T^{A}(y_t)\ =0\quad 4e,f$$

$$\left[T^{A}(y_t)-\bar{T}\right].\left[K_t^{A}-K^{T}\right]=0\qquad 4g$$

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{A}\mid y_t]-P^{B}(y_t)\le K_t^{B};\ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^{A}\mid y_t]-P^{B}(y_t)-K_t^{B}\right].T^{B}(y_t)\ =0\quad 4h,i$$

$$\left[T^{B}(y_t)-\bar{T}\right].\left[K_t^{B}-K^{T}\right]=0\qquad 4j$$

where

$P^{i}(y_t)=D_i^{-1}(X_t^{i}+M_t^{i}-S^{i}(y_t)-T^{i}(y_t))$,

$M_{t+1}^{i}(y_t)=(1-\delta)\left(S^{i}(y_t)+T^{j}(y_t)\right)$, and

$$E\left[P_{t+1}^{i}\mid y_t\right]=\iint_X D_i^{-1}(X_{t+1}^{i}+M_{t+1}^{i}(y_t)-S^{i}(y_{t+1})-T^{i}(y_{t+1}))f\left(X_{t+1}^{i},X_{t+1}^{j}\right)dX_{t+1}^{i}dX_{t+1}^{j}\quad (5)$$

Inequalities 4a, 4b and 4c, 4d are the conditions for profitable storage in either centre. Inventories in each centre will be zero if the expected future price exceeds the current spot price by less than the costs of storage; otherwise, arbitrageurs hold a quantity that ensures the expected future price exactly equals the current price plus the storage costs. Equations 4e, 4f and 4g are the conditions for trade from centre A to centre B. Equations 4e and 4f say that trade will be zero if the expected future price in centre B exceeds the spot price in centre A by less than the costs of trade; otherwise, arbitrageurs ship a quantity that ensures the expected future price exactly equals the current price plus the trade cost. Equation 4g says that the transport cost will equal $K^T$ if the traded amount is less than the shipping capacity; otherwise, the transport price will exceed $K^T$ by the difference between the expected future price in centre B (adjusted for the amount lost in transit and interest costs) and the spot price in centre A. The triple 4h, 4i, and 4j are similar, but describe the conditions for trade from centre B to centre A.

The model solution, which is found numerically, comprises two parts. The first part is the set of optimal storage and trade functions [$S^A(.)$, $S^B(.)$, $T^A(.)$, $T^B(.)$] that satisfy the ten equations 4a – 4j. Each function depends on the vector of four state variables. The second part of the solution is the distribution of the state variables that occurs in equilibrium, which depends on the assumed stochastic process determining output and the optimal storage and trade functions. The solution fulfils two conditions: first, that storage and trading decisions are profit-maximising conditional on expectations of future prices; and, secondly, that price expectations are consistent with the storage and trading decisions and expectations of future output quantities.

The model is solved in a similar fashion to the method used by Coleman (2004), and the reader is referred there for details. Three points should be noted. First, a numerical solution to the model is calculated over a discrete four-dimensional grid corresponding to the four state variables. The solution technique has four steps. First, a discrete joint probability distribution over the grid values for the stochastic variables $X^A$ and $X^B$ is chosen, and the double integral formula in equation 7 is replaced by the equivalent summation formula. The joint probability density for $X$ is chosen to mimic an autocorrelated process with normal innovations, and is represented by an $m^2$ x $m^2$ Markov transition matrix Π specifying the probability of going from one point $(X_{i1}^A, X_{j1}^B)$ to a second point $(X_{i2}^A, X_{j2}^B)$ .

The second step is to solve the optimal storage problem for the limiting “combined centre” case when transport costs are zero and trade is instantaneous, using techniques similar to those used by Deaton and Laroque (1992, 1996). Linear demand functions for each centre are specified:

$$D_i^{-1}(Q_t^i) = \begin{cases} \alpha^i & if \quad Q_t^i = 0 \\ \alpha^i - \beta^i Q_t^i & if \quad 0 < Q_t^i \le \alpha^i / \beta^i \\ 0 & if \quad Q_t^i > \alpha^i / \beta^i \end{cases} \tag{6}$$

The third step is an algorithm that calculates the optimal amounts of storage and trade in the two centres. The algorithm, which is similar to that described by Coleman(2004), constructs a series of successive approximations to the optimal storage and trade functions, and is repeated until the difference between successive values of the control values is small.

The fourth step, once the optimal storage and trade functions are found, is the calculation of the invariant probability distribution of the model solution. The invariant distribution of the model is the unconditional probability of being at a particular grid point, which is used to calculate various statistics about the price distributions in each centre. The method used to calculate the invariant distribution is also similar to that described in Coleman(2004).

## 3. Properties of the Model

The model solution depends on the basic parameters of the model including the demand and supply functions, interest rates and the depreciation rate, and the marginal shipping cost. The most important parameter choice is the extent to which output is regionally specialised. When the centres are identical, goods are exported as frequently one direction as the other, and average trade flows are small; but when one centre produces a disproportionate fraction of output, it exports most of the time, and the average volume of goods traded increases. The solutions are sufficiently distinctive that numerical results corresponding to the two cases are presented.

**Analytical Results**

The key results of the paper are derived analytically by considering various combinations of the complementary conditions 4b, 4d, 4f, and 4i that indicate whether inventories and trade volumes were zero or positive. Under a wide range of parameters, the invariant probability distribution indicates that most of the time either (a) both centres had positive inventories but neither centre exported or (b) both centres had positive inventories and one centre exported, or (c) one centre had positive inventories and exported, while the other centre had zero inventories and imported. The other combinations occurred rarely[5]. The set of conditions 4a – 4j indicates how prices adjust in each of these cases.

First, consider a point $y_t$ when inventories are positive in each centre, but there is no trade. Because inventories are positive, the price in each centre is expected to increase; more precisely, by equations 4a — 4d

$$E[P_{t+1}^{i} \mid y_t] = \left(\frac{1+r}{1-\delta}\right)\left(P^{i}(y_t) + K^{S}\right) \qquad i = A, B \tag{7}$$

and consequently

$$E[P_{t+1}^{A} - P_{t+1}^{B} \mid y_t] = \left(\frac{1+r}{1-\delta}\right)\left(P^{A}(y_t) - P^{B}(y_t)\right) \tag{8a}$$

Furthermore, equations 4e, 4f, 4h, and 4i imply the spatial price difference lies within the range

$$(K^{T} - K^{S}) \le P_t^{A} - P_t^{B} \le (K^{T} - K^{S}) \tag{8b}$$

This result is the same as Coleman (2004) and Williams and Wright (1991).

[5] As the stochastic process determining output is changed, the optimal storage and trade functions change but the solution still fulfills the set of conditions 4a-4j. Consequently, analytic statements about the solution will hold irrespective of the assumed stochastic process, but the distribution of the state variables in equilibrium will differ. As the modeling assumptions are changed, other combinations of the state variables might become more important.

Secondly, consider a point $y_t$ at which there are positive inventories in centre B, and arbitrageurs there export to centre A. There are several cases of interest. If centre A also has positive inventories, equations 4a, 4c, and 4h hold with equality and imply

$$E[P_{t+1}^A - P_{t+1}^B \mid y_t] = \frac{1+r}{1-\delta}(K_t^B - K^S) \tag{9a}$$

$$P^A(y_t) = P^B(y_t) + K_t^B - K^S \tag{9b}$$

Equation 9b indicates that if centre A has positive inventories at the time goods are exported from centre B, the import price will equal the export price plus the difference between the transport cost and the storage cost, and the law of one price will hold exactly. The transport cost will equal $K^T$ if an amount less than the shipping capacity is sent; otherwise the transport cost will be bid up until it equals the difference between the export price and the expected future import price, adjusted for storage costs.

Alternatively, if centre B has positive inventories and exports, but centre A has zero inventories, equations 4c and 4h hold and imply

$$E[P_{t+1}^A - P_{t+1}^B \mid y_t] = \frac{1+r}{1-\delta}(K_t^B - K^S) \tag{10a}$$

$$P^A(y_t) = P^B(y_t) + K_t^B - K^S + \varepsilon_t, \qquad \varepsilon_t > 0 \tag{10b}$$

In this case, the spatial price difference at time $t$ exceeds the difference between the transport cost and the inventory holding cost, as prices are unusually high in the importing centre, where inventories have been exhausted and where imports will not arrive until the next period. The price is expected to fall in the importing centre when the goods arrive, however. Once again the transport cost will equal $K^T$ if an amount less than the shipping capacity is exported, and greater than $K^T$ if an amount equal to the shipping capacity is exported.

Equations 8b, 9b, and 10b describe the possible variation in the difference between the two spot prices. The absolute value of the price difference is usually less than or equal to $K^T - K^S$; but it can exceed this amount if either the importing centre depletes its inventories, or the amount shipped is equal to the shipping capacity and shipping prices are high.

Equations 9a and 10a state that when goods are exported at time t, the expected future price difference is equal to $\frac{1+r}{1-\delta}(K_t^B - K^S)$. At time t+1 when the goods arrive, however, equations 8b, 9b, and 10b indicate the actual spot price differential will be either:

(i) less than $(K^T - K^S)$ if there are no further exports at time t+1;

(ii) equal to $(K_{t+1}^B - K^S)$ if there are exports at time t+1 and centre A has inventories;

or (iii) greater than $(K_{t+1}^B - K^S)$ if there are exports at time t+1 and centre A has no inventories.

Hence in order to cover interest costs and depreciation on average, the goods must sometimes arrive at time t+1 when prices in centre A are unusually high either because transport costs at time t+1 are unusually high or centre A has run out of inventories. Put differently, shippers cover their costs in this model only by having goods arrive at times when goods are unusually scarce in the destination market[6].

[6] Note that this logic means there are times when an importing centre will import even though it has positive inventories, and is certain to have positive inventories in the next period. If a centre has a particularly bad (negative) output shock, it will start to run down its inventories and simultaneously import. Because the amount it can import this period and next period is limited, it will not want to deplete inventories too fast as it knows it will need to use them to supplement the limited imports in the future. This possibility is usually deemed to be impossible in models without capacity constraints.

**Numerical Results**

In the rest of this section, numerical simulations are presented to illustrate how transport capacity constraints affect trade flows, storage quantities, and prices. Simulations are presented for the case that the centres are the same, so that trade flows as often one direction as the other, and for the case that output is regionally specialised. The parameters are chosen so that the centres have identical demand functions, the price elasticity in each centre at average consumption is one, the storage cost $K^S$ is zero, marginal transport price $K^T$ is 5 percent of average prices, the period is one week, and the annual interest and depreciation rates are five per cent[7]. These are the same parameters used in Coleman (2004) to enable easy comparison with the model with no capacity constraints. The simulations first show how prices are distributed for different values of the capacity constraint (tables 1-3), and how this depends on the size of the underlying shocks to the economy (table 4). The capacity constraint is then endogenised to show how much capacity is needed to reach a target rate of return as the size of the shocks to the economy is varied (table 5). Obviously a variety of other simulations such as the effect of changes in shipping costs could be simulated, although they are not reported here due to space constraints.

Tables 1, 2, and 3 show how trade flows, transport costs, storage quantities, and prices vary as transport capacity is decreased. Table 1 describes the case when the centres are identical, so that centre A produces 50 per cent of output on average; tables 2 and 3 describes the case when centre A only produces 45 per cent and 35 per cent of output and frequently imports. In all cases, the effects of reducing capacity on shipping prices and commodity prices are similar. First, as the transport capacity is reduced the mean volume of trade decreases and the fraction of occasions on which the capacity limit is binding increases. This raises the mean and variance of transport costs.

[7] In the baseline case, the following model parameters are used: the demand function $D_i^{-1}(Q) = \alpha - \beta Q = 200 - Q$; mean production is 100 in each centre; the production conditional variance $\sigma^2 = 100$; the production autocorrelation $\rho = 0.9$ ; the weekly interest rate r = 0.001; the weekly depreciation rate $\delta = 0.001$; $K^S = 0$; and $K^T = 5$. The mean price is 100.

The relationship between transport costs and transport capacity is convex, but the effect would be even more marked except there is a large increase in the size of inventories in both importing and exporting centres in anticipation of the occasions when the capacity constraint binds. Secondly, as the capacity constraint is reduced, price dispersion, measured either by the variance of $P_t^A - P_t^B$ or the fraction of times that $P_t^A - P_t^B$ exceeds $K^T - K^S$, increases. The effect of capacity constraints is particularly marked when one centre is the dominant producer, for then inventory management is less useful for smoothing prices than when both centres are the same.

Table 4 shows a similar set of numerical results, but this time it shows how the effect of capacity constraints depends on the size of the underlying shocks to the economy. In this table centre A produces 45 per cent of output, so two-way trade does occur but A imports more than it exports. The model is solved for a variety of capacity constraints when the standard deviation of the underlying production shock is changed from 10 per cent of output to 5 per cent of output. The table shows how the effect of a given capacity constraint depends on the volatility of output.

As volatility increases, inventory management becomes much more important, and average storage levels increase markedly. When output shocks are small, trade is more frequent, but when goods are sent the transport capacity is less likely to be fully utilized[8]. The most notable effect of the increase in output volatility, however, is the increase in the fraction of the time that the transport capacity binds, for any level of capacity. This raises the fraction of times the transport cost is bid above the marginal cost, and thus the mean transport cost, as well as the variance of transport costs. In turn, this increases price dispersion, as measured either by the variance of $P_t^A - P_t^B$ or the fraction of times that $P_t^A - P_t^B$ exceeds $K^T - K^S$. One of the major effects of an

[8] Note that under this parameterization goods would always be sent from B to A if there were no uncertainty. Uncertainty increases the fraction of time that no trade occurs, and the fraction of time that A exports to B because it has a temporary surplus and B a temporary shortfall.

increase in output volatility, therefore, is to increase the extent of price dispersion and to increase the revenue of transport operators.

Table 5 takes this analysis one step further by calculating how transport capacity endogenously responds to an increase in output volatility. It calculates the transport capacity needed to obtain a target return in the transport sector, in this case an average transport price of 7, or 40 per cent higher than marginal cost. In turn various statistics about the prices, transport costs, storage quantities and trade volumes that occur in equilibrium are calculated. The table calculates the effect of changes in the variance of output shocks when average output in centre A is either 50 per cent, 45 per cent, or 35 per cent of the total.

The table indicates that as the variance of output shocks increases, the amount of transport capacity increases. The increase in transport capacity means the fraction of time that trade occurs, and the fraction of time that the capacity limit binds, are lower the larger the variance of the shocks. Yet the variance of transport costs increases, for even though capacity limits bind less often, when they do bind the transport price is very high. In turn, this means that spatial price dispersion increases. Thus even when one takes into account the endogenous expansion of transport capacity, an economy with a high variance of output shocks has greater price dispersion and greater transport price volatility than an economy with a low variance of output shocks.

## 4. Empirical Evidence: the U.S. Corn Trade, 1878-1891

There are two strands of empirical work that provide some support for the model in this paper. First, there is evidence that transport costs respond to short term changes in demand. Examples of this work are Kloveland (2004), who shows that in the nineteenth century cycles in economic activity were a major determinant of shipping freight rates, and Harley (2004) who documented how trans-Atlantic shipping prices for agricultural goods (wheat and live cows) varied at the end of the nineteenth century. The second strand is a series of papers that has demonstrated that the difference between two spatially separate prices is positively correlated with transport prices. Examples of this work include Snodgrass (1926), Goodwin, Grennes, and Wohlgenant (1990), Persson (2004), Nason, Paterson and Shearer (2004) and Coleman (2004). All of these papers analyse agricultural commodities, presumably because high frequency transport price data is more easily obtained for these commodities than other types of goods. Most but not all of them analyse commodity prices in the nineteenth century. This paper uses the dataset assembled by Coleman (2004) as it is the most comprehensive of all of these datasets, containing transport cost and trade volume data, inventory data, and spot and future price data for both cities, all collected at weekly frequencies.

Coleman (2004) analysed weekly corn prices in Chicago and New York between 1878 and 1891. New York imported corn from Chicago and the paper analysed whether or not there were localized price spikes in New York when inventories in the city fell to very low levels. He found that such spikes did indeed occur. In particular, he found that when New York inventories were low, the spot price in New York regularly exceeded the spot price in Chicago by more than the transport cost, but that when New York inventories were high, the New York spot price was very close to the Chicago price plus the transport cost. Furthermore, he found the price for future delivery in New York was close to the Chicago spot price plus the transport cost, irrespective of the New York inventory level, as predicted by equations 4e, 4f and 4g.

Because Coleman's model had fixed transport costs, and because his empirical focus was the behaviour of prices when inventories in the importing centre were very low, he ignored the other facet of the corn market that he documented — the extremely high variation in weekly transport costs. Yet figures he provided showed that between 1878 and 1891 the price of shipping corn varied almost continuously week to week, ranging from 4 cents per bushel to 18 cents per bushel. Moreover he showed that two thirds of the week to week variation in the contemporaneous difference between the New York future price (for delivery in three weeks time) and the Chicago spot price could be explained by the week to week variation in the transport cost.

In this section, I revisit Coleman's analysis to emphasis how the variation in transport costs affected the New York and Chicago corn market. The section has three parts: a brief description of the market, a statistical description of transport costs, and an analysis of the relationship between transport costs, prices, and inventory levels in Chicago and New York.

**The late nineteenth century corn market[9].**

Corn was first sent to Chicago, and then forwarded to New York one of three ways. The slowest method was to ship corn to Buffalo via the Great Lakes, and then to send it to New York via the Erie Canal. This method took three weeks, but was unavailable between November and late April when the lakes were frozen. A faster method, taking 10 days, was to ship corn to Buffalo via the Great Lakes and then to send it to New York by rail. The fastest and most expensive method was to send corn to New York by rail, a trip that took 3 or 4 days. Between 1881 and 1891, when average annual costs were reasonably 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[10]. The average price of a bushel of corn in Chicago during this time was 45 cents.

Most corn was shipped from Chicago by water to Buffalo, where it was transferred to canal boats and forwarded to New York. The lakes and canals were frozen from December to April, so shipments typically stopped sometime in November and recommenced in April or early May.

[9] This section draws heavily on Coleman (2004).
[10] Chicago Board of Trade, 1892, p122.

There was practically no export of corn from Chicago to New York during the winter[11]. Over 85 percent of the corn sent from Chicago to New York during the open water season went by the lake and canal route, so it is appropriate to compare the New York – Chicago price differential to the lake and canal transport cost. When grain arrived in New York it was transferred to an elevator or a lighter and either sold or delivered in fulfillment of a futures contract. Grain was often stored temporarily, but the storage capacity was rarely fully utilised, even in winter. In 1888, it cost ⅝ cents per bushel to deposit grain in an elevator, including the cost of 10 days storage; thereafter, storage cost ¼ cents per bushel per ten days. There were additional charges for trimming from canal boats and to ocean ships. Charges in Chicago were similar.

The standard spot and futures contracts in both New York and Chicago were settled by the delivery of grain to a warehouse or elevator. The main contracts were for immediate delivery (the spot contract) or for delivery at any time within the current month, the next month, two months' time, or in May of a particular year (the futures contracts). The seller had the option as to the date in a particular month the grain was delivered, so spot prices normally exceeded or were equal to the zero-month future price. This paper uses the Wednesday closing price for all of the analysis.

**Transport prices between Chicago and New York.**

There was a marked seasonal pattern in shipping costs (see Figure 1). Lake and canal (and lake and rail) transport prices were typically high at the beginning and end of the season, but were low at the height of summer before the new harvest. The rates were affected by rail competition, for if lake and canal rates became too high shippers further west would choose to bypass Chicago and ship grain directly to New York by rail. Average shipping rates were lower in 1891 than in 1878, but throughout the whole period rates were quoted as low as six cents per bushel.

[11] This statement needs minor qualification. Grain was shipped by rail through Chicago to New York from points further west. However, very little grain sold in Chicago was sent to New York. Typically the New York price exceeded the Chicago price by less than the rail transport cost.

Figure 2 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[12]. 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[13]. Figure 2 indicates there was a positive relationship between the volume of grain shipped and the transport price, particularly between 1878 and 1887. The relationship is weaker from 1888 to 1891, possibly because the shipping tonnage increased[14].

The relationship between transport prices and shipping volumes can be estimated formally, using feasible generalized least squares to take into account first order serial correlation in the errors. The best fitting lines for the two sub-periods are:

**1878-1887**

$$Transport\ \ Cost_t = \underset{(0.63)}{2.39} + \underset{(0.12)}{0.53} Transport\ volume_t + u_t$$

$$u_t = 0.39 u_{t-1} + e_t \qquad\qquad R^2 = 0.55 \quad N = 56$$

[12] 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.
[13] Monthly data is used because the weekly data does shipment data does not describe which transport mode was used to move the grain.
[14] 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.

**1888-1891**

$$Transport\ \ Cost_t = 2.56 + 0.18 Transport\ volume_t + u_t$$
$$(0.55)\quad(0.07)$$
$$u_t = 0.40u_{t-1} + e_t \qquad R^2 = 0.37 \quad N = 23$$

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, it is not clear that they are consistent with a model in which transport prices are perfectly elastic until the capacity limit is reached, at which point they become perfectly inelastic. 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 transport price-volume relationship of the type modeled in this paper at daily frequency, it would not be detected in a monthly average if transport volumes varied from day to day. Unfortunately, higher frequency data is not easily obtained[15]. However, there is anecdotal evidence that provides some support for the way transport costs are modeled in this paper. 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

[15] Weekly data on corn, wheat and other grain shipments from Chicago is available. The difficulty with the weekly data is that it does 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.

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)[16]. While such statements are anecdotal, in combination with the above statistical evidence it does appear that one of the components of the model, a positive relationship between high frequency transport prices and transport volumes, is defensible.

**Price Arbitrage and Transport Cost**

Coleman (2004) analysed the relationship between New York prices, Chicago prices, and the transport cost. Given his focus on the role of inventory management in the determination of commodity prices, however, he completely ignored the relevance of his finding that 70 per cent of the weekly variation in the difference between Chicago and New York prices was explained by weekly variation in the transport cost.

[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.

Figure 3 is a time series graph of the Chicago and New York corn spot prices for the period. The two tend to move together, and the estimated correlation coefficient of the series is 0.92[17]. Figure 4 is a scatterplot of the difference between the New York price for future delivery (in three weeks time) and the Chicago spot price, and the transport cost for weeks in which the transport price is available. (As the seller had the option of delivering any time during the month, the price for delivery "this month" was used if the date of the month was before the eleventh, and the price for delivery in the subsequent month was used if the date occurred on or after the eleventh[18].) Finally figure 5 shows the difference between the New York spot price and the Chicago spot price versus the weekly transport cost. Observations when New York inventories were lower than 300 000 bushels are indicated. Both figure 4 and figure 5 are from Coleman (2004). Casual observation suggests that the spatial price difference increased one for one with the transport cost, and that New York spot prices (but not future prices) were high when inventories in New York were low.

Coleman(2004) used feasible least squares to estimate the relationships pictured in figures 4 and 5[19]. He included a dummy variable indicating whether inventories of corn in New York were less than 300 000 bushels, an unusually low number[20]. The regressions for the future price and the spot price were:

$$
\begin{aligned}
&(F_{t,t+3}^{NY} - P_t^{CH}) = \underset{(0.23)}{1.11} + \underset{(0.044)}{0.95}\ \ Transport\ \ Cost_t + \underset{(0.22)}{0.22}\ \ 1(Storage_t < 300{,}000) + u_t \\
&u_t = 0.41u_{t-1} + e_t \qquad\qquad R^2 = 0.74 \quad N = 358
\end{aligned}
$$

and

[17] Purists could note that one cannot reject the hypothesis of a unit root in either series, whereas one can reject the hypothesis that the residuals of a regression of one series against the other is a unit root.
[18] Ten of the futures prices were not available, and these observations were omitted.
[19] The regressions were estimated using feasible generalised least squares to take into account first order autocorrelation amongst the error process.
[20] The observation for 23 September 1884 is omitted as there was a corner in the Chicago market and the Chicago price was 16 cents higher than the New York price.

$$(P_t^{NY} - P_t^{CH}) = \underset{(0.29)}{1.75} + \underset{(0.06)}{0.85}\ Transport\ \ Cost_t + \underset{(0.29)}{2.05}\ \ 1(Storage_t < 300{,}000) + u_t$$

$$u_t = 0.45u_{t-1} + e_t \qquad R^2 = 0.69 \quad N = 368$$

where 1(Storage <300,000) has a value of one if inventories were less than 300,000 and zero otherwise. He emphasized that the transport cost coefficient is very close to, and insignificantly different from 1 in the first regression, providing clear evidence that the law of one price as described by equation 4e and 4f held in these markets. Yet equally remarkable, but unremarked, are the estimated $R^2$. It proves that nearly three quarters of the variation in the difference between the New York future price and the Chicago spot prices can be explained by high frequency variation in transport costs. Similarly, over two thirds of the variation in the difference between the New York and Chicago spot prices can be explained by the variation in transport costs and inventory levels.

These regressions attest to the importance of having high frequency transport cost data when analyzing the extent to which the law of one price holds. During this time, both the weekly transport cost and the spatial price difference were very volatile, the former having a mean of 8.2 cents per bushel and a standard deviation of 2.6, and the latter (the New York future minus Chicago spot) having a mean of 9.6 and a standard deviation of 3.2. If one did not know that most of the variation in the spatial price difference was associated with variation in transport costs, it would appear that New York and Chicago prices were not properly arbitraged; yet with the proper high frequency transport data, this false conclusion can be rejected. Indeed, these data provide considerable support for three aspects of the model: that transport costs are positively correlated with trading volumes; that the expected future price in New York was very close to the Chicago spot price plus the transport cost, so that variation in transport costs was high correlated with variation in the spot-future spatial price difference; and that the spot New York price considerably exceeded the spot Chicago price plus the transport cost when New York inventories were low, but not when they were high.

## 5. Discussion and conclusion

The theory of price arbitrage has a long history, dating back to at least Cournot (1838). Most of the analysis has been predicated on the assumption that transport is supplied elastically to move goods, and that transport costs are constant. This paper suggests these assumptions may not be innocuous. Rather, if transport operators plan to use their capital intensive machinery as much as possible, there will be limited capacity and transport prices will rise when this capacity is in demand. Under these circumstances, the law of one price will hold because shipping prices adjust to make it hold, and prices will vary substantially between locations. This variation is not evidence against the law of one price but the mechanism by which transport operators earn their cost of capital. Arbitrageurs only cover their capital costs if they make large profits at times when demand is especially high, that is at times when spatial price differences are especially large.

The model suggests that prices in different locations adjust to shocks in a way quite different to that usually postulated. In most models, a region experiencing a negative output shock will smooth consumption by importing sufficient quantities of goods to ensure the local price does not exceed the world price by more than a fixed transport cost. In this model, the same region would not be able to fully smooth consumption because not enough goods can be imported; rather, the output shock is expressed as large profits for the shipping companies, and high international price dispersion. As the variance of these output shocks rises, shipping margins increase, attracting new capacity; yet price dispersion still increases, as the volatility of shipping prices rises, with demand for shipping either being a famine or a feast.

The data used in this paper is useful because the shipping service was sold, so that prices are available. Yet even if the service was not sold — the shipping was done on own account, for example, or the transport service was broadly interpreted to include distribution services such as retailing — the same logic would remain. Capital intensive distribution services would have limited capacity, and would make different returns depending on the relative size of supply and demand. When demand was low relative to supply the price difference between locations would be small and they would make low margins; when demand was high relative to supply the price difference between locations would be high and they would make large margins. Again, evidence that price differences between locations varied significantly over time would not be evidence that arbitrage was not working, but a necessary condition to attract arbitrageurs into the industry.

The theoretical and the empirical results in the paper raise several issues for further enquiry. The first concerns the number of sectors and time periods for which this model is applicable. The model is designed to examine the behaviour of prices of commodities that are traded in competitive markets, and which are transported by competitive shipping firms. Many agricultural and extractive commodities appear to fit this bill; according to Stopford (1988) the maritime shipping firms that transport most bulk commodities (but not general cargo) are competitive, and shipping prices vary substantially in the short term in accordance with supply and demand[21]. Contemporary data on grain shipments between the United States and Japan, and the United States and Europe show that trade volumes and shipping prices are positively correlated[22]. Whether or not goods prices and transport prices in other industries can be appropriately described by this model needs to be determined on a case by case basis.

[21] According to Stopford (p15, p229) 74 per cent of total seaborne cargoes in 1985 were bulk goods, of which 36 per cent was oil and 23 per cent was iron ore, coal or grain.
[22] For example, for 1995-2000, the correlation coefficient between monthly Gulf of Mexico-Antwerp grain shipping prices and the total volume of US grain shipments is 0.54. Data is from International Grains Council (1995-2000).

Secondly, this paper indicates that the way in which the transport sector is incorporated into trade models is important. Seemingly small changes to a model such as the incorporation of transport capacity constraints have large effects on the properties of the model. It may be the case that more realistic modeling of the transport sector in models that describe trade in other industrial sectors would also have large effects on the properties of these models.

Thirdly, the paper has a very simple model of output and output shocks. Williams and Wright (1991) have demonstrated in simpler settings that it is reasonably straightforward to make the supply side of the model more complex, and that such changes do not have major qualitative consequences for the properties of these models. Yet there has been little work examining how exchange rate shocks would affect the model, if the centres were located in different currency zones. If currency shocks had a similar effect to output shocks, their main effect would be to affect the size and the profitability of the distribution sector and to increase the variance of international price differences. An appreciation of the local exchange rate would have only a limited affect on local prices because of limits to the amount that could be imported, for instance, although it would increase the short term profitability of the distribution (shipping) sector.

Finally, the paper raises questions about the meaning of empirical work that examines high frequency deviations from the law of one price without having high frequency transport cost data. In line with several other papers that have used high frequency transport cost data, this paper shows that when the law of one price is properly examined using a dataset that includes transport price and inventory data, there is evidence that it holds tolerably well. In this case, over two thirds of the variation in the difference between New York and Chicago prices could be explained in terms of the variation of high frequency transport costs. It is perhaps worth wondering whether much of the empirical evidence that the law of one price does not hold in the short and medium terms is due to a lack of appropriate transport cost data.

# Appendix: Data Sources

The data for this paper is described in Coleman (2004), and this appendix is copied from there. Six kinds of data have been assembled for this project: the spot price of corn in New York and Chicago; the future price of corn in New York and Chicago; transport costs between Chicago and New York; transport volumes between Chicago and New York; storage prices in Chicago and New York; and storage volumes in Chicago and New York.

**Spot Price of Corn.**

Prices were collected for Number 2 Yellow corn. Number 2 corn was the primary future grade and comprised a large fraction of the spot market. Grades were defined as follows.

New York: "YELLOW CORN shall be sound, dry, plump and well cleaned; an occasional white or red grain shall not deprive it of this grade. No.1 CORN shall be mixed corn of choice quality, sound, dry and reasonably clean. No.2 CORN shall be mixed corn, sound, dry and reasonably clean. " New York Produce Exchange (1882) p207

Chicago: "No. 1 YELLOW CORN shall be yellow, sound, dry, plump and well cleaned.
No. 2 CORN shall be dry, reasonably clean, but not plump enough for No. 1" Chicago Board of Trade (1882) p 79-80

Spot prices for both cities were collected in the Thursday edition of the New York Times, 1878-1891. The prices were for the preceding Wednesday. If the Wednesday were a public holiday, the Tuesday price was collected. If the markets were closed on both Wednesday and Tuesday, the data was skipped for that week.

Daily spot prices for New York are also available in some years in the Annual Report of the New York Produce Exchange. However, since The New York Times had to be used to collect the Chicago spot price and the New York future price, as well as the New York spot price in years where it was not reported in the Annual Report, the weekly New York Times data was used.

**Future Price of Corn.**

Prices were collected for Number 2 Yellow corn. The Chicago future price was collected from the Annual Report of the Chicago Board of Trade. The quotes is for seller delivery: the seller could choose any day to deliver within the said month.  Wednesday quotes were collected.

The New York Wednesday future prices were collected from the Thursday edition of the New York Times. The seller also had the option as to the delivery date.

**Corn Trade and Storage Data.**

Storage and trade 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 these documents had little data between 1882 and 1887. Storage data for these years came from the weekly Commercial and Financial Chronicle. Export data for several years came from the Chicago Board of Trade Annual Reports.

**Transport Data**

The transport cost data were published by the Chicago Board of Trade and New York Produce Exchange Annual Reports.

**Table 1: Prices, storage, transport costs, and trade statistics corresponding to the model. (Centre A produces 50% of output, σ=10, changing transport capacity.)**

| Statistic | $\overline{T}=5$ | $\overline{T}=10$ | $\overline{T}=20$ | $\overline{T}=30$ | $\overline{T}=40$ | $\overline{T}=50$ | **No Limit** |
|---|---|---|---|---|---|---|---|
| **Prices** | | | | | | | |
| Mean($P^A$) | 100.4 | 100.3 | 100.3 | 100.3 | 100.3 | 100.3 | 100.3 |
| S. Dev.($P^A$) | 10.3 | 9.6 | 8.5 | 8.6 | 8.6 | 8.5 | 8.5 |
| Mean($P^A$-$P^B$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S. Dev.($P^A$-$P^B$) | 13.0 | 10.5 | 7.3 | 5.8 | 5.1 | 4.8 | 4.6 |
| % (\| $P^A$-$P^B$\| >$K^T$-$K^S$) | 54.2% | 40.2% | 23.8% | 13.8% | 7.8% | 4.4% | 3.1% |
| **Storage** | | | | | | | |
| Mean($S^A$) | 361 | 325 | 288 | 273 | 265 | 269 | 261 |
| S. Dev.($S^A$) | 305 | 275 | 252 | 253 | 253 | 257 | 251 |
| % ($S^A$ > 0) | 95% | 96% | 97% | 97% | 97% | 97% | 97% |
| **Trade** | | | | | | | |
| Mean($T^A$) | 1.4 | 2.2 | 2.9 | 3.1 | 3.1 | 3.1 | 3.2 |
| S. Dev.($T^A$) | 2.2 | 4.1 | 6.8 | 8.2 | 9.0 | 9.1 | 10.5 |
| Mean($T^A$)\|$T^A$>0 | 4.9 | 9.4 | 16.7 | 19.4 | 19.7 | 20.0 | 20.0 |
| % ($T^A$ > 0) | 28.4% | 23.5% | 17.5% | 15.9% | 15.9% | 15.7% | 16.0% |
| % ($T^A=\overline{T}$ ) | 27.1% | 20.1% | 11.4% | 6.1% | 2.8% | 0.8% | 0% |
| **Transport Cost** | | | | | | | |
| Mean ( $K_t^A$ ) | 7.27 | 6.40 | 5.54 | 5.20 | 5.08 | 5.04 | 5 |
| S. Dev( $K_t^A$ ) | 5.9 | 4.5 | 2.5 | 1.5 | 0.9 | 0.6 | 0 |
| Excess return | 4.54 | 2.80 | 1.08 | 0.32 | 0.16 | 0.08 | 0 |

$P^A$: the price in centre A. $S^A$: storage in centre A. $T^A$: trade from centre A to centre B. $K_t^A$ is the transport cost incurred sending a ship from A to B (and an empty ship from B to A).
% (| $P^A$-$P^B$| >$K^T$-$K^S$): the fraction of time the price difference exceeds the difference between the marginal trade cost and the storage cost. Note $K^S$=0 in these simulations.
% ($S^A$[$T^A$] > 0): the fraction of time storage [exports] > 0. % ($T^A=\overline{T}$ ) is the fraction of times the quantity traded is equal to the transport capacity (and hence the fraction of times $K_t^A > K^T$.
The "No limit centre" column refers to the case that unlimited quantities of goods can be sent at marginal cost $K^T$.

**Table 2: Prices, storage, transport costs, and trade statistics corresponding to the model. (Centre A produces 45% of output, σ=10, changing transport capacity.)**

| Statistic | $\overline{T}=5$ | $\overline{T}=10$ | $\overline{T}=20$ | $\overline{T}=30$ | $\overline{T}=40$ | $\overline{T}=50$ | No Limit |
|---|---|---|---|---|---|---|---|
| **Prices** | | | | | | | |
| Mean($P^A$) | 107 | 105 | 103 | 102 | 102 | 102 | 102 |
| S. Dev.($P^A$) | 12 | 11 | 10 | 9 | 9 | 9 | 9 |
| Mean ($P^B$) | 94 | 96 | 98 | 98 | 99 | 99 | 99 |
| S. Dev($P^B$) | 10 | 9 | 9 | 9 | 9 | 9 | 9 |
| Mean($P^A$-$P^B$) | 13.1 | 8.5 | 4.8 | 3.7 | 3.4 | 3.3 | 3.3 |
| S. Dev.($P^A$-$P^B$) | 14.5 | 11.7 | 7.6 | 5.5 | 4.5 | 4.1 | 3.9 |
| % ($\|P^A-P^B\| > K^T-K^S$) | 80% | 66% | 42% | 25% | 15% | 8% | 3% |
| **Storage** | | | | | | | |
| Mean($S^A$) | 362 | 349 | 284 | 221 | 203 | 179 | 169 |
| S. Dev.($S^A$) | 299 | 278 | 233 | 198 | 190 | 180 | 173 |
| Mean ($S^B$) | 381 | 338 | 273 | 226 | 287 | 293 | 297 |
| S.Dev($S^B$) | 335 | 298 | 239 | 254 | 268 | 279 | 289 |
| **Trade** | | | | | | | |
| Mean($T^A$) | 0.3 | 0.6 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| S. Dev.($T^A$) | 1.2 | 2.3 | 3.8 | 4.3 | 4.5 | 4.6 | 5.4 |
| Mean($T^A$)\|$T^A$>0 | 5 | 9.6 | 14.8 | 18 | 18 | 19 | 20 |
| % ($T^A > 0$) | 6.3% | 6.3% | 5.6% | 4.6% | 4.4% | 4.3% | 4.1% |
| % ($T^A = \overline{T}$) | 6.0% | 5.1% | 3.2% | 1.0% | 0.4% | 0.3% | 0% |
| Mean($T^B$) | 3.8 | 6.3 | 8.4 | 8.9 | 9.1 | 9.1 | 9.1 |
| S. Dev.($T^B$) | 2.1 | 4.8 | 9.6 | 13 | 15 | 15 | 15 |
| Mean($T^A$)\|$T^B$>0 | 4.95 | 9.7 | 17.1 | 28.3 | 25.7 | 27.0 | 23 |
| % ($T^B > 0$) | 76% | 65% | 49% | 37% | 35% | 37% | 39% |
| % ($T^B = \overline{T}$) | 75% | 61% | 37% | 23% | 13% | 6% | 0% |
| **Transport Cost** | | | | | | | |
| Mean ( $K_t^A$ ) | 5.46 | 5.35 | 5.14 | 5.04 | 5.02 | 5.01 | 5 |
| S. Dev( $K_t^A$ ) | 2.5 | 2.1 | 1.2 | 0.7 | 0.5 | 0.3 | 0 |
| Mean ( $K_t^B$ ) | 14.80 | 10.43 | 6.78 | 5.63 | 5.20 | 5.06 | 5 |
| S. Dev( $K_t^B$ ) | 11.1 | 8.5 | 4.7 | 2.6 | 0.3 | 0.7 | 0 |
| Excess return | 10.26 | 5.78 | 1.92 | 0.67 | 0.22 | 0.07 | 0 |

$P^A$: the price in centre A. $S^A$: storage in centre A. $T^A$: trade from centre A to centre B. $K_t^A$ is the transport cost incurred sending a ship from A to B (and an empty ship from B to A).
% ($|P^A-P^B| > K^T-K^S$): the fraction of time the price difference exceeds the difference between the marginal trade cost and the storage cost. Note $K^S$=0 in these simulations.
% ($S^A[T^A] > 0$): the fraction of time storage [exports] > 0. % ($T^A = \overline{T}$ ) is the fraction of times the quantity traded is equal to the transport capacity (and hence the fraction of times $K_t^A > K^T$.
The "No limit centre" column refers to the case that unlimited quantities of goods can be sent at marginal cost $K^T$.

**Table 3: Prices, storage, transport costs, and trade statistics corresponding to the model. (Centre A produces 35% of output, σ=10, changing transport capacity.)**

| **Statistic** | $\bar{T}=10$ | $\bar{T}=20$ | $\bar{T}=30$ | $\bar{T}=40$ | $\bar{T}=50$ | **No Limit** |
|---|---|---|---|---|---|---|
| **Prices** | | | | | | |
| Mean($P^A$) | 120 | 112 | 106 | 104 | 103 | 103 |
| S. Dev.($P^A$) | 13 | 12 | 11 | 10 | 9 | 9 |
| Mean ($P^B$) | 80 | 89 | 95 | 97 | 98 | 98 |
| S. Dev($P^B$) | 10 | 9 | 8 | 8 | 9 | 10 |
| Mean($P^A$-$P^B$) | 40.3 | 22.6 | 10.8 | 6.6 | 5.5 | 5.1 |
| S. Dev.($P^A$-$P^B$) | 16.4 | 14.4 | 9.8 | 5.7 | 3.2 | 1.9 |
| % ($\lvert P^A-P^B \rvert > K^T-K^S$) | 98% | 92% | 76% | 52% | 31% | 2% |
| **Storage** | | | | | | |
| Mean($S^A$) | 405 | 417 | 357 | 297 | 213 | 91 |
| S. Dev.($S^A$) | 332 | 330 | 286 | 242 | 173 | 81 |
| Mean ($S^B$) | 458 | 367 | 233 | 178 | 213 | 300 |
| S.Dev($S^B$) | 399 | 350 | 252 | 184 | 227 | 304 |
| **Trade** | | | | | | |
| Mean($T^A$) | 0.0 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 |
| S. Dev.($T^A$) | 0.2 | 1.0 | 1.4 | 1.2 | 0.8 | 0.4 |
| Mean($T^A$)\|$T^A$>0 | 10 | 15 | 20 | 16.7 | 14.3 | 12.8 |
| % ($T^A > 0$) | 0.04% | 0.4% | 0.4% | 0.3% | 0.1% | 0.1% |
| % ($T^A = \bar{T}$) | 0.04% | 0.2% | 0.1% | 0.0% | 0.0% | 0% |
| Mean($T^B$) | 9.8 | 18.8 | 24.7 | 26.8 | 27.3 | 27.4 |
| S. Dev.($T^B$) | 1.3 | 4.4 | 11 | 17 | 21 | 21 |
| Mean($T^A$)\|$T^B$>0 | 9.94 | 19.7 | 28.3 | 34.8 | 37.0 | 32.7 |
| % ($T^B > 0$) | 99% | 96% | 87% | 77% | 74% | 84% |
| % ($T^B = \bar{T}$) | 98% | 91% | 74% | 54% | 35% | 0% |
| **Transport Cost** | | | | | | |
| Mean ( $K_t^A$ ) | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5 |
| S. Dev( $K_t^A$ ) | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0 |
| Mean ( $K_t^B$ ) | 40.18 | 22.58 | 10.96 | 6.60 | 5.42 | 5 |
| S. Dev( $K_t^B$ ) | 15.6 | 13.2 | 8.5 | 4.3 | 1.9 | 0 |
| Excess return | 35.18 | 17.58 | 5.96 | 1.60 | 0.42 | 0 |

$P^A$: the price in centre A. $S^A$: storage in centre A. $T^A$: trade from centre A to centre B. $K_t^A$ is the transport cost incurred sending a ship from A to B (and an empty ship from B to A).

% ($\lvert P^A-P^B \rvert > K^T-K^S$): the fraction of time the price difference exceeds the difference between the marginal trade cost and the storage cost. Note $K^S$=0 in these simulations.

% ($S^A$[$T^A$] > 0): the fraction of time storage [exports] > 0. % ($T^A = \bar{T}$ ) is the fraction of times the quantity traded is equal to the transport capacity (and hence the fraction of times $K_t^A > K^T$.

The "No limit centre" column refers to the case that unlimited quantities of goods can be sent at marginal cost $K^T$.

**Table 4: Prices, storage, transport costs, and trade statistics corresponding to the model. (Centre A produces 45% of output, changing transport capacity, σ=5 or σ=10)**

| **Statistics** | $\bar{T}=5$ **σ = 5** | $\bar{T}=10$ **σ = 5** | $\bar{T}=20$ **σ = 5** | $\bar{T}=\infty$ **σ = 5** | $\bar{T}=5$ **σ = 10** | $\bar{T}=10$ **σ = 10** | $\bar{T}=20$ **σ = 10** | $\bar{T}=\infty$ **σ =10** |
|---|---|---|---|---|---|---|---|---|
| **Prices** | | | | | | | | |
| Mean($P^A$-$P^B$) | 11.8 | 7.1 | 4.7 | 4.5 | 13.1 | 8.5 | 4.8 | 3.3 |
| S. Dev.($P^A$-$P^B$) | 7.0 | 6.0 | 2.8 | 2.3 | 14.5 | 11.7 | 7.6 | 3.9 |
| % (\| $P^A$-$P^B$\| >$K^T$-$K^S$) | 82% | 61% | 24% | 6% | 80% | 66% | 42% | 3% |
| **Storage** | | | | | | | | |
| Mean($S^A$) | 92 | 78 | 45 | 31 | 362 | 349 | 284 | 169 |
| Mean ($S^B$) | 88 | 63 | 65 | 74 | 381 | 338 | 273 | 297 |
| **Trade** | | | | | | | | |
| Mean($T^A$) | 0.05 | 0.07 | 0.05 | 0.04 | 0.3 | 0.6 | 0.8 | 0.8 |
| Mean($T^B$) | 4.1 | 6.5 | 7.7 | 7.8 | 3.8 | 6.3 | 8.4 | 9.1 |
| % ($T^A$ +$T^B$> 0) | 86% | 72% | 58% | 65% | 82% | 71% | 55% | 43% |
| % ($T^A$ or $T^B$=$\bar{T}$ ) | 81% | 59% | 21% | 0% | 81% | 66% | 40% | 0% |
| **Transport Costs** | | | | | | | | |
| Mean ( $K_t^A$ ) | 5.01 | 5.01 | 5.00 | 5 | 5.46 | 5.35 | 5.14 | 5 |
| S. Dev( $K_t^A$ ) | 0.2 | 0.1 | 0.0 | 0 | 2.5 | 2.1 | 1.2 | 0 |
| Mean ( $K_t^B$ ) | 12.27 | 7.68 | 5.23 | 5 | 14.80 | 10.46 | 6.78 | 5 |
| S. Dev( $K_t^B$ ) | 7.1 | 4.4 | 1.0 | 0 | 11.1 | 8.5 | 4.7 | 0 |
| Excess return | 7.28 | 2.69 | 0.23 | 0 | 10.26 | 5.78 | 1.92 | 0 |

σ : the standard deviation of the shock hitting output in each centre

$P^A$: the price in centre A. $S^A$: storage in centre A. $T^A$: trade from centre A to centre B. $K_t^A$ is the transport cost incurred sending a ship from A to B (and an empty ship from B to A).

% (| $P^A$-$P^B$| >$K^T$-$K^S$): the fraction of time the price difference exceeds the difference between the marginal trade cost and the storage cost. Note $K^S$=0 in these simulations.

% ($S^A$[$T^A$] > 0): the fraction of time storage [exports] > 0. % ($T^A$ =$\bar{T}$ ) is the fraction of times the quantity traded is equal to the transport capacity (and hence the fraction of times $K_t^A$ > $K^T$.

The "No limit centre" column refers to the case that unlimited quantities of goods can be sent at marginal cost $K^T$.

**Table 5: Equilibrium transport capacity as a function of output shock variance.**

| **Statistics**<br>**Centre A output**<br>**σ** | **50%**<br>**Σ=2.5** | **50%**<br>**σ = 5** | **50%**<br>**σ =10** | **45%**<br>**σ =2.5** | **45%**<br>**σ = 5** | **45%**<br>**σ = 10** | **35%**<br>**σ =2.5** | **35%**<br>**σ = 5** | **35%**<br>**σ = 10** |
|---|---|---|---|---|---|---|---|---|---|
| **Capacity limit** | 0.01* | 3.0 | 13.6 | 8.2 | 11.3 | 19.6 | 28.1 | 30.8 | 38.3 |
| **Prices** | | | | | | | | | |
| Mean($P^A$-$P^B$) | 0 | 0 | 0 | 7.1 | 6.4 | 4.9 | 7.2 | 7.2 | 6.9 |
| S. Dev.($P^A$-$P^B$) | 6.0 | 8.1 | 9.2 | 3.4 | 5.3 | 7.8 | 3.4 | 4.2 | 6.1 |
| % (\| $P^A$-$P^B$\| >$K^T$-$K^S$) | 36% | 41% | 33% | 61% | 55% | 43% | 61% | 58% | 57% |
| **Storage** | | | | | | | | | |
| Mean($S^A$) | 25 | 86 | 308 | 21 | 73 | 286 | 25 | 86 | 323 |
| Mean ($S^B$) | 25 | 86 | 308 | 13 | 59 | 274 | 13 | 34 | 179 |
| **Trade** | | | | | | | | | |
| Mean($T^A$) | 0.002 | 0.64 | 2.54 | 0.0 | 0.1 | 0.8 | 0.0 | 0.0 | 0.1 |
| Mean($T^B$) | 0.002 | 0.64 | 2.54 | 6.5 | 6.9 | 8.4 | 26.4 | 26.4 | 26.7 |
| % ($T^A$ +$T^B$> 0) | 36% | 44% | 42% | 90% | 68% | 53% | 100% | 99% | 80% |
| % ($T^A$ or $T^B$=$\overline{T}$ ) | 36% | 41% | 34% | 61% | 52% | 41% | 56% | 55% | 57% |
| **Transport Costs** | | | | | | | | | |
| Mean ( $K_t^A$ ) | 5.54 | 5.99 | 6.01 | 5.00 | 5.01 | 5.14 | 5.00 | 5.00 | 5.00 |
| S. Dev( $K_t^A$ ) | 1.6 | 2.8 | 3.7 | 0.0 | 0.1 | 1.3 | 0.0 | 0.0 | 0.1 |
| Mean ( $K_t^B$ ) | 5.54 | 5.99 | 6.01 | 7.00 | 6.98 | 6.86 | 7.00 | 7.00 | 7.00 |
| S. Dev( $K_t^B$ ) | 1.6 | 2.8 | 3.7 | 2.9 | 3.8 | 4.9 | 2.9 | 3.7 | 4.8 |
| Excess return | 1.04* | 1.98 | 2.01 | 2.00 | 1.99 | 2.00 | 2.00 | 2.00 | 2.00 |

The table shows equilibrium values of prices, transport costs, and trade when transport capacity is determined endogenously to generate an excess return of 2.00. Centre A output is the fraction of output made in centre A on average. σ is the standard deviation of the shock hitting output in each centre. $P^A$ is the price in centre A. $S^A$ is the storage in centre A. $T^A$ is trade from centre A to centre B. $K_t^A$ is the transport cost incurred sending a ship from A to B, and an empty ship from B to A. % (| $P^A$-$P^B$| >$K^T$-$K^S$) is the fraction of time the price difference exceeds the difference between the marginal trade cost and the storage cost. (Note $K^S$=0 in these simulations.) % ($S^A$[$T^A$] > 0) is the fraction of time storage [exports] > 0. % ($T^A$ =$\overline{T}$ ) is the fraction of times the quantity traded is equal to the transport capacity, and hence the fraction of times $K_t^A$ > $K^T$.

*Note that the minimum return to capital is not earned in this case. Output has so little volatility that consumption is almost completely soothed through inventory adjustment.

Figure 1

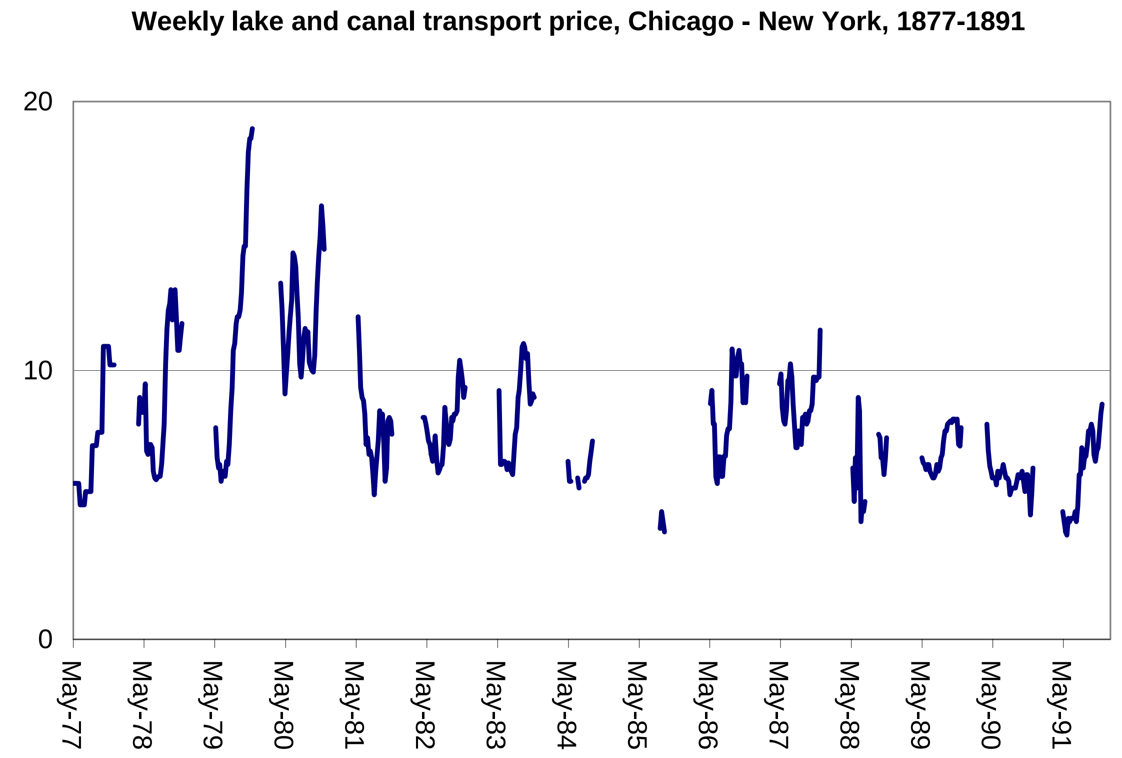



Figure 2

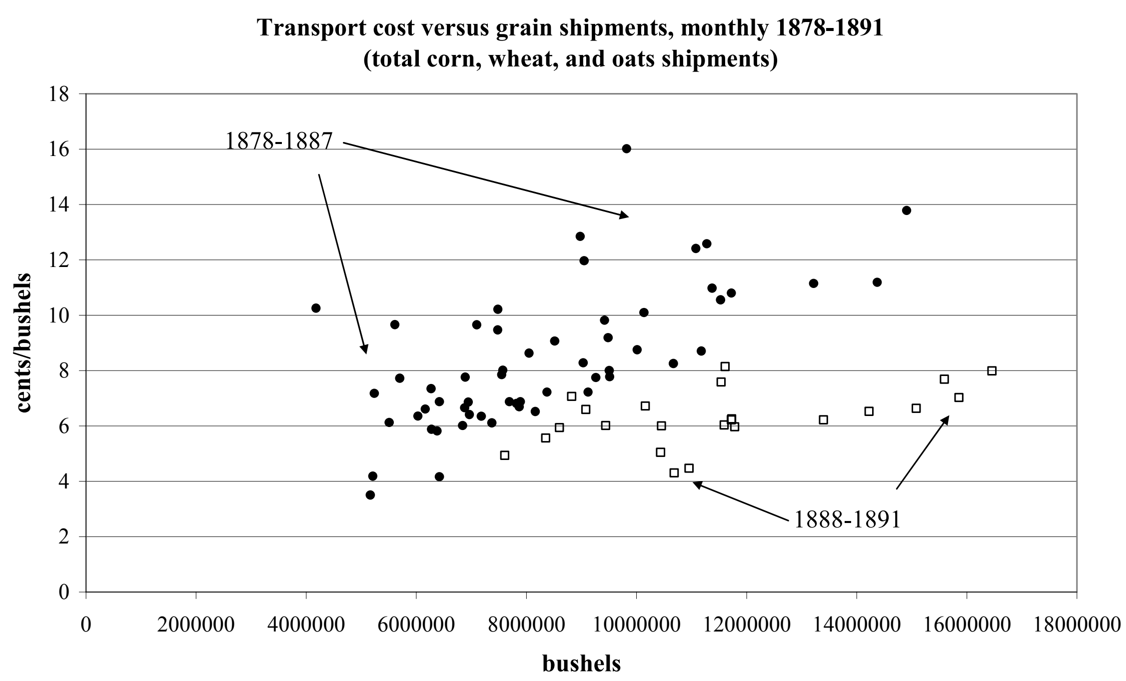


Figure 3

**New York and Chicago Corn Prices, 1878-1891**

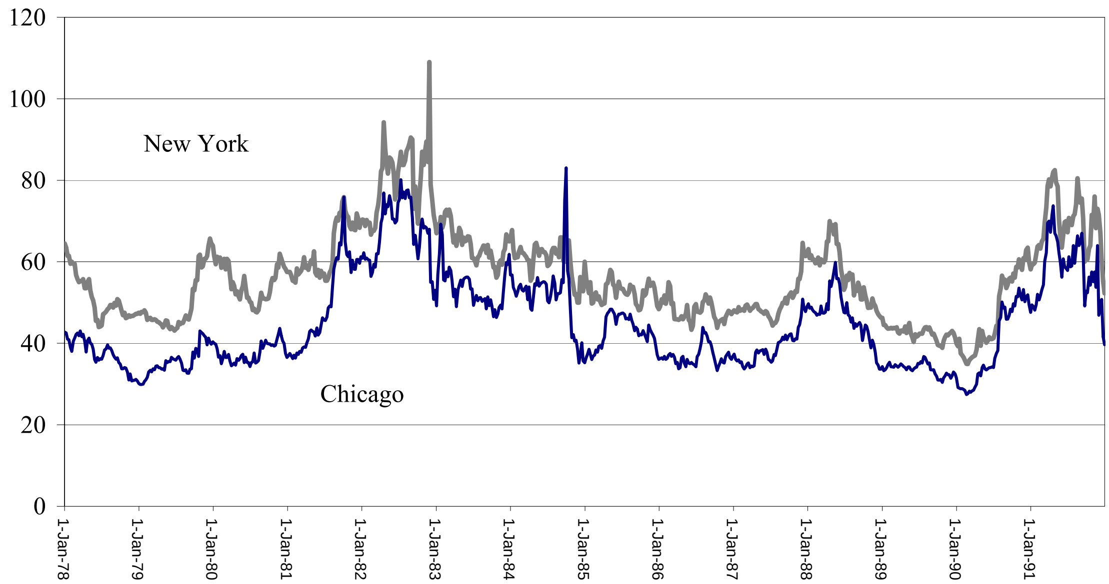



Figure 4

**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"**

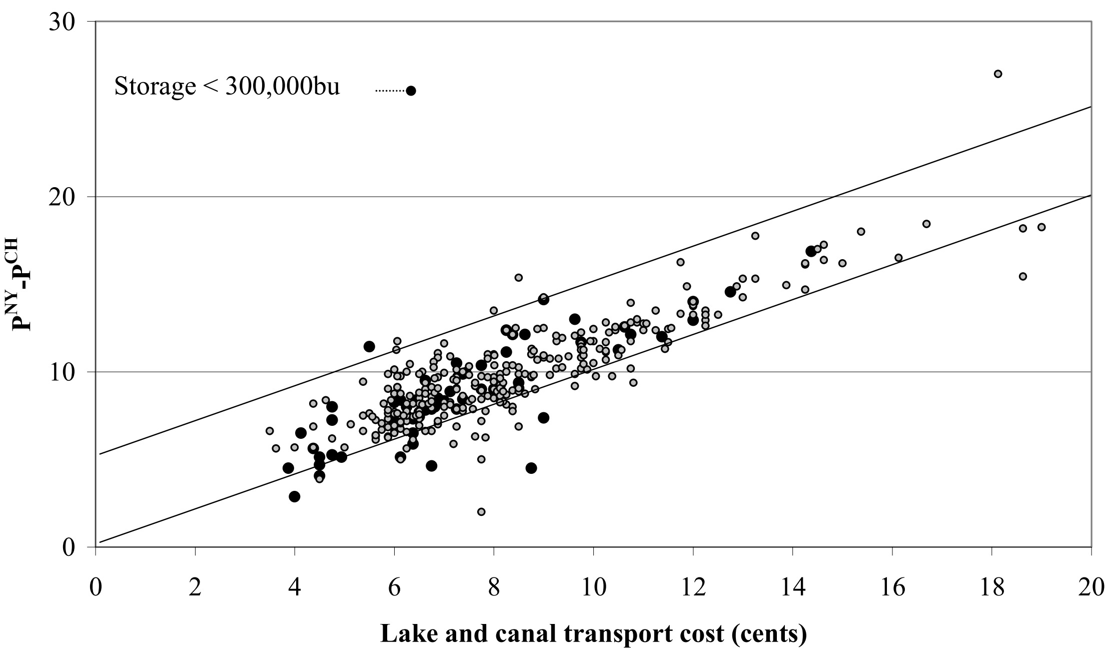
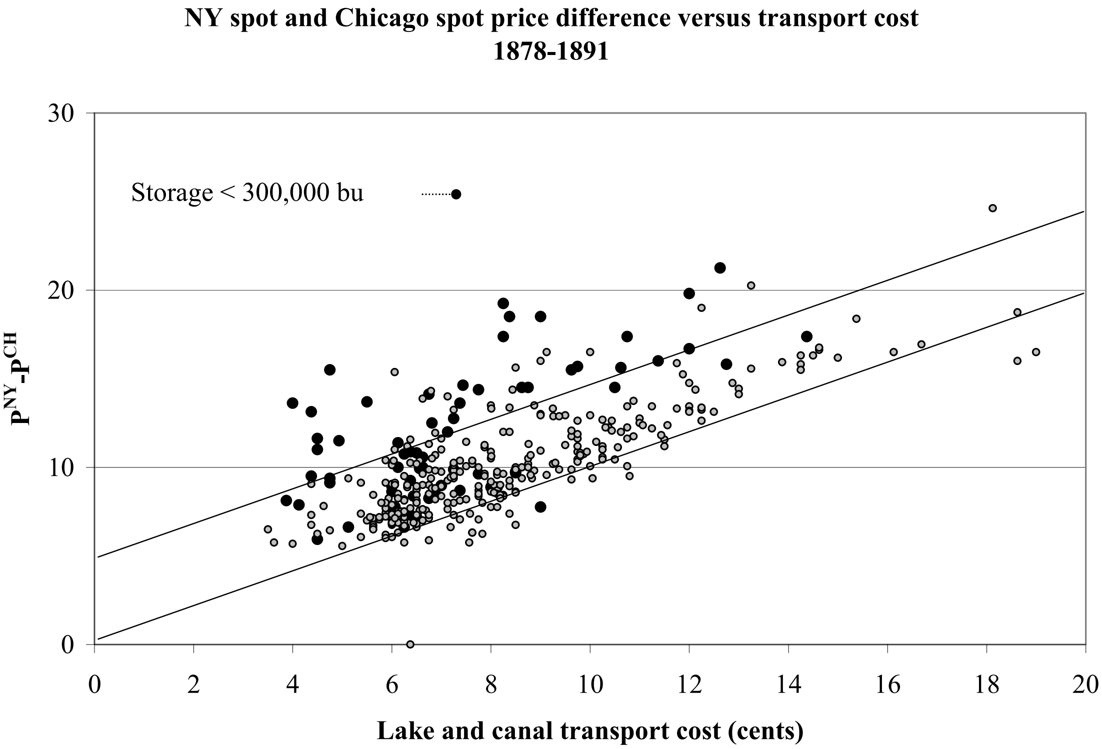


Figure 5


NY spot and Chicago spot price difference versus transport cost
1878-1891
Storage < 300,000 bu
$P^{NY}$-$P^{CH}$
Lake and canal transport cost (cents)
0
10
20
30
0
2
4
6
8
10
12
14
16
18
20

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