J.P.Morgan

Pair trading with FX vols

Should vol mean-reversion be your friend?

- **With the ultra-depressed FX volatility levels creating more than one headache to both outright vol buyers and sellers, market-neutral long/short strategies can prove beneficial for delivering a positive source of returns in a low-vol/yield market, without taking a directional view on future vol levels.**

- **In this piece, we introduce a pair-trading strategy that benefits from the well-known observation that volatility variables tend to oscillate around long-term reference values, by proposing a rule-based approach for benefits from such patterns. The resulting strategy, applied to a wide number of vol spreads, delivers a steady source of PnL, over time and different market environments.**

- **We review the empirical properties that support the notion of volatility mean-reversion from a statistical perspective and recommend an implementation into a vol pair-trade format.**

- **Plain vanillas, vol swaps and FVAs are the (liquid) products of choice throughout the piece for implementing the strategy. 1y maturity is used as a benchmark for isolating Vega exposure vs. other Greeks and maximizing the directional sensitivity on vol levels.**

- **We consider a number of solutions for boosting the potential associated with the dislocation theme and increasing expected returns per trade. Amongst them, choosing holding periods of around 3m naturally allows one to capture the correction of the mean-reversion signals, while containing the impact of trading costs.**

- **In the final section of the piece, we supplement the potential displayed by the mean-reversion theme with additional market intelligence, by considering four extra indicators for controlling the dislocation trades. Such combined use of filters allows reducing the drawdown occasionally experienced by the benchmark strategy and improving target PnL in terms of vol points per trade.**

- **Given the promising results obtained, and the multitude of possible extensions of the proposed framework, we leave the door open for further research and trading implementations in future pieces.**

Global Quantitative and Derivatives Strategy

Lorenzo Ravagli, PhD AC
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com
J.P. Morgan Securities plc

Dobromir Tzotchev, PhD
(44-20) 7134-5331
dobromir.tzotchev@jpmorgan.com
J.P. Morgan Securities plc

Marko Kolanovic, PhD
(1-212) 622-3677
marko.kolanovic@jpmorgan.com
J.P. Morgan Securities LLC

Global FX Strategy

Juan Duran-Vara AC
(44-20) 3493-7685
juan.duran-vara@jpmorgan.com
J.P. Morgan Securities plc

Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

Should mean reversion be your friend?

The current ultra-depressed levels are creating more than one headache to both outright buyers and sellers of FX volatility. The former struggle to deliver positive PnL in a market where trends in rate differentials, and consequently spot moves, are contained. Consequently, global macro players tend to express FX views in a long/short format (as call/put spreads) in order to reduce the negative time decay associated with long volatility positions. The latter, having enjoyed a steady flow of positive returns over the past two years, might feel (and rightly so) uncomfortable in taking on trades at such a low entry point that the distribution of the expected PnL does not look very attractive.

Exhibit 1. High correlations for 1 year ATM volatilities

Correlation matrix for daily changes in 1Y ATM vols in both G10 (above) and EM (below), with data from 2004 to 2019.

	EUR-USD	USD-NOK	USD-SEK	GBP-USD	USD-CAD	AUD-USD	NZD-USD	USD-CHF	USD-JPY
EUR-USD	100%	89%	94%	68%	53%	55%	50%	93%	52%
USD-NOK	89%	100%	92%	64%	53%	54%	50%	83%	50%
USD-SEK	94%	92%	100%	66%	53%	55%	51%	89%	50%
GBP-USD	68%	64%	66%	100%	47%	49%	45%	62%	44%
USD-CAD	53%	53%	53%	47%	100%	59%	54%	51%	46%
AUD-USD	55%	54%	55%	49%	59%	100%	88%	51%	60%
NZD-USD	50%	50%	51%	45%	54%	88%	100%	47%	55%
USD-CHF	93%	83%	89%	62%	51%	51%	47%	100%	50%
USD-JPY	52%	50%	50%	44%	46%	60%	55%	50%	100%

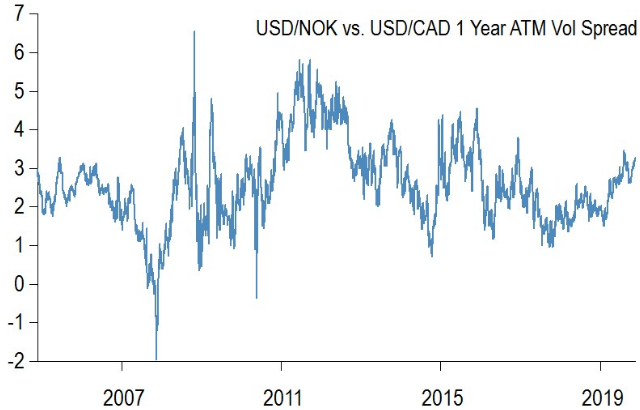
	USD-BRL	USD-MXN	USD-TRY	USD-ZAR	USD-HUF	USD-SGD	USD-PLN	USD-KRW
USD-BRL	100%	55%	29%	28%	24%	16%	29%	27%
USD-MXN	55%	100%	35%	36%	28%	18%	36%	32%
USD-TRY	29%	35%	100%	48%	28%	19%	37%	21%
USD-ZAR	28%	36%	48%	100%	27%	28%	37%	30%
USD-HUF	24%	28%	28%	27%	100%	18%	52%	20%
USD-SGD	16%	18%	19%	28%	18%	100%	30%	47%
USD-PLN	29%	36%	37%	37%	52%	30%	100%	27%
USD-KRW	27%	32%	21%	30%	20%	47%	27%	100%

Source: J.P. Morgan

We expand on previous research (*Cheap won't get cheaper (probably)*, Sandilya et al, 26 November) and propose a systematic framework for trading the FX vol mean-reversion theme. Mean-reversion strategies are usually looked after as the holy grail of the investment process. Their low correlation with other well-established investment strategies (within FX, delta-one *risk premia* or *short-vol* strategies, for instance) makes them a powerful ally for reducing volatility and drawdown of diversified portfolios. The typically good performance in high-vol markets makes them an appealing implementation of risk-off strategies. Trading the theme in a long/short format should insulate the strategy from sharp corrections in volatility levels (lower or higher). A recent piece by the research team investigated the potential of screening for RV trades on cross-asset volatilities (*Cross Asset Volatility: From Relative Value Signals to Optimal Portfolio Weights*, Cheng et al, 5 February).

Exhibit 2. Vol spreads typically exhibit strong mean reversion

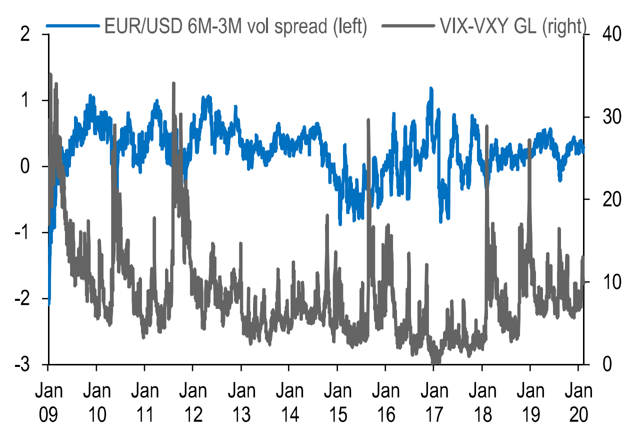
Time series of the volatility spread between USD/NOK 1Y ATM vol and USD/CAD 1Y ATM vol. The scale of the graph is Vol points.



Source: J.P. Morgan

Cross-asset volatilities tend to exhibit large and positive correlations with each other. This is confirmed when looking at the FX vol space (Exhibit 1, daily correlations, 15yrs of data), and especially so for G10 than for EM vols. This suggests that, by considering vol spreads, directional sensitivities might cancel out, thus allowing to isolate and trade the mean-reverting component associated with volatility dynamics. A direct inspection of the USD/NOK - USD/CAD 1y ATM vol spread (Exhibit 2), suggests its mean-stationary and heteroscedastic properties. A general overview of the statistical properties enjoyed by market volatilities is presented in Appendix 1.

Exhibit 3. Vol curves (here 6M-3M EUR/USD) and x-asset vol spreads (VIX-VXY GL Index) display mean-reversion properties too.



Source: J.P. Morgan

Similar conclusions would apply to vol curve segments or to cross-asset vol spreads (Exhibit 3): in the chart, the 6M-

Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

3M EUR/USD vol spread and the difference between VIX and J.P. Morgan VXY Global Indices are considered as two proxy examples displaying mean-reversion properties.

In other words, the concept of mean-reversion is a broad one, even in the context of derivatives. The goal of this paper is to present an example of a well-defined setup for measuring and trading mean-reversion that FX volatilities exhibit. We will start by introducing a statistical model for defining these properties more precisely, before turning to actual trading implementations.

Measuring FX vol mean-reversion

We now introduce a more precise statistical assessment of the mean-reversion properties of (financial) volatility time series. 1y ATM vols will be used as the benchmark case for our investigations, for technical reasons (i.e., interplay between Vega and other options Greeks) that will be clarified in the next section.

Exhibit 4. FX volatility spreads show significant mean reversion

p–values obtained when fitting an augmented Dickey–Fuller test (ADF) to 1Y ATM Volatilities (diagonal elements) and spreads of those volatilities (non-diagonal elements). Top (bottom) table is for G10 (EM) currencies. Daily data between 2004 and 2020.

	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD	45%	19%	1%	0%	2%	0%	7%	0%	0%
GBP-USD	19%	8%	0%	14%	0%	5%	5%	1%	7%
USD-JPY	1%	0%	30%	1%	1%	0%	0%	1%	6%
USD-CHF	0%	14%	1%	28%	4%	4%	8%	1%	2%
USD-CAD	2%	0%	1%	4%	27%	0%	1%	0%	0%
USD-NOK	0%	5%	0%	4%	0%	35%	5%	0%	0%
USD-SEK	7%	5%	0%	8%	1%	5%	41%	0%	0%
AUD-USD	0%	1%	1%	1%	0%	0%	0%	16%	1%
NZD-USD	0%	7%	6%	2%	0%	0%	0%	1%	36%

	USD-BRL	USD-MXN	USD-TRY	USD-ZAR	USD-PLN	USD-HUF	USD-SGD	USD-KRW
USD-BRL	1%	9%	1%	0%	19%	15%	0%	4%
USD-MXN	9%	1%	2%	1%	16%	19%	0%	3%
USD-TRY	1%	2%	0%	3%	18%	21%	2%	5%
USD-ZAR	0%	1%	3%	0%	21%	27%	0%	4%
USD-PLN	19%	16%	18%	21%	16%	0%	26%	0%
USD-HUF	15%	19%	21%	27%	0%	24%	22%	4%
USD-SGD	0%	0%	2%	0%	26%	22%	10%	1%
USD-KRW	4%	3%	5%	4%	0%	4%	1%	2%

Source: J.P. Morgan

The first concept we introduce is that of stationarity, i.e. whether an asset displays the property of oscillating around long-term reference levels (or not). For the purpose, we introduce an augmented Dickey-Fuller (ADF) test. Without entering into technicalities here, low levels of the corresponding statistics support the hypothesis that an asset satisfies mean-reversion properties. If we take a look at Exhibit 4 we can see that most FX volatility spreads in both G10 and EM pass the stationarity test (81% of cases for G10 and 61% for EM, at the 5% significance level). By using the same metric, only 29% of the vol levels would pass the same test, thus highlighting the advantage of playing with volatility spreads instead of volatility levels.

The second question we tackle is that of measuring the expected time interval over which we could expect a dislocation to correct. For the purpose, we rely on a simple autoregressive AR(1) model, already introduced in the context of vol strategies for linking mean-reversion properties on the underlying asset with an optimal delta-hedging strategy (*Optimal option delta-hedging – Uncovering the link between mean-reversion and options strategies across markets*, Ravagli et al, November 2018)

$$\sigma_t - \mu_p = \rho \left(\sigma_{t-\Delta t} - \mu_p\right) + \varepsilon_t$$

where σ_t is the value of the time series process at time t, μ_p is the mean of the time series process, ρ is the autoregressive coefficient and ε_t is the noise term at time t. The autoregressive coefficient, driving the serial correlation properties, can be traded for the more "hands-on" half-life one, which measures the typical time horizon over which a dislocation corrects back by half; more details on this are shared in Appendix II. Empirical analysis shows that vol spreads tend to have shorter half-lives than vol levels (Exhibit 5) and also have lower p-values in the ADF test (Exhibit 6), reinforcing the view that the former are more mean reverting than the latter and, thus, a better trading vehicle from this standpoint.

Exhibit 5. Half-lives of volatility levels and spreads

Half-lives (in business days) for 1Y ATM Volatilities (diagonal elements) and spreads (non-diagonal elements). Daily data between 2004 and 2020.

	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD	333	175	84	161	90	129	256	48	50
GBP-USD	175	267	83	179	78	134	173	80	85
USD-JPY	84	83	171	82	77	80	92	97	79
USD-CHF	161	179	82	213	111	174	268	80	66
USD-CAD	90	78	77	111	371	54	76	44	28
USD-NOK	129	134	80	174	54	352	98	24	27
USD-SEK	256	173	92	268	76	98	386	33	38
AUD-USD	48	80	97	80	44	24	33	266	63
NZD-USD	50	85	79	66	28	27	38	63	245

	USD-BRL	USD-MXN	USD-TRY	USD-ZAR	USD-PLN	USD-HUF	USD-SGD	USD-KRW
USD-BRL	94	69	85	38	117	118	44	57
USD-MXN	69	102	112	53	69	84	48	24
USD-TRY	85	112	111	101	284	258	121	131
USD-ZAR	38	53	101	131	189	166	61	69
USD-PLN	117	69	284	189	517	25	232	39
USD-HUF	118	84	258	166	25	429	181	47
USD-SGD	44	48	121	61	232	181	245	75
USD-KRW	57	24	131	69	39	47	75	145

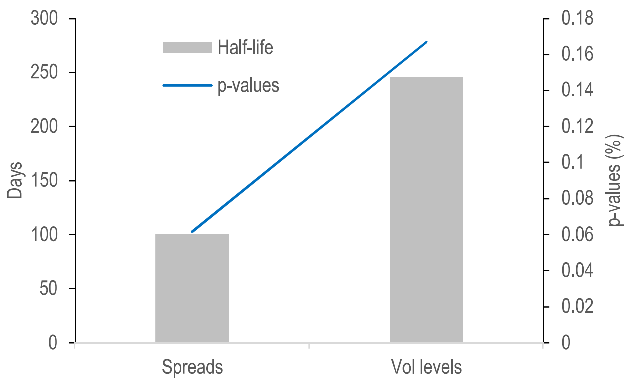
Source: J.P. Morgan

The combination of Exhibit 4 and 5 highlights practical trading opportunities, namely spreads that are not only statistically mean-reverting (low ADF p-value), but also have a short half-life. It would be of little use for trading purposes to have a very mean reverting volatility spread whose half-life spans multi-year periods.

Also, the observation that dislocations tend to correct over 2/3 month horizons, for the majority of cases considered, will guide us in the choice of sensible holding periods for each trade, as discussed extensively in the following.

Exhibit 6. Spreads are more mean revering than volatility levels

Half-lives (left) and p–values (right) obtained when fitting an AR (1) model and augmented Dickey–Fuller test (ADF) repectively to 1Y ATM volatility spreads in EM and G10. Time period considered between 2004 and 2019.

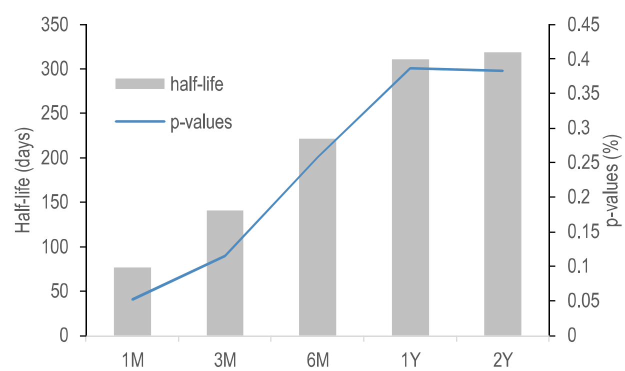


Source: J.P. Morgan

Results shown so far point to the observation that FX vols and spread display good mean reverting properties. Another very legitimate question could be, which segment of the vol curve is more mean reverting. A case study on EUR/USD (Exhibit 7) points to front-end of the curve as displaying stronger mean-reversion properties, and opens the way for investigating the potential (not covered in this piece) of vol curve mean reversion strategies. While short-dated vols display stronger mean-reversion, they would be associated with weaker Vega sensitivity, exposing the trades to other spurious factors (most notably, vol Carry); for this reason, to start with, we have opted to focusing on 1y vol spreads as our benchmark case (see later section).

Exhibit 7. Front end of volatility curve is more mean reverting

Half-lives (left) and p–values (right) for different maturities of the EUR/USD ATM volatility curve. Time period considered between 2004 and 2019



Source: J.P. Morgan

As an another example, similar conclusions can be reached when checking half-lives for spreads of G10 USD-riskies (Exhibit 8). For simplicity, and avoiding the sign fluctuations that some risk-reversals can undergo over time, we apply the test on absolute value of skews (and their differences). It is confirmed that, on average, spreads tend to be more mean reversing than riskies themselves, at least in terms of shorter half-lives.

Exhibit 8. Half-lives of absolute values of risk-reversals and spreads

Half-lives	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD	236.1	150.3	341.0	137.5	36.1	34.7	41.7	98.8	96.9
GBP-USD	150.3	231.5	252.5	95.6	116.8	121.4	128.7	124.5	121.0
USD-JPY	341.0	252.5	252.3	199.6	355.6	340.9	340.5	301.2	255.3
USD-CHF	137.5	95.6	199.6	53.2	95.4	137.6	137.1	149.6	145.9
USD-CAD	36.1	116.8	355.6	95.4	214.4	40.7	36.7	109.2	110.8
USD-NOK	34.7	121.4	340.9	137.6	40.7	246.1	27.1	96.4	95.0
USD-SEK	41.7	128.7	340.5	137.1	36.7	27.1	258.7	96.5	94.8
AUD-USD	98.8	124.5	301.2	149.6	109.2	96.4	96.5	220.5	20.9
NZD-USD	96.9	121.0	255.3	145.9	110.8	95.0	94.8	20.9	210.0

Source: J.P. Morgan

Having assessed that vol variables do mean-revert (and Exhibit 7, 8 recall us that the notion can be applied to different vol surface combinations), the next question is how to identify the timing of the trades. Dislocations within the AR(1) model framework can be measured via standard z-score analysis (Exhibit 9). At the time of writing, G10 opportunities regard the cheapness of CAD vs. CHF vols; in EM, Latam vols are cheap vs CEEMEA and Asian vols and so is PLN vs. HUF vol.

Exhibit 9. There are currently more opportunities in EM than G10

Current 2-year z-score of the 1Y ATM Volatilities and spreads for G10 and EM. For row X1 and column X2, the spread is defined as X1-X2.

	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD	-2.26	0.49	-0.40	-0.96	1.18	-0.45	0.09	0.32	-0.07
GBP-USD	-0.49	-1.99	-0.58	-0.78	-0.20	-0.69	-0.47	-0.48	-0.58
USD-JPY	0.40	0.58	-2.09	-0.93	1.29	-0.11	0.33	0.53	0.31
USD-CHF	0.96	0.78	0.93	-2.10	1.51	0.45	0.74	0.89	0.79
USD-CAD	-1.18	0.20	-1.29	-1.51	-2.26	-0.89	-0.64	-0.58	-1.07
USD-NOK	0.45	0.69	0.11	-0.45	0.89	-3.20	0.55	0.58	0.36
USD-SEK	-0.09	0.47	-0.33	-0.74	0.64	-0.55	-2.35	0.19	-0.10
AUD-USD	-0.32	0.48	-0.53	-0.89	0.58	-0.58	-0.19	-2.31	-0.91
NZD-USD	0.07	0.58	-0.31	-0.79	1.07	-0.36	0.10	0.91	-2.26

	USD-BRL	USD-MXN	USD-TRY	USD-ZAR	USD-PLN	USD-HUF	USD-SGD	USD-KRW	USD-CNH
USD-BRL	-2.07	0.68	0.54	-1.48	-1.24	-1.79	-1.85	-1.55	-1.62
USD-MXN	-0.68	-2.71	0.27	-1.74	-3.08	-3.05	-2.95	-3.27	-2.46
USD-TRY	-0.54	-0.27	-1.26	-1.13	-0.78	-0.95	-1.05	-0.91	-1.04
USD-ZAR	1.48	1.74	1.13	-1.10	0.46	-0.10	-0.51	-0.16	-0.44
USD-PLN	1.24	3.08	0.78	-0.46	-1.87	-1.72	-1.72	-1.42	-1.16
USD-HUF	1.79	3.05	0.95	0.10	1.72	-1.73	-1.17	-0.23	-0.64
USD-SGD	1.85	2.95	1.05	0.51	1.72	1.17	-1.89	0.96	0.33
USD-KRW	1.55	3.27	0.91	0.16	1.42	0.23	-0.96	-1.54	-0.40
USD-CNH	1.62	2.46	1.04	0.44	1.16	0.64	-0.33	0.40	-1.86

Source: J.P. Morgan

After a general review of empirical properties that support the notion of FX vol mean reversion, in the next section we move on to actual trading implementations.

Trading dislocations of FX vol spreads

We now want to build a trading system that benefits from the earlier empirical findings. In order to achieve that, we implement a back-testing strategy that trades when the difference between the current vol spread level and its historical average is high (in either direction). As discussed, we measure such dislocations via z-scores. We use an arbitrary (yet common) z-score threshold of 1.5 (both ways), and a look-back period of 2-years, which is a compromise between having sufficient data (long window) to measure dislocations and enough reactivity (short window). Such an under-fitted approach should deliver more stable results when running the system live. The z-score signal is monitored on a daily basis, meaning that if it breaches the threshold for a given day, a new trade is initiated that day regardless of what is in the book already.

PnLs are calculated in the limit of zero trading costs: a later section of the piece will assess a proxy impact of costs and will provide some guidance on the selection of the currencies whose combination into a pair-trade format could offer value from a liquidity/costs perspective. All backests refer to early 2007 / end of 2019 for being consistent in terms of data between vanillas and exotics.

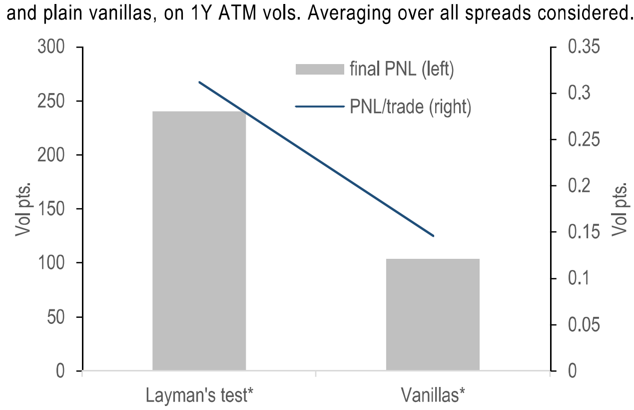
We start by implementing the strategy on 1yr vols. This offers a good tradeoff between higher Vega sensitivity on the farther end of the curve, allowing the trades to be pure bets on vol levels, and stronger mean-reversion on the front end (as seen in Exhibit 7). To start with, we consider a holding period of 1 month for all trades. The low holding period to time to maturity ratio should allow a clean Vega sensitivity for the trades before other Greeks (i.e., Gamma) kick in. We'll come back to the choice of an optimal holding period later, especially when reviewing the impact trading costs. Also, previous research (*Timing FX short vol strategies*, Ravagli, Duran-Vara, March 2019) suggested that it is not optimal to play for a correction of dislocations on the Gamma end of the curve, as such moves could be associated with spikes in realized vols. From that perspective, the Vega end of the curve is less impacted by these adverse moves than front-dated vols.

The next question regards the choice of the instruments for trading the mean reversion strategy described above. For simplicity, and for ensuring a good liquidity for both G10 and EM USD pairs, we start looking at plain vanillas. In order to track the performance of our strategy we introduce a benchmark we refer to as "Layman's test" (LMT). This test mimics the strategy described above, assuming that the change in rolling, fixed maturity ATM vol, was a tradable quantity. So for instance, if we look at Exhibit 9 we could say that, using that data, the Layman's test would bet on a higher USD/PLN 1Y vol and a lower USD/HUF 1Y vol – given the z-score of the spread. The final PnL for that trade would be the difference in the levels of the vols for both legs of the trade at the end of the 1 month holding period. This Layman's test is by no means a tradable strategy and is solely introduced as a proxy strategy, useful for assessing the potential of each mean reversion trade by isolating the Vega component that might otherwise be overshadowed when using real securities; for instance, with vanillas one would be exposed to other Greeks, with volatility swaps to realized vol, and with FVAs to the roll- down in the vol curve.

The spreads considered in the back-test include all the possible combinations for all the 9 volatilities in the USD/G10 crosses, as well as 6 USD/EM crosses (TRY, PLN, MXN, SGD, KRW, and BRL). The PnL is reported in vol points for both the Layman's test and the actual securities strategy. As a starting test, trading costs are not taken into account in the following back-tests. The inclusion of the average PnL per trade in the reported statistics might offer some guidance of how this might affect the final performance. We also stress that all PnLs as shown in this piece are not marked-to-market, i.e., we only consider PnL at time trades are unwound.

Exhibit 10. Vanilla strategy captures 43% of the Layman's test PnL

Total PnL (left) and PnL per trade (right) for the vol spread strategy, LMT and plain vanillas, on 1Y ATM vols. Averaging over all spreads considered.



*USD/SGD not included in this back-test for ensuring homogeneous data set

Source: J.P. Morgan

We first notice that our trading setup for capturing vol spreads mean-reversion performs reasonably well (Exhibit 10). LMT achieves almost a 95% success rate, that is, the proportion of the spreads that end up with a positive cumulative PnL, it also averages about 0.31 vol points per trade, and it scores about an average of 240 vol points per spread over the entire 12.5 years. However, when looking at the results on the plain vanillas, we see that the performance is more modest; the success rate (as defined above) drops to 70%, the average vol points per trade is

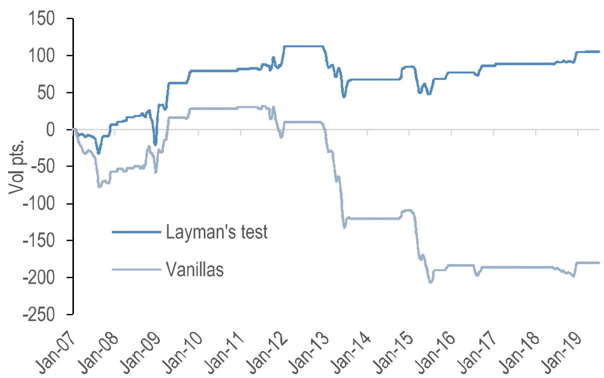
Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

0.145, and the average final PnL per spread is just 103.8 vols over the same horizon. That means we only capture 43% of the Layman's test benchmark PnL. Both the vanilla strategy and the Layman's test perform best on spreads involving MXN, BRL, NOK and SEK.

The daily difference in performance between the vanilla strategy and LMT can be to a large extent explained by the difference between realized and implied vol at that time. The R-square for such relationship reaches values of up to 80% for some spreads. For the case in Exhibit 11, the R-square is 40%. Another factor affecting the difference in PnL is the roll down in the curve, although its impact is more modest in terms of R-square.

Exhibit 11. Plain vanillas don't always match the Layman's test

PnL of the Layman's test and of the strategy using plain vanillas for the EUR/USD vs. USD/JPY 1Y ATM vols.

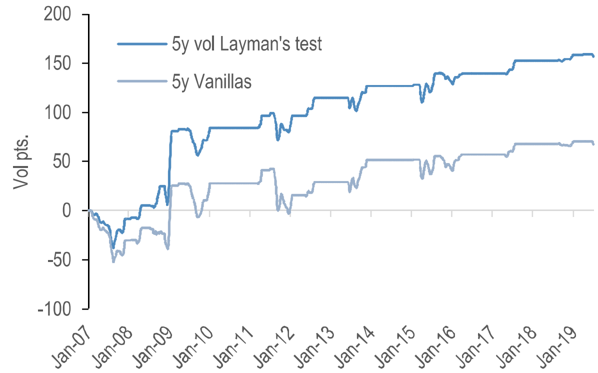


Source: J.P. Morgan

The fact that the difference between realized and implied vol explains the bulk of the difference in PnL (i.e., between actual strategy and LMT) means that if we implement the back-test using longer dated instruments, we could hope to obtain a better profile match between Layman's test and the vanilla strategy. This is because, the longer the maturity, the more vanillas become more of a pure Vega play, less sensitive to other factors. This is indeed the case when we compare Exhibit 12 to Exhibit 11. We can see there that by using 5Y vols instead of 1Y vols we would obtain a much closer profile match. Indeed the R-squared for the regression between the vanilla strategy returns and Layman's test returns are only 60% with 1Y vols but 82% with 5Y vols. However, given the reduced liquidity for such long-dated vols, making them unsuitable for systematic trading purposes, such comparisons are drawn for illustrative purposes only.

Exhibit 12. Longer dated vanillas behave similarly to LMT

PnL of the Layman's test and of the strategy using 5Y vanillas for the EUR/USD vs.USD/JPY 5Y vols.



Source: J.P. Morgan

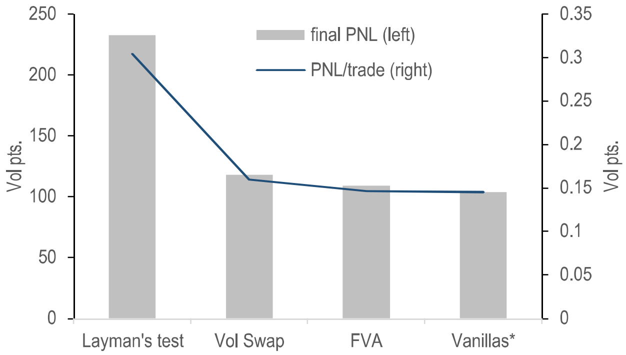
The scarce liquidity of 5Y vanillas naturally calls for the use of suitable exotic products for implementing the trades, with the goal of outperforming plain vanillas. The path sensitivity of the Greeks of plain vanillas could also play a role in determining the mismatch in PnLs referred to above (this could cause an asymmetric sensitivity PnL-wise to widening vs. tightening of the spreads). In the following, we will rely on 1Y Volatility Swaps (Vol Swaps) and 1Y x 1M Forward Volatility Agreements (FVAs). While Vol Swaps are naturally exposed to realized volatility, FVAs are pure Vega instruments, although they differ with respect to LMT given their direct exposure to the roll down of the curve. Both instruments resolve the issue of the Gamma/Vega path sensitivity associated with plain vanillas. For the back-test, the Vol Swaps are held for 1 month, and in the case of the FVAs they are held until expiry, which coincides with the 1 month holding period set for the strategy.

Indeed, in Exhibit 13 we see that the difference in performance between the strategy and the Layman's test is reduced when we use FVAs and Vol Swaps (albeit just modestly). For the 1Y vanillas we saw that we capture 43% of the LMT PNL across spreads. In the case of FVAs this is increased to 47%, and for Vol Swaps to 51%. The success rate also rises from 70% in the case of the 1Y vanillas to 78% in FVAs – however it remains 70% for Vol Swaps. FVAs perform best on spreads involving MXN, BRL, SEK and NOK. Vol Swaps perform best on spreads involving MXN, BRL, EUR and GBP.

Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

Exhibit 13. Exotics capture mean reversion better than vanillas

Final PnL (left) and PnL per trade (right) for the spread strategy. LMT, FVA strategy and Vol Swap strategy for the 1Y ATM vols and averaging over all spreads considered



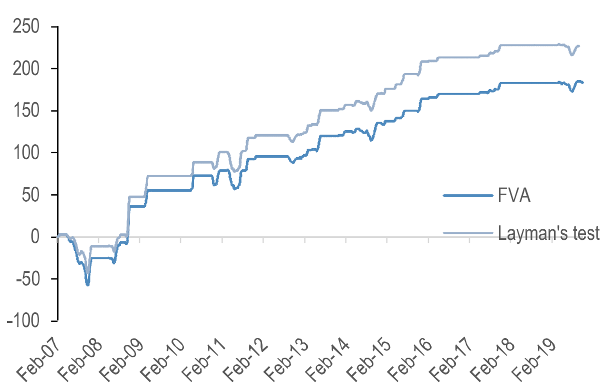
*USD/SGD not included in this back-test for ensuring homogeneous data set

Source: J.P. Morgan

We display two case studies, USD/CAD vs USD/NOK with FVAs (Exhibit 14) and GBP/USD vs USD/JPY with Vol Swaps (Exhibit 15), where actual PNLs match nicely LMT PNLs.

Exhibit 14. FVAs profile closely matches that of the Layman's test

PNL of Layman's test and of the strategy using FVAs for the USD/CAD vs. USD/NOK 1Y vols.

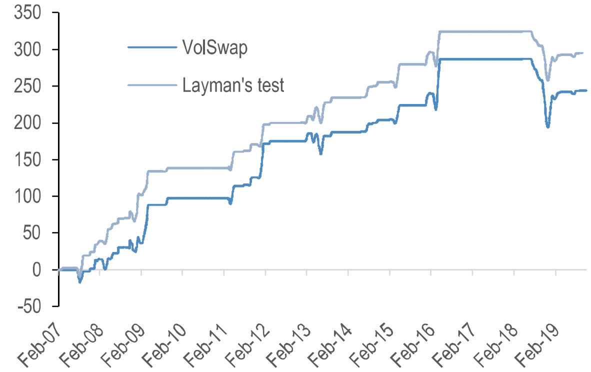


Source: J.P. Morgan

To summarize, we have defined three conditions for defining an appealing mean-reversion trade: an established mean-reversion property, a short half-life and a current dislocation. Current 2yr z-scores for 1y ATM vols and spreads are reported in Exhibit 9: at present, there are more dislocations in the EM than G10 spaces. Results of this section show that these properties can be successfully captured by trading liquid derivatives instruments.

Exhibit 15. Vol Swap profile also closely matches the LMT one

PNL of Layman's test and of the strategy using Vol Swaps for the GBP/USD vs. USD/JPY 1Y vols.



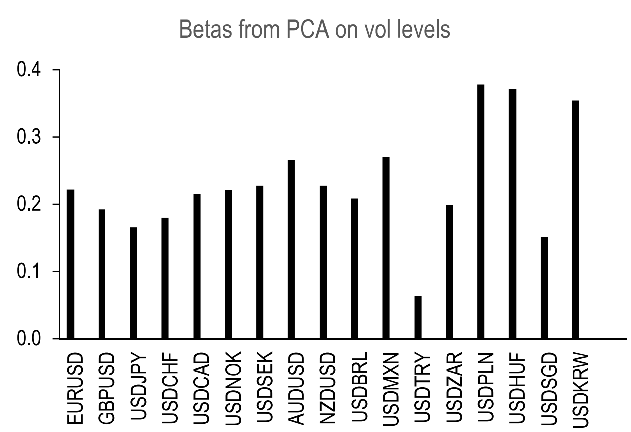
Source: J.P. Morgan

Checking the beta-neutrality constraint

The results presented in the previous section are promising, especially as the PnL generation appears steady over time and not limited to a specific period or market regime. However, the potential of the strategy (expressed in vol points per trade) appears too tight vs. a proxy estimate of trading costs, leaving investors little to take home (if anything). In the following, we will review a few options for improving the potential of the strategy.

We begin by testing the possibility of introducing a relative scaling between the long/short legs accounting for the different sensitivity of vols to market factors. Without entering into technicalities we rely on PCA for estimating vol sensitivities to market factors (a review of PCA as a statistical tool is provided in *Market-neutral carry strategies*, Tzotchev et al, October 2018).

Exhibit 16. In-sample PCA estimation of vol-betas

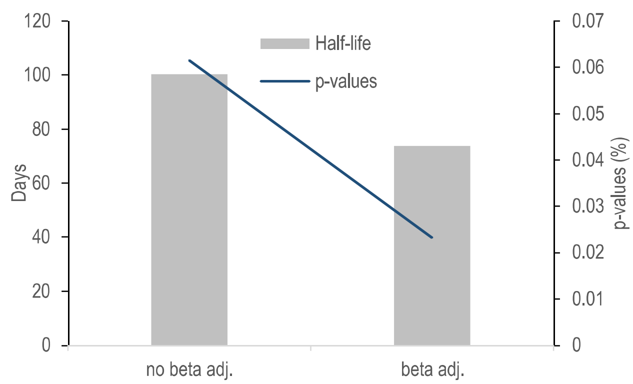


Source: J.P. Morgan

We compute betas to first principal component (i.e., the statistical factor explaining the highest variance amongst those extracted by the algo, all orthogonal to each other) from a basket of G10/EM USD-vols (Exhibit 16). We start by carrying out a "one-shot" estimation of these betas, using data from 2004 to November 2019. When used in backtests, these betas will contain an in-sample bias, issue we will assess at the end of this section. We can see that EM vols betas tend to be higher than for G10 vols, as the former move more than the latter during risk-off markets. However, for a couple of cases (TRY and SGD) the low betas to the "volatility market factor" can be explained by the higher relevance of idiosyncratic factors.

Exhibit 17. Beta adjusting significantly improves stationarity

AR(1) model half-lives (left) and ADF test p–values (right) applied repectively to beta and non-beta adjusted 1Y ATM volatility spreads in EM and G10. Time period considered between 2004 and 2019



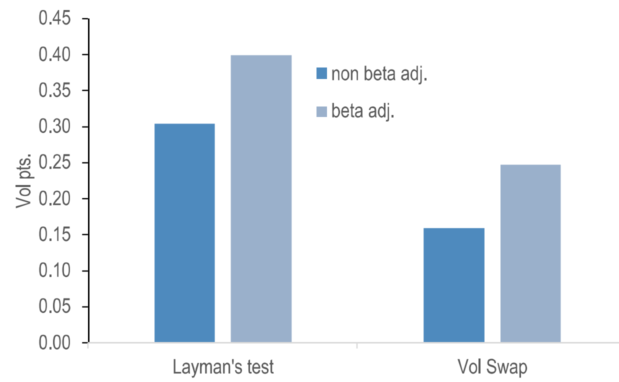
Source: J.P. Morgan

The beta adjustment then consists in scaling each volatility by the inverse of the coefficient obtained in this regression, before calculating the spread. This adjustment, further reducing the directionality element associated with a spread, helps isolating its idiosyncratic component, thus making it significantly more mean reverting (shorter half-lives and lower ADF test p-value) – as it can be seen in Exhibit 17. However, the rules adopted imply that volatilities whose market-beta is comparatively low will receive a higher weight in the spread: this might create asymmetries and instabilities when analyzing results.

We now check the added value of the beta-adjustment described before on the potential of the mean-reversion trades. We do so by relying on the instruments whose non-beta adjusted back-tests looked more promising – Vol Swaps. Exhibit 18 suggests that such added value is significant: the average PnL per trade for LMT is increased by 31%, while that of the Vol Swaps by 55% - narrowing the gap between LMT and Vol Swap strategy performance. For Vol Swaps, the 51% captured of the LMT potential for no beta-adjustment rises to 60% after beta-adjustment. The success rate on the cumulative PnL increases is increased for both LMT and Vol Swap strategies. Beta-adj. LMT performs best on MXN, PLN, GBP and KRW spreads. Beta adj. Vol Swaps perform best on MXN, CHF, PLN, EUR and GBP spreads.

Exhibit 18. Beta adjustment appears to increase mean-reversion potential

Average PNL per trade across spreads for beta adj. and non-beta adj. Layman's test and Vol Swap strategy for 1Y vols



Source: J.P. Morgan

Having already presented the results above in the most recent FX derivatives outlook piece (*Cheap won't get cheaper (probably)*, Sandilya et al, 26 November), given the apparent significant added value brought by the beta adjustment, we want to assess the impact of the in-sample bias mentioned earlier. The goal is also the one of applying a consistent approach towards parameters optimization throughout the piece - parameters/ rules are not optimized in sample other than in the betas above.

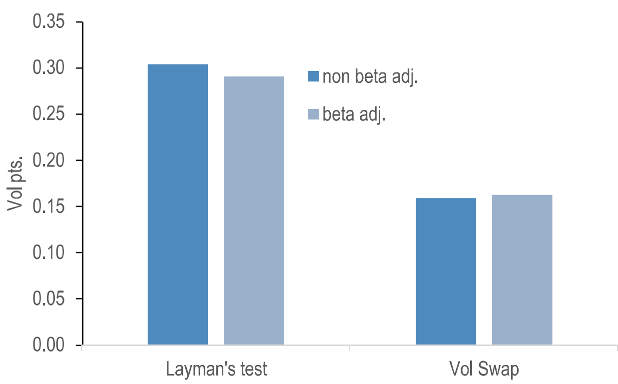
We repeat the PnL analyses as carried out earlier by removing any form of in-sample bias. For simplicity, and for allowing to potentially test the algo on a set of currencies whose availability of data is not homogeneous (some starting later than others, like CNH), rather than applying PCA we opt for a similar approach, namely computing rolling regressions of the vols on the J.P. Morgan VXY Global Index, on an expanding window. When tested over the same baskets and periods, the two calculations give very similar results on the final weights to be used in the spreads. For removing the in-sample bias, we now simply re-estimate the betas every 2 years and use such betas for computing z-scores, PnL etc. before a newer estimation of the betas is carried out.

Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

When removing the in-sample bias on the estimation of the betas, results are rather disappointing PnL-wise (Exhibit 19), with all the added value compared to the benchmark disappearing. The actual effect of the in-sample bias could be the one of artificially reducing the exposure to the high-beta vols that will undergo vol shocks at some point in the future. Also, the low-betas associated with some other vols imply that these beta-adjusted spreads are mostly exposed to the correction of just these vols rather than being proper RV plays. These instabilities don't make the current setup robust enough for trading implementations, and guide towards other solutions for improving the strategy's PnL profile. Still, we are confident that, after addressing such instabilities, there could be some potential with the beta-adjustment approach as pursued above. For clarity, in the following all PnL calculations will refer to the not beta-adjusted case.

Exhibit 19. When removing the in-sample bias, beta adjustment no longer adds value towards PnL generation

Final PNL for beta adj. and non-beta adj. Layman's test and Vol Swap strategy



Source: J.P. Morgan

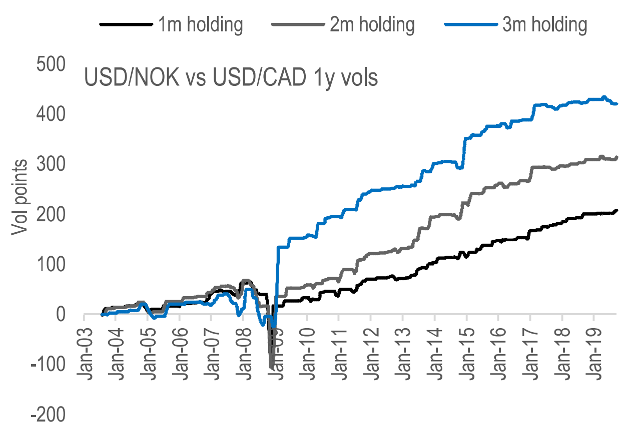
Testing longer holding periods

A second attempt, described in this section, for improving average returns deals with extending the holding period of the trades from the 1m benchmark case considered so far. It is also quite natural to introduce here a treatment on the expected impact on the strategy from trading costs, for guiding us in the selection of an optimal holding period.

We start by showing (Exhibit 20) a case study where, for a given spread (USD/CAD vs USD/NOK), we apply the LMT strategy by simply increasing the holding period, with no additional risk controls. By moving from 1m to 2m and 3m, the rise in cumulative PnL is steady, but not linear, in that the 3m strategy is less than three times as large as the 1m. This observation calls for a more careful assessment of the risk-management properties of these vol-spread strategies, which we do here.

Exhibit 20. Longer holding periods might lead to higher PnLs

LMT PNL for USD/NOK vs. USD/CAD 1Y vols for different holding periods.



Source: J.P. Morgan

Let's consider holding each position T (business) days. The PnL in vol points per trade (as presented earlier) for zero costs is:

$$\frac{{PnL_{ZC}}^T}{V_0} = \Delta\sigma^T$$

The quantity $\Delta\sigma^T$ can depend on the holding period T. If we assume that costs are entirely set at inception and are constant over time, the final PnL including costs for the single trade will be:

$${PnL_C}^T = V_0(\Delta\sigma^T - Vol_{TC})$$

And in vol points:

$${PnL_C}^T/V_0 = (\Delta\sigma^T - Vol_{TC})$$

As we trade daily, this means that at any point in time the open portfolio will be composed of T positions entered over consecutive days. Let's assume all new trades are associated with the same Vega at inception ${V_0}^T$

$$Cum - {PnL_C}^T = {V_0}^T \sum_{i=1}^{T} ({\Delta\sigma_i}^T - Vol_{TC})$$

By taking expectation values:

$$E(Cum - {PnL_C}^T) = T{V_0}^T(E({\Delta\sigma_i}^T) - Vol_{TC})$$

By imposing a control on the Vega of the portfolio, Vega notionals of each trades are adjusted in order to ensure a constant Vega budget on the portfolio. If one further neglects the sensitivity of the Vega of each trade to the time to maturity, the scaling above will be approximately linear with the holding period

$$T{V_0}^T \cong Vega_{TGT} \rightarrow {V_0}^T = Vega_{TGT}/T$$

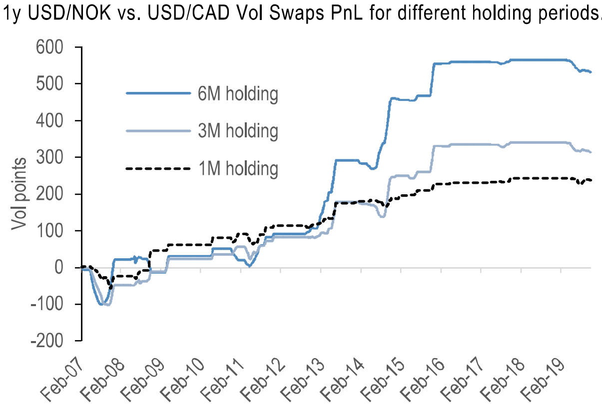
Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

The (rather technical, or tedious, depending on the point of view) introduction above is necessary for an understanding on the impact of costs. Longer holding periods are typically associated with higher vol points per trade, but Vega notionals of each trades would have to be scaled down. In the limit of zero costs, the optimal T for maximizing total PnL would be the one for which the quantity $\Delta\sigma^T/T$ reaches its maximum. Results of Exhibit 20 (and of following charts) would favor choices of short T, as the cumulative PnL rises less than linearly for increasing T; from the chart, there is roughly a factor 2 in rise of cumulative PnL when moving from 1m to 3m holding periods (factor 3 rise). This can be interpreted via the time-decaying features of the potential of the trades after a certain target is reached.

However, the formula above teaches us that the crucial aspect is to increase T in a way that vol points per trade rise at least above Vol_{TC}, which typically recommends choosing longer holding periods than the 1m considered so far. The formula above can provide with an actual semi-analytical solution for optimizing the choice of T once the scaling $\Delta\sigma^T/T$ and Vol_{TC} are known empirically.

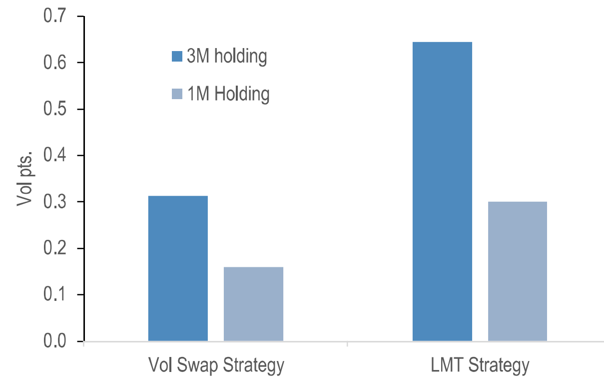
We repeat the earlier case study by considering the actual vol swap strategy with 1m, 3m and 6m holding periods (Exhibit 21). It is confirmed that the potential of the zero cost strategy rises with the holding period, in terms of vols points per trade, although less than linearly. In order to find an optimal choice for the holding period, one will need to find a tradeoff between management of costs and reduction of spurious Greeks sensitivities other than Vega.

Exhibit 21. Longer holding periods lead to higher PnLs
1y USD/NOK vs. USD/CAD Vol Swaps PnL for different holding periods.



By averaging, as done before, over all possible spreads, we can see that the average PnL per trade roughly doubles for both LMT and actual vol swap strategy when increasing the holding period from 1m to 3m (Exhibit 22). With these results in mind, we converge to 1y Expiry / 3m holding period as our benchmark implementation for the strategy.

Exhibit 22. Summary of results on actual Vol swap PnLs by increasing holding period



Source: J.P. Morgan

From the previous chart, we can see that even for longer holding periods, the strategy captures roughly 50% of the potential set by the proxy LMT strategy, trading on vol levels, which leaves the door open for finding other ways for reducing such gap.

Exhibit 23. Matrix of average PnL per trade (vol pts), per pair (G10)

	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD		0.06	-0.28	0.55	0.00	0.10	-0.03	-0.05	0.16
GBP-USD	0.06		0.13	-0.11	0.36	0.51	0.25	0.37	0.49
USD-JPY	-0.28	0.13		-0.14	0.60	-0.11	-0.30	0.04	0.26
USD-CHF	0.55	-0.11	-0.14		-0.01	0.12	0.10	0.06	0.12
USD-CAD	0.00	0.36	0.60	-0.01		0.35	-0.03	0.07	0.65
USD-NOK	0.10	0.51	-0.11	0.12	0.35		0.05	0.74	0.69
USD-SEK	-0.03	0.25	-0.30	0.10	-0.03	0.05		0.21	0.30
AUD-USD	-0.05	0.37	0.04	0.06	0.07	0.74	0.21		-0.17
NZD-USD	0.16	0.49	0.26	0.12	0.65	0.69	0.30	-0.17	

Source: J.P. Morgan

Exhibit 24. Matrix of average PnL per trade (vol pts), per pair (EM)

	USD-BRL	USD-MXN	USD-TRY	USD-PLN	USD-SGD	USD-KRW
USD-BRL		0.20	1.44	0.15	0.82	0.37
USD-MXN	0.20		0.56	0.12	0.92	-1.07
USD-TRY	1.44	0.56		-1.63	0.00	-1.00
USD-PLN	0.15	0.12	-1.63		-0.55	1.21
USD-SGD	0.82	0.92	0.00	-0.55		-0.58
USD-KRW	0.37	-1.07	-1.00	1.21	-0.58	

Source: J.P. Morgan

We further breakdown the average PnL per trade, with the settings above, across all G10 (Exhibit 23) and EM spreads (Exhibit 24). In the G10 space, best spreads include EUR vs. CHF, GBP and JPY vs. CAD and most of NZD spreads; in EM, TRY vs. BRL, SGD vs. Latam and

KRW vs. PLN look best historically. We stress that, while G10/EM spreads are not reported in the tables, they are still counted in the averages as in Exhibit 22 for instance.

We are now in the position of assessing more carefully a tentative impact of trading costs on the strategy, as it is well known that costs tend to eat up a good portion of potential of RV trades (especially when playing RV with options). In recent research pieces (see for instance *Late-cycle currency investing with FX options*, Jankovic and Sandilya, Marc 2019), we have typically assumed trading costs (bid/ask spreads) of roughly 0.2 (0.5) vol points per trade for USD/G10 (USD/EM).

When considering pair trades that involve two vols belonging to the same trading book, it is reasonable to assume that when trading the spread, one pays costs on the leg associated with wider bid/ask while trading the other at mid (it is "choiced" in jargon). Trading books are typically broken into currencies belonging to the same region, for instance EUR, GBP and CHF are typically in one book, Scandies and Antipodeans in two separate ones; same rules apply to EM (CEEMEA, Latam, Asian ex-JPY). For vols belonging to different books, one would be expected to pay spreads on the two legs separately. When unwinding the trades, depending on liquidity conditions, one might be required to pay again the spread or not. Illiquid vols or crosses typically are associated with higher spreads at inception but also with a higher likelihood of unwinding these trades at mid, given the higher propensity of trading desks to reduce exposure to such risks. However, the difficulty of defining a systematic rule for deciding if/when a spread can be traded at favorable conditions recommends caution as far as the assessment of the impact of costs is concerned, as done below.

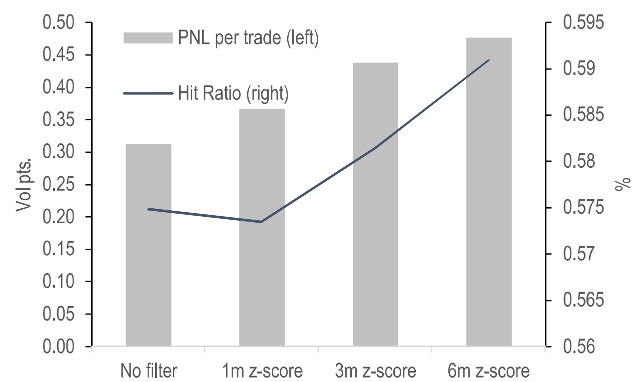
A practical rule of thumb suggests then to choose regional currencies when playing spread trades, in order to minimize impact of costs. Assuming to pay costs both at inception and when unwinding, a proxy estimate of the total impact of entering/unwinding the trades for these spreads can be of 0.2 and 0.5 vols, for G10 and EM respectively. This sets to 0.5 vol points per trade (zero cost) a conservative lower bound for the strategy to be viable. The average PnL per trade of around 0.3 vols (for zero costs), as seen in Exhibit 22, naturally calls for further research for enhancing the potential of the strategy.

Introducing further market intelligence

The third solution for improving performance measures regards the inclusion of additional filters beyond the dislocations one. Such an approach was pursued in earlier research pieces (see for instance *Testing systematic predictability of FX option market signals for exchange rate moves*, Jankovic, April 2017). Rather than going through a brute-force optimization procedure, we select here a number of indicators that can add market intelligence to the dislocation measures. As for the trading settings, the results of the previous section let us naturally converge to the 1y vol swaps held 3m.

The first filter we consider monitors dislocation z-scores over shorter periods than the 2yrs one described earlier, and recommends not trading when the short-dated z-score gives the same trading signal as the 2yr one. Spikes in the short-dated z-scores are indicative of stressed market conditions. Intuitively, while we see 2yrs dislocations as opportunities to capture, we want avoid doing so when such dislocations are widening in the near term.

Exhibit 25. Performance of the short-term z-score indicators (measured over different periods) as extra filter

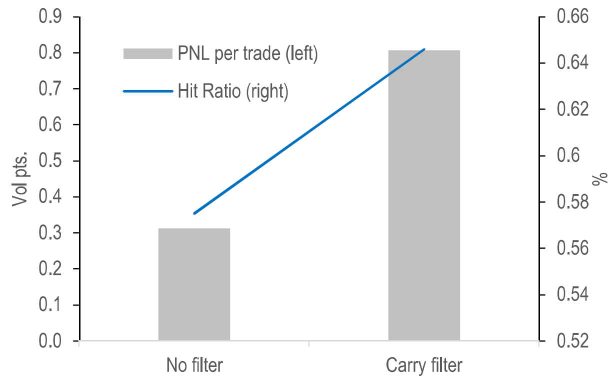


Source: J.P. Morgan

The added value of this filter when combined with the dislocation one is clear (Exhibit 25), with a modest added value also in terms of hit ratios. In the chart, we consider estimating the extra filter from 1m to 6m periods, with the latter giving better results. This result is fully aligned with an earlier piece (*Timing FX short vol strategies*, Ravagli, Duran-Vara, March 2019) where we found that it is not optimal to sell vol at a time when vol premia are widening, especially as such moves are typically associated with spikes in realized vol that damage the strategy.

A second filter we consider takes into account a short-dated estimate of vol carry: we trade only when the recommended L/S spread by the dislocation analysis is associated with a positive vol carry. Here vol carry is simply estimated via the comparison of at-the-money 1-year implied volatility with the 3m realized volatility (matching our choice for the holding period). This filter also successfully allows improving PnL per trade and hit ratios (Exhibit 26), more substantially than for the short-dated z-score indicator above.

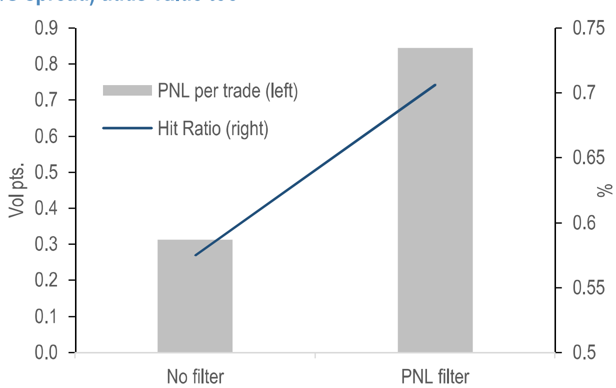
Exhibit 26. Short-term estimate of carry also improves results



Source: J.P. Morgan

The third filter we consider focuses on the long term potential of buying or selling a certain vol spread. At any point in time, we simply check whether the L/S position as recommended by the dislocation signal would be consistent with a positive long-term cumulative PnL as of the time of trading. Again, this filter proves successful in terms of improving the average PnL (in vol points, over all possible pairs) per trade (Exhibit 27), 2.7 as high as for the benchmark case (i.e., just dislocation signal), although as before at the expense of reducing the total number of trades (in this case, by roughly 50%). Also, this is the indicator associated with the highest hit ratio across the four considered, when coupled with the dislocation signal.

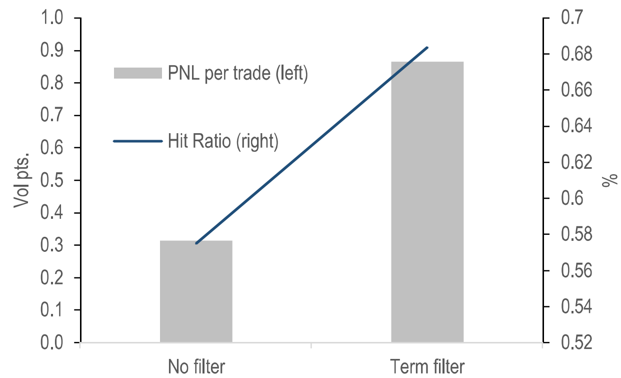
Exhibit 27. Long-term estimate of carry (structural profitability of L/S spread) adds value too



Source: J.P. Morgan

We then consider looking at the shape of the vol curves, by trading only when a L/S spread is associated with a positive roll-down. The latter is estimated for the spread as the difference in current estimates of 3m roll-downs (in vol points) consistent with the current vol curves. PnL per trade is the highest across the four market indicators coupled with the mean reversion signals, and hit ratio is also improved vs. the benchmark (Exhibit 28).

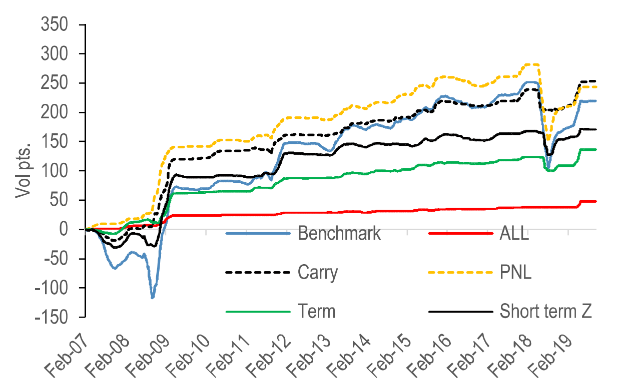
Exhibit 28. Vol curves roll-down is another indicator worth monitoring



Source: J.P. Morgan

The four market-based indicators described all possess value in improving the PnL per trade; in principle one could consider a broader set of additional filters, amongst which it would appealing to have one which selects *ex ante* the most mean-reverting spreads based on a statistical property (i.e., reduction of half-life, ADF tests etc.).

Exhibit 29. Time series of average PnL over all pairs: no filters vs I, II, III, IV filters



Source: J.P. Morgan

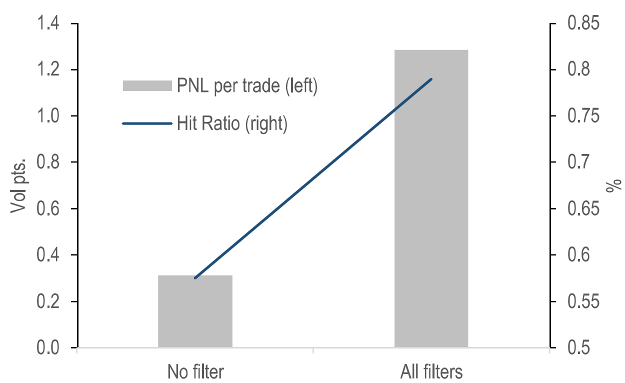
The chart above (Exhibit 29) investigates the time series behavior of the portfolio allocating to all possible vol spreads (within the G10/EM space considered), by considering just dislocation signals (benchmark case) and adding each of the four filters above. We notice that the PnL generation by the benchmark strategy is steady over time, by incurring in two major drawdown episodes.

Lorenzo Ravagli, PhD
(44-20) 7742-7947
lorenzo.ravagli@jpmorgan.com

Using the additional market indicators allows reducing the sharp drawdowns experienced by the passive strategy in Q3/Q4 2008 and late 2018. At the same time, imposing additional constraints reduces the total number of trades, so that cumulative PnL drops despite a higher PnL per trade. In practice, the combination of multiple filters would hinge on a viable trade-off between reduction of risk and capability of capturing a minimum target PnL per year. Most naturally, such a compromise could be struck via a suitable optimization framework, but the topic will not be covered in the current piece, as for computation speed purposes we have not reported performance measures that depend on mark-to-market PnL.

From this perspective, the case study where the four extra filters are combined (i.e., one trades when all conditions are satisfied) is shown in the chart (Exhibit 29). Keeping in mind the caveat above, performance measures when using the four filters (Exhibit 30) would greatly improve, with hit ratio rising by 30% to around 80%, and average PnL per trade quadrupling at around 1.3 vols per trade. As an extra comment, while a proper treatment of the impact of trading costs would deserve additional investigation, the use of these market filters should allow sitting comfortably above the ~0.5 vol points threshold required for the strategy to be profitable after costs.

Exhibit 30. Aggregation of the filters – show average PnL per trade, different combinations

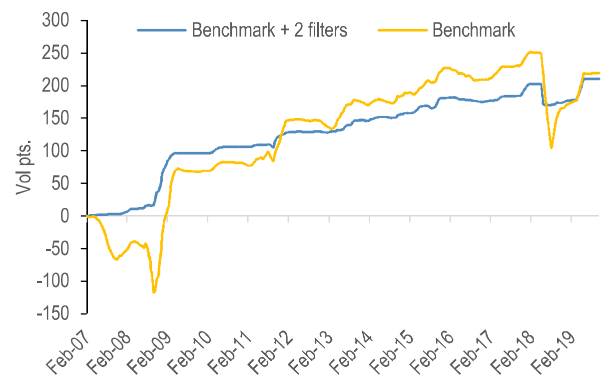


Source: J.P. Morgan

In the following, for illustrative purposes, we allow ourselves some freedom in selecting two extra filters (out of the four considered) and defining a reference strategy. By looking at Exhibit 29, we can see that by relying on short-term Carry and long-term estimate of PnL, one should obtain solid performance measures and more active trading than by using all four filters at once.

The time series of the average PnL generated by the reference strategy above is reported in Exhibit 31. The comparison with the case where just mean-reversion signals are used as an input shows a much smoother evolution of the PnL, with a sharp reduction of drawdowns.

Exhibit 31. Time-series of average PnL by using short-term Carry and long-term PnL as two extra filters



Source: J.P. Morgan

The matrices of average PnLs generated by G10 and EM vol spreads (Exhibit 32) point to some significant improvements compared to the earlier cases (Exhibits 23 and 24) where the extra filters were not taken into account. Some of the best G10 spreads include USD/NOK vs. AUD/USD and NZD/USD, USD/CAD vs. USD/JPY, EUR/USD vs. USD/SEK. In EM, the vast majority of spreads delivers solid results (for instance, USD/BRL vs. USD/MXN, USD/KRW vs. USD/SGD, USD/TRY vs. USD/PLN amongst regional peers). The average PnL per trade with this setup amounts to 1.07 vol points, well above the 0.5 vol points proxy impact of costs.

Exhibit 32. Average PnL per trade for G10 and EM spreads by using the two extra filters

	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD		0.77	-0.28	0.98	0.68	0.40	1.49	0.55	0.90
GBP-USD	0.77		-0.92	-0.24	0.60	0.81	0.92	1.18	1.08
USD-JPY	-0.28	-0.92		0.30	1.54	0.27	-1.45	-1.25	0.28
USD-CHF	0.98	-0.24	0.30		0.40	0.63	1.02	0.26	0.70
USD-CAD	0.68	0.60	1.54	0.40		0.60	0.11	0.30	0.95
USD-NOK	0.40	0.81	0.27	0.63	0.60		-0.06	3.10	1.49
USD-SEK	1.49	0.92	-1.45	1.02	0.11	-0.06		0.83	0.92
AUD-USD	0.55	1.18	-1.25	0.26	0.30	3.10	0.83		0.57
NZD-USD	0.90	1.08	0.28	0.70	0.95	1.49	0.92	0.57	

	USD-BRL	USD-MXN	USD-TRY	USD-PLN	USD-SGD	USD-KRW
USD-BRL		1.45	-0.15	0.34	1.19	0.49
USD-MXN	1.45		3.18	1.39	2.44	1.27
USD-TRY	-0.15	3.18		0.66	1.54	0.86
USD-PLN	0.34	1.39	0.66		1.14	1.01
USD-SGD	1.19	2.44	1.54	1.14		2.03
USD-KRW	0.49	1.27	0.86	1.01	2.03	

Source: J.P. Morgan

Similarly, the vast majority of hit ratios for G10 and EM vol spreads (Exhibit 35) are well above 50% (74% on average), with some of them very close to 100% (EUR/USD vs. USD/SEK, AUD/USD vs. USD/NOK and NZD/USD, USD/SGD vs. USD/KRW).

Exhibit 33. Hit ratios for G10 and EM spreads by using the two extra filters

	EUR-USD	GBP-USD	USD-JPY	USD-CHF	USD-CAD	USD-NOK	USD-SEK	AUD-USD	NZD-USD
EUR-USD		76%	49%	86%	67%	82%	96%	64%	80%
GBP-USD	76%		24%	51%	62%	72%	77%	68%	81%
USD-JPY	49%	24%		56%	66%	65%	32%	43%	55%
USD-CHF	86%	51%	56%		63%	75%	93%	20%	76%
USD-CAD	67%	62%	66%	63%		55%	57%	50%	83%
USD-NOK	82%	72%	65%	75%	55%		58%	95%	85%
USD-SEK	96%	77%	32%	93%	57%	58%		92%	80%
AUD-USD	64%	68%	43%	20%	50%	95%	92%		98%
NZD-USD	80%	81%	55%	76%	83%	85%	80%	98%	

	USD-BRL	USD-MXN	USD-TRY	USD-PLN	USD-SGD	USD-KRW
USD-BRL		87%	62%	46%	75%	60%
USD-MXN	87%		88%	64%	83%	80%
USD-TRY	62%	88%		73%	82%	82%
USD-PLN	46%	64%	73%		72%	64%
USD-SGD	75%	83%	82%	72%		99%
USD-KRW	60%	80%	82%	64%	99%	

Source: J.P. Morgan

To conclude, the setup where mean-reversion indicators are supplemented by two additional estimates of short-term and long-term Carry of the vol spreads appears to deliver very encouraging results.

Concluding remarks

In this piece we have introduced a novel methodology for tackling FX vol spread mean reversion, whose potential appears significant. We first provide some justification, based on market data, why the pair trade implementation would offer an edge for capturing the general notion that volatility variables are mean reverting.

We then propose a trading framework where signals are based on a dislocation measure. The dislocation potential would deliver good results only in the limit of zero costs, but might suffer when actual costs are taken into account. The inclusion of additional market-based filters proves beneficial for improving markedly the results of the backtests, across the wide number of pairs considered (around 105). Also, we display how holding periods of 3m or longer would be sufficient for the potential of the trades to unfold and to capture a positive PnL after costs.

The topic sees potential for widening the scope of the analysis into future research pieces. Relaxing calculation constraints would allow taking into account MtM PnL performance, properly assessing volatility and drawdown properties for the strategies and relying on optimization algorithms for select the best portfolios or filters to rely on. A coverage of a wider spectrum of currency pairs (especially in the EM space) and of non USD-crosses, and a more precise assessment of time varying trading costs could also shed some light on the selection of the most promising candidates to be used in the pair trading format. A dynamic assessment of the strength of mean-reversion could also suggest which candidate pairs exhibit the most persistent features at any point in time.

On the implementation side, we have somehow arbitrarily relied on 1y vols for isolating Vega sensitivity and playing pure vol plays, but it would be worth investigating shorter-dated options too; while spurious effects from other Greeks than Vega would necessarily become more relevant, at the same time, the empirical observation that the front-end of the curve is more mean-reverting could increase the potential of the trades.

Appendix I – Garch volatility models

Financial assets volatility variables, although not directly observable (unlike the corresponding implied volatilities directly related to option prices), are known to satisfy a few empirical properties. Amongst them, volatility is a time-varying variable that tends to cluster (vol can be high for certain periods and low for other periods), which is referred to as heteroscedasticity property. Volatility does not diverge to infinity, and normally varies within a well-defined range, which implies that vol often satisfies the requirements of being a stationary variable, and that mean-reversion patterns are evident. The evolution from low-vol to high-vol markets (and vice-versa) is typically a smooth process, i.e. volatility jumps are not very frequent.

A general framework introduced by Engle[1] and Bollerslev[2] for describing the earlier statistical properties of assets volatilities is that of GARCH models. If r_t is the return process, and $a_t = r_t - \mu_t$ is the mean-corrected return, a_t follows a GARCH*(m,s)* process if

$$a_t = \sigma_t \epsilon_t$$

$$\sigma_t{}^2 = \alpha_0 + \sum_{i=1}^{m} \alpha_i \, a_{t-i}{}^2 + \sum_{j=1}^{s} \beta_j \, \sigma_{t-j}{}^2$$

where ϵ_t is a iid sequence of random variables with mean 0 and variance 1. The framework can be seen as an application of autoregressive-moving average (ARMA)

[1] "Autoregressive conditional heteroscedasticity with estimates of the variance of United Kingdom inflations", R.F. Engle, Econometrica 50, 1982

[2] "Generalized autoregressive conditional heteroscedasticity", T. Bollerslev, Journal of Econometrics 31, 1986

models to the squared series $a_t{}^2$. The GARCH framework naturally accounts for fat tails (positive excess kurtosis) enjoyed by financial times series. The unconditional (long-term) mean of the volatility (squared series) process is

$$E(a_t{}^2) = \frac{\alpha_0}{1 - \sum_{i=1}^{\max(m,s)} (\alpha_i + \beta_i)}$$

The time-varying process σ_t is expected to oscillate around its long-term unconditional average, depending on the interplay of α_i, β_i parameters. The latter dynamics supports the notion of volatility mean-reversion within the GARCH framework.

Appendix II – Autoregressive models applied to implied volatilities

Autoregressive models can be seen as a simpler, limit case of the broader GARCH family presented above. For the hands-on application of measuring half-lives as introduced in the piece, time-series analysis can be directly applied to implied volatilities (levels).

In the AR(1) framework:

$$\sigma_t - \mu_p = \rho \; \left(\sigma_{t-\Delta t} - \mu_p\right) + \varepsilon_t$$

where σ_t is the implied volatility at time t, and $\rho > 0$ is the auto-regressive coefficient, the half-life, expressed in Δt time units, can be obtained as

$$half - life = -\ln(2)/\ln(\rho)$$

If Δt =1 business day, the formula above will express the half-life in business days. While $|\rho|$<1 are is required for the model to be weakly stationary, when applied to level (and not returns) time series, constraints are $0 < \rho < 1$. In the limit of $\rho \rightarrow 1$, half-life rises indefinitely, whereas for $\rho \rightarrow 0$ it drops to 0. Strong linear correlation properties call ibn this context for lower ρ and shorter half-lives.

Disclosures

Analyst Certification: The research analyst(s) denoted by an "AC" on the cover of this report certifies (or, where multiple research analysts are primarily responsible for this report, the research analyst denoted by an "AC" on the cover or within the document individually certifies, with respect to each security or issuer that the research analyst covers in this research) that: (1) all of the views expressed in this report accurately reflect the research analyst's personal views about any and all of the subject securities or issuers; and (2) no part of any of the research analyst's compensation was, is, or will be directly or indirectly related to the specific recommendations or views expressed by the research analyst(s) in this report. For all Korea-based research analysts listed on the front cover, if applicable, they also certify, as per KOFIA requirements, that their analysis was made in good faith and that the views reflect their own opinion, without undue influence or intervention.

All authors named within this report are research analysts unless otherwise specified. In Europe, Sector Specialists may be shown on this report as contacts but are not authors of the report or part of the Research Department.

Important Disclosures

This report is a product of the research department's Global Quantitative and Derivatives Strategy group. Views expressed may differ from the views of the research analysts covering stocks or sectors mentioned in this report. Structured securities, options, futures and other derivatives are complex instruments, may involve a high degree of risk, and may be appropriate investments only for sophisticated investors who are capable of understanding and assuming the risks involved. Because of the importance of tax considerations to many option transactions, the investor considering options should consult with his/her tax advisor as to how taxes affect the outcome of contemplated option transactions.

Company-Specific Disclosures: Important disclosures, including price charts and credit opinion history tables, are available for compendium reports and all J.P. Morgan–covered companies by visiting https://www.jpmm.com/research/disclosures, calling 1-800-477-0406, or e-mailing research.disclosure.inquiries@jpmorgan.com with your request. J.P. Morgan's Strategy, Technical, and Quantitative Research teams may screen companies not covered by J.P. Morgan. For important disclosures for these companies, please call 1-800-477-0406 or e-mail research.disclosure.inquiries@jpmorgan.com.

Explanation of Equity Research Ratings, Designations and Analyst(s) Coverage Universe:
J.P. Morgan uses the following rating system: Overweight [Over the next six to twelve months, we expect this stock will outperform the average total return of the stocks in the analyst's (or the analyst's team's) coverage universe.] Neutral [Over the next six to twelve months, we expect this stock will perform in line with the average total return of the stocks in the analyst's (or the analyst's team's) coverage universe.] Underweight [Over the next six to twelve months, we expect this stock will underperform the average total return of the stocks in the analyst's (or the analyst's team's) coverage universe.] Not Rated (NR): J.P. Morgan has removed the rating and, if applicable, the price target, for this stock because of either a lack of a sufficient fundamental basis or for legal, regulatory or policy reasons. The previous rating and, if applicable, the price target, no longer should be relied upon. An NR designation is not a recommendation or a rating. In our Asia (ex-Australia and ex-India) and U.K. small- and mid-cap equity research, each stock's expected total return is compared to the expected total return of a benchmark country market index, not to those analysts' coverage universe. If it does not appear in the Important Disclosures section of this report, the certifying analyst's coverage universe can be found on J.P. Morgan's research website, www.jpmorganmarkets.com.

J.P. Morgan Equity Research Ratings Distribution, as of January 02, 2020

	Overweight (buy)	**Neutral** (hold)	**Underweight** (sell)
J.P. Morgan Global Equity Research Coverage	45%	41%	15%
IB clients*	51%	47%	39%
JPMS Equity Research Coverage	43%	42%	14%
IB clients*	75%	64%	56%

*Percentage of subject companies within each of the "buy," "hold" and "sell" categories for which J.P. Morgan has provided investment banking services within the previous 12 months. Please note that the percentages might not add to 100% because of rounding.
For purposes only of FINRA ratings distribution rules, our Overweight rating falls into a buy rating category; our Neutral rating falls into a hold rating category; and our Underweight rating falls into a sell rating category. Please note that stocks with an NR designation are not included in the table above. This information is current as of the end of the most recent calendar quarter.

Equity Valuation and Risks: For valuation methodology and risks associated with covered companies or price targets for covered companies, please see the most recent company-specific research report at http://www.jpmorganmarkets.com, contact the primary analyst or your J.P. Morgan representative, or email research.disclosure.inquiries@jpmorgan.com. For material information about the proprietary models used, please see the Summary of Financials in company-specific research reports and the Company Tearsheets, which are available to download on the company pages of our client website, http://www.jpmorganmarkets.com. This report also sets out within it the material underlying assumptions used.

Analysts' Compensation: The research analysts responsible for the preparation of this report receive compensation based upon various factors, including the quality and accuracy of research, client feedback, competitive factors, and overall firm revenues.

Registration of non-US Analysts: Unless otherwise noted, the non-US analysts listed on the front of this report are employees of non-US affiliates of J.P. Morgan Securities LLC, may not be registered as research analysts under FINRA rules, may not be associated persons of J.P. Morgan Securities LLC, and may not be subject to FINRA Rule 2241 or 2242 restrictions on communications with covered companies, public appearances, and trading securities held by a research analyst account.

Analysts' Compensation: The research analysts responsible for the preparation of this report receive compensation based upon various factors, including the quality and accuracy of research, client feedback, competitive factors, and overall firm revenues.

Other Disclosures

J.P. Morgan is a marketing name for investment banking businesses of JPMorgan Chase & Co. and its subsidiaries and affiliates worldwide.

All research reports made available to clients are simultaneously available on our client website, J.P. Morgan Markets. Not all research content is redistributed, e-mailed or made available to third-party aggregators. For all research reports available on a particular stock, please contact your sales representative.

Any data discrepancies in this report could be the result of different calculations and/or adjustments.

Any long form nomenclature for references to China; Hong Kong; Taiwan; and Macau within this research report are Mainland China; Hong Kong SAR, China; Taiwan, China; Macau SAR, China.

Options and Futures related research: If the information contained herein regards options or futures related research, such information is available only to persons who have received the proper options or futures risk disclosure documents. Please contact your J.P. Morgan Representative or visit https://www.theocc.com/components/docs/riskstoc.pdf for a copy of the Option Clearing Corporation's Characteristics and Risks of Standardized Options or http://www.finra.org/sites/default/files/Security_Futures_Risk_Disclosure_Statement_2018.pdf for a copy of the Security Futures Risk Disclosure Statement.

Principal Trading: J.P. Morgan trades or may trade as principal in the derivatives or the debt securities (or related derivatives) that are the subject of this report.

Private Bank Clients: Where you are receiving research as a client of the private banking businesses offered by JPMorgan Chase & Co. and its subsidiaries ("J.P. Morgan Private Bank"), research is provided to you by J.P. Morgan Private Bank and not by any other division of J.P. Morgan, including but not limited to the J.P. Morgan corporate and investment bank and its research division.

Legal entity responsible for the production of research: The legal entity identified below the name of the Reg AC research analyst who authored this report is the legal entity responsible for the production of this research. Where multiple Reg AC research analysts authored this report with different legal entities identified below their names, these legal entities are jointly responsible for the production of this research.

Legal Entities Disclosures
U.S.: JPMS is a member of NYSE, FINRA, SIPC and the NFA. JPMorgan Chase Bank, N.A. is a member of FDIC. **Canada**: J.P. Morgan Securities Canada Inc. is a registered investment dealer, regulated by the Investment Industry Regulatory Organization of Canada and the Ontario Securities Commission and is the participating member on Canadian exchanges. **U.K.**: JPMorgan Chase N.A., London Branch, is authorised by the Prudential Regulation Authority and is subject to regulation by the Financial Conduct Authority and to limited regulation by the Prudential Regulation Authority. Details about the extent of our regulation by the Prudential Regulation Authority are available from J.P. Morgan on request. J.P. Morgan Securities plc (JPMS plc) is a member of the London Stock Exchange and is authorised by the Prudential Regulation Authority and regulated by the Financial Conduct Authority and the Prudential Regulation Authority. Registered in England & Wales No. 2711006. Registered Office 25 Bank Street, London, E14 5JP. **Germany**: This material is distributed in Germany by J.P. Morgan Securities plc, Frankfurt Branch which is regulated by the Bundesanstalt für Finanzdienstleistungsaufsich and also by J.P. Morgan AG (JPM AG) which is a member of the Frankfurt stock exchange and is regulated by the Federal Financial Supervisory Authority (BaFin), JPM AG is a company incorporated in the Federal Republic of Germany with registered office at Taunustor 1, 60310 Frankfurt am Main, the Federal Republic of Germany. **South Africa**: J.P. Morgan Equities South Africa Proprietary Limited is a member of the Johannesburg Securities Exchange and is regulated by the Financial Services Board. **Hong Kong**: J.P. Morgan Securities (Asia Pacific) Limited (CE number AAJ321) is regulated by the Hong Kong Monetary Authority and the Securities and Futures Commission in Hong Kong and/or J.P. Morgan Broking (Hong Kong) Limited (CE number AAB027) is regulated by the Securities and Futures Commission in Hong Kong. JP Morgan Chase Bank, N.A., Hong Kong is organized under the laws of U.S.A. with limited liability. **Korea**: This material is issued and distributed in Korea by or through J.P. Morgan Securities (Far East) Limited, Seoul Branch, which is a member of the Korea Exchange(KRX) and is regulated by the Financial Services Commission (FSC) and the Financial Supervisory Service (FSS). **Australia**: J.P. Morgan Securities Australia Limited (JPMSAL) (ABN 61 003 245 234/AFS Licence No: 238066) is regulated by ASIC and is a Market, Clearing and Settlement Participant of ASX Limited and CHI-X. **Taiwan**: J.P. Morgan Securities (Taiwan) Limited is a participant of the Taiwan Stock Exchange (company-type) and regulated by the Taiwan Securities and Futures Bureau. **India:** J.P. Morgan India Private Limited (Corporate Identity Number - U67120MH1992FTC068724), having its registered office at J.P. Morgan Tower, Off. C.S.T. Road, Kalina, Santacruz - East, Mumbai – 400098, is registered with Securities and Exchange Board of India (SEBI) as a 'Research Analyst' having

registration number INH000001873. J.P. Morgan India Private Limited is also registered with SEBI as a member of the National Stock Exchange of India Limited and the Bombay Stock Exchange Limited (SEBI Registration Number – INZ000239730) and as a Merchant Banker (SEBI Registration Number - MB/INM000002970). Telephone: 91-22-6157 3000, Facsimile: 91-22-6157 3990 and Website: www.jpmipl.com. For non local research reports, this material is not distributed in India by J.P. Morgan India Private Limited. **Thailand**: This material is issued and distributed in Thailand by JPMorgan Securities (Thailand) Ltd., which is a member of the Stock Exchange of Thailand and is regulated by the Ministry of Finance and the Securities and Exchange Commission and its registered address is 3rd Floor, 20 North Sathorn Road, Silom, Bangrak, Bangkok 10500. **Indonesia**: PT J.P. Morgan Sekuritas Indonesia is a member of the Indonesia Stock Exchange and is regulated by the OJK a.k.a. BAPEPAM LK. **Philippines**: J.P. Morgan Securities Philippines Inc. is a Trading Participant of the Philippine Stock Exchange and a member of the Securities Clearing Corporation of the Philippines and the Securities Investor Protection Fund. It is regulated by the Securities and Exchange Commission. **Brazil**: Banco J.P. Morgan S.A. is regulated by the Comissao de Valores Mobiliarios (CVM) and by the Central Bank of Brazil. **Mexico**: J.P. Morgan Casa de Bolsa, S.A. de C.V., J.P. Morgan Grupo Financiero is a member of the Mexican Stock Exchange and authorized to act as a broker dealer by the National Banking and Securities Exchange Commission. **Singapore:** This material is issued and distributed in Singapore by or through J.P. Morgan Securities Singapore Private Limited (JPMSS) [MCI (P) 058/04/2019 and Co. Reg. No.: 199405335R], which is a member of the Singapore Exchange Securities Trading Limited and/or JPMorgan Chase Bank, N.A., Singapore branch (JPMCB Singapore) [MCI (P) 070/09/2019], both of which are regulated by the Monetary Authority of Singapore. This material is issued and distributed in Singapore only to accredited investors, expert investors and institutional investors, as defined in Section 4A of the Securities and Futures Act, Cap. 289 (SFA). This material is not intended to be issued or distributed to any retail investors or any other investors that do not fall into the classes of "accredited investors," "expert investors" or "institutional investors," as defined under Section 4A of the SFA. Recipients of this document are to contact JPMSS or JPMCB Singapore in respect of any matters arising from, or in connection with, the document. **Japan**: JPMorgan Securities Japan Co., Ltd. and JPMorgan Chase Bank, N.A., Tokyo Branch are regulated by the Financial Services Agency in Japan. **Malaysia**: This material is issued and distributed in Malaysia by JPMorgan Securities (Malaysia) Sdn Bhd (18146-X) which is a Participating Organization of Bursa Malaysia Berhad and a holder of Capital Markets Services License issued by the Securities Commission in Malaysia. **Pakistan**: J. P. Morgan Pakistan Broking (Pvt.) Ltd is a member of the Karachi Stock Exchange and regulated by the Securities and Exchange Commission of Pakistan. **Dubai**: JPMorgan Chase Bank, N.A., Dubai Branch is regulated by the Dubai Financial Services Authority (DFSA) and its registered address is Dubai International Financial Centre - Building 3, Level 7, PO Box 506551, Dubai, UAE. **Russia:** CB J.P. Morgan Bank International LLC is regulated by the Central Bank of Russia. **Argentina:** JPMorgan Chase Bank Sucursal Buenos Aires is regulated by Banco Central de la República Argentina ("BCRA"- Central Bank of Argentina) and Comisión Nacional de Valores ("CNV"- Argentinian Securities Commission")

Country and Region Specific Disclosures
U.K. and European Economic Area (EEA): Unless specified to the contrary, issued and approved for distribution in the U.K. and the EEA by JPMS plc. Investment research issued by JPMS plc has been prepared in accordance with JPMS plc's policies for managing conflicts of interest arising as a result of publication and distribution of investment research. Many European regulators require a firm to establish, implement and maintain such a policy. Further information about J.P. Morgan's conflict of interest policy and a description of the effective internal organisations and administrative arrangements set up for the prevention and avoidance of conflicts of interest is set out at the following link https://www.jpmorgan.com/jpmpdf/1320742677360.pdf. This report has been issued in the U.K. only to persons of a kind described in Article 19 (5), 38, 47 and 49 of the Financial Services and Markets Act 2000 (Financial Promotion) Order 2005 (all such persons being referred to as "relevant persons"). This document must not be acted on or relied on by persons who are not relevant persons. Any investment or investment activity to which this document relates is only available to relevant persons and will be engaged in only with relevant persons. In other EEA countries, the report has been issued to persons regarded as professional investors (or equivalent) in their home jurisdiction. **Australia:** This material is issued and distributed by JPMSAL in Australia to "wholesale clients" only. This material does not take into account the specific investment objectives, financial situation or particular needs of the recipient. The recipient of this material must not distribute it to any third party or outside Australia without the prior written consent of JPMSAL. For the purposes of this paragraph the term "wholesale client" has the meaning given in section 761G of the Corporations Act 2001. J.P. Morgan's research coverage universe spans listed securities across the ASX All Ordinaries index, securities listed on offshore markets, unlisted issuers and investment products which Research management deem to be relevant to the investor base from time to time. J.P. Morgan seeks to cover companies of relevance to the domestic and international investor base across all GIC sectors, as well as across a range of market capitalisation sizes. **Germany:** This material is distributed in Germany by J.P. Morgan Securities plc, Frankfurt Branch which is regulated by the Bundesanstalt für Finanzdienstleistungsaufsicht. **Korea:** This report may have been edited or contributed to from time to time by affiliates of J.P. Morgan Securities (Far East) Limited, Seoul Branch. **Singapore:** As at the date of this report, JPMSS is a designated market maker for certain structured warrants listed on the Singapore Exchange where the underlying securities may be the securities discussed in this report. Arising from its role as designated market maker for such structured warrants, JPMSS may conduct hedging activities in respect of such underlying securities and hold or have an interest in such underlying securities as a result. The updated list of structured warrants for which JPMSS acts as designated market maker may be found on the website of the Singapore Exchange Limited: http://www.sgx.com. In addition, JPMSS and/or its affiliates may also have an interest or holding in any of the securities discussed in this report – please see the Important Disclosures section above. For securities where the holding is 1% or greater, the holding may be found in the Important Disclosures section above. For all other securities mentioned in this report, JPMSS and/or its affiliates may have a holding of less than 1% in such securities and may trade them in ways different from those discussed in this report. Employees of JPMSS and/or its affiliates not involved in the preparation of this report may have investments in the securities (or derivatives of such securities) mentioned in this report and may trade them in ways different from those discussed in this report. **Taiwan**: Research relating to equity securities is issued and distributed in Taiwan by J.P. Morgan Securities (Taiwan) Limited, subject to the license scope and the applicable laws and the regulations in Taiwan. According to Paragraph 2, Article 7-1 of Operational Regulations Governing Securities Firms Recommending Trades in Securities to Customers (as amended or supplemented) and/or other applicable laws or regulations, please note that the recipient of this material is not permitted to engage in any activities in connection with the material which may give rise to conflicts of interests, unless otherwise disclosed in the "Important Disclosures" in this material. **India:** For private circulation only, not for sale. **Pakistan:** For private circulation only, not for sale. **New Zealand:** This material is issued and distributed by JPMSAL in New Zealand only to "wholesale clients" (as defined in the Financial Advisers Act 2008). The recipient of this material must not distribute it to any third party or outside New Zealand without the prior written consent of JPMSAL. **Canada:** This report is distributed in Canada by or on behalf of J.P.Morgan Securities Canada Inc. The information contained herein is not, and under no circumstances is to be construed as an offer to sell securities described herein, or solicitation of an offer to buy securities described herein, in Canada or any province or territory thereof. The information contained herein is under no circumstances to be construed as investment advice in any province or territory of Canada and is not tailored to the needs of the recipient. **Dubai:** This

report has been distributed to persons regarded as professional clients or market counterparties as defined under the DFSA rules. **Brazil:** Ombudsman J.P. Morgan: 0800-7700847 / ouvidoria.jp.morgan@jpmorgan.com.

General: Additional information is available upon request. Information has been obtained from sources believed to be reliable but JPMorgan Chase & Co. or its affiliates and/or subsidiaries (collectively J.P. Morgan) do not warrant its completeness or accuracy except with respect to any disclosures relative to JPMS and/or its affiliates and the analyst's involvement with the issuer that is the subject of the research. All pricing is indicative as of the close of market for the securities discussed, unless otherwise stated. Opinions and estimates constitute our judgment as of the date of this material and are subject to change without notice. Past performance is not indicative of future results. This material is not intended as an offer or solicitation for the purchase or sale of any financial instrument. The opinions and recommendations herein do not take into account individual client circumstances, objectives, or needs and are not intended as recommendations of particular securities, financial instruments or strategies to particular clients. The recipient of this report must make its own independent decisions regarding any securities or financial instruments mentioned herein. JPMS distributes in the U.S. research published by non-U.S. affiliates and accepts responsibility for its contents. Periodic updates may be provided on companies/industries based on company specific developments or announcements, market conditions or any other publicly available information. Clients should contact analysts and execute transactions through a J.P. Morgan subsidiary or affiliate in their home jurisdiction unless governing law permits otherwise.

"Other Disclosures" last revised January 01, 2020.