Wherefore art thou, Libor?

Recruiting deep learning to improve short-term forecasts

- Market-based forecasts for daily changes in Libor have become increasingly unreliable at just as the fixings became harder to interpret …
- … and more generally we find a relatively weak relationship between Libor panel bank submissions and both their CDS spreads and CP/CD transactions from DTCC data
- A non-parametric analysis suggests Libor has primarily followed an autoregressive process over the past ten years …
- … from which we can use neutral networks to obtain forecasts for daily changes that perform reasonably well
- These model forecasts provide somewhat different information than do 1-day FRAs; stacking the two results in clear improvement in forecasting both typical moves and outliers in cross-validation and quarantine
- This combination of market- and model-based forecasts offers valuable additional information regarding short-term changes in Libor, and should be seen as a complement to more fundamental analysis

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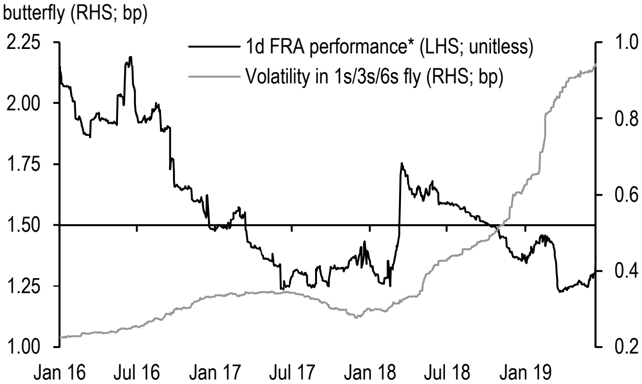
Recruiting deep learning to forecast short-term changes in Libor

Amidst all the talk of benchmark reform and the process to move the markets away from their reliance on Libor, it can be easy to forget that we are likely stuck with this index for at least the next 2-3 years. Indeed, it is highly unlikely that the vast majority of loan, securities, and derivative exposures will be shifted to SOFR until much closer to the 2021 deadline. **There is, in fact, a significant risk that the market will rely primarily on fallbacks to achieve the final stages of the transition, which suggests significant migration will be back-loaded**. Though Libor may not be long for this world when viewed with a sufficiently long-term perspective, those with more quarterly concerns will be contending with this index for some time to come. And that makes a thorough understanding of its behavior still a critical component of market participation in any range of asset classes.

Achieving this goal has been complicated by recent events. Simply as an empirical matter, forecasting changes in Libor—even over very short horizons—has been increasingly difficult. This is clear in declining information content of 1-day FRAs, which imply daily changes that are increasingly at odds with actual changes, as measured by the signal-to-noise (S/N) ratio[1] (**Exhibit 1**). We observe complementary evidence of odd behavior in the 1s/3s/6s fixing butterfly, which has become much more volatile in recent months than in all the years prior.

Exhibit 1: Libor has become increasingly difficult to forecast over short horizons, as evidenced by low S/N in 1-day FRAs and rising volatility in the 1s/3s/6s fly

1-year rolling signal-to-noise ratio* for 1-day FRA forecast changes in Libor (LHS; unitless) and 1-year trailing volatility of daily changes in the 1s/3s/6s Libor fixing butterfly (RHS; bp)

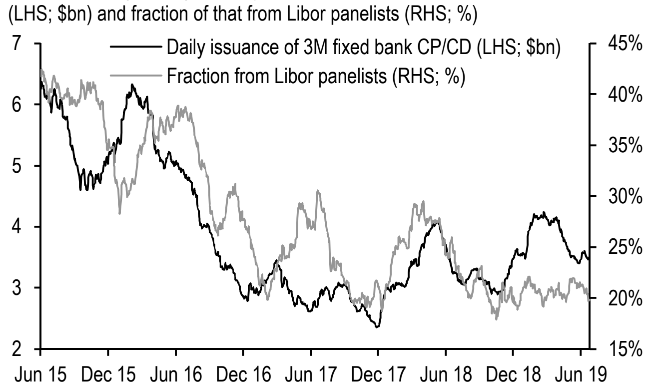


* S/N ratio is defined as MSE of market-implied daily changes (*ex-ante* 1-day FRA versus that day's fixing) versus actual, divided by the variance of daily changes.

Source: J.P. Morgan

Exhibit 2: Banks have relied less and less on unsecured wholesale funding, particularly Libor panelists …

3-month moving average of daily issuance in 3-month fixed-rate bank CP and CDs (LHS; $bn) and fraction of that from Libor panelists (RHS; %)



Source: J.P. Morgan, DTCC

That Libor is difficult to forecast is certainly nothing new. As has been discussed at length, the shift in regulatory environment severely disincentivized short-term wholesale funding among banks in general. This was particularly acute in the

[1] We define signal-to-noise as the inverse of MSE/VAR where MSE is the average squared error of *ex-ante* market expectations (i.e., 1-day FRA versus Libor fixing the day prior) and actual daily change in the fixing.

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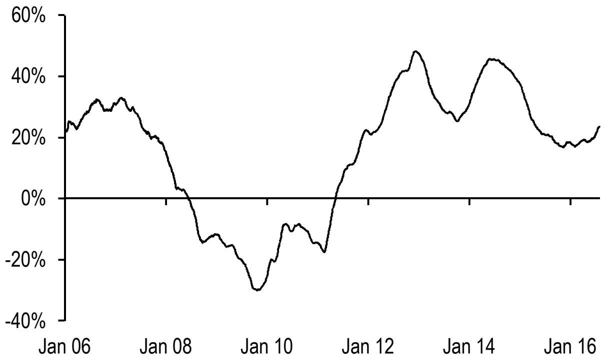
interbank market, but also CP/CD markets. Money market fund reform exacerbated the situation by pushing most prime MMF assets to government funds. Though we have seen notable recovery in prime fund AUM—up 45% since last June and 18% YTD—daily activity in bank CP/CD markets remains a small faction of what prevailed in 2015—not to mention pre-crisis (**Exhibit 2**). **Further, among that more limited set of deals, only 20% are issued by Libor panel banks, down from 40% prior to the implementation of MMF reform**.

In a world with few prints in Libor-esque instruments, yet a need to quote every day, it stands to reason that panelists would increasingly rely more on so-called market-based indicators. This led the ICE to streamline and standardize the submission process by introducing a waterfall; quarterly volume reports suggest more than 75% of 3-month Libor quotes are level 3, or market data-based. **It should also be noted that the increase in 1s/3s/6s butterfly volatility came around the same time as the phase-in period for this waterfall methodology** (Exhibit 1).

Exhibit 3: The rank order of Libor submissions is not particularly well correlated with the CDS spreads of panelists, and has in fact been negative at times …

Rolling 1-year average correlation between the rank order of Libor submissions and the same for 1-year CDS spreads for panel banks; %



Source: J.P. Morgan, ICE, BBA

Exhibit 4: … and these submissions appear to be drawn from a clearly different distribution than actual unsecured bank transactions captured in DTCC data

Distributional statistics for demeaned Libor quotes and 3-month fixed-rate CP/CD issuance from panel banks, aggregated by year; bp for stddev, unitless for skew and K-S test

	Stddev		Skew		K-S Test	
Year	Libor	DTCC	Libor	DTCC	Stat	Prob
2015	3.2	6.9	0.6	13.5	0.09	5.0E-06
2016	10.2	4.9	6.1	0.6	0.15	4.9E-18
2017	7.5	13.6	3.3	2.3	0.11	1.1E-09
2018	6.5	9.7	-0.7	-2.4	0.08	5.8E-05
2019	7.2	5.5	-0.4	1.4	0.18	2.5E-08

Note: K-S is the Kolmogorov-Smirnov test, a nonparametric test of similarly between samples drawn from two distributions, with the probability that they are as indicated—and it is exceedingly small.

Source: J.P. Morgan, ICE, BBA, DTCC

Given this backdrop, perhaps a more fundamental question we can ask is: to what extent do Libor submissions reflect other short-term credit market transactions. We address this question two ways. First, BBA conveniently provided the identity of each quote in addition to its level in public data, which can be sourced at a granular level for a period of roughly ten years through mid-2016. **We then consider whether these submissions reflect credit markets, specifically comparing the rank order of Libor quotes from all panel banks to 1-year CDS par spreads for the same**. In others, we are trying to determine to what extent the highest Libor quote comes from the panelist with the widest 1-year CDS spread, the second highest quote is associated with the second widest spread, and so on—effectively a Pearson correlation coefficient between Libor quotes and credit spreads. **The results suggest this correlation has rarely been high; in fact, it has been negative for extended periods of time (Exhibit 3)**. This indicates that there have been consistently significant—even sometimes glaring—differences between credit spreads as inferred from Libor submission and CDS markets.

For more recent periods, we have the benefit of data including all CP/CD issuance cleared through DTCC, which in principle should be more tightly tied to Libor quotes than CDS spreads. Unfortunately, new complications emerge. Public

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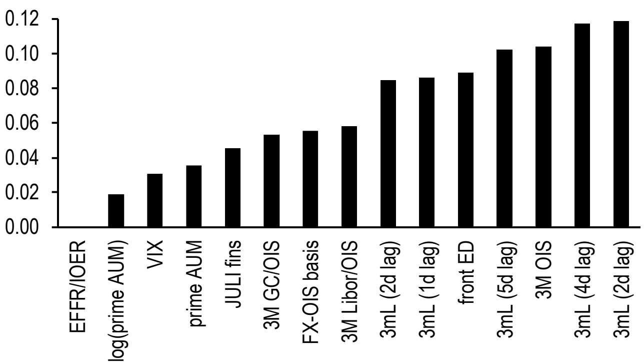
submission data has been anonymized since mid-2016, and as discussed above CP/CD issuance covers only a small subset of the panel on any given day. We can, however, ask a more general question: **are Libor quotes drawn from the same distribution as CP/CD transactions over some period of time?** This allows us to stack days and cover most, if not the whole, panel in DTCC data, and to compare anonymous quotes to identified transactions. The results suggest clear differences in the moments of these distributions, and clearly fail a statistical test of consistency (**Exhibit 4**). In other words, **over reasonably long periods of time, actual transactions in CP/CD markets do not appear to be statistically similar to Libor submissions**.

Given this setup, there is clearly a need to incorporate all available market information in a more flexible, non-parametric, and adaptive way. Towards this end, in this piece we consider the potential utility of taking a more modern statistical approach to modeling Libor. In particular, we leverage machine learning techniques that have found success in generating trading signals for Treasuries[2] as well as dynamic asset allocation[3].

Exhibit 5: A long-run feature importance analysis suggests daily moves in 3mL are mostly driven by recent changes, making our efforts effectively a modified/non-linear autoregressive model

Feature importance statistics for various drivers in a GBM model for daily changes in 3-month Libor, trained on data from 2010-19; unitless

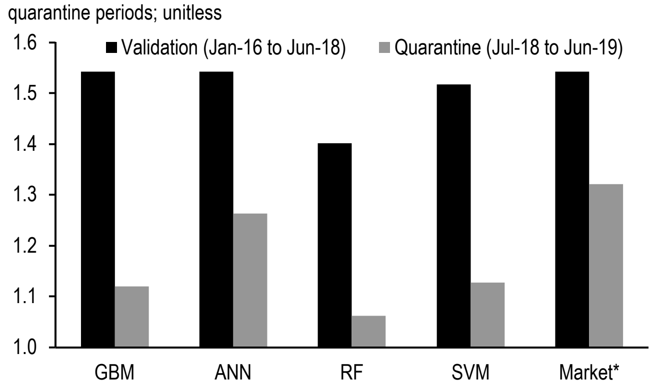


Note: Libor, 3M OIS, FX-OIS, front Eurodollar, and GC/OIS are daily changes; EFFR/IOER, VIX, log(prime fund AUM) and JULI financials spread are weekly changes, prime fund AUM is monthly change; 3M FRA/OIS is level. All features are *ex-ante* predictors of daily changes in 3M Libor fixings. Feature importance measured via a GBM model trained on 2010-19 data.

Source: J.P. Morgan, DataQuery, iMoneyNet, Reuters

Exhibit 6: Artificial neutral networks produce the best out of sample performance when forecasting daily moves in Libor for out of sample testing in both the validation and quarantine periods

Ratio of variance to model MSE for various techniques in the validation and quarantine periods; unitless



Source: J.P. Morgan, DataQuery, iMoneyNet, Reuters

For this work, we are specifically interested in forecasting daily changes in 3-month Libor. We approach this problem by following what has become a familiar set of steps. First, we decide by what metric to judge the success of our model, preferably a scalar measure of performance versus a benchmark. Second, we decide a list of features using a combination of statistical tests and domain knowledge. Third, we separate the data into a cross-validation period (including test/train splits) for hyperparameter optimization and a quarantined set for truly out of sample testing.

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[2] For details, see *Do Androids dream of electric bonds?*, M. Salem et al., 11/22/17; *TradeRunner*, M. Salem et al., 8/16/18; *#SquadGoals*, M. Salem et al., 9/21/18; *Where's the beef?* J. Younger et al., 1/25/19

[3] See *Can Machine Learning help with Tactical Asset Allocation*, M. Inkinen et al., 11/1/18; *Automating asset allocation in fixed income*, J. Younger et al., 4/5/19.

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Finally, we consider a range of models, including stacked regressors, before settling on a final calibration.

In contrast to the classifiers we have relied on in the previous work cited above, this model will be a regression. Therefore rather than seeking to maximize hit rate or Sharpe ratio, **we want to achieve the highest possible signal-to-noise, defined as the inverse of the ratio of the mean squared error (MSE) of model forecasts versus actual changes, and the variance of daily changes** in the testing period. This can be thought of as a generalization of the R-squared statistic we typically seek to maximize in linear regressions, but in this case we are minimizing MSE—equivalent to maximizing the signal—relative to variance—a measure of noise.

We can then move on to identifying the feature set. We consider a wide range of possible features, including recent changes in Libor itself (to account for autocorrelation in the fixings), moves in risk-free rates (3-month OIS), money market flows (prime and government MMF AUM, WAMs, etc.), other market-based transactions that are included in the ICE waterfall (e.g., FX forwards, GC repo), transactional data from DTCC, and credit markets (e.g., CDX.IG spreads, high-grade financials).

We slimmed down this broader list to a subset of features which appear to have more statistical relevance and sufficient history—feature importance statistics[4] which are presented in **Exhibit 5**. Particularly notable, from our perspective, is the prevalence of recent changes in Libor within this list. **Its inclusion suggests that, in essence, our final model will mostly resemble a non-linear auto-regressive (AR) model than anything else**. Also notable is the relatively low importance of several drivers we would have otherwise expected to play a more prominent role: FX-OIS basis, GC/OIS, VIX, and prime fund AUM/WAM. Finally, we confirm which of these improve the predictive power of the model (using the S/N metric described below). In the case of credit spreads pulls JULI financials into the final feature list despite a relatively low feature importance rank.

We then follow a similar test/train approach to those prior experiments:

1. Perform a hyperparameter search using a test/train split on a subset of the data (the cross-validation period, in this case starting training in January 2010 and allowing for 10 validation quarters from January 2016 to June 2018)
2. Identify our favored model based on that exercise, and freeze its specifications (technique, hyperparameters, etc.)
3. Re-test that model on a quarantined set of data (in this case July 2018 to June 2019)

We performed this experiment for a wide variety of techniques, including **classical (e.g., SVM, kNN), ensemble (e.g., random forest [RF], gradient boosting machines [GBM]) and deep learning (an artificial neural network [ANN])**. We then compare these results to the performance of short-term market expectations as inferred from 1-day FRAs on 3-month Libor. The results are summarized for the cross-validation and quarantine periods in **Exhibit 6**. Interestingly, in this case, we find that deep learning techniques produce the highest S/N ratio. That said, **the out**

[4] We present feature important statistics covering the full time span, including both cross-validation and quarantine, as an illustration. In practice we only considered feature importance over cross-validation in our selection process.

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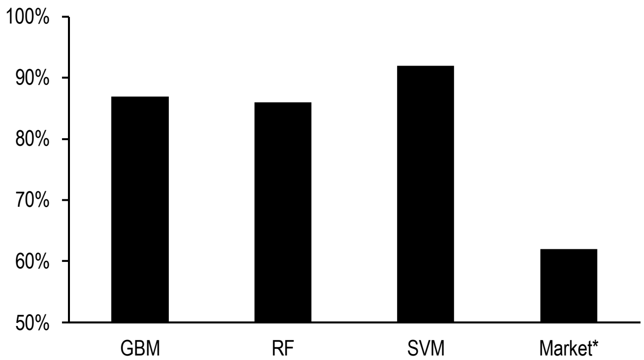
of sample performance of even this model does not significantly outperform the market in both periods.

We need not stop there, however. **As we discovered in forecasting short-term returns on Treasuries, there is often value in stacking models**. To review, doing so involves training an executive model for which the individual models are used as features, and which we train on the testing periods of the original cross-validation. This approach tends to work best when the models to be stacked do not produce highly correlated results, which in principle makes it more likely that the executive regressor extracts additional information from the interaction between them. Given the relatively higher degree of correlation between ANN-based projections and other techniques in the validation period (**Exhibit 7**), it comes as no surprise that stacking these methods does not improve the performance much.

Exhibit 7: Different techniques produce highly correlated signals, which makes stacking relatively ineffective, but market-based estimates are more orthogonal …

Correlation coefficient of model and market* projections for daily changes in 3-month Libor over the validation period (January 2016 to June 2018); %

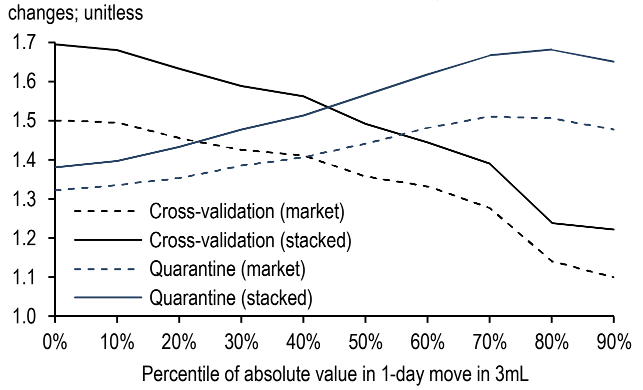


* Market predictions from *ex-ante* 1-day FRAs versus that day's fixing.

Source: J.P. Morgan, DataQuery, Reuters

Exhibit 8: … and stacking model and market signals produces better signal-to-noise in forecasts both in cross-validation and quarantine as well as tail moves in addition to globally

Ratio of variance to model MSE for various techniques in the validation and quarantine periods for market-based* forecasts and a model produced by stacking MLP and market-based forecast, split into percentiles by the absolute value of daily changes; unitless



* Market predictions from *ex-ante* 1-day FRAs versus that day's fixing.

Note: Validation period is July 2016 to June 2018, quarantine period is July 2018 to June 2019.

Source: J.P. Morgan, DataQuery, Reuters

The market, on the other hand, offers a more orthogonal signal, and in that sense shows promise. We therefore tried stacking ANN and FRA-implied changes for the period over which we have data[5]. **The results show not only clear improvement for both validation and quarantine periods, but also that the increase in S/N is true of the tails as well as globally**. For example, segregating the testing data (again both validation and quarantine) into large and small out of sample moves by percentile over each period, we find the stacked model outperforms the market in all buckets (**Exhibit 8**). In fact, though the quarantine period is admittedly rather short, it is striking how model S/N actually increases for larger, less frequent moves.

We would also be remiss if we were not to yet again to consider the statistical significance of our results. In contrast to classification, we cannot simply shuffle the dates; rather, we randomly subsample the validation and quarantine periods, keeping

[5] We experimented with simply incorporating the 1-day FRAs as a feature as well. However, given the shorter history for which we have reliable data (only back to 2012), the results were not as good as a model trained on a longer dataset (back to 2010) and then stacked with what FRA levels were available.

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half the dates, and re-computing the S/N ratio. We find this statistic is relatively well behaved in both periods (**Exhibit 9**). More importantly, in each of these realizations the stacked model performs better than the market—not just in validation (that is virtually guaranteed by construction) but also in quarantine (**Exhibit 10**).

Exhibit 9: A simulation on randomly selected subsets of the data confirms that the model results are statistically significant ...

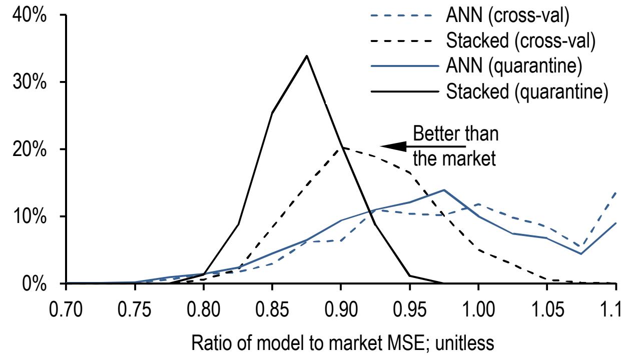
Statistics of a simulation in which we recompute S/N ratios for 1000 randomly selected subsets of the validation and quarantine data

	Attribute	GBM	ANN	Stacking	Market
Cross-Val	All data	1.56	1.54	1.69	1.49
	Median	1.56	1.53	1.70	1.51
	IQR	1.49/1.64	1.46/1.62	1.61/1.79	1.42/1.59
	Min/Max	1.19/1.92	1.11/1.91	1.31/2.15	1.13/1.98
Quarantine	All data	1.14	1.32	1.39	1.32
	Median	1.13	1.31	1.40	1.31
	IQR	1.09/1.16	1.23/1.39	1.33/1.47	1.25/1.36
	Min/Max	0.93/1.28	1/1.71	1.1/1.74	1.04/1.54

Note: We perform 1000 simulations on random subsets of half the data.
Source: J.P. Morgan, DataQuery, Reuters

Exhibit 10: ... as is the outperformance of the stacked model relative to the market alone, in both cross-validation and quarantine

Frequency of MSE ratios for model versus market forecasts for daily changes in Libor, cross-validation versus quarantine for both ANN alone and stacked with the market; %



Note: We perform 1000 simulations on random subsets of half the data.
Source: J.P. Morgan, DataQuery, Reuters

Finally, more active observers of Libor will surely note that we have thus far ignored transactional data. Indeed we can track daily yields for CP/CD fixed-rate transactions cleared through DTCC. Unfortunately, this series is only available for a relatively short history—at best back to late-2014 per their website. Until a longer series is available, this would seem to make such data difficult to incorporate into models of the type explored here, for which a longer histories are needed for proper out of sample testing. In the meantime, we have performed a much more limited experiment, incorporating the relevant transactions into a model trained on a subset of the data. Though limited history leaves little room for a proper cross-validation, let alone quarantine, the results suggest that incorporating DTCC transactions into the model only improves the MSE by ~5% versus just using the features described above, suggesting that, at least on a daily basis, **those feature capture the vast majority of potential drivers of Libor**.

What are we to learn from this exercise? First and foremost, Libor followed an auto-regressive process over short periods: daily moves are highly informed by the prior day's moves. This is broadly consistent with historical evidence for Libor's lack of direct connection to other more market-based measures of bank credit and actual transactions in CP/CD markets. **Second**, models can frequently do as well as the market, but do not significantly outperform. However, and **third,** we can use the relatively low correlation of market- and model-based forecasts to produce a more reliable forecast, both in general and in the tails.

That said, though we believe there is value in this exercise, it is also important to note that even the stacked model/market forecasts are far from a panacea. Rather, as with other such exercises, **we view deep learning as one more tool**, to be used in combination with both a more structural view and a more anecdotal interpretation of observed transactions. **It also highlights the necessity to move away from Libor, and towards another benchmark which is more clearly tied to actual transactions, and, by extension, presumably more predictable and transparent**.

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