

Quantifying the High-Frequency Trading “Arms Race”

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Financial Markets: Humans to Computers

- ▶ Financial markets have changed dramatically over the past few decades
- ▶ 1990s and early 00s: human beings on trading floors / pits / desks intermediated large majority of financial market volume
- ▶ Now: financial markets across wide array of financial instruments almost entirely electronic
 - ▶ Equities, futures, treasuries, currencies, options
- ▶ This electronification on the whole has brought clear, measurable benefits:
 - ▶ Trading fees, various measures of cost of liquidity
 - ▶ Key cites: Hendershott Jones and Menkveld (2011), Angel Harris and Spatt (2015), Frazzini Israel and Moskowitz (2018)
- ▶ But controversy as well, particularly around the role of speed in modern electronic markets

Latency Arbitrage

“The market is rigged” - Michael Lewis

“Latency arbitrage is a myth” - Modern Markets Initiative

- ▶ At center of controversy over speed: *latency arbitrage*
 - ▶ aka “sniping” or “picking off”
- ▶ In plain English:
 - ▶ Latency arbitrage = arbitrage opportunity that is mechanical / obvious, capturing it is a contest in speed
 - ▶ Examples: futures/ETF; same stock multiple venues; treasuries futures/cash; currency triangles; etc.
- ▶ In conceptual terms:
 - ▶ Latency arbitrage = rents from symmetrically-observable public-information signals (Budish, Cramton and Shim 2015)
 - ▶ Distinct from asymmetrically-observable private information signals at the heart of classic models of market microstructure (Kyle 1985, Glosten and Milgrom 1985)

“Rigged”, “Myth”, “Mis-Designed”

- ▶ You likely have intuition that arbitrage rents from symmetric public information does not make sense
 - ▶ To make money, you have to know something the rest of the market doesn't know
- ▶ Budish, Cramton and Shim (2015): latency arbitrage is a consequence of flawed market design. Modern electronic markets:
 1. treat time as continuous
 2. process requests to trade serially
- ▶ BCS: continuous+serial → latency arbitrage
 - ▶ Intuition: even if *exactly* same speed, someone is always processed first
- ▶ These rents:
 - ▶ Harm liquidity (like a “tax”)
 - ▶ Lead to never-ending arms race for speed
- ▶ Fixing the market design:
 - ▶ Preserves the useful functions of algorithmic trading
 - ▶ Enhances liquidity and stops a wasteful arms race

Measuring Latency Arbitrage

- ▶ Empirical evidence on magnitude of latency arbitrage has been elusive
 - ▶ BCS provide estimate for one specific trade, S&P 500 futures - ETF arbitrage
 - ▶ Aquilina et al (2016) study stale reference prices in UK dark pools
 - ▶ Challenge with both: how to extrapolate from one trade the researcher knows how to measure to overall magnitudes?
- ▶ Several studies have looked at price discrepancies for the same symbol across venues
 - ▶ Ding, Hanna and Hendershott (2014), Wah (2016), Dewhurst et al (2019)
 - ▶ Challenge 1: which discrepancies are actually exploitable / exploited?
 - ▶ Challenge 2: only within-symbol arbitrage, would miss futures-ETF and other highly correlated assets
- ▶ In absence of comprehensive empirical evidence:
 - ▶ Hard to assess importance of latency arbitrage. Rigged? Myth?
 - ▶ Hard to do cost-benefit analysis on market design reforms.

Message Data, Simple Methodology

- ▶ This paper uses a simple new kind of data to shed light on HFT, and specifically latency arbitrage: “Message data”
- ▶ Limit-order book data provide the complete “play-by-play” of the order book:
 - ▶ Every new limit order that posts to the book, every canceled order, every trade, etc.
 - ▶ Often with ultra-precise timestamps (or even firm IDs)
- ▶ But ... limit-order book data are missing the messages that *do not affect the state of the order book, because they fail*.
 - ▶ *Attempts* to snipe a stale quote that are too late
 - ▶ *Attempts* to cancel a stale quote that are too late
- ▶ Simple insight: these failure messages are a direct empirical signature of speed-sensitive trading
 - ▶ The essence of a race is that there are winners and losers ...
 - ▶ But limit order book data doesn't let you see the losers!

Message Data, Simple Methodology

- ▶ We obtained message data from the London Stock Exchange (by a request under Section 165 of the Financial Service and Markets Act)
 - ▶ All message data for all FTSE 350 stocks for a 9 week period in Fall 2015
 - ▶ Timestamps accurate to the microsecond (0.000001s)
 - ▶ Timestamps at the right location in the exchange architecture
 - ▶ Anonymized participant IDs
- ▶ Using this data we can directly measure:
 - ▶ Quantity of races
 - ▶ How long they take
 - ▶ How many participants there are
 - ▶ The diversity / concentration of winners and losers
 - ▶ The economic stakes – per-race and overall

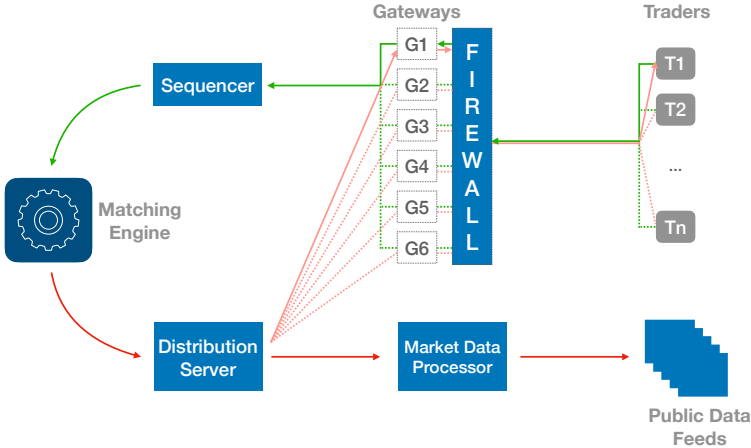
Preview of Main Results

1. Races are frequent: one per minute per symbol for FTSE 100
2. Races are fast: mode is 5-10 microseconds
3. Large volume in races: 22% of FTSE 100 volume
4. Races are small per race: average half a tick, 2GBP
5. Race participation is concentrated: Top 6 win 82%, lose 87%.
The top firms disproportionately snipe: Top 6 take 80%, provide 42%.
6. Adds up to meaningful proportion of price impact and effective spread: races are 31% of price impact, 33% of effective spread
7. Adds up to meaningful harm to liquidity: latency arbitrage tax is 0.42bps of volume. Market designs that eliminate latency arbitrage would reduce investors' cost of liquidity by 17%
8. Adds up to meaningful total "size of the prize": 0.42bps is about \$5bn annually in global equities

Discussion Topics and Broader Implications

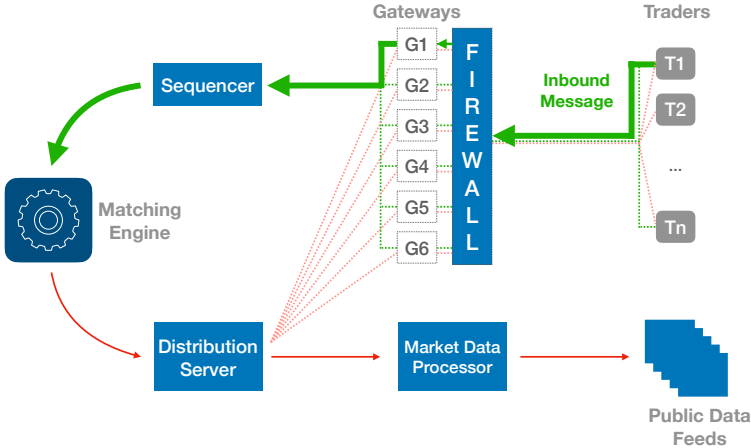
1. Are magnitudes big or small? Depends on your vantage point
...
2. Market design reforms: frequent batch auctions, speed bumps, etc.
3. Market cost of liquidity: importance of sniping alongside traditional adverse selection.
4. Volume puzzle: Cochrane calls trading volume “The Great Unsolved Problem of Financial Economics.” Trading races are a big piece of the puzzle ... 20% in baseline, up to 44% of volume in 3-millisecond race window sensitivity
5. Value of message data: more studies measuring latency arb; liquidity in crisis/stress; etc.

Exchange Schematic



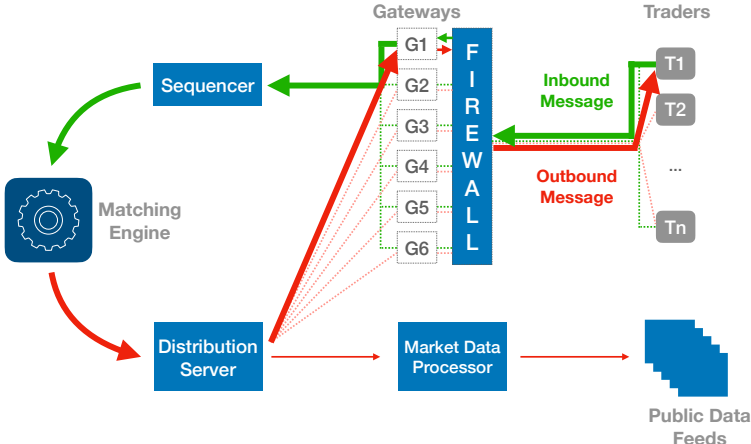
Notes: Please see the text of Section 2.1 for supporting details for this figure.

Exchange Schematic



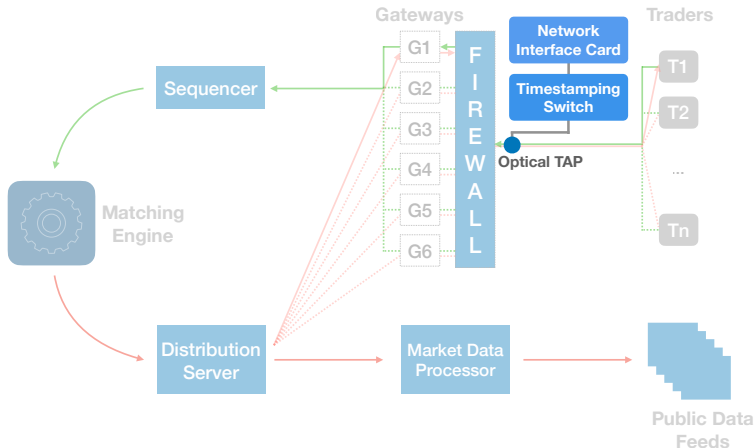
Notes: Please see the text of Section 2.1 for supporting details for this figure.

Exchange Schematic



Notes: Please see the text of Section 2.1 for supporting details for this figure.

Where the Message Data are Captured and Timestamped



Notes: Please see the text of Section 2.2 for supporting details for this figure.

Event Classification

Event Name	Inbound Message Type	Outbound Message Type
New order posted to book	New Order (Limit)	New Order Accepted
New order aggressively executed in full	New Order (Limit)	Full Fill (Aggressive)
	New Order (IOC)	Partial Fill (Aggressive) - multiple such orders that sum to the full quantity
New order aggressively executed in part	New Order (Limit)	Partial Fill (Aggressive) - one or more that sum to less than the full quantity
	New Order (IOC)	Order Expire - for IOCs, not Limits which will post the remainder
Order passively executed in part	-	Partial Fill (Passive)
Order passively executed in full	-	Full Fill (Passive)
Cancel accepted	Cancel	Cancel Accept
Failed cancel	Cancel	Cancel Reject
Failed IOC	New Order (IOC)	Order Expire

Notes: Please see the text of Section 2.3.3 for a description of Event Classification. Please see Section 2.3.1 and 2.3.2 for a description of the contents of inbound and outbound messages.

Defining a Race

- ▶ The theory suggests that the empirical signature of a BCS-style latency-arbitrage race, as distinct from Glosten-Milgrom-style informed trading, is:
 1. Multiple market participants acting on the same symbol, price and side
 2. Either mix of takes + cancels (eqm emphasized in BCS) or all takes (if liquidity provider is slow)
 3. Some succeed, some fail
 4. All at the “same time”
- ▶ Items #1-#3 are relatively straightforward to implement
 - ▶ Please see paper for various sensitivities
- ▶ Item #4 is harder
 - ▶ In theory, such a thing as “same time”
 - ▶ But in data, no two things happen at *exactly* the same time

Defining “At the Same Time”

Main approach: Information Horizon

- ▶ Defined as the amount of time such that we can be sure that message 2 is not responding to message 1:

Information Horizon

=

Actual Observed Latency : M1 In → M1 Out

+

Minimum Reaction Time : M1 Out → M2 In

- ▶ In our data
 - ▶ Median observed *M1 In → M1 Out* latency: 157 microseconds
 - ▶ Minimum *M1 Out → M2 In* reaction time: 29 microseconds
- ▶ Truncate above at 500 micros (per FCA supervisors).

Alternative approach: Sensitivity analysis

- ▶ Consider a range from 50 microseconds to 3 milliseconds

Races Per Symbol Per Day

Table 4.1: Races Per Day (Per Symbol)

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
FTSE 100	537.24	473.26	132	184	240	352	619	1,134	2,067
FTSE 250	70.05	93.53	0	0	2	44	104	166	404
Full Sample	206.03	340.73	0	1	14	87	239	511	1,814

Notes: Please see Section 4.1 of the text and the table notes for Table 4.1

Races Per Symbol Per Day

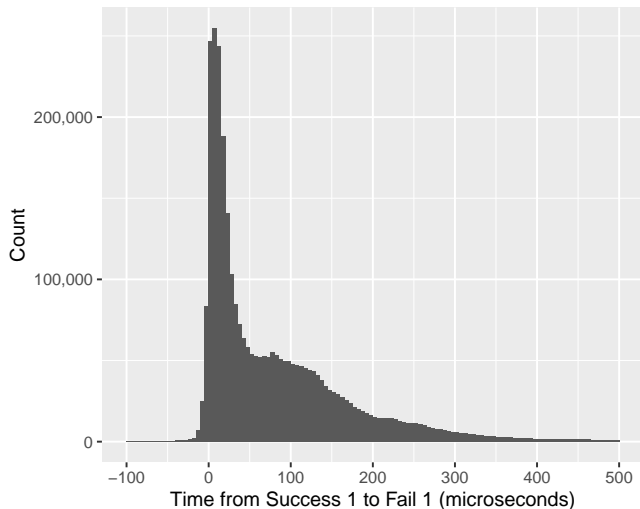
Table 4.1: Races Per Day (Per Symbol)

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
FTSE 100	537.24	473.26	132	184	240	352	619	1,134	2,067
FTSE 250	70.05	93.53	0	0	2	44	104	166	404
Full Sample	206.03	340.73	0	1	14	87	239	511	1,814

Notes: Please see Section 4.1 of the text and the table notes for Table 4.1

Race Duration

Figure 4.1: Duration of Races



Notes: The figure plots the distribution of F1's timestamp minus S1's timestamp in microseconds, as defined in Table B.2, for the full sample. The histogram has a bin size of 5 microseconds.

Volume and Trades in Races

Panel A: Percentage of volume (value-weighted) in races across dates

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	22.15	1.90	17.84	20.09	21.15	22.02	23.11	24.85	26.08
FTSE 250	16.90	1.78	11.58	14.73	15.71	17.07	18.19	19.21	20.13
Full Sample	21.46	1.75	17.63	19.70	20.50	21.41	22.53	24.02	25.02

Panel B: Percentage of number of trades in races across dates

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	20.69	1.59	16.91	18.62	19.83	20.80	21.58	22.93	23.51
FTSE 250	16.96	1.50	13.29	15.24	16.01	17.01	18.07	18.91	19.31
Full Sample	19.70	1.42	16.07	18.04	18.94	19.65	20.68	21.73	22.22

Notes: Please see Section 4.1 of the text and the table notes for Table 4.2.

Volume and Trades in Races

Panel A: Percentage of volume (value-weighted) in races across dates

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	22.15	1.90	17.84	20.09	21.15	22.02	23.11	24.85	26.08
FTSE 250	16.90	1.78	11.58	14.73	15.71	17.07	18.19	19.21	20.13
Full Sample	21.46	1.75	17.63	19.70	20.50	21.41	22.53	24.02	25.02

Panel B: Percentage of number of trades in races across dates

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	20.69	1.59	16.91	18.62	19.83	20.80	21.58	22.93	23.51
FTSE 250	16.96	1.50	13.29	15.24	16.01	17.01	18.07	18.91	19.31
Full Sample	19.70	1.42	16.07	18.04	18.94	19.65	20.68	21.73	22.22

Notes: Please see Section 4.1 of the text and the table notes for Table 4.2.

Number of Participants and Messages

Panel A: Number of participants

Description	Mean	sd	Min	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99	Max
Participants within 50us	1.77	0.86	1	1	1	1	2	2	3	5	12
Participants within 100us	2.08	0.97	1	1	1	1	2	2	3	5	13
Participants within 200us	2.56	1.13	1	1	2	2	2	3	4	6	16
Participants within 500us	3.27	1.56	2	2	2	2	3	4	5	9	23
Participants within 1000us	3.64	1.94	2	2	2	2	3	4	6	11	26

Panel B: Number of take messages

Description	Mean	sd	Min	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99	Max
Takes within 50us	1.66	0.97	0	0	1	1	1	2	3	5	14
Takes within 100us	1.93	1.08	0	0	1	1	2	2	3	5	15
Takes within 200us	2.37	1.30	0	1	1	1	2	3	4	7	17
Takes within 500us	3.07	1.78	1	1	1	2	3	4	5	9	29
Takes within 1000us	3.45	2.19	1	1	1	2	3	4	6	11	40

Panel C: Number of cancel messages

Description	Mean	sd	Min	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99	Max
Cancels within 50us	0.17	0.41	0	0	0	0	0	0	1	1	8
Cancels within 100us	0.22	0.47	0	0	0	0	0	0	1	2	8
Cancels within 200us	0.30	0.56	0	0	0	0	0	1	1	2	12
Cancels within 500us	0.40	0.70	0	0	0	0	0	1	1	3	14
Cancels within 1000us	0.44	0.78	0	0	0	0	0	1	1	3	21

Notes: Please see Section 4.2 of the text and the table notes for Table 4.3.

Number of Participants and Messages

Panel A: Number of participants

Description	Mean	sd	Min	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99	Max
Participants within 50us	1.77	0.86	1	1	1	1	2	2	3	5	12
Participants within 100us	2.08	0.97	1	1	1	1	2	2	3	5	13
Participants within 200us	2.56	1.13	1	1	2	2	2	3	4	6	16
Participants within 500us	3.27	1.56	2	2	2	2	3	4	5	9	23
Participants within 1000us	3.64	1.94	2	2	2	2	3	4	6	11	26

Panel B: Number of take messages

Description	Mean	sd	Min	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99	Max
Takes within 50us	1.66	0.97	0	0	1	1	1	2	3	5	14
Takes within 100us	1.93	1.08	0	0	1	1	2	2	3	5	15
Takes within 200us	2.37	1.30	0	1	1	1	2	3	4	7	17
Takes within 500us	3.07	1.78	1	1	1	2	3	4	5	9	29
Takes within 1000us	3.45	2.19	1	1	1	2	3	4	6	11	40

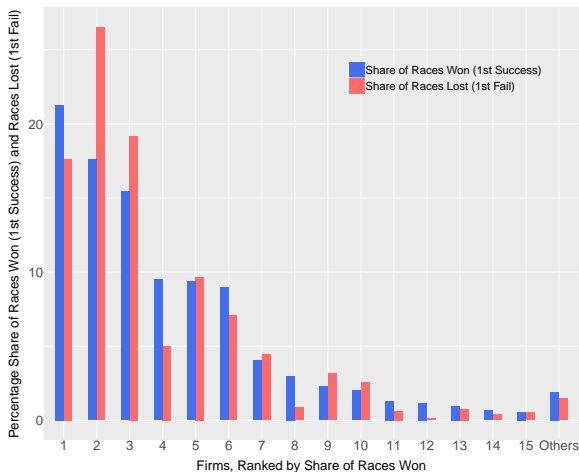
Panel C: Number of cancel messages

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Cancels within 100us	0.22	0.47	0	0	0	0	0	0	1	2	8
Cancels within 200us	0.30	0.56	0	0	0	0	0	1	1	2	12
Cancels within 500us	0.40	0.70	0	0	0	0	0	1	1	3	14
Cancels within 1000us	0.44	0.78	0	0	0	0	0	1	1	3	21

Notes: Please see Section 4.2 of the text and the table notes for Table 4.3.

Pattern of Winners and Losers

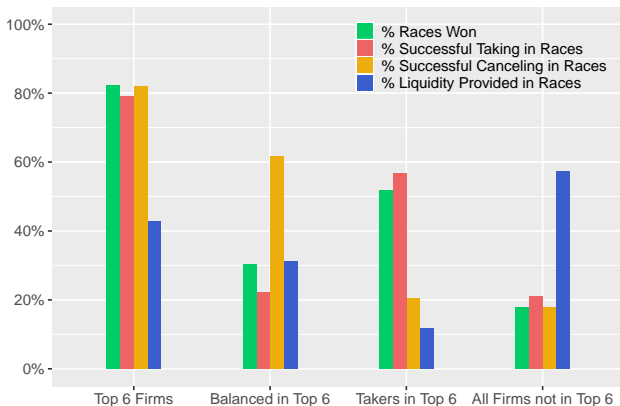
Figure 4.2: Percentage of 1st Successful and 1st Failed Messages by Firm (FTSE 100 Races)



Notes: FTSE 100 races. Please see Section 4.2 of the text and the table notes for Table 4.3.

Pattern of Takes, Cancels, and Liquidity Provision

Figure 4.3 Panel B: Pattern by Firm Groups



Notes: FTSE 100 races. Please see Section 4.2 of the text and the table notes for Figure 4.3.

Liquidity Taker-Provider Matrix

% of Race Volume by Taker-Provider Combination

		Provider		
		Takers in Top 6	Balanced in Top 6	Non-Top 6
Taker	Takers in Top 6	5.7	17.2	34.3
	Balanced in Top 6	2.5	6.4	13.3
	Non-Top 6	3.2	7.4	10.1

Notes: FTSE 100 races. Please see Section 4.2 of the text and the table notes for Table 4.4.

Liquidity Taker-Provider Matrix

% of Race Volume by Taker-Provider Combination

		Provider		
		Takers in Top 6	Balanced in Top 6	Non-Top 6
Taker	Takers in Top 6	5.7	17.2	34.3
	Balanced in Top 6	2.5	6.4	13.3
	Non-Top 6	3.2	7.4	10.1

Notes: FTSE 100 races. Please see Section 4.2 of the text and the table notes for Table 4.4.

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Taker	Takers in Top 6	5.7	17.2	34.3
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	Non-Top 6	3.2	7.4	10.1

Notes: FTSE 100 races. Please see Section 4.2 of the text and the table notes for Table 4.4.

Races By Chance

Table 4.5: Expected Number of Potential Race Events By Chance

	FTSE 100		FTSE 250	
	Average Rate	Busiest 30 Mins	Average Rate	Busiest 30 Mins
Expected Occurrences by Chance				
2+ within 50 μs	0.35	1.33	0.00	0.02
2+ within 100 μs	0.71	2.65	0.01	0.04
2+ within 200 μs	1.42	5.31	0.02	0.09
2+ within 500 μs	3.55	13.26	0.04	0.21
2+ within 1000 μs	7.09	26.49	0.08	0.43
3+ within 1000 μs	0.00	0.03	0.00	0.00
Actual Number of Races				
Baseline analysis		537.24		70.05
3+ within Info Horizon		228.98		30.68

Notes: Please see Section 4.2 of the text and the table notes for Table 4.5.

Races By Chance

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	Average Rate	Busiest 30 Mins	Average Rate	Busiest 30 Mins
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2+ within 50 μ s	0.35	1.33	0.00	0.02
2+ within 100 μ s	0.71	2.65	0.01	0.04
2+ within 200 μ s	1.42	5.31	0.02	0.09
2+ within 500 μ s	3.55	13.26	0.04	0.21
2+ within 1000 μ s	7.09	26.49	0.08	0.43
3+ within 1000 μ s	0.00	0.03	0.00	0.00
Actual Number of Races				
Baseline analysis	537.24		70.05	
3+ within Info Horizon	228.98		30.68	

Notes: Please see Section 4.2 of the text and the table notes for Table 4.5.

Profits Per Race (Mark to Market 10s)

Table 4.6: Detail on Race Profits Marked to Market at 10s

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
Per-share profits (ticks)	0.55	3.92	-6.50	-1.50	-0.50	0.50	1.00	3.00	10.00
Per-share profits (GBX)	0.17	1.48	-2.00	-0.50	-0.05	0.01	0.25	1.00	3.50
Per-share profits (basis points)	1.66	8.71	-15.00	-4.26	-1.29	0.50	3.89	7.98	27.02
Per-race profits displayed depth (GBP)	1.85	16.27	-20.00	-2.76	-0.34	0.00	2.15	7.27	41.50
Per-race profits qty trade/cancel (GBP)	1.76	15.57	-18.13	-2.56	-0.32	0.00	2.02	6.78	38.44

Notes: Full sample. Please see Section 4.3 of the text and the table notes for Table 4.6.

Profits Per Race (Mark to Market 10s)

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Per-share profits (basis points)	1.66	8.71	-15.00	-4.26	-1.29	0.50	3.89	7.98	27.02
Per-race profits displayed depth (GBP)	1.85	16.27	-20.00	-2.76	-0.34	0.00	2.15	7.27	41.50
Per-race profits qty trade/cancel (GBP)	1.76	15.57	-18.13	-2.56	-0.32	0.00	2.02	6.78	38.44

Notes: Full sample. Please see Section 4.3 of the text and the table notes for Table 4.6.

Profits Per Race: Different Mark-to-Market Horizons

Table 4.7: Average Race Profits for Different Mark to Market Horizons

Description	1ms	10ms	100ms	1s	10s	30s	60s	100s
Mean per-share profits (ticks)	0.03	0.21	0.29	0.40	0.55	0.59	0.63	0.64
Mean per-share profits (GBX)	0.03	0.08	0.10	0.13	0.17	0.18	0.18	0.18
Mean per-share profits (basis points)	0.18	0.67	0.89	1.20	1.66	1.83	1.94	1.97
Mean per-race profits displayed depth (GBP)	0.28	0.96	1.24	1.54	1.85	1.86	1.88	1.84
Mean per-race profits qty trade/cancel (GBP)	0.31	0.94	1.18	1.45	1.76	1.76	1.77	1.74

Notes: Full sample. Please see Section 4.3 of the text and the table notes for Table 4.7.

Profits Per Race: Different Mark-to-Market Horizons

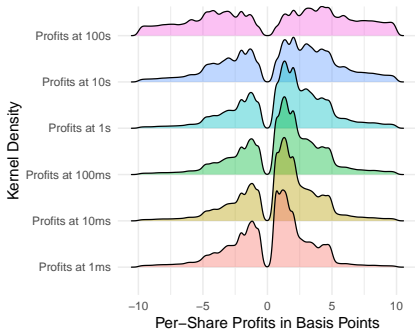
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Mean per-share profits (GBX)	0.03	0.08	0.10	0.13	0.17	0.18	0.18	0.18
Mean per-share profits (basis points)	0.18	0.67	0.89	1.20	1.66	1.83	1.94	1.97
Mean per-race profits displayed depth (GBP)	0.28	0.96	1.24	1.54	1.85	1.86	1.88	1.84
Mean per-race profits qty trade/cancel (GBP)	0.31	0.94	1.18	1.45	1.76	1.76	1.77	1.74

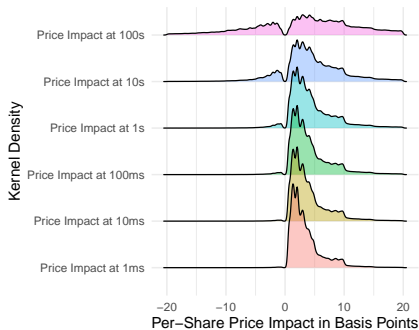
Notes: Full sample. Please see Section 4.3 of the text and the table notes for Table 4.7.

Profits and Price Impact at Different Time Horizons

Panel A: Race Profits



Panel B: Race Price Impact



Notes: Please see Section 4.3 of the text and the table notes for Figure 4.4.

Daily Profits (GBP)

Panel A: Per Symbol (Averages over all Dates)

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
FTSE 100	1,046.9	729.6	199.7	340.5	526.6	909.3	1,410.5	1,967.2	3,431.8
FTSE 250	108.3	134.1	-0.7	0.5	7.6	67.1	160.8	257.2	606.3
Full Sample	381.5	590.7	-0.6	1.5	26.7	135.1	466.2	1,184.5	2,273.8

Panel B: Overall (Summed over all Symbols)

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	105,734	32,852	62,980	78,777	87,038	93,074	117,979	153,712	223,187
FTSE 250	26,643	8,592	14,667	19,501	21,376	23,100	30,392	40,100	49,066
Full Sample	132,378	40,266	82,391	99,363	108,706	116,636	147,814	183,227	272,253

Notes: Please see Section 4.4 of the text and the table notes for Table 4.8.

Daily Profits (GBP)

Panel A: Per Symbol (Averages over all Dates)

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
FTSE 100	1,046.9	729.6	199.7	340.5	526.6	909.3	1,410.5	1,967.2	3,431.8
FTSE 250	108.3	134.1	-0.7	0.5	7.6	67.1	160.8	257.2	606.3
Full Sample	381.5	590.7	-0.6	1.5	26.7	135.1	466.2	1,184.5	2,273.8

Panel B: Overall (Summed over all Symbols)

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	105,734	32,852	62,980	78,777	87,038	93,074	117,979	153,712	223,187
FTSE 250	26,643	8,592	14,667	19,501	21,376	23,100	30,392	40,100	49,066
Full Sample	132,378	40,266	82,391	99,363	108,706	116,636	147,814	183,227	272,253

Notes: Please see Section 4.4 of the text and the table notes for Table 4.8.

Latency-Arbitrage Tax (Basis Points)

Panel A: Latency Arbitrage Profits / All Trading Volume (basis points)

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	0.383	0.053	0.286	0.329	0.345	0.381	0.415	0.456	0.516
FTSE 250	0.663	0.099	0.495	0.552	0.591	0.653	0.725	0.790	0.912
Full Sample	0.419	0.053	0.313	0.360	0.382	0.416	0.450	0.495	0.537

Panel B: Latency Arbitrage Profits / Non-Race Trading Volume (basis points)

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	0.493	0.075	0.351	0.418	0.443	0.487	0.533	0.603	0.656
FTSE 250	0.800	0.133	0.577	0.653	0.712	0.788	0.899	0.969	1.136
Full Sample	0.534	0.076	0.384	0.454	0.481	0.531	0.581	0.652	0.680

Notes: Please see Section 4.4 of the text and the table notes for Table 4.9.

Latency-Arbitrage Tax (Basis Points)

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Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
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Full Sample	0.419	0.053	0.313	0.360	0.382	0.416	0.450	0.495	0.537

Panel B: Latency Arbitrage Profits / Non-Race Trading Volume (basis points)

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	0.493	0.075	0.351	0.418	0.443	0.487	0.533	0.603	0.656
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Full Sample	0.534	0.076	0.384	0.454	0.481	0.531	0.581	0.652	0.680

Notes: Please see Section 4.4 of the text and the table notes for Table 4.9.

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Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
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FTSE 250	0.663	0.099	0.495	0.552	0.591	0.653	0.725	0.790	0.912
Full Sample	0.419	0.053	0.313	0.360	0.382	0.416	0.450	0.495	0.537

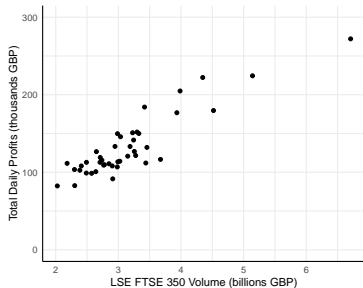
Panel B: Latency Arbitrage Profits / Non-Race Trading Volume (basis points)

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FTSE 250	0.800	0.133	0.577	0.653	0.712	0.788	0.899	0.969	1.136
Full Sample	0.534	0.076	0.384	0.454	0.481	0.531	0.581	0.652	0.680

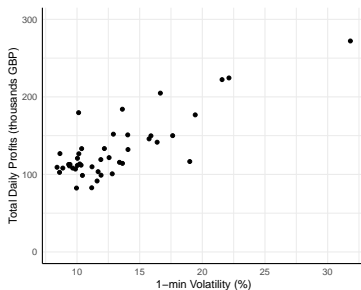
Notes: Please see Section 4.4 of the text and the table notes for Table 4.9.

Latency Arbitrage Profits: Correlation with Volume and Volatility

Panel A: Profit vs. Volume



Panel B: Profits vs. Volatility



Notes: Please see Section 4.4 of the text and the table notes for Figure 4.5.

Latency Arbitrage: Share of the Market's Cost of Liquidity

- ▶ Approach #1: Bid-Ask Spread Decomposition
- ▶ Traditional Decomposition

$$EffectiveSpread = PriceImpact + RealizedSpread \quad (5.1)$$

- ▶ Using equilibrium bid-ask spread with both latency arbitrage and traditional adverse selection (see Budish, Lee and Shim (2019))

$$\lambda_{invest} \frac{s^{CLOB}}{2} = (\lambda_{public} + \lambda_{private}) \cdot L\left(\frac{s^{CLOB}}{2}\right) \quad (5.2)$$

- ▶ We derive a novel decomposition:

$$EffectiveSpread = PriceImpact_{Race} + PriceImpact_{NonRace} \\ + LossAvoidance + RealizedSpread \quad (5.3)$$

Spread Decomposition - FTSE 100 Symbols

Table 4.10: Spread Decomposition

Description	Mean	sd	Pct01	Pct25	Median	Pct75	Pct99
Effective spread paid - overall (bps)	3.27	1.22	1.22	2.28	3.18	4.13	5.79
Effective spread paid - in races (bps)	3.18	1.22	0.99	2.21	3.17	4.05	5.98
Effective spread paid - not in races (bps)	3.29	1.22	1.25	2.30	3.17	4.15	5.71
Price impact - overall (bps)	3.62	1.36	1.40	2.52	3.56	4.52	6.99
Price impact - in races (bps)	5.11	1.83	2.02	3.48	4.90	6.50	8.81
Price impact - not in races (bps)	3.15	1.16	1.21	2.21	3.17	3.97	5.99
Loss avoidance (bps)	0.01	0.01	0.00	0.00	0.01	0.01	0.03
Realized spread - overall (bps)	-0.36	0.32	-1.07	-0.55	-0.35	-0.17	0.39
Realized spread - in races (bps)	-1.93	0.70	-3.72	-2.40	-1.79	-1.42	-0.88
Realized spread - not in races (bps)	0.15	0.30	-0.35	-0.05	0.08	0.34	0.90
PI in races / PI total (%)	33.16	6.09	19.99	29.53	32.13	37.23	44.72
PI in races / Effective spread (%)	36.90	7.18	19.79	33.06	36.59	41.97	51.67

Notes: Please see Section 4.5 of the text and the table notes for Table 4.10.

Spread Decomposition - FTSE 100 Symbols

Table 4.10: Spread Decomposition

Description	Mean	sd	Pct01	Pct25	Median	Pct75	Pct99
Effective spread paid - overall (bps)	3.27	1.22	1.22	2.28	3.18	4.13	5.79
Effective spread paid - in races (bps)	3.18	1.22	0.99	2.21	3.17	4.05	5.98
Effective spread paid - not in races (bps)	3.29	1.22	1.25	2.30	3.17	4.15	5.71
Price impact - overall (bps)	3.62	1.36	1.40	2.52	3.56	4.52	6.99
Price impact - in races (bps)	5.11	1.83	2.02	3.48	4.90	6.50	8.81
Price impact - not in races (bps)	3.15	1.16	1.21	2.21	3.17	3.97	5.99
Loss avoidance (bps)	0.01	0.01	0.00	0.00	0.01	0.01	0.03
Realized spread - overall (bps)	-0.36	0.32	-1.07	-0.55	-0.35	-0.17	0.39
Realized spread - in races (bps)	-1.93	0.70	-3.72	-2.40	-1.79	-1.42	-0.88
Realized spread - not in races (bps)	0.15	0.30	-0.35	-0.05	0.08	0.34	0.90
PI in races / PI total (%)	33.16	6.09	19.99	29.53	32.13	37.23	44.72
PI in races / Effective spread (%)	36.90	7.18	19.79	33.06	36.59	41.97	51.67

Notes: Please see Section 4.5 of the text and the table notes for Table 4.10.

Realized Spreads by Firm Group

Table 4.11: Realized Spreads in Races by Firm Group

Firm Group	Realized Spread (bps)			Cancel Attempt Rate (%)		
	Overall	Non-Race	Race	In Race	Within 1ms	Ever
All Firms	-0.209	0.236	-1.833	19.29	21.89	24.53
Fast vs. Slow						
Top 6	-0.086	0.347	-1.699	35.35	38.94	39.88
All Others	-0.302	0.152	-1.930	7.57	9.47	13.35
Within Fast						
Takers in Top 6	0.016	0.455	-1.493	45.16	47.56	47.82
Balanced in Top 6	-0.120	0.311	-1.775	30.97	35.09	36.33

Notes: Please see Section 4.5 of the text and the table notes for Table 4.11.

Realized Spreads by Firm Group

Table 4.11: Realized Spreads in Races by Firm Group

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Notes: Please see Section 4.5 of the text and the table notes for Table 4.11.

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Within Fast						
Takers in Top 6	0.016	0.455	-1.493	45.16	47.56	47.82
Balanced in Top 6	-0.120	0.311	-1.775	30.97	35.09	36.33

Notes: Please see Section 4.5 of the text and the table notes for Table 4.11.

Potential Reduction in Market's Cost of Liquidity

- ▶ Approach #2: quantify reduction in market's cost of liquidity in a counterfactual market design without latency arbitrage
- ▶ Formally, we seek to measure

$$\frac{\frac{s^{CLOB}}{2} - \frac{s^{FBA}}{2}}{\frac{s^{CLOB}}{2}} \quad (5.4)$$

- ▶ Algebraic manipulations: above can be re-expressed as

$$\frac{\frac{s^{CLOB}}{2} - \frac{s^{FBA}}{2}}{\frac{s^{CLOB}}{2}} = \frac{\lambda_{public} L\left(\frac{s^{CLOB}}{2}\right)}{(\lambda_{invest} + \lambda_{private}) \frac{s^{CLOB}}{2}} \quad (5.6)$$

- ▶ Both numerator and denominator can be directly empirically quantified:

$$= \frac{\text{Race Profits (GBP)}}{\text{Non-Race Effective Spread (GBP)}} \quad (5.7)$$

$$= \frac{\text{Latency Arbitrage Tax (Non-Race Volume)}}{\text{Non-Race Effective Spread (bps)}}$$

Potential Reduction in Market's Cost of Liquidity

Table 4.12: Percentage Reduction in Liquidity Cost, if Latency Arbitrage Eliminated

Panel A: Symbol level

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
FTSE 100	19.95	5.29	8.87	13.30	16.79	19.69	23.58	26.50	32.54
FTSE 250	11.93	6.31	0.58	3.12	8.05	11.91	15.33	18.58	31.31
Full Sample	14.77	7.09	0.70	5.55	10.03	14.55	19.41	24.10	32.22

Panel B: Date level

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	19.06	3.29	7.49	16.53	17.53	18.97	21.48	22.25	25.40
FTSE 250	11.39	1.66	8.27	9.43	10.22	11.17	12.45	13.36	16.18
Full Sample	16.73	2.57	7.88	14.57	15.19	16.82	18.66	19.17	21.58

Notes: Please see Section 4.5 of the text and the table notes for Table 4.12.

Potential Reduction in Market's Cost of Liquidity

Table 4.12: Percentage Reduction in Liquidity Cost, if Latency Arbitrage Eliminated

Panel A: Symbol level

Description	Mean	sd	Pct01	Pct10	Pct25	Median	Pct75	Pct90	Pct99
FTSE 100	19.95	5.29	8.87	13.30	16.79	19.69	23.58	26.50	32.54
FTSE 250	11.93	6.31	0.58	3.12	8.05	11.91	15.33	18.58	31.31
Full Sample	14.77	7.09	0.70	5.55	10.03	14.55	19.41	24.10	32.22

Panel B: Date level

Description	Mean	sd	Min	Pct10	Pct25	Median	Pct75	Pct90	Max
FTSE 100	19.06	3.29	7.49	16.53	17.53	18.97	21.48	22.25	25.40
FTSE 250	11.39	1.66	8.27	9.43	10.22	11.17	12.45	13.36	16.18
Full Sample	16.73	2.57	7.88	14.57	15.19	16.82	18.66	19.17	21.58

Notes: Please see Section 4.5 of the text and the table notes for Table 4.12.

Sensitivity Analysis

- ▶ Wide range of sensitivity analyses. Some key findings:
- ▶ Finding #1: Effect of Race Horizon
 - ▶ Main pattern: longer window -> more races, similar profits
 - ▶ T=50us: 297 races per symbol per day, 0.20bps LA tax
 - ▶ T=3ms: 800 races per symbol per day, 0.74bps LA tax
- ▶ Finding #2: Number of Race Participants
 - ▶ Main pattern: more participants -> fewer races, higher profits
 - ▶ Ex: 3+ reduces races 60%, profits per race +60%
 - ▶ 2+ baseline, 3+ 500us, 5+ 1ms relatively similar overall
- ▶ Finding #3: Takes and Cancels
 - ▶ Requiring a cancel significantly reduces the number of races (as already noted)
- ▶ Races with Negative Profits Ex-Post
 - ▶ Robust feature of our data. Even in races with 5+ within 50us, ~10% have strictly negative profits 100 milliseconds ex-post
 - ▶ Observed races are closer to pure arb than 51/49, but healthy distance from 100/0

Sensitivity Analysis

Table 5.1: Sensitivity Analysis: Selected Scenarios

Measure	Baseline	Low Scenarios			Middle Scenarios			High Scenarios		
		2+, 50 μ s	2+, 100 μ s	3+, 1H	2+, 200 μ s	2+, 500 μ s	3+, 500 μ s	2+, 1ms	2+, 3ms	3+, 3ms
Frequency and Duration of Races										
Races per day										
FTSE 100 - per symbol	537.24	296.66	388.58	228.98	521.53	719.71	458.94	768.02	799.91	609.01
% of volume in races										
Full Sample	21.46	9.77	13.32	12.30	19.21	34.89	26.42	40.03	43.72	38.14
Per-Race Profits										
Per-share profits										
ticks	0.55	0.54	0.53	0.71	0.51	0.52	0.60	0.54	0.55	0.64
GBX	0.17	0.16	0.16	0.23	0.16	0.16	0.19	0.16	0.16	0.19
basis points	1.66	1.68	1.63	2.24	1.57	1.59	1.90	1.64	1.64	1.92
Per-race profits GBP										
displayed depth	1.85	1.58	1.59	2.98	1.60	1.91	2.54	2.04	2.09	2.67
qty trade/cancel	1.76	1.38	1.44	2.87	1.51	1.92	2.59	2.07	2.16	2.76
Aggregate Profits and LA Tax										
Daily Profits										
Full Sample - aggregate (GBP)	132,378	63,573	83,233	91,506	111,722	187,989	158,444	215,794	232,457	221,526
Latency Arbitrage Tax, All Volume (bps)										
Full Sample	0.42	0.20	0.26	0.29	0.35	0.60	0.50	0.68	0.74	0.70
Latency Arbitrage Tax, Non-Race Volume (bps)										
Full Sample	0.53	0.22	0.30	0.33	0.44	0.92	0.70	1.14	1.31	1.14
Spread Decomposition										
Price impact in races / All price impact %	30.58	12.84	17.89	19.13	25.69	47.38	37.08	55.27	61.61	55.54
Price impact in races / Effective spread %	32.82	13.77	19.19	20.54	27.57	50.84	39.61	59.31	66.11	59.61
Implied Reduction in Cost of Liquidity										
Full Sample - % Reduction	16.73	6.96	9.49	10.43	13.62	28.12	20.96	35.37	41.64	36.20

Notes: Please see Section 5.1 of the text and the table notes for Table 5.1.

Total Sums at Stake: Extrapolation Models

Table 6.1: Extrapolation Models

	<i>Dependent variable:</i>					
	Latency Arbitrage Profits (GBP)					
	(1)	(2)	(3)	(4)	(5)	(6)
Volume (10,000 GBP)	0.4319*** (0.0326)	0.4213*** (0.0082)			0.3405*** (0.0544)	0.3354*** (0.0415)
Volatility (1 min) * Average Volume			0.0228*** (0.0025)	0.0313*** (0.0009)	0.0065** (0.0032)	0.0066** (0.0031)
Constant	-3,562 (10,611)		39,226*** (11,032)		-1,532 (10,263)	
Observations	43	43	43	43	43	43
R ²	0.811	0.810	0.661	0.567	0.829	0.829

*p<0.1; **p<0.05; ***p<0.01

Notes: Please see Section 6.1 of the text and the table notes for Table 6.1.

Total Sums at Stake: Extrapolation Models

Table 6.1: Extrapolation Models

	<i>Dependent variable:</i>					
	Latency Arbitrage Profits (GBP)					
	(1)	(2)	(3)	(4)	(5)	(6)
Volume (10,000 GBP)	0.4319*** (0.0326)	0.4213*** (0.0082)			0.3405*** (0.0544)	0.3354*** (0.0415)
Volatility (1 min) * Average Volume			0.0228*** (0.0025)	0.0313*** (0.0009)	0.0065** (0.0032)	0.0066** (0.0031)
Constant	-3,562 (10,611)		39,226*** (11,032)		-1,532 (10,263)	
Observations	43	43	43	43	43	43
R ²	0.811	0.810	0.661	0.567	0.829	0.829

*p<0.1; **p<0.05; ***p<0.01

Notes: Please see Section 6.1 of the text and the table notes for Table 6.1.

Annual Profits: UK Equity Markets

Table 6.2: Annual Latency Arbitrage Profits in UK Equity Markets
(GBP Millions)

Year	(1) Volume- Volatility	(2) Volume- Only	(3) Low Scenario	(4) High Scenario
2014	52.0	56.7	20.5	99.1
2015	58.9	61.6	22.3	107.7
2016	63.3	63.8	23.0	111.4
2017	51.0	57.5	20.8	100.4
2018	55.8	60.6	21.9	105.9

Notes: Please see Section 6.2 of the text and the table notes for Table 6.2.

Annual Profits: UK Equity Markets

Table 6.2: Annual Latency Arbitrage Profits in UK Equity Markets
(GBP Millions)

Year	(1) Volume- Volatility	(2) Volume- Only	(3) Low Scenario	(4) High Scenario
2014	52.0	56.7	20.5	99.1
2015	58.9	61.6	22.3	107.7
2016	63.3	63.8	23.0	111.4
2017	51.0	57.5	20.8	100.4
2018	55.8	60.6	21.9	105.9

Notes: Please see Section 6.2 of the text and the table notes for Table 6.2.

Annual Profits: UK Equity Markets

Table 6.2: Annual Latency Arbitrage Profits in UK Equity Markets
(GBP Millions)

Year	(1) Volume- Volatility	(2) Volume- Only	(3) Low Scenario	(4) High Scenario
2014	52.0	56.7	20.5	99.1
2015	58.9	61.6	22.3	107.7
2016	63.3	63.8	23.0	111.4
2017	51.0	57.5	20.8	100.4
2018	55.8	60.6	21.9	105.9

Notes: Please see Section 6.2 of the text and the table notes for Table 6.2.

Annual Profits: Global Equity Markets

Table 6.3: Annual Latency Arbitrage Profits in Global Equity Markets in 2018 (USD Millions)

Exchange Group	(1) Volume- Volatility	(2) Volume- Only	(3) Low Scenario	(4) High Scenario
NYSE Group	1,006	1,023	370	1,787
BATS Global Markets - U.S.	895	910	329	1,590
Nasdaq - U.S.	847	862	311	1,505
Shenzhen Stock Exchange	327	336	122	588
Japan Exchange Group	281	286	103	500
Shanghai Stock Exchange	260	268	97	468
Korea Exchange	118	120	43	209
London Stock Exchange Group**	109	119	43	207
BATS Chi-X Europe	110	119	43	207
Hong Kong Exchanges and Clearing	102	104	38	182
Euronext	89	96	35	168
Deutsche Börse Group	78	85	31	148
TMX Group	56	61	22	107
National Stock Exchange of India	47	49	18	86
SIX Swiss Exchange	40	43	16	76
Global Total (WFE Data Universe)	4,674	4,799	1,734	8,383

**London Stock Exchange Group includes London Stock Exchange as well as Borsa Italiana

Notes: Please see Section 6.3 of the text and the table notes for Table 6.3.

Annual Profits: Global Equity Markets

Table 6.3: Annual Latency Arbitrage Profits in Global Equity Markets in 2018 (USD Millions)

Exchange Group	(1) Volume- Volatility	(2) Volume- Only	(3) Low Scenario	(4) High Scenario
NYSE Group	1,006	1,023	370	1,787
BATS Global Markets - U.S.	895	910	329	1,590
Nasdaq - U.S.	847	862	311	1,505
Shenzhen Stock Exchange	327	336	122	588
Japan Exchange Group	281	286	103	500
Shanghai Stock Exchange	260	268	97	468
Korea Exchange	118	120	43	209
London Stock Exchange Group**	109	119	43	207
BATS Chi-X Europe	110	119	43	207
Hong Kong Exchanges and Clearing	102	104	38	182
Euronext	89	96	35	168
Deutsche Börse Group	78	85	31	148
TMX Group	56	61	22	107
National Stock Exchange of India	47	49	18	86
SIX Swiss Exchange	40	43	16	76
Global Total (WFE Data Universe)	4,674	4,799	1,734	8,383

**London Stock Exchange Group includes London Stock Exchange as well as Borsa Italiana

Notes: Please see Section 6.3 of the text and the table notes for Table 6.3.

Discussion of Magnitudes

- ▶ Whether magnitudes in our study seem large or small depends on the vantage point
- ▶ Cost per transaction: small.
 - ▶ Roughly half a tick per race.
 - ▶ Roughly 0.5 bps tax on trading.
 - ▶ Does not sound alarming.
- ▶ Overall sums: large.
 - ▶ 17% reduction in cost of liquidity meaningful for large investors
 - ▶ \$5bn per year in equities alone — not even counting futures, currencies, US Treasuries, etc.
- ▶ Consistent with aspects of both “myth” and “rigged”
 - ▶ Small enough that ordinary households need not worry.
 - ▶ But: billions of dollars per year for a small number of parties in the speed race ...
 - ▶ ... who then have significant incentive to preserve status quo.

Conclusion: Summary of Contributions

- ▶ Three intellectual contributions
 1. Methodology: using message data to measure latency arbitrage
 2. Facts: frequency, volume, speed, concentration, per-race profits, overall magnitudes
 3. Theory: how to quantify latency arbitrage as a proportion of the overall cost of liquidity

Conclusion: Hopes for Future Research

1. Better understand sources of races

- ▶ What proportion arise from same symbol on a different venue?
- ▶ Correlated assets within the same market?
- ▶ Correlated assets across asset classes / geographies?
- ▶ News?

2. More studies using message data!

- ▶ U.S. equities would be of special interest because of
 - ▶ Size / importance
 - ▶ Role of ETFs
 - ▶ Level of fragmentation
- ▶ More asset classes: ETFs, futures, currencies, treasuries
- ▶ “Hard” part is getting the data ... analysis itself is relatively straightforward
- ▶ (and you can have our code)

Conclusion: Discussion Topics and Broader Implications

1. Are magnitudes big or small? Depends on your vantage point ...
2. Market design reforms: frequent batch auctions, speed bumps, etc.
3. Market cost of liquidity: importance of sniping alongside traditional adverse selection.
4. Volume puzzle: Cochrane calls trading volume “The Great Unsolved Problem of Financial Economics.” Trading races are a big piece of the puzzle ... 20% in baseline, up to 44% of volume in 3-millisecond race window sensitivity
5. Value of message data: more studies measuring latency arb; liquidity in crisis/stress; etc.