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No-Dynamic-Arbitrage and Market Impact

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# No-Dynamic-Arbitrage and Market Impact

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## Abstract

Starting from a no-dynamic-arbitrage principle that imposes that trading costs should be non-negative on average and a simple model for the evolution of market prices, we demonstrate a relationship between the shape of the market impact function describing the average response of the market price to traded quantity and the function that describes the decay of market impact. In particular, we show that the widely-assumed exponential decay of market impact is compatible only with linear market impact. We derive various inequalities relating the typical shape of the observed market impact function to the decay of market impact, noting that empirically, these inequalities are typically close to being equalities.

## 1 Introduction

Market impact modeling and estimation has long been central to the market microstructure literature and also of course of great interest to traders. Indeed today, any pre-trade analytic software worthy of the name generates a pre-trade estimate of the expected cost of a proposed trade as a function of the trade size and other parameters such as liquidity and volatility.

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In practice, trading costs are estimated (for example in Barra (1997), Almgren, Thum, Hauptmann, and Li (2005) and Engle, Ferstenberg, and Russell (2008)) by aggregating all executions of a certain type, such as all VWAP<sup>1</sup> executions, and bucketing by trade characteristics such as duration. Expectations such as market impact functions should therefore be thought of as unconditional averages over different market conditions. In particular, we do not consider the price impact associated with strategies, such as liquidity-seeking strategies, that are conditioned on the state of the order book or other aspects of the market.

Starting from the observations that the autocorrelation of trade signs decays very slowly with time and that the variance of the price changes is empirically linear in time, and with a simple model for the evolution of market prices, Bouchaud, Gefen, Potters, and Wyart (2004) argue convincingly that market impact is temporary and that it decays as a power-law. The exponent  $\gamma$  of the decay of market impact and the exponent  $\alpha$  of the power-law of decay of autocorrelation of order signs are related as  $\gamma \approx (1 - \alpha)/2$ . The empirically observed linear growth of the variance of price changes with time can be viewed as a consequence of the principle that price changes should be unpredictable.

In unrelated work, starting from a principle of no-quasi-arbitrage, Huberman and Stanzl (2004) show that permanent market impact must be linear in the trade quantity and symmetric between buys and sells.

In this article, we impose a no-dynamic-arbitrage principle that merely states that the expected cost of trading should be non-negative so that price manipulation is not possible. Starting from this principle, we extend the above-mentioned results by linking the decay of market impact to the shape of the market impact function.

In Section 2, we describe the price process, showing with specific examples that it generalizes price processes previously considered in the literature. In Section 3, we state the principle of no-dynamic-arbitrage and explore the special cases of permanent impact and trading in and out of a position at the same rate, independent of specific assumptions on the shapes of the market impact and decay functions. In Section 4, we study exponential decay of temporary market impact, eliminating this assumption on empirical grounds. In

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<sup>1</sup> *VWAP* stands for “volume-weighted average price”. The corresponding strategy attempts to deviate as little as possible from the VWAP benchmark by trading evenly in volume (or “business”) time. In this article, time should always be thought of as business time.

Section 5, we study power-law decay of market impact, deriving inequalities imposed by no-dynamic-arbitrage and studying compatibility with different forms of the market impact function. In Section 6, we explore the implications of various stylized facts: the observation by Bouchaud, Gefen, Potters, and Wyart (2004) that market impact must be temporary and decay as a power law, the remarkable success of the well-known square-root market impact formula, and the tail-behavior of the limit order book. In Section 7, we summarize our findings and in Section 8, offer some concluding remarks.

## 2 Model Setup

In what follows, we suppose that the stock price  $S_t$  at time  $t$  is given by

$$S_t = S_0 + \int_0^t f(\dot{x}_s) G(t-s) ds + \int_0^t \sigma dZ_s \quad (1)$$

where  $\dot{x}_s$  is our rate of trading in dollars at time  $s < t$ ,  $f(\dot{x}_s)$  represents the impact of trading at time  $s$  and  $G(t-s)$  is a decay factor.

$S_t$  follows an arithmetic random walk with a drift that depends on the accumulated impacts of previous trades. The cumulative impact of others' trading (the *trading crowd* in the terminology of Huberman and Stanzl) is assumed to be implicitly in  $S_0$  and the noise term. Drift is ignored for two reasons: drift is a lower order effect and when estimating market impact in practice, we typically average buys and sells.

We refer to  $f(\cdot)$  as the *instantaneous market impact function* and to  $G(\cdot)$  as the *decay kernel*.

The continuous time process (1) can be viewed as a limit of the discrete time process:

$$S_t = \sum_{i < t} f(\delta x_i) G(t-i) + \text{noise}$$

where  $\delta x_i = \dot{x}_i \delta t$  is the quantity traded in some small time interval  $\delta t$  characteristic of the stock, and by abuse of notation,  $f(\cdot)$  is the market impact function.  $\delta x_i > 0$  represents a purchase and  $\delta x_i < 0$  represents a sale.  $\delta t$  could be thought of as  $1/\nu$  where  $\nu$  is the trade frequency. Increasing the rate of trading  $\dot{x}_i$  is equivalent to increasing the quantity traded each  $\delta t$ .

As we will show in Section 2.3, expression (1) may be viewed as a generalization of processes previously considered by Almgren, Thum, Hauptmann, and Li (2005), Bouchaud, Gefen, Potters, and Wyart (2004) and Obizhaeva

and Wang (2005). Consistent with our earlier comments related to not conditioning on the state of the market, our assumed price process (1) corresponds to the “bare propagator” formulation of Bouchaud, Gefen, Potters, and Wyart (2004) rather than the state-dependent formulation of Farmer, Gerig, Lillo, and Mike (2006).

## 2.1 Price impact and slippage

The cost of trading can be decomposed into two components. First, the impact of our trading on the market price (the mid-price for example): We refer to this effect as *price impact*. Our *price impact* is described by the *price update function* in the terminology of Huberman and Stanzl. However, whereas in the Huberman and Stanzl setup, price impact must be permanent, in our setup, price impact may decay over time. In particular, price impact may decay as a power-law as argued by Bouchaud, Gefen, Potters, and Wyart (2004).

The second component of the cost of trading corresponds to market frictions such as effective bid-ask spread that affect only our execution price; We refer to this component of trading cost as *slippage* (*temporary impact* in the terminology of Huberman and Stanzl). For small volume fractions, we could think of slippage as being proxied by VWAP slippage, the average difference in price between an actual VWAP execution and the market VWAP. In what follows, we will neglect slippage; the inequalities we derive will all be weakened in practice to the extent that slippage is significant.

## 2.2 Cost of trading

Denote the number of shares outstanding at time  $t$  by  $x_t$ . Then from (1), neglecting slippage, the expected cost  $C[\Pi]$  associated with a given trading strategy  $\Pi = \{x_t\}$  is given by

$$\begin{aligned} C[\Pi] &= \mathbb{E} \left[ \int_0^T \dot{x}_t (S_t - S_0) dt \right] \\ &= \int_0^T \dot{x}_t dt \int_0^t f(\dot{x}_s) G(t-s) ds \end{aligned} \quad (2)$$

The  $dx_t = \dot{x}_t dt$  shares traded at time  $t$  are traded at an expected price

$$S_t = S_0 + \int_0^t f(\dot{x}_s) G(t-s) ds$$

which reflects the residual cumulative impact of all our prior trading. Obviously, cost by this definition is equivalent to expected implementation shortfall.

## 2.3 Special cases

### Almgren et al.

In our notation, the temporary component of the model of Almgren, Thum, Hauptmann, and Li (2005) corresponds to setting  $G(t-s) = \delta(t-s)$  and  $f(v) = \eta \sigma v^\beta$  with  $\beta = 0.6$ . Here,  $\sigma$  is volatility and  $v_t = \dot{x}_t/V$  is a dimensionless measure of the rate of trading, where  $V$  is the market volume per unit time (average daily volume say).

In this model, temporary market impact decays instantaneously. Our trading affects only the price of our own executions; other executions are not affected. The cost of trading becomes:

$$C[\Pi] = \int_0^T \dot{x}_t dt \int_0^t f(\dot{x}_s) G(t-s) ds = \eta \sigma \int_0^T \dot{x}_t^{1+\beta} dt$$

### Obizhaeva and Wang

In the setup of Obizhaeva and Wang (2005), we have  $G(\tau) = e^{-\rho\tau}$  and  $f(v) \propto v$ . In this model, market impact decays exponentially and instantaneous market impact is linear in the rate of trading. The cost of trading becomes:

$$\begin{aligned} C[\Pi] &= \int_0^T \dot{x}_t dt \int_0^t f(\dot{x}_s) G(t-s) ds \\ &\propto \int_0^T \dot{x}_t dt \int_0^t \dot{x}_s \exp\{-\rho(t-s)\} ds \end{aligned}$$

Alfonsi, Schied, and Schulz (2007) also assume exponential decay of market impact but they assume a nonlinear market impact function.

### Bouchaud et al.

In the setup of Bouchaud, Gefen, Potters, and Wyart (2004), we have  $f(v) \propto \log(v)$  and

$$G(t-s) \propto \frac{l_0}{(l_0 + t-s)^\beta}$$

with  $\beta \approx (1-\gamma)/2$  where  $\gamma$  is the exponent of the power law of autocorrelation of trade signs. In this model, market impact decays as a power law and instantaneous market impact is concave in the rate of trading. The cost of trading becomes:

$$\begin{aligned} C[\Pi] &= \int_0^T \dot{x}_t dt \int_0^t f(\dot{x}_s) G(t-s) ds \\ &\propto \int_0^T \dot{x}_t dt \int_0^t \frac{\log(\dot{x}_s)}{(l_0 + t-s)^\beta} ds \end{aligned}$$

### 3 The principle of no-dynamic-arbitrage

Huberman and Stanzl define a *round trip trade* as a sequence of trades whose sum is zero. In our notation, a trading strategy  $\Pi = \{x_t\}$  is a *round-trip trade* if

$$\int_0^T \dot{x}_t dt = 0$$

By analogy with another of Huberman and Stanzl's definitions, we define a *price manipulation* to be a round-trip trade  $\Pi$  whose expected cost  $C[\Pi]$  is negative.

The principle of no-dynamic-arbitrage states that price manipulation is not possible.

Equivalently, the cost of trading is non-negative on average.

More formally, for any strategy  $\{x_t\}$  such that  $\int_0^T \dot{x}_t dt = 0$ ,

$$C[\Pi] = \int_0^T \dot{x}_t dt \int_0^t f(\dot{x}_s) G(t-s) ds \geq 0$$

We see that the no-dynamic-arbitrage condition imposes a relationship between the shape of the market impact function  $f(\cdot)$  and the decay kernel  $G(\cdot)$ . We say that a market impact function  $f(\cdot)$  and a decay kernel  $G(\cdot)$  are *consistent* if the combination precludes price manipulation.

### 3.1 Permanent impact

Suppose we trade into a position at the rate  $+v$  and out at the same rate  $-v$ . If market impact is permanent, without loss of generality,  $G(\cdot) = 1$  and the cost of trading becomes

$$\begin{aligned} C[\Pi] &= v f(v) \left\{ \int_0^{T/2} dt \int_0^t ds - \int_{T/2}^T dt \int_0^{T/2} ds \right\} \\ &\quad + v f(-v) \int_{T/2}^T dt \int_{T/2}^t ds \\ &= v \frac{T^2}{8} \{-f(-v) - f(v)\} \end{aligned}$$

If  $f(v) > -f(-v)$ , we could manipulate the market price by buying then selling at the same rate and conversely if  $f(v) < -f(-v)$ , we could manipulate the market price by selling then buying at the same rate. Thus, as originally shown by Huberman and Stanzl (2004), no-dynamic-arbitrage imposes that if market impact is permanent,  $f(v) = -f(-v)$ .

Motivated by this observation and the empirical observation that there appears to be no substantial difference between  $f(v)$  and  $-f(-v)$ , we henceforth assume that  $f(v) = -f(-v)$ .

### 3.2 A specific strategy

Consider a strategy where shares are accumulated at the (positive) constant rate  $v_1$  and then liquidated again at the (positive) constant rate  $v_2$ . According to equation (2), and assuming  $f(v) = -f(-v)$ , the cost of this strategy is given by  $C_{11} + C_{22} - C_{12}$  with

$$\begin{aligned} C_{11} &= v_1 f(v_1) \int_0^{\theta T} dt \int_0^t G(t-s) ds \\ C_{22} &= v_2 f(v_2) \int_{\theta T}^T dt \int_{\theta T}^t G(t-s) ds \\ C_{12} &= v_2 f(v_1) \int_{\theta T}^T dt \int_0^{\theta T} G(t-s) ds \end{aligned} \tag{3}$$

where  $\theta$  is such that  $v_1 \theta T - v_2 (T - \theta T) = 0$  so

$$\theta = \frac{v_2}{v_1 + v_2}$$



The principle of no-dynamic-arbitrage imposes that

$$C_{11} + C_{22} - C_{12} \geq 0$$

Intuitively, the cross-term  $C_{12}$  represents the component of the cost of stock sales (purchases) associated with the price impact of prior stock purchases (sales). If the cross-term  $C_{12} = 0$ , there is no dynamic arbitrage and price manipulation is not possible. In particular, in the model of Almgren, Thum, Hauptmann, and Li (2005) where market impact decays instantaneously and the market price has no history of prior trading, there is no dynamic arbitrage.

### 3.3 Trading in and out at the same rate

Now, suppose only that  $G(\cdot)$  is strictly decreasing (again with  $f(v) = -f(-v)$ ). Then the cost of acquiring a position at the constant rate  $v$  then liquidating it again at the same rate is given by

$$\begin{aligned} C[\text{II}] &= v f(v) \left\{ \int_0^{T/2} dt \int_0^t G(t-s) ds + \int_{T/2}^T dt \int_{T/2}^t G(t-s) ds \right. \\ &\quad \left. - \int_{T/2}^T dt \int_0^{T/2} G(t-s) ds \right\} \\ &= v f(v) \left\{ \int_0^{T/2} dt \int_0^t [G(t-s) - G(t+T/2-s)] ds \right. \\ &\quad \left. + \int_{T/2}^T dt \int_{T/2}^t [G(t-s) - G(T-s)] ds \right\} > 0 \end{aligned}$$

and there is no price manipulation.

We conclude that if price manipulation is possible with this specific strategy, it must involve trading in and out of a position at different rates.

## 4 Exponential decay of market impact

Suppose now that the decay kernel has the form

$$G(t-s) = e^{-\rho(t-s)}$$

and that we acquire a position at rate  $v_1$ , liquidating it again at the rate  $v_2$ . Then, explicit computation of all the integrals in (3) gives

$$\begin{aligned} C_{11} &= v_1 f(v_1) \frac{1}{\rho^2} \{e^{-\rho\theta T} - 1 + \rho\theta T\} \\ C_{12} &= v_2 f(v_1) \frac{1}{\rho^2} \{1 + e^{-\rho T} - e^{-\rho\theta T} - e^{-\rho(1-\theta)T}\} \\ C_{22} &= v_2 f(v_2) \frac{1}{\rho^2} \{e^{-\rho(1-\theta)T} - 1 + \rho(1-\theta)T\} \end{aligned} \quad (4)$$

Again, the no-dynamic-arbitrage principle forces a relationship between the instantaneous impact function  $f(\cdot)$  and the decay kernel  $G(\cdot, \cdot)$ :

$$C_{11} + C_{22} - C_{12} \geq 0$$

After making the substitution  $\theta = v_2/(v_1 + v_2)$ , we obtain

$$\begin{aligned} &v_1 f(v_1) \left[ e^{-\frac{v_2 \rho}{v_1 + v_2}} - 1 + \frac{v_2 \rho}{v_1 + v_2} \right] \\ &+ v_2 f(v_2) \left[ e^{-\frac{v_1 \rho}{v_1 + v_2}} - 1 + \frac{v_1 \rho}{v_1 + v_2} \right] \\ &- v_2 f(v_1) \left[ 1 + e^{-\rho} - e^{-\frac{v_1 \rho}{v_1 + v_2}} - e^{-\frac{v_2 \rho}{v_1 + v_2}} \right] \geq 0 \end{aligned} \quad (5)$$

where, without loss of generality, we have set  $T = 1$ . We note that the first two terms are always positive so price manipulation is only possible if the third term ( $C_{12}$ ) dominates the others.

**Example:**  $f(v) = \sqrt{v}$

Let  $v_1 = 0.2$ ,  $v_2 = 1$ ,  $\rho = 1$ . Then the cost of liquidation is given by

$$C = C_{11} + C_{22} - C_{12} = -0.001705 < 0$$

Since  $\rho$  really represents the product  $\rho T$ , we see that for any choice of  $\rho$ , we can find a combination  $\{v_1, v_2, T\}$  such that a round trip with no net purchase or sale of stock is profitable. We conclude that if market impact decays exponentially, no-dynamic-arbitrage excludes a square root instantaneous impact function.

More generally, expanding expression (5) in powers of  $\rho$ , no-dynamic-arbitrage imposes that

$$\frac{v_1 v_2 [v_1 f(v_2) - v_2 f(v_1)] \rho^2}{2(v_1 + v_2)^2} + O(\rho^3) \geq 0$$

We see that price manipulation is always possible for small  $\rho$  unless  $f(v) \propto v$  and so we may state<sup>2</sup>:

**Lemma 4.1.** *If temporary market impact decays exponentially, price manipulation is possible unless the instantaneous market impact function  $f(v)$  is directly proportional to  $v$ .*

Taking the limit  $\rho \rightarrow 0^+$ , we obtain

**Corollary 4.2.** *Non-linear permanent market impact is inconsistent with the principle of no-dynamic-arbitrage.*

again as originally shown by Huberman and Stanzl.

## 4.1 Linear permanent market impact

If  $f(v) = \eta v$  for some  $\eta > 0$  and  $G(t - s) = 1$ , the cost of trading becomes

$$C[\Pi] = \eta \int_0^T \dot{x}_t dt \int_0^t \dot{x}_s ds = \frac{\eta}{2} (x_T - x_0)^2$$

The trading cost per share is then given by

$$\frac{C[\Pi]}{|x_T - x_0|} = \eta |x_T - x_0|$$

which is *independent* of the details of the trading strategy (depending only on the initial and final positions) and linear in the trade quantity.

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<sup>2</sup>In a forthcoming paper, Peter Friz proves that  $f(v) \propto v$  is consistent with any convex non-increasing decay kernel  $G(\cdot)$ .

## 4.2 Excluding exponential decay of market impact

Empirically (see Almgren, Thum, Hauptmann, and Li (2005) for example), market impact is concave in  $v$  for small  $v$ . Also, market impact must be convex for very large  $v$ ; imagine submitting a sell order whose size is much greater than the quantity available on the bid side of the order book<sup>3</sup>. It follows that no-dynamic-arbitrage together with any reasonable instantaneous market impact function  $f(\cdot)$  excludes exponential decay of market impact as a realistic assumption.

## 5 Power-law decay of market impact

Having excluded exponential decay of market impact as a realistic assumption, suppose instead that the decay kernel has the form

$$G(t-s) = \frac{1}{(t-s)^\gamma}, \quad 0 < \gamma < 1$$

Then, explicit computation of all the integrals in (3) gives

$$\begin{aligned} C_{11} &= v_1 f(v_1) \frac{T^{2-\gamma}}{(1-\gamma)(2-\gamma)} \theta^{2-\gamma} \\ C_{22} &= v_2 f(v_2) \frac{T^{2-\gamma}}{(1-\gamma)(2-\gamma)} (1-\theta)^{2-\gamma} \\ C_{12} &= v_2 f(v_1) \frac{T^{2-\gamma}}{(1-\gamma)(2-\gamma)} \{1 - \theta^{2-\gamma} - (1-\theta)^{2-\gamma}\} \end{aligned} \quad (6)$$

According to the principle of no-dynamic-arbitrage, substituting  $\theta = v_2/(v_1 + v_2)$ , we must have

$$f(v_1) \{v_1 v_2^{1-\gamma} - (v_1 + v_2)^{2-\gamma} + v_1^{2-\gamma} + v_2^{2-\gamma}\} + f(v_2) v_1^{2-\gamma} \geq 0 \quad (7)$$

If  $\gamma = 0$ , the no-dynamic-arbitrage condition (7) reduces to

$$f(v_2) v_1 - f(v_1) v_2 \geq 0$$

so again, we must have  $f(v) \propto v$ .

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<sup>3</sup>As has happened in the past, notably on the Tokyo Stock Exchange

If  $\gamma = 1$ , equation (7) reduces to

$$f(v_1) + f(v_2) \geq 0$$

So long as  $f(\cdot) \geq 0$ , there is no constraint on  $f(\cdot)$  when  $\gamma = 1$ . We see that in contrast with the case of exponential decay of market impact, power-law decay of market impact may be compatible with realistic shapes of the market impact function  $f(\cdot)$ .

### 5.1 The limit $v_1 \ll v_2$ and $0 < \gamma < 1$

In this limit, we accumulate stock much more slowly than we liquidate it. Let  $v_1 = \epsilon v$  and  $v_2 = v$  with  $\epsilon \ll 1$ . Then, in the limit  $\epsilon \rightarrow 0$ , with  $0 < \gamma < 1$ , equation (7) becomes

$$\begin{aligned} & f(\epsilon v) \{ \epsilon - (1 + \epsilon)^{2-\gamma} + \epsilon^{2-\gamma} + 1 \} + f(v) \epsilon^{2-\gamma} \\ \sim & -f(\epsilon v) (1 - \gamma) \epsilon + f(v) \epsilon^{2-\gamma} \geq 0 \end{aligned}$$

so for  $\epsilon$  sufficiently small we have

$$\frac{f(\epsilon v)}{f(v)} \leq \frac{\epsilon^{1-\gamma}}{1 - \gamma} \quad (8)$$

If the condition (8) is not satisfied, price manipulation is possible by accumulating stock slowly, maximally splitting the trade, then liquidating it rapidly.

### 5.2 Special cases

**Power-law impact:**  $f(v) \propto v^\delta$

If  $f(v) \sim v^\delta$  as found by for example Almgren, Thum, Hauptmann, and Li (2005), the no-dynamic-arbitrage condition (8) reduces to  $\epsilon^{1-\gamma-\delta} \geq 1 - \gamma$  so we must have  $\gamma + \delta \geq 1$ . Stating this result formally:

**Lemma 5.1.** *Small  $v$  no-dynamic-arbitrage condition.*

*If  $G(\tau) = \tau^{-\gamma}$  and  $f(v) \propto v^\delta$ , dynamic-no-arbitrage imposes that*

$$\gamma + \delta \geq 1.$$

**Log impact:**  $f(v) \propto \log(v/v_0)$

Bouchaud, Gefen, Potters, and Wyart (2004) find that their empirical results are well-described by  $f(v) \sim \log v$ . Of course,  $f(\cdot)$  must be non-negative, so the trading rate  $v$  must always be greater than some minimum trading rate  $v_0$ . For example, one could think of one share every trade as being the minimum rate. In the case of a stock that trades 10 million shares a day, 10,000 times, and where the average trade size is 1,000, we would obtain  $v_0 = 0.10\%$ . Noting that

$$\log v = \lim_{\delta \rightarrow 0} \frac{v^\delta - 1}{\delta},$$

we might guess that price manipulation is possible for all  $\gamma < 1$ . In fact, the precise condition on  $\gamma$  depends on the minimum trading rate  $v_0$ .

For example, substituting  $v_0 = 0.001$ ,  $v_1 = 0.15$ ,  $v_2 = 1.0$  and  $\gamma = 1/2$  into the arbitrage condition (7) with  $f(v) = \log(v/v_0)$  gives the expected cost of the round-trip trade as  $-0.0028$  which constitutes price manipulation (*i.e.* dynamic arbitrage).

For the general case, suppose that we trade into a position at some rate  $v$  with  $v/v_0 > 1$  and  $v \ll 1$ . The substituting into (7) gives

$$\begin{aligned} & \log(v/v_0) \{v - (1+v)^{2-\gamma} + v^{2-\gamma} + 1\} + \log(1/v_0) v^{2-\gamma} \\ &= \log(v/v_0) \{- (1-\gamma)v + O(v^{2-\gamma})\} + \log(1/v_0) v^{2-\gamma} \end{aligned}$$

So, for every  $\gamma < 1$ , provided  $v_0$  is sufficiently small, we can find a small enough  $v > v_0$  such that price manipulation is possible.

The choice of market impact function  $f(v) \sim \log(v)$  is therefore inconsistent with power-law decay (with  $\gamma < 1$ ) of market impact in the limit  $v_0 \rightarrow 0$ .

### 5.3 The limit $v_1 > v_2$ and $0 < \gamma < 1$

Suppose we accumulate stock at some very high rate  $v_1$  and liquidate at some lower rate  $v_2$ . This is the well-known *pump and dump* strategy<sup>4</sup>. Setting  $v = v_2/v_1 < 1$  and substituting into the dynamic-no-arbitrage condition (7) with power-law decay of market impact, we obtain

$$f(v_1) \{v^{1-\gamma} - (1+v)^{2-\gamma} + 1 + v^{2-\gamma}\} + f(v_2) \geq 0 \quad (9)$$

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<sup>4</sup>See <http://www.sec.gov/answers/pumpdump.htm> for a definition.

Since  $f(v_2)$  is always positive, price manipulation is possible only if

$$h(v, \gamma) := v^{1-\gamma} - (1+v)^{2-\gamma} + 1 + v^{2-\gamma} < 0 \quad (10)$$

Expression (10) is shown in Appendix A to be equivalent to the condition:

$$\gamma < \gamma^* := 2 - \frac{\log 3}{\log 2} \approx 0.415$$

So if  $\gamma > \gamma^*$ , price manipulation is not possible.

Is price manipulation possible if  $\gamma < \gamma^*$ ? We first note that  $h(v, \gamma)$  decreases as  $v \rightarrow 1$  so price manipulation is maximized near  $v = 1$ . From Section 3.3, we already know that there is no dynamic arbitrage when trading in and out at the same rate as can be checked again easily in this case by substituting  $v_2 = v_1$  into equation (9) to obtain

$$f(v_1) \{4 - 2^{2-\gamma}\} \geq 0 \text{ for all } \gamma \geq 0$$

Observe that in practice, we cannot exceed some maximum rate of trading  $v_{max}$  corresponding for example to continuously exhausting the available quantity in the order book. Without loss of generality, set  $v_{max} = 1$ . Then, as  $v_i \rightarrow 1$ , we must have  $f(v_i) \rightarrow \infty$ . Specifically, in Section 6.3, we will argue that

$$f(v_i) \sim \frac{1}{(1-v_i)^\nu} \text{ as } v_i \rightarrow 1$$

for some  $\nu > 0$ .

With  $\epsilon \ll 1$ , substituting  $v_1 = 1 - \epsilon^2$  and  $v_2 = 1 - \epsilon$  into equation (9) and in the limit  $\epsilon \rightarrow 0$ , we see that price manipulation is possible if

$$\frac{3 - 2^{2-\gamma}}{\epsilon^{2\nu}} + \frac{1}{\epsilon^\nu} < 0$$

For any  $\gamma < \gamma^*$ , we can choose  $\epsilon$  sufficiently small to ensure that the first term dominates the second resulting in price manipulation.

We deduce that, for a market impact function  $f(\cdot)$  of the above form with any exponent  $\nu > 0$ , the no-arbitrage condition is:

**Lemma 5.2.** *Large size no arbitrage condition*

$$\gamma \geq \gamma^* = 2 - \frac{\log 3}{\log 2}$$

## 6 Stylized facts

### 6.1 Power law decay of market impact

As mentioned earlier, Bouchaud, Gefen, Potters, and Wyart (2004) have argued convincingly that price impact is temporary and that it decays as a power-law. We proceed to outline their argument:

Suppose market impact is permanent and proportional to some function  $f(n)$  of the trade-size  $n$ . Then the change in price after  $N$  trades is given by

$$\Delta P = \sum_i^N \eta \epsilon_i f(n_i)$$

where  $\epsilon_i$  and  $n_i$  denote the sign and size of the  $i$ th trade respectively. If  $\text{Cov}[\epsilon_i, \epsilon_j] = 0$  for  $i \neq j$ , the variance of the price change is given by

$$\text{Var}[\Delta P] = \eta^2 N \mathbb{E}[f(n_i)^2]$$

which grows linearly with  $N$ . Empirically however, we find that autocorrelation of trade signs shows power-law decay with a small exponent  $\alpha$  (corresponding to very slow decay). In this case, with  $\text{Cov}[\epsilon_i, \epsilon_j] \propto |j - i|^{-\alpha}$ , the cross-term in the computation of daily variance dominates and we obtain

$$\begin{aligned} \text{Var}[\Delta P] &\sim \sum_{i \neq j} \text{Cov}[\epsilon_i, \epsilon_j] \mathbb{E}[f(n_i)] \mathbb{E}[f(n_j)] \\ &\sim N^{2-\alpha} \text{ as } N \rightarrow \infty \end{aligned}$$

The variance of price changes grows superlinearly with  $N$ .

Empirically, we find that, to a very good approximation,  $\text{Var}[\Delta P] \propto N$ . If the variance of price changes grew superlinearly as  $N^{2-\alpha}$ , returns would be serially correlated and market efficiency would be glaringly violated: simple trend-following strategies would be consistently profitable. We conclude that market impact cannot be permanent.

If on the other hand, market impact were temporary and decayed as  $1/T^\gamma$ , we would have

$$\begin{aligned} \text{Var}[\Delta P] &\sim \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \frac{\mathbb{E}[f(n_i)] \mathbb{E}[f(n_j)]}{(N-i)^\gamma (N-j)^\gamma |j-i|^\alpha} \\ &\sim N^{2-\alpha-2\gamma} \text{ as } N \rightarrow \infty \end{aligned}$$



In this case, the variance of price changes grows linearly with  $N$  only if

$$\gamma = \frac{1 - \alpha}{2}$$

For the French stocks considered by Bouchaud, Gefen, Potters, and Wyart (2004), the exponent  $\alpha \approx 0.2$  so  $\gamma \approx 0.4$ .

## 6.2 The square-root formula, $\gamma$ and $\delta$

The *square-root formula* has the following form:

$$\text{Cost} = \text{Spread term} + c \sigma \sqrt{\frac{n}{V}}$$

where  $n$  is the number of shares to be traded,  $\sigma$  is the volatility of the stock (in daily units), and  $V$  is the average daily volume of the stock. With the terminology of Section 2.1, we could think of the spread term as representing slippage and the second square-root term as representing price impact.

The square-root formula has been widely used in practice for many years to generate a pre-trade estimate of transactions cost. As noted in Chapter 16 of Grinold and Kahn (1995), this formula is consistent with the trader rule-of-thumb that says that it costs roughly one day's volatility to trade one days' volume. Moreover, various studies of market impact costs, notably the study documented in Chapter 7 of the Barra Market Impact Model Handbook (Barra 1997), have found the square-root formula to fit transactions cost data remarkably well.

Interestingly, the square-root formula implies that the cost of liquidating a stock is independent of the time taken: the formula refers neither to the duration of the trade nor to the trading strategy adopted. Fixing market volume and volatility, price impact depends only on trade-size. At first, this claim seems to contradict our intuition that expected price impact should increase as the rate of trading  $v$  increases. Indeed, this intuition is empirically verified for very large trading rates that necessitate trading in sizes large relative to the quantity available in the order book. For reasonable trading rates however (volume fractions of 1% to 25% say), it does seem to be the case that price impact is roughly independent of trade duration, as can be checked for example by referring to Tables 1 and 2 of Engle, Ferstenberg, and Russell (2008) where conditioning on trade-size, cost seems to be only weakly dependent on trade duration.

According to our simple trade superposition model, from equation (6), the price impact associated with a VWAP execution with duration  $T$  is proportional to

$$v f(v) T^{2-\gamma}$$

Noting that  $v = n/(VT)$  (again with  $V$  denoting average daily volume), and putting  $f(v) \propto v^\delta$ , the impact cost per share is then proportional to

$$v^{1+\delta} T^{1-\gamma} = \left(\frac{n}{V}\right)^\delta T^{1-\gamma-\delta}$$

If  $\gamma + \delta = 1$ , the cost per share is *independent* of  $T$  and in particular, if  $\gamma = \delta = 1/2$ , the impact cost per share is proportional to  $\sqrt{n/V}$ , recovering the square-root formula.

We see that the square-root formula is consistent with both power-law decay of market impact and a power-law form of the market impact function  $f(\cdot)$ . Almgren, Thum, Hauptmann, and Li (2005) estimate  $\delta \approx 0.6$  and from Section 6.1, we have the Bouchaud et al. estimate of  $\gamma \approx 0.4$ .

Recall the no-dynamic-arbitrage condition from Section 5.1:

$$\gamma + \delta \geq 1$$

Putting the two empirical estimates together, we have  $\gamma + \delta \approx 0.4 + 0.6 = 1$ !

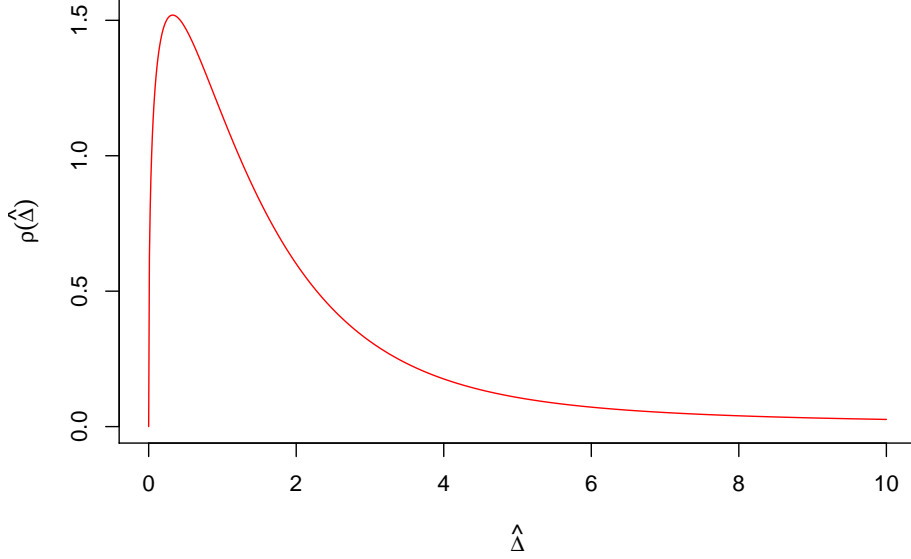
### 6.3 Very high trading rates

Bouchaud, Mézard, and Potters (2002) derive the following approximation to the average density  $\rho(\hat{\Delta})$  of orders as a function of a rescaled distance  $\hat{\Delta}$  from the price level at which the order is placed to the current price:

$$\rho(\hat{\Delta}) = e^{-\hat{\Delta}} \int_0^{\hat{\Delta}} du \frac{\sinh(u)}{u^{1+\mu}} + \sinh(\hat{\Delta}) \int_{\hat{\Delta}}^\infty du \frac{e^{-u}}{u^{1+\mu}} \quad (11)$$

where  $\mu$  is the exponent in the empirical power-law distribution of new limit orders. With  $\mu = 0.6$  as estimated by Bouchaud, Mézard, and Potters (2002), we obtain the density plotted in Figure 1. Computing the cumulative order density (book depth) as a function of the price-level  $\hat{\Delta}$  and switching the axes, we may compute the virtual impact function of Weber and Rosenow (2005), a function that measures the price impact conditional on trading a given quantity instantaneously using a single market order. With  $\mu = 0.6$ , we obtain the virtual impact function graphed in Figure 2.

Figure 1: The red line is a plot of the order density  $\rho(\hat{\Delta})$  with  $\mu = 0.6$ .



The virtual impact function is convex for large size. Also, it's not possible to trade in a size greater than the quantity currently available in the order book so price impact increases without limit as  $n \rightarrow n_{max}$ . Given the  $\hat{\Delta}^{-1-\mu}$  shape of the tail of the order book, we have

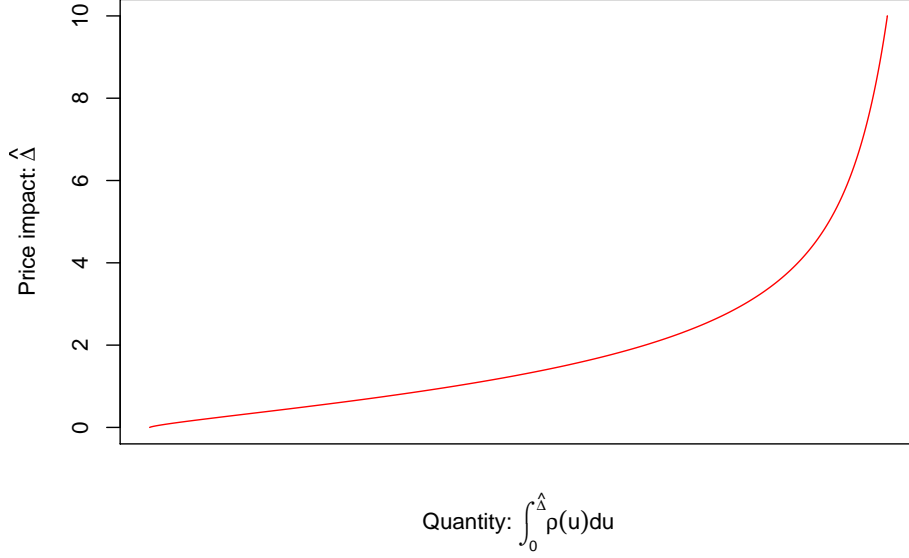
$$n_{max} - n(\hat{\Delta}) \sim \int_{\hat{\Delta}}^{\infty} \frac{du}{u^{1+\mu}} = \frac{\mu}{\hat{\Delta}^{\mu}}$$

where  $n(\hat{\Delta})$  is the cumulative share quantity available up to level  $\hat{\Delta}$  in the order book. Inverting this relationship, we see that instantaneous market impact has the tail behavior

$$\Delta P \sim \frac{1}{(n - n_{max})^{1/\mu}}$$

Then, following the discussion of Section 2 where the trading rate  $v$  was

Figure 2: Switching  $x$ - and  $y$ -axes in a plot of the cumulative order density gives the virtual impact function plotted below. The red line corresponds to  $\mu = 0.6$  as before.



argued to be a proxy for the size  $n$  of individual trades, we have

$$\Delta P \sim \frac{1}{(v - v_{max})^{1/\mu}}$$

for sufficiently large  $v$ .

We observe that the form of this relationship is consistent with the assumptions of Lemma 5.2 so we must have

$$\gamma \geq 2 - \frac{\log 3}{\log 2} \approx 0.415$$

We further observe that the estimate  $\gamma \approx 0.4$  of Bouchaud, Gefen, Potters, and Wyart (2004) is also roughly consistent with this inequality.

## 7 Summary

Bouchaud, Gefen, Potters, and Wyart (2004) have previously noted that the market self-organizes in a subtle way such that the exponent  $\gamma$  of the power law of decay of market impact and the exponent  $\alpha$  of the decay of autocorrelation of trade signs balance to ensure diffusion (variance increasing linearly with time).

$$\gamma \approx (1 - \alpha)/2 \quad (12)$$

In particular, if the autocorrelation of trade signs has long memory, we must have  $\gamma \leq 1/2$ .

By imposing no-dynamic-arbitrage we show that if the market impact function is of the form  $f(v) \propto v^\delta$ , we must have

$$\gamma + \delta \geq 1$$

We exclude various other frequently-considered combinations of functional forms for market impact and decay such as exponential decay with nonlinear market impact.

We then observe that if the average cost of a (not-too-aggressive) VWAP execution is roughly independent of duration, the exponent  $\delta$  of the power law of market impact should satisfy:

$$\delta + \gamma \approx 1$$

and by considering the tails of the limit-order book, we deduce that

$$\gamma \geq \gamma^* := 2 - \frac{\log 3}{\log 2} \approx 0.415 \quad (13)$$

Note in passing that (12) together with (13) imposes the following constraint on the autocorrelation of trade-signs:

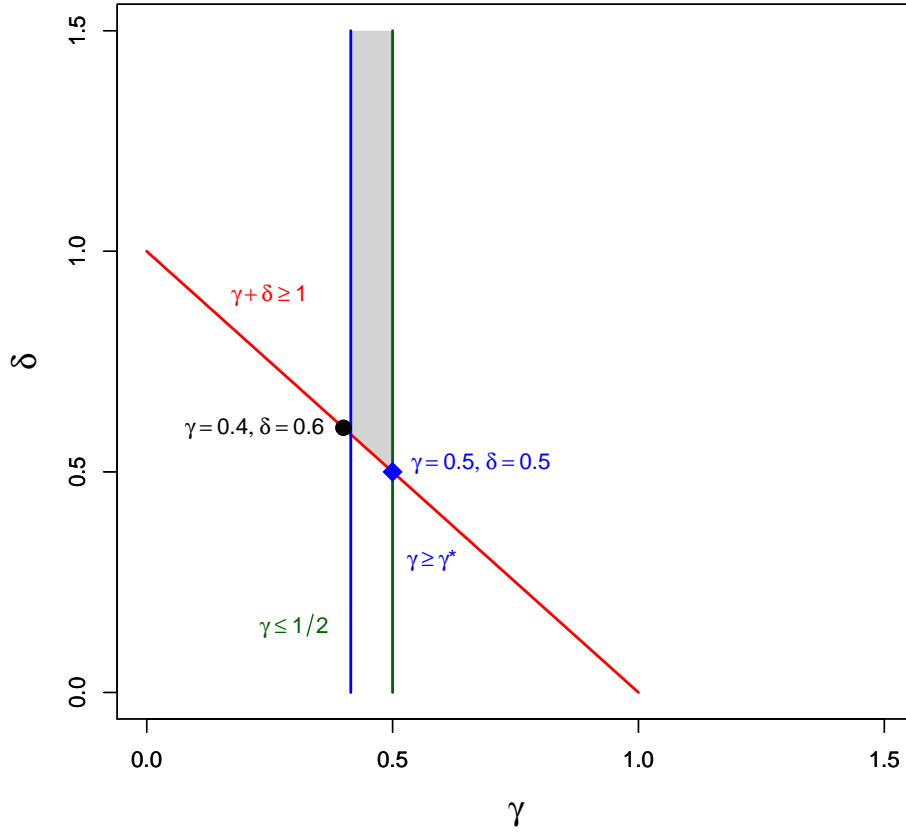
$$\alpha \leq 1 - 2\gamma^* \approx 0.17$$

Faster decay is ruled out by no-dynamic-arbitrage.

Recall also that empirical estimates are  $\gamma \approx 0.4$  (Bouchaud, Gefen, Potters, and Wyart 2004) and for not-too-aggressive trading strategies,  $\delta \approx 0.6$  (Almgren, Thum, Hauptmann, and Li 2005).

Figure 3 has a schematic representation of our results. In particular, we note that although values of  $\delta$  and  $\gamma$  may be close to the boundary of allowable

Figure 3: Combinations to the right of the red line satisfy  $\gamma + \delta \geq 1$ , to the right of the blue line  $\gamma \geq \gamma^*$ , to the left of the green line  $\gamma \leq 1/2$  and in the shaded intersection, the allowable values of  $\gamma$  and  $\delta$  consistent with the stylized facts of market impact. The black dot represents the empirical estimates  $\gamma \approx 0.4$  and  $\delta \approx 0.6$  and the blue diamond, the values  $\gamma = 0.5$  and  $\delta = 0.5$  consistent with the square-root formula.



values for typical not-too-aggressive trading strategies, nothing precludes  $\delta$  from moving away from this boundary when the trading strategy is aggressive and the rate of trading is very high. For example, an exponent  $\mu = 0.6$  in the power-law of limit order arrivals would give rise to  $\delta = 1/0.6 \approx 1.67$ .

We emphasize that none of the inequalities we have derived are hard in practice; as noted earlier in Section 2.1, all the above inequalities are weakened to the extent that market frictions such as slippage become significant.

Also, our results are all in the context of our simple price process (1): It could be for example that the decay of market impact is dependent on trade-size. Nor have we investigated every possible combination of price impact function  $f(\cdot)$  and decay kernel  $G(\cdot)$ ; understanding what combinations of functions are consistent with no-dynamic-arbitrage would be interesting in its own right. And even under the assumptions  $f(v) \propto v^\delta$  and  $G(\tau) \sim \tau^{-\gamma}$ , we have only demonstrated that if the parameter inequalities we derived are violated, price manipulation is possible; we have not proved the converse.

## 8 Concluding remarks

On a final philosophical note, the ability of no-dynamic-arbitrage principles to explain patterns in empirical observations is related to the self-organizing properties of markets with heterogenous agents, specifically statistical arbitrageurs. Agents will act so as to cancel any local trend in the observed price series, ensuring that the autocorrelation of returns is zero to a good approximation: that is, ensuring that variance varies linearly with time. Agents continuously monitor the reaction of market prices to volume, trading to take advantage of under- or over-reaction, ensuring that on average, it costs money to trade stock and precluding price manipulation.

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## A Proof of large size no-arbitrage condition

We want to find the minimum value  $\gamma^*$  of the exponent  $\gamma$  in the power-law of decay of market impact such that there is no dynamic arbitrage for  $\gamma > \gamma^*$ .

According to (9), there is arbitrage only if

$$h(v, \gamma) := v^{1-\gamma} - (1+v)^{2-\gamma} + 1 + v^{2-\gamma} < 0 \text{ for some } v \in (0, 1) \quad (\text{A-1})$$

Setting  $v = 1$  in (A-1), and solving for  $\gamma$ , we find that there is arbitrage only if

$$\gamma < 2 - \frac{\log 3}{\log 2} =: \gamma^*$$

We note that

$$\begin{aligned} \partial_\gamma h(v, \gamma) &= (1+v)^{2-\gamma} \log(1+v) - v^{1-\gamma} (1+v) \log v \\ &\geq 0 \quad \forall v \in (0, 1). \end{aligned}$$

So, if  $h(v, \gamma^*)$  reaches its minimum at  $v = 1$ , the result is proved. To show this, with  $\alpha := \log 3 / \log 2$ , define the function

$$\tilde{h}(v) := h(v, \gamma^*) - h(1, \gamma^*) = v^{\alpha-1} - (v+1)^\alpha + 1 + v^\alpha$$

Then  $\tilde{h}(1) = \tilde{h}(0) = 0$  and the second derivative of  $\tilde{h}(\cdot)$  with respect to  $v$  is given by

$$\begin{aligned} \partial_{v,v} \tilde{h}(v) &= (\alpha-1) \left\{ \frac{v\alpha + \alpha - 2}{v^{3-\alpha}} - \frac{\alpha}{(1+v)^{2-\alpha}} \right\} \\ &\leq (\alpha-1) \left\{ \frac{v\alpha + \alpha - 2}{v^{3-\alpha}} - \frac{3}{4} \alpha \right\} \end{aligned}$$

This latter expression reaches its maximum at

$$v^* := \frac{3}{\alpha} - 1 \approx 0.89$$

Then

$$\begin{aligned} \partial_{v,v} \tilde{h}(v) &\leq (\alpha-1) \left\{ \frac{v^* \alpha + \alpha - 2}{v^{*3-\alpha}} - \frac{3}{4} \alpha \right\} \\ &= (\alpha-1) \left\{ \frac{1}{v^{*3-\alpha}} - \frac{3}{4} \alpha \right\} \\ &< 0 \end{aligned}$$

Thus over the range  $(0, 1)$ ,  $\tilde{h}(\cdot)$  is convex down and  $\tilde{h}(1) = \tilde{h}(0) = 0$ . Then  $\tilde{h}(v) \geq 0$  for all  $v \in (0, 1)$ , proving the result.