

TFB: Towards Comprehensive and Fair Benchmarking of Time Series Forecasting Methods

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ABSTRACT

Time series are generated in diverse domains such as economic, traffic, health, and energy, where forecasting of future values has numerous important applications. Not surprisingly, many forecasting methods are being proposed. To ensure progress, it is essential to be able to study and compare such methods empirically in a comprehensive and reliable manner. To achieve this, we propose **TFB**, an automated benchmark for Time Series Forecasting (TSF) methods. TFB advances the state-of-the-art by addressing shortcomings related to datasets, comparison methods, and evaluation pipelines: 1) insufficient coverage of data domains, 2) stereotype bias against traditional methods, and 3) inconsistent and inflexible pipelines. To achieve better domain coverage, we include datasets from 10 different domains: traffic, electricity, energy, the environment, nature, economic, stock markets, banking, health, and the web. We also provide a time series characterization to ensure that the selected datasets are comprehensive. To remove biases against some methods, we include a diverse range of methods, including statistical learning, machine learning, and deep learning methods, and we also support a variety of evaluation strategies and metrics to ensure a more comprehensive evaluations of different methods. To support the integration of different methods into the benchmark and enable fair comparisons, TFB features a flexible and scalable pipeline that eliminates biases.

Next, we employ TFB to perform a thorough evaluation of 21 Univariate Time Series Forecasting (UTSF) methods on 8,068 univariate time series and 14 Multivariate Time Series Forecasting (MTSF) methods on 25 datasets. The results offer a deeper understanding of the forecasting methods, allowing us to better select the ones that are most suitable for particular datasets and settings. Overall, TFB and this evaluation provides researchers with improved means of designing new TSF methods. The benchmark code and data are available at <https://github.com/decisionintelligence/TFB>.

PVLDB Reference Format:

Xiangfei Qiu, Jilin Hu, Lekui Zhou, Xingjian Wu, Junyang Du, Buang Zhang, Chenjuan Guo, Aoying Zhou, Christian S. Jensen, Zhenli Sheng and Bin Yang. TFB: Towards Comprehensive and Fair Benchmarking of Time Series Forecasting Methods. PVLDB, 14(1): XXX-XXX, 2020.
doi:XX.XX/XXX.XX

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PVLDB Artifact Availability:

The source code, data, and/or other artifacts have been made available at <https://github.com/decisionintelligence/TFB>.

1 INTRODUCTION

As part of the ongoing digitalization, time series are generated in a variety of domains, such as economic [35, 70], traffic [29, 32–34, 58, 66, 79, 88, 90], health [44, 57, 77, 83], energy [1, 28], and AIOps [7, 40, 41, 68, 81, 82, 98]. Time Series Forecasting (TSF) is essential in key applications in these domains [27, 63, 89, 92]. Given historical observations, it is valuable if we can know the future values ahead of time. Correspondingly, TSF has been firmly established as an active research field, witnessing the proposal of numerous methods.

Time series organize data points chronologically and are either univariate or multivariate depending on the number of variables in each data point. Accordingly, TSF methods can be classified as either Univariate Time Series Forecasting (UTSF) or Multivariate Time Series Forecasting (MTSF) methods. Among early methods, Autoregressive Integrated Moving Average (ARIMA) [4] and Vector Autoregression (VAR) [76] are arguably the most popular univariate and multivariate forecasting methods, respectively. Subsequent methods that exploit machine learning, e.g., XGBoost [10, 94] and Random Forest [5, 55] offer better performance than the early methods. Most recently, methods based on deep learning have demonstrated state-of-the-art (SOTA) forecasting performance on a variety of datasets [9, 11, 13–15, 56, 60, 84, 86, 87, 91, 96, 97, 99].

As more and more methods are being proposed for different datasets and settings, there is an increasing need for fair and comprehensive empirical evaluations. To achieve this, we identify and address three issues in existing evaluation frameworks, thereby advancing our evaluation capabilities.

Issue 1. Insufficient Coverage of Data Domains. Time series from different domains may exhibit diverse characteristics. Figure 1a depicts a time series from the environment domain called AQShunyi [95] that records temperature information at hourly intervals, exhibiting a distinct seasonal pattern. This pattern is reasonable in this scenario because temperatures in nature often cycle around the year. Figure 1b shows a time series from FRED-MD [54] belongs to economic domain that describes the monthly macroeconomic from 114 regional, national, and international sources with a clear increasing tendency. This may attributed to overall economic

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Proceedings of the VLDB Endowment, Vol. 14, No. 1 ISSN 2150-8097.

doi:XX.XX/XXX.XX

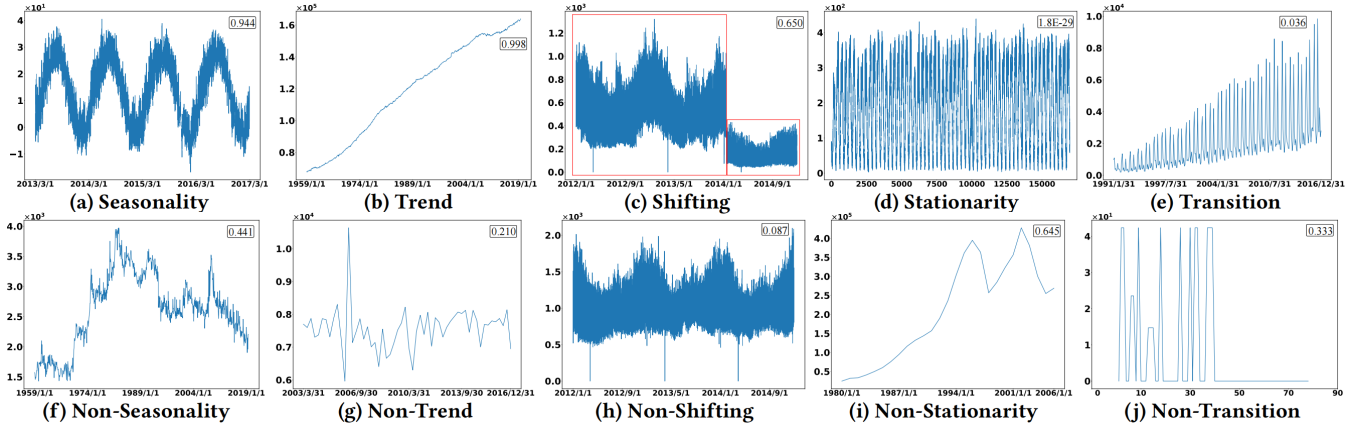


Figure 1: Visualization of data with different characteristics.

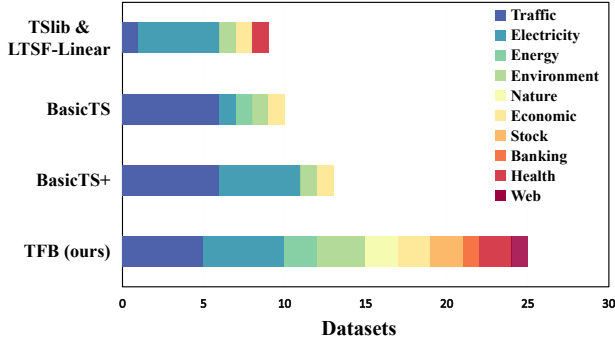


Figure 2: Statistics of data domains covered by existing multivariate time series benchmarks.

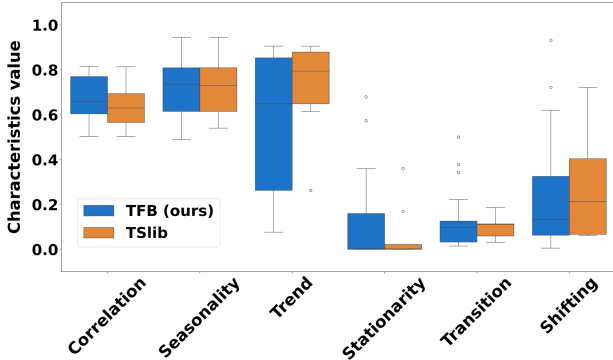


Figure 3: Box plot of the variations in normalized values of characteristics across the multivariate datasets in the TFB and TSlib.

stability with minimal fluctuations, reflecting sustained growth in the macroeconomic indicators. Figure 1c depicts a series among Electricity [78] which comes from electricity domain and has a significant change in the data at a certain point in time, which might indicate an abrupt event, etc. However, these simple patterns are only the tip of the iceberg, and time series from different domains may exhibit much more complex patterns that either combine the above characteristics or are entirely different. Therefore, using only limited domains results in limited coverage of time series characteristics, which cannot offer a full picture.

However, few empirical studies and benchmarks cover a wide variety of data domains. Figure 2 summarizes the multivariate data domains used in existing forecasting benchmarks which include MTSF. We observe that TSlib [84], LTSF-Linear [93], BasicTS [48], and BasicTS+ [71] only include around 10 datasets, covering less than or equal to 5 domains. We observe that these datasets are concentrated in mainly two domains, namely traffic and electricity. Since the multivariate time series datasets in TSlib are the most used, we investigate the variations in the values of the characteristics of datasets in TSlib and TFB—see Figure 3. We observe that the TFB datasets exhibit more diverse distributions than those of TSlib across the six characteristics. *We argue that it is beneficial to broaden the coverage of domains, thereby enabling a more extensive assessment of method performance.*

Issue 2. Stereotype bias against traditional methods. It is difficult for a single method to exhibit the best performance across all datasets. Methods exhibit varying performance across different datasets. To illustrate the issue, we conduct experiments on three datasets (NASDAQ [22], Wind [46], and ILI [85]) from different domains (stock markets, energy, health) on methods VAR [76], PatchTST [60], LinearRegression (LR) [31, 39], NLinear [93], FEDformer [101], and Crossformer [96]. Results are shown in Table 1. Surprisingly, VAR outperforms all recently proposed SOTA methods on NASDAQ and is better than FEDformer and Crossformer on ILI. Furthermore, LR performs better than recently proposed SOTA methods on Wind. However, the experimental studies in their original papers [60, 96, 101] do not include VAR and LR in their baselines and rather assume that traditional methods are incapable of obtaining competitive performance. From Table 3, it follows that no existing MTSF benchmark has evaluated statistical methods. Moreover, as the training mechanisms for statistical methods differ from those of deep learning-based methods, it is difficult for existing benchmarks to accommodate statistical methods. *We argue that it is beneficial to eliminate stereotype bias against traditional methods by comparing a wide range of methods.*

Table 1: VAR, LR versus other methods, using MAE as the evaluation metric and a forecasting horizon of 24 steps.

Datasets	VAR	LR	PatchTST	NLinear	FEDformer	Crossformer
NASDAQ	0.462	0.705	0.567	<u>0.522</u>	0.547	0.745
Wind	0.620	0.583	0.652	<u>0.640</u>	0.697	<u>0.590</u>
ILI	1.012	14.244	0.835	<u>0.919</u>	1.020	1.096

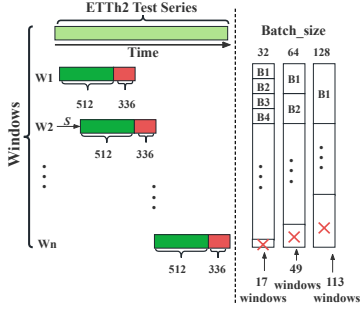


Figure 4: “Drop last” illustration.

Issue 3. Lack of consistent and flexible pipelines. The performance of different methods varies with changing experimental settings, e.g., splits among training/validation/testing data, the choice of normalization method, and the selection of hyper-parameter settings. For example, implementations of existing methods often employ a “Drop Last” trick in the testing phase [60, 80, 101]. To accelerate the testing, it is common to split the data into batches. However, if we discard the last incomplete batch with fewer instances than the batch size, this causes unfair comparisons. For example, in Figure 4, the ETTh2 [99] has a testing series of length 2,880, and we need to predict 336 future time steps using a look-back window of size 512. If we select the batch sizes to be 32, 64, and 128, the number of samples in the last batch are 17, 49, and 113, respectively. Discarding those last-batch testing samples is inappropriate unless all methods use the same strategy. Table 2 shows the testing results of PatchTST [60], DLinear [93] and FEDformer [101] on the ETTh2 with different batch sizes and the “Drop Last” trick turned on. We observe that the performance of the methods changes when varying the batch size. However, some existing benchmarks, such as TSlib [84], adopt the “Drop Last.” TSlib uses almost the same batch size across all methods in the evaluation phase to achieve consistent comparisons. However, when the users select different batch sizes inadvertently, inconsistent comparisons occur. In addition, the pipelines in most benchmarks are inflexible and do not support simultaneous evaluation of statistical learning, machine learning, and deep learning methods. *We argue that it is crucial to ensure a consistent and flexible pipeline so that methods are evaluated in the same setting, thereby improving the fairness of the findings.*

Robust and extensive benchmarks enable researchers to evaluate proposals for new methods more rigorously across diverse range of datasets, which is crucial for advancing the state-of-the-art [75]. For example, ImageNet [19], that encompasses a substantial dataset has been instrumental in ensuring progress in computer vision. ImageNet has established itself as a standard for assessing methods in image processing due to its support for rigorous evaluation. Table 3 compares existing benchmarks for TSF according to seven properties. No existing benchmark possesses all properties.

We propose the Time series Forecasting Benchmark (TFB) to facilitate the empirical evaluation and comparison of TSF methods more comprehensively across application domains and methods, and with improved fairness. TFB contributes a collection of challenging and realistic datasets and provides a user-friendly, flexible, and scalable evaluation pipeline that offers robust evaluation support. TFB possesses the following key characteristics:

Table 2: Impact of batch sizes with “drop last.”

Size	PatchTST	DLinear	FEDformer
1	0.4203	0.4874	0.4120
32	0.4138	0.4831	0.4084
64	0.3999	0.4726	0.4022
128	0.3750	0.4539	0.3921
256	0.3561	0.4360	0.3825
512	0.3483	0.4251	0.3736

Table 3: Time series forecasting benchmark comparison.

Benchmark	M3 [52]	M4 [53]	LTSE-Linear [93]	TSlib [84]	BasicTS [48]	BasicTS+ [71]	Monash [26]	Libra [3]	TFB (Ours)
Property									
Univariate forecasting	✓	✓	×	✓	×	×	✓	✓	✓
Multivariate forecasting	×	×	✓	✓	✓	✓	×	×	✓
Statistical method	✓	✓	×	×	×	×	✓	✓	✓
Machine learning method	✓	✓	×	×	✓	×	✓	✓	✓
Deep learning method	×	×	✓	✓	✓	✓	×	×	✓
Taxonomy of data	×	×	×	×	×	×	×	×	✓
Flexible & scalable pipeline	×	×	○	○	○	○	○	○	✓

× indicates absent, ✓ indicates present, ○ indicates incomplete.

- A comprehensive collection of datasets organized according to a taxonomy (to address **Issue 1**): Its collection of datasets offer diverse characteristics, encompassing time series from multiple domains and complex settings. This contributes to ensuring more robust and extensive evaluations.
- Broad coverage of existing methods and extended support for evaluation strategies and metrics (to address **Issue 2**): TFB covers a diverse range of methods, including statistical learning, machine learning, and deep learning methods, accompanied by a variety of evaluation strategies and metrics. This richness enables more comprehensive evaluations across methods and evaluation settings.
- Flexible and scalable pipeline (to address **Issue 3**): By its design, TFB improves the fairness of comparisons of methods. Methods are evaluated using a unified pipeline, consistent and standardized evaluation strategy and datasets are employed, eliminating biases and enabling more accurate performance comparisons. This enables more fair and meaningful conclusions regarding the effectiveness and efficiency of methods.

Based on the experiments conducted using TFB, we make the following key observations: (1) The statistical methods VAR [76] and LinearRegression (LR) [31, 39] perform better than recently proposed SOTA methods on some datasets—see Table 8. (2) Linear-based methods perform well when datasets exhibit an increasing trend or significant shifts. (3) Transformer-based methods outperform linear-based methods on datasets with marked seasonality, and nonlinear patterns, as well as more pronounced patterns or strong internal similarities. (4) Methods that consider dependencies between channels can enhance the performance of MTSF substantially, particularly on datasets with strong correlations, compared to methods that assume channel independence.

We make the following main contributions.

- We present TFB which is specifically designed to further improve fair comparisons in TSF, include UTSE and MTSF. TFB facilitates comparisons with 20+ UTSE methods on 8,068 univariate time series and 14 MTSF methods on 25 multivariate datasets.
- We identify, collect, and process previously proposed TSF datasets to determine a comprehensive dataset covering diverse domains and characteristics and organize them in a standardized format. Then, we design experiments to study the performance of different methods over different characteristics of datasets.
- TFB offers an automated end-to-end pipeline for evaluating forecasting methods, streamlining and standardizing the steps of loading time series datasets, configuring experiments, and evaluating methods. This simplifies the evaluation process for researchers. Additionally, all datasets and code are available at <https://github.com/decisionintelligence/TFB>.

- We use TFB to evaluate and compare a diverse set of methods, covering statistical learning, machine learning, and deep learning methods and a rich array of evaluation tasks and strategies. We summarize the evaluation results into some key findings.

The rest of the paper is structured as follows. We review related work in Section 2 and introduce terms and definitions in Section 3. In Section 4, we cover the design of TFB, and in Section 5, we use TFB to benchmark existing forecasting methods. We offer conclusions in Section 6.

2 RELATED WORK

We proceed to first cover approaches to TSF and then review existing benchmarking proposals.

Time series forecasting: Existing methods for TSF can be categorized broadly into three main categories: statistical learning, machine learning, and deep learning methods.

Early proposals primarily employed statistical learning methods. ARIMA [4], ETS [36], Theta [21], VAR [26], and Kalman Filter (KF) [30] are classical and widely utilized methods. These forecasting methods are based on the idea that future values of time series can be predicted from observed, past values. With the rapid advances in machine learning technologies, machine learning methods for TSF have emerged [23]. Notably, XGBoost [10, 94], Gradient Boosting Regression Trees (GBRT) [24], Random Forests [5, 55] and LightGBM [38] have been applied extensively to better accommodate nonlinear relationships and complex patterns. Machine learning methods are flexible at handling different types and lengths of time series and generally offer better forecasting accuracy than traditional methods.

However, these methods still require manual feature engineering and model design. Taking advantage of the representation learning capabilities offered by deep neural networks (DNNs) on rich data, numerous deep learning methods have been proposed. In many cases, these methods outperform traditional techniques in terms of forecasting accuracy. TCN [2] and DeepAR [69] treat time series as sequences of vectors and utilize CNNs or RNNs to capture temporal dependencies. Additionally, Transformer architectures, including Informer [99], FEDformer [101], Autoformer [85], Triformer [12], and PatchTST [60] can capture more complex temporal dynamics, significantly improving forecasting performance. MLP-based models such as N-HiTS [8], N-BEATS [62], NLinear [93], and DLinear [93] employ a simple architecture with relatively few parameters and have also demonstrated good forecasting accuracy. **Benchmarks:** Several benchmarks for TSF have been proposed: Libra [3], BasicTS [48], BasicTS+ [71], Monash [26], M3 [52], M4 [53], LTSF-Linear [93] and TSlib [84]. However, these benchmarks fall short in different aspects—see Table 3.

First, most benchmarks consider either univariate or multivariate time series forecasting. Early works, i.e., M3 [52], M4 [53], Libra [3] and Monash [26], only pay attention to univariate time series. And recent works, e.g., LTSF-Linear [93], BasicTS [48] and BasicTS+ [71], just consider multivariate. Only TSlib [84] considers both.

Second, a notable issue arises regarding the assessment of method diversity. In the early times, the deep learning methods are not dominant in TSF, so most early benchmarks do not have deep learning methods in their comparison, e.g., M3 [52], M4 [53] and Libra [3].

On the contrary, with more deep learning methods demonstrating their performance in TSF, recent benchmarks focus solely on deep learning methods, e.g., LTSF-Linear [93], TSlib [84], BasicTS [48] and BasicTS+ [71]. As mentioned in Section 1, this limited coverage of different method paradigms is a concern.

Moreover, there is a challenge regarding scalable and unified pipelines. In the earliest works, M3 [52] and M4 [53] do not provide a pipeline in their benchmark at all, making it hard to integrate new methods. Monash [26] and Libra [3] have pipelines but it is designed for statistical methods, which are unable to integrate deep learning methods. On the contrary, LTSF-Linear [93] and TSlib [84] have pipelines specific to deep learning methods, which are unable to evaluate statistical methods. We consider these pipelines to be incomplete, reducing scalability and hindering their broader application of these benchmarks.

Furthermore, the majority of benchmarks do not categorize the dataset; only BasicTS+ [71] provides a coarse-grained classification. We consider this taxonomy to be incomplete. In contrast, TFB involves a fine-grained classification of the dataset.

Generally, TFB aims to enable a more reliable, thorough, and user-friendly evaluation. Thus, the proposed benchmark encompasses a broader range of methods and utilizes more scalable implementation pipelines than existing benchmarks, ensuring a fair comparison of TSF methods and promoting progress in the field of TSF.

3 PRELIMINARIES

We provide definitions of time series and time series forecasting, and we cover key dataset characteristics, including trend, seasonality, stationarity, shifting, transition, and correlation.

DEFINITION 1 (TIME SERIES). A time series $X \in \mathbb{R}^{T \times N}$ is a time-oriented sequence of N -dimensional time points, where T is the number of time points, and N is the number of variables. When $N = 1$, a time series is called univariate. When $N > 1$, it is called multivariate.

DEFINITION 2 (TIME SERIES FORECASTING). Given a historical time series $X \in \mathbb{R}^{H \times N}$ of H time points, time series forecasting aims to predict the next F future time points, i.e., $Y \in \mathbb{R}^{F \times N}$, where F is called the forecasting horizon.

DEFINITION 3 (TREND). The trend of a time series refers to the long-term changes or patterns that occur over time. Intuitively, it represents the general direction in which the data is moving. Referring to the explained variance [61], Trend Strength can be defined as follows.

$$\text{Trend_Strength} = \max \left(0, 1 - \frac{\text{var}(R)}{\text{var}(X - S)} \right), \quad (1)$$

where X is a time series that can be decomposed into a trend (T), seasonality (S), and the remainder (R): $X = S + T + R$ by employing Seasonal and Trend decomposition using Loess, which is a highly versatile and robust method for time series decomposition [16].

DEFINITION 4 (SEASONALITY). Seasonality refers to the phenomenon where changes in a time series repeat at specific intervals. Similar to the measurement of trend, the strength of Seasonality of a time series X can be estimated as follows.

$$\text{Seasonality_Strength} = \max \left(0, 1 - \frac{\text{var}(R)}{\text{var}(X - T)} \right) \quad (2)$$

DEFINITION 5 (STATIONARITY). Stationarity refers to the mean of any observation in a time series $X = \langle x_1, x_2, \dots, x_n \rangle$ is constant,

Algorithm 1 Calculating Shifting Values of Time Series

Input: Time series $X \in \mathbb{R}^{T \times 1}$
Output: Shifting value $\delta \in (0, 1)$ of X

- 1: Normalize X by calculating the z-score to obtain $Z \in \mathbb{R}^{T \times 1}$
- 2: $Z_{\min} \leftarrow \min(Z)$, $Z_{\max} \leftarrow \max(Z)$
- 3: $S = \{s_i \mid s_i \leftarrow Z_{\min} + (i - 1) \frac{Z_{\max} - Z_{\min}}{m}, 1 \leq i \leq m\}$ where m is the number of thresholds
- 4: **for** s_i in S **do**
- 5: $K \leftarrow \{j \mid Z_j > s_i, 1 \leq j \leq T\}$, $M_i \leftarrow \text{median}(K)$, $1 \leq i \leq m$
- 6: $M'_i \leftarrow \frac{2M_i - N}{N}$, $1 \leq i \leq m$
- 7: **end for**
- 8: **return** $\delta \leftarrow \text{abs}(\text{median}(\{M'_1, M'_2, \dots, M'_m\}))$

Algorithm 2 Calculating Transition Values of Time Series

Input: Time series $X \in \mathbb{R}^{T \times 1}$
Output: Transition value $\Delta \in (0, \frac{1}{3})$ of X

- 1: Calculate the first zero crossing of the autocorrelation function:
 $\tau \leftarrow \text{firstzero_ac}(X)$
- 2: Generate $Y \in \mathbb{R}^{T' \times 1}$ by downsampling X with stride τ
- 3: Define index $I = \text{argsort}(Y) \in \mathbb{R}^{T' \times 1}$, then characterize Y to obtain $Z \in \mathbb{R}^{T' \times 1}$:
- 4: **for** $j \in [0 : T']$ **do**
- 5: $Z[j] \leftarrow \text{floor}(I[j] / \frac{1}{3} T')$
- 6: **end for**
- 7: Generate a transition matrix $M \in \mathbb{R}^{3 \times 3}$:
- 8: **for** $j \in [0 : T']$ **do**
- 9: $M[Z[j] - 1][Z[j + 1] - 1]++$
- 10: **end for**
- 11: $M' \leftarrow \frac{1}{T'} M$
- 12: Compute the covariance matrix C between the columns of M'
- 13: **return** $\Delta \leftarrow \text{tr}(C)$

and the variance is finite for all observations. Also, the covariance $\text{cov}(x_i, x_j)$ between any two observations x_i and x_j depends only on their distance $|j - i|$, i.e., $\forall i + r \leq n, j + r \leq n$ ($\text{cov}(x_i, x_j) = \text{cov}(x_{i+r}, x_{j+r})$). Strictly stationary time series are rare in practice. Therefore, weak stationarity conditions are commonly applied [45] [59]. In our paper, we also exclusively focus on weak stationarity.

We adopt the Augmented Dick-Fuller (ADF) test statistic [20] to quantify stationarity. The stationarity can be calculated as follows.

$$\text{stationarity} = \begin{cases} \text{Stationary}, & \text{ADF}(X) \leq 0.05 \\ \text{Non-Stationary}, & \text{ADF}(X) > 0.05 \end{cases} \quad (3)$$

DEFINITION 6 (SHIFTING). *Shifting refers to the phenomenon where the probability distribution of time series changes over time. This behavior can stem from structural changes within the system, external influences, or the occurrence of random events. As the value approaches 1, the degree of shifting becomes more severe. Algorithm 1 details the calculation process.*

DEFINITION 7 (TRANSITION). *Transition refers to the trace of the covariance of transition matrix between symbols in a 3-letter alphabet [51]. It captures the regular and identifiable fixed features present in a time series, such as the clear manifestation of trends, periodicity, or the simultaneous presence of both seasonality and trend. Algorithm 2 details the calculation process.*

DEFINITION 8 (CORRELATION). *Correlation refers to the possibility that different variables in a multivariate time series may share common trends or patterns, indicating that they are influenced by similar factors or have some underlying relationship. Correlation is calculated as follows.*

Table 4: Statistics of univariate datasets.

Frequency	#Series	Seasonality	Trend	Shifting	Transition	Stationarity	Lens<300	F
Yearly	1,500	611	1,086	978	633	354	1,499	6
Quarterly	1,514	486	933	889	894	471	1,508	8
Monthly	1,674	883	884	778	1,212	667	1,026	18
Weekly	805	253	330	445	407	372	473	13
Daily	1,484	374	502	487	1,176	714	442	14
Hourly	706	435	276	284	680	472	0	48
Other	385	75	248	236	195	124	215	8
Total	8,068	3,117	4,259	4,097	5,197	3,174	5,163	

First, use Catch22 [51] to extract 22 features for each variable in X , serving as a representation for each variable. $F = \langle F^1, F^2, \dots, F^N \rangle \in \mathbb{R}^{22 \times N}$ is obtained using the formulation specified in Equation 4.

$$F = \text{Catch22}(X) \quad (4)$$

Second, according to Equation 5 we calculate the Pearson correlation coefficient between all variable pairs.

$$P = \{r(F^i, F^j) \mid 1 \leq i \leq N, i + 1 \leq j \leq N, i, j \in N^*\} \quad (5)$$

Third, compute the mean and variance of all Pearson correlation coefficients (PCCs) [17] to obtain the correlation, as shown in Equation 6.

$$\text{Correlation} = \text{mean}(P) + \frac{1}{1 + \text{var}(P)} \quad (6)$$

Figure 1 shows time series exhibit diverse characteristics in real-world scenarios. For each characteristic, the calculated characteristic values in the upper right corner of the image corresponding to series with distinct and indistinct characteristic are significantly different. In summary, the time series characteristics define here enable a deep understanding of time series. Using these characteristics for classifying time series, we can more selectively choose forecasting methods that are appropriate for specific scenarios.

4 TFB: BENCHMARK DETAILS

We proceed to cover the design of the TFB benchmark. First, we provide a detailed overview of the dataset in TFB, including the process of collection, accompanied by a comprehensive demonstration. (Section 4.1). Second, we categorize the existing methods supported (Section 4.2). Third, we cover evaluation strategies and metrics (Section 4.3). Finally, we describe the full benchmark pipeline (Section 4.4).

4.1 Datasets

We equip TFB with a set of 25 multivariate and 8,068 univariate datasets with the following desirable properties. All datasets are formatted consistently. The collection is comprehensive, covering a wide range of domains and characteristics. The values of key characteristics of the multivariate and univariate datasets, as well as their classification based on the characteristics, can be found in our code repository. This marks an improvement, addressing challenges such as different formats, varied documentation, and the time-consuming nature of dataset collection. We will provide a brief introduction to these datasets (Section 4.1.1), demonstrating their comprehensiveness (Section 4.1.2).

4.1.1 Dataset overview.

Univariate time series. The univariate datasets are carefully curated from 16 open-source datasets, thus covering dozens of domains. To fully reflect the complexity of real-world time series, we employed Pattern Frequency Analysis (PFA) [50], a variation of

Table 5: Statistics of multivariate datasets.

Dataset	Domain	Frequency	Lengths	Dim	Split
METR-LA [47]	Traffic	5 mins	34,272	207	7:1:2
PEMS-BAY [47]	Traffic	5 mins	52,116	325	7:1:2
PEMS04 [72]	Traffic	5 mins	16,992	307	6:2:2
PEMS08 [72]	Traffic	5 mins	17,856	170	6:2:2
Traffic [85]	Traffic	1 hour	17,544	862	7:1:2
ETTh1 [99]	Electricity	1 hour	14,400	7	6:2:2
ETTh2 [99]	Electricity	1 hour	14,400	7	6:2:2
ETTm1 [99]	Electricity	15 mins	57,600	7	6:2:2
ETTm2 [99]	Electricity	15 mins	57,600	7	6:2:2
Electricity [78]	Electricity	1 hour	26,304	321	7:1:2
Solar [43]	Energy	10 mins	52,560	137	6:2:2
Wind [46]	Energy	15 mins	48,673	7	7:1:2
Weather [85]	Environment	10 mins	52,696	21	7:1:2
AQShunyi [95]	Environment	1 hour	35,064	11	6:2:2
AQWan [95]	Environment	1 hour	35,064	11	6:2:2
ZafNoo [67]	Nature	30 mins	19,225	11	7:1:2
CzeLan [67]	Nature	30 mins	19,934	11	7:1:2
FRED-MD [54]	Economic	1 month	728	107	7:1:2
Exchange [43]	Economic	1 day	7,588	8	7:1:2
NASDAQ [22]	Stock	1 day	1,244	5	7:1:2
NYSE [22]	Stock	1 day	1,243	5	7:1:2
NN5 [74]	Banking	1 day	791	111	7:1:2
ILI [85]	Health	1 week	966	7	7:1:2
Covid-19 [64]	Health	1 day	1,392	948	7:1:2
Wike2000 [25]	Web	1 day	792	2,000	7:1:2

Principal Component Analysis (PCA) [6]. PFA preserves the original values of individual time series data points. We employ the concept of explained variance, representing the ratio between the variance of a single time series and the sum of variances across all individual time series. A threshold t for the explained variance is set to 0.9. This implies that for each dataset, we choose to retain the minimum number of time series required to encompass 90% of the variance contributed by the remaining time series. As a result, the selected data exhibits pronounced heterogeneity. Compared to datasets with strong homogeneity, it can better reflect methods performance. In the end, we select 8,068 time series to enable the combined dataset to capture the diversity of real-world time series. Statistical information is reported in Table 4.

Multivariate time series. Table 5 lists statistics of the 25 multivariate time series datasets, which cover 10 domains. The frequencies vary from 5 minutes to 1 month, the range of feature dimensions varies from 5 to 2,000, and the sequence length varies from 728 to 57,600. This substantial diversity of the datasets enables comprehensive studies of forecasting methods. To ensure fair comparisons, we choose a fixed data split ratio for each dataset chronologically, i.e., 7:1:2 or 6:2:2, for training, validation and testing.

4.1.2 Dataset comprehensiveness. We proceed to investigate the coverage of the selected univariate and multivariate datasets.

Univariate time series. Since time series have different lengths, we first represent time series as vectors that consist of five feature indicators: trend, seasonality, stationarity, shifting, and transition. For ease of visualization, we adopt PCA [6] to reduce the dimensionality from five to two and visualize the eight most widely distributed univariate time series datasets in hexbin—see Figure 5. We observe that TFB and M4 cover the most cells, while all other benchmarks are smaller than TFB. This emphasizes the coverage of our dataset in terms of diversity in characteristic distribution. In addition, compared to M4, our dataset covers a wider range of domains. Further, we note that M4 has a much larger sample size, totaling 100,000, compared to our dataset that contains only 8,068 time series. We believe that testing on diverse datasets is essential to better reflect

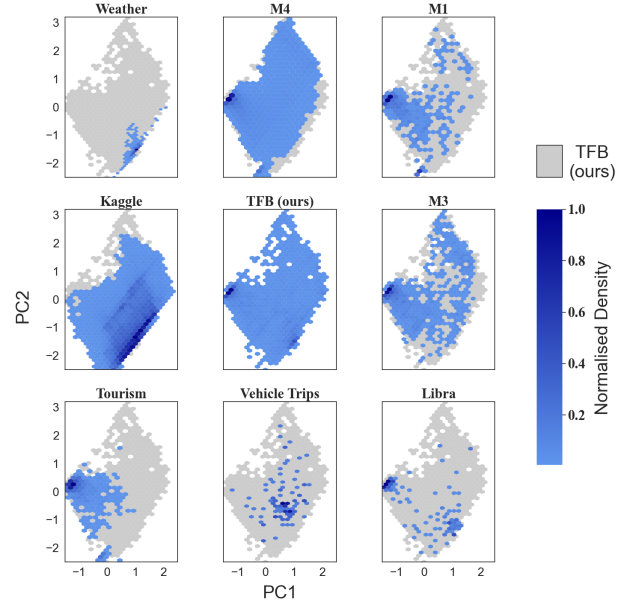


Figure 5: Hexbin plots showing normalised density values of the low-dimensional feature spaces generated by PCA across trend, seasonality, stationarity, shifting, and transition for 9 univariate datasets.

the practical performance of methods. Yet, we can run much fewer experiments with TFB than the M4 dataset, i.e., around 8%.

Multivariate time series. Figure 2 shows a comparison of TFB and existing multivariate time series benchmarks according to dataset domain distribution. Our benchmark includes more diverse datasets in terms of both quantity and domain categories. Next, we select TSlib, whose multivariate time series datasets are the most popular, to compare the characteristic distributions with TFB, which are shown in Figure 3. We can observe that the datasets in TFB also represent a more diverse characteristic distribution.

4.2 Comparison Methods

To investigate the strengths and limitations of different forecasting methods, we include 22 methods that can be categorized as statistical learning, machine learning, and deep learning methods. In terms of statistical learning methods, we include ARIMA [4], ETS [36], Kalman Filter (KF) [30], and VAR [76]. Among the machine learning methods, we include XGBModel (XGB) [31], LinearRegression (LR) [31, 39], and Random Forest (RF) [5]. Finally, we further split the deep learning methods into RNN-based models (RNN [42]), CNN-based models (MICN [80], TimesNet [84], and TCN [2]), MLP-based models (NLinear [93], DLinear [93], TiDE [18], N-HiTS [8], and N-BEATS [62]), Transformer-based models (PatchTST [60], Crossformer [96], and FEDformer [101], Non-stationary Transformer (Stationary) [49], Informer [99], and Triformer [12]), and Model-Agnostic models (FiLM [100]). Figure 6 gives an overview of the diverse technical approaches of the methods covered by the benchmark. This wide selection of comparison methods aims to

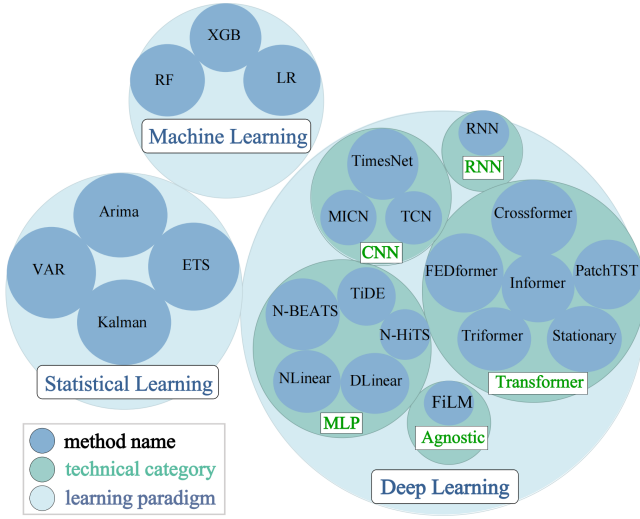


Figure 6: Categorization of comparison methods.

offer a deeper understanding of the technical nuances and performance variations across methods.

4.3 Evaluation Settings

4.3.1 Evaluation strategies. To assess the forecasting accuracy of a method, TFB implements two distinct evaluation strategies: 1) *Fixed forecasting*; and 2) *Rolling forecasting*.

Fixed forecasting. Given a time series on length n , f future time points are predicted from $n - f$ historical time points, which is illustrated in Figure 7a.

Rolling forecasting. In Rolling forecasting, illustrated in Figure 7b, the blue squares represent historical data, the green squares represent the forecasting horizon, and the white squares represent the remaining data in the time series. During rolling forecast, excluding the last iteration, the historical data expands by a fixed number of steps (called the stride) in each iteration. In the final iteration, the historical data is extended to cover the entire time series along with the forecasting horizon. In each iteration of the inference process, the forecasting model is applied based on the historical data to forecast the designated forecasting horizon. Then, we calculate the average of the error metrics for each iteration. In statistical learning methods (e.g., ARIMA [4], ETS [21]), it is common to use the entire or a subset of the historical data for training and then make forecasting during each iteration. In contrast, in deep learning or machine learning methods, each iteration often involves using only the last portion of the historical data, with a length equal to the look-back windows size, for inference to make forecasting. The current evaluation strategy for TSF, such as TimesNet [84], aligns with our defined criteria.

From a practical perspective, despite some limitations in the generalization capabilities of statistical learning methods, their relatively short runtimes prompts us to adopt the approach of retraining and then making inference predictions to support rolling forecasting. However, in the case of deep learning and machine learning methods, each iteration of retraining typically takes much longer

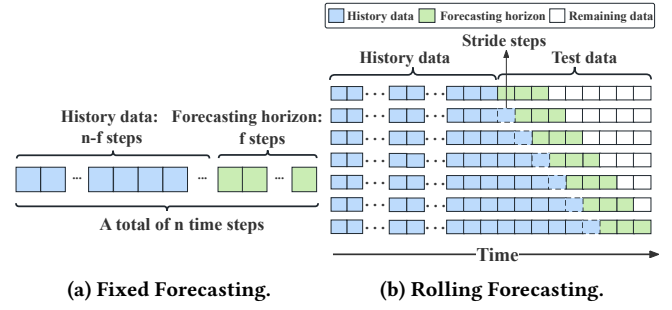


Figure 7: Time series forecasting evaluation strategies.

time. Therefore, to balance timeliness and prediction accuracy, machine learning and deep learning methods opt for the strategy of reinferring during each iteration in rolling forecasting.

4.3.2 Evaluation metrics. To achieve an extensive evaluation of forecasting performance, we employ eight error metrics, namely the Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Percentage Error (MAPE), Symmetric Mean Absolute Percentage Error (SMAPE), Weighted Absolute Percent Error (WAPE), Mean Absolute Scaled Error (MASE) [37], and Modified Symmetric Mean Absolute Percentage Error (MSMAPE) [73], which are defined in Equations 7–14.

$$MAE = \frac{1}{h} \sum_{k=1}^h |F_k - Y_k| \quad (7) \quad MAPE = \frac{1}{h} \sum_{k=1}^h \frac{|Y_k - F_k|}{Y_k} \times 100\% \quad (10)$$

$$MSE = \frac{1}{h} \sum_{k=1}^h (F_k - Y_k)^2 \quad (8) \quad SMAPE = \frac{100\%}{h} \sum_{k=1}^h \frac{|F_k - Y_k|}{\frac{|Y_k| + |F_k|}{2}} \quad (11)$$

$$RMSE = \sqrt{\frac{1}{h} \sum_{k=1}^h (F_k - Y_k)^2} \quad (9) \quad WAPE = \frac{\sum_{k=1}^h |Y_k - F_k|}{\sum_{k=1}^h |Y_k|} \quad (12)$$

$$MASE = \frac{\sum_{k=M+1}^{M+h} |F_k - Y_k|}{\frac{h}{M-S} \sum_{k=S+1}^M |Y_k - Y_{k-S}|} \quad (13)$$

$$MSMAPE = \frac{100\%}{h} \sum_{k=1}^h \frac{|F_k - Y_k|}{\max(|Y_k| + |F_k| + \epsilon, 0.5 + \epsilon)/2}, \quad (14)$$

where M is the length of the training series, S is the seasonality of the dataset, h is the forecasting horizon, F_k are the generated forecasts, and Y_k are the actual values. We set the parameter ϵ in Equation 14 to its proposed default of 0.1. For rolling forecasting, we further calculate the average of error metrics for all samples (windows) on each time series to assess the method performance.

4.4 Unified Pipeline

As mentioned in Section 1, small implementation differences can impact evaluation results profoundly. To enable fair and comprehensive comparisons of methods, we introduce a unified pipeline that is structured into a data layer, a method layer, an evaluation layer, and a reporting layer—see Figure 8. The details of each component are listed as follows.

- The data layer is a repository of univariate and multivariate time series from diverse domains, structured according to their distinct characteristics, frequencies, and sequence lengths. The data is uniformly according to a standardized format. When a new dataset becomes available, this layer can assess whether the distribution of existing datasets across the six features can be expanded. If yes, it is accepted as a new dataset.

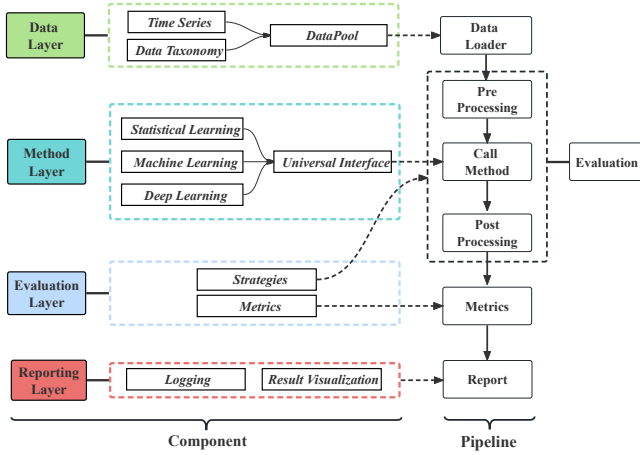


Figure 8: The TFB pipeline.

- The method layer supports embedding statistical learning, machine learning and deep learning methods. However, other benchmarks have not achieved this, most of them can only embed deep learning methods. Additionally, TFB is designed to be compatible with any third-party TSF library, such as Darts [31], TSlib [84]. Users can easily integrate forecasting methods implemented in third-party libraries into TFB by writing a simple Universal Interface, facilitating fair comparisons. TFB goes beyond benchmarks that only support Direct Multi-Step (DMS) forecasting to support also Iterative Multi-Step (IMS) forecasting. The method layer thus contributes to the applicability of TFB by offering support for a broad range of methods.
- The evaluation layer offers support for a diverse range of evaluation strategies and metrics. It thus supports both fixed and rolling forecasting strategies, increasing again the applicability of the benchmark to a wider range of methods and applications. The layer also covers evaluation metrics found in other studies and enables the use of customized metrics for a more comprehensive assessment of method performance. Besides, for each evaluation strategy, TFB offers standardized dataset handling, splitting, and normalization. Additionally, it provides a standard configuration file that can be customized by users. This aims to facilitate deeper understanding of method performance in different settings.
- The reporting layer encompasses a logging system for tracking information, enabling the capture of experimental settings to enable traceability. Further, it encompasses a visualization module to facilitate a clear understanding of method performance. This design is to offer exhaustive support and transparency throughout the evaluation process.

Users only need to deploy their method architecture at the method layer and choose or configure the configuration file, then TFB can automatically run the pipeline in Figure 8.

The TFB pipeline supports various extensible features. Compatibility with CPU and GPU hardware enables evaluation in different computing environments. TFB also supports both sequential and parallel program execution, providing users with multiple options.

In summary, TFB is a unified, flexible, scalable, and user-friendly benchmarking tool for TSF methods. It enables to better understand, compare, and select TSF methods for specific application scenarios.

5 EXPERIMENTS

We report on experiments with the 14 multivariate and 22 univariate forecasting methods covered in Section 4.2 on all the datasets covered in Section 4.1. We adopt the pipeline covered in Section 4.4 to do so. For each method, we conduct comprehensive hyper-parameters selection, such that its performance result approach or surpass the performance reported in its original paper. Our goal is to showcase TFB as an easy-to-use and powerful resource, providing a convenient and fair evaluation platform for TSF methods.

5.1 Experimental Setup

5.1.1 Datasets. We utilized all the datasets included in TFB, encompassing 25 multivariate datasets and 8,068 univariate time series. The detailed data splits for the multivariate datasets are given in Table 5, and the forecasting horizons F of the univariate datasets are given in Table 4.

5.1.2 Comparison methods. To reduce the stereotype bias on comparison methods, all methods mentioned in Section 4.2 are included for a comprehensive comparison.

5.1.3 Implementation details. For multivariate forecasting, we use the rolling forecasting strategy. We consider four forecasting horizon F : 24, 36, 48, and 60, for FredMd, NASDAQ, NYSE, NN5, ILI, Covid-19, and Wike2000, and we use another four forecasting horizon, 96, 192, 336, and 720, for all other datasets which have longer lengths. The look-back window H underwent testing with lengths 36 and 104 for FredMd, NASDAQ, NYSE, NN5, ILI, Covid-19, and Wike2000, and 96, 336, and 512 for all other datasets. For univariate forecasting, we adopt a fixed forecasting strategy to maintain consistency with the setting of the M4 competition [53], forecasting horizons go from 6 to 48, with the look-back window H set to 1.25 times forecasting horizon F .

For each method, we adhere to the hyper-parameter as specified in their original papers. Additionally, we perform hyper-parameter searches across multiple sets, with a limit of 8 sets. The optimal result is then selected from these evaluations, contributing to a comprehensive and unbiased assessment of each method’s performance. Due to space constraints, we only report the results of a subset of metrics in the paper, additional metrics results can be found in the code repository.

All experiments are conducted using PyTorch [65] in Python 3.8 and execute on an NVIDIA Tesla-A800 GPU. The training process is guided by the L2 loss, employing the ADAM optimizer. Initially, the batch size is set to 32, with the option to reduce it by half (to a minimum of 8) in case of an Out-Of-Memory (OOM) situation. We do not use the “Drop Last” operation during testing. To ensure reproducibility and facilitate experimentation, datasets and code are available at: <https://github.com/decisionintelligence/TFB>.

5.2 Experimental Results

5.2.1 Univariate time series forecasting. Table 6 reports the average results of UTSF in terms of the metrics MASE, MSMAPE, and

Table 6: Univariate forecasting results.

Dataset	Metric	PatchTST	Crossformer	FEDformer	Stationary	Informer	Triformer	DLlinear	NLinear	TiDe	N-BEATS	N-HITS	TimesNet	TCN	RNN	FiLM	LR	RF	XGB	ARIMA	ETS	KF	
Seasonality	✓	mase	1.660	29.704	2.100	2.384	2.390	19.378	2.409	2.850	2.074	2.081	2.189	1.446	24.159	30.231	1.882	7.8e+9	1.649	1.715	2.830	4.091	9.002
		mssape	12.263	161.074	19.041	15.190	14.301	107.957	19.628	20.938	14.566	15.794	13.557	10.927	121.335	149.830	13.537	19.183	12.790	13.404	19.868	26.386	57.409
		Ranks	167	14	59	40	85	15	22	45	162	168	213	314	14	8	141	603	425	250	225	92	43
	×	mase	1.639	23.704	1.879	1.638	1.601	16.496	1.949	1.733	2.526	1.677	1.678	1.478	15.441	23.889	1.769	2.5e+10	1.731	1.814	1.496	1.544	3.318
		mssape	21.671	166.859	26.766	22.050	21.413	138.945	26.966	27.154	30.968	25.705	24.127	20.497	140.174	162.648	22.331	33.413	25.316	26.838	24.491	25.190	44.551
		Ranks	214	35	208	200	303	72	61	157	189	383	556	371	64	40	138	326	423	273	355	268	292
Trend	✓	mase	2.220	41.287	2.758	2.651	2.658	28.091	3.016	2.914	3.316	2.512	2.553	1.911	28.716	44.365	2.492	7.9e+9	2.271	2.355	2.822	3.615	8.486
		mssape	10.679	184.125	13.917	11.709	11.216	133.424	14.435	13.463	13.747	11.583	11.090	9.247	136.243	180.218	11.442	16.920	10.832	11.221	11.686	12.986	50.062
		Ranks	201	2	114	113	188	20	51	113	201	270	375	402	6	2	162	737	298	246	403	222	123
	×	mase	1.007	8.941	1.077	1.127	1.064	5.878	1.131	1.326	1.272	1.073	1.116	0.968	7.718	8.282	1.052	3.1e+10	1.059	1.127	1.104	1.311	2.185
		mssape	26.261	142.824	34.808	27.894	26.993	119.760	34.972	37.374	36.802	33.385	30.053	25.243	129.153	136.076	27.307	40.210	31.262	33.307	35.019	39.814	48.911
		Ranks	180	47	153	127	200	67	32	89	150	281	394	283	72	46	117	192	550	277	177	138	212
Stationarity	✓	mase	1.004	9.380	1.057	1.132	1.133	6.309	1.139	1.290	1.343	1.162	1.212	0.961	7.870	8.305	1.066	15.848	1.043	1.100	1.257	1.618	3.172
		mssape	27.024	135.888	35.122	28.539	27.546	114.323	35.434	37.306	37.594	33.519	31.080	26.120	122.194	129.738	28.172	38.320	32.232	34.281	36.212	41.513	52.234
		Ranks	154	45	128	105	177	67	24	69	124	214	285	242	66	42	99	197	444	219	150	117	180
	×	mase	2.065	36.826	2.553	2.451	2.408	24.945	2.768	2.732	3.007	2.269	2.305	1.793	25.907	39.090	2.297	3.1e+10	2.125	2.214	2.500	3.118	7.032
		mssape	12.206	183.264	16.425	13.397	12.904	135.177	16.800	16.610	16.225	14.325	12.885	10.754	139.836	178.312	12.940	21.168	12.853	13.455	13.942	15.365	47.757
		Ranks	227	4	139	135	211	20	59	133	227	337	484	443	12	6	180	732	404	304	430	243	155
Transition	✓	mase	1.397	19.759	1.571	1.744	1.779	11.972	1.820	1.985	1.827	1.543	1.601	1.282	13.744	19.901	1.505	5.7e+4	1.380	1.474	1.930	2.723	3.998
		mssape	21.932	155.700	24.803	23.707	22.978	117.240	25.741	29.013	27.664	23.031	22.672	20.869	125.136	150.624	22.973	29.179	23.002	24.545	25.020	28.725	45.521
		Ranks	242	44	187	153	263	79	44	121	230	373	527	464	73	48	187	560	533	382	304	186	166
	×	mase	2.102	37.372	2.676	2.277	2.136	27.831	2.682	2.489	3.303	2.358	2.371	1.799	27.987	39.651	2.369	5.3e+10	2.278	2.323	2.157	2.172	8.259
		mssape	10.984	180.775	21.932	11.399	10.860	144.591	21.216	17.039	19.143	19.785	15.284	9.435	146.942	173.676	11.622	25.629	15.905	16.404	18.520	20.089	56.754
		Ranks	139	5	80	87	125	8	39	81	121	178	242	221	5	0	92	369	315	141	276	174	169
Shifting	✓	mase	2.138	36.092	2.646	2.507	2.314	25.570	2.823	2.747	2.975	2.289	2.345	1.857	24.925	37.921	2.352	3.7e+10	2.224	2.306	2.331	2.799	6.862
		mssape	13.453	173.924	19.874	14.454	13.509	133.554	19.930	19.013	17.860	16.573	14.248	11.873	137.113	167.496	14.074	21.775	14.877	16.159	17.550	20.517	50.844
		Ranks	181	13	107	86	194	27	47	123	173	268	380	384	14	18	143	556	401	220	370	227	157
	×	mase	1.142	15.639	1.262	1.355	1.485	9.401	1.410	1.563	1.709	1.363	1.390	1.062	12.499	15.066	1.257	7.4e+4	1.159	1.229	1.681	2.248	4.122
		mssape	22.763	155.031	27.811	24.258	23.983	120.183	28.465	30.674	31.618	27.347	26.022	21.881	128.544	148.943	23.945	34.251	26.254	27.310	28.022	30.950	48.150
		Ranks	200	36	160	154	194	60	36	79	178	283	389	301	64	30	136	373	447	303	210	133	178

the Ranks in MSMAPE that indicates how many times the best performance is achieved on the datasets. We observe that the recently proposed deep learning methods, including TimesNet [84], PatchTST [60], and N-HITS [8], exhibit substantially better average performance on univariate datasets in terms of MASE and MSMAPE. However, when considering Ranks, the (non-deep) machine learning methods LinearRegression (LR) [31, 39] and RandomForest (RF) [5] outperform all competitors. This suggests that the machine learning methods may be more suitable in specific scenarios. In this scenario, each individual univariate time series is adopted to train a separate model, and deep learning methods require large amount of training data to be effective. Therefore, the performance of the deep learning methods falls short. Next, we can observe that LR performs better on the time series with seasonality, trend, and shifting characteristics, while RF is better when those patterns are absent. Further, we notice that LR is more suitable for data without stationarity than RF. Finally, both LR and RF are sensitive to the transition characteristic: the stronger the characteristic, the better. These results offer guidance on choosing the right method for a specific setting.

5.2.2 Multivariate time series forecasting. Due to the large number of results, we report them in two tables, Tables 7 and 8. The datasets in these tables are ordered based on their trend characteristic, where datasets with weaker trend are occur first. In both tables, we report the MAE and MSE on normalized data considering four different forecasting horizons for each dataset. "nan" represents the inability of a method to generate effective predictions, while "inf" represents infinite results. We see that no single method achieves the best performance on all datasets. We also see that the Transformer-based methods generally outperform other methods on datasets with weak

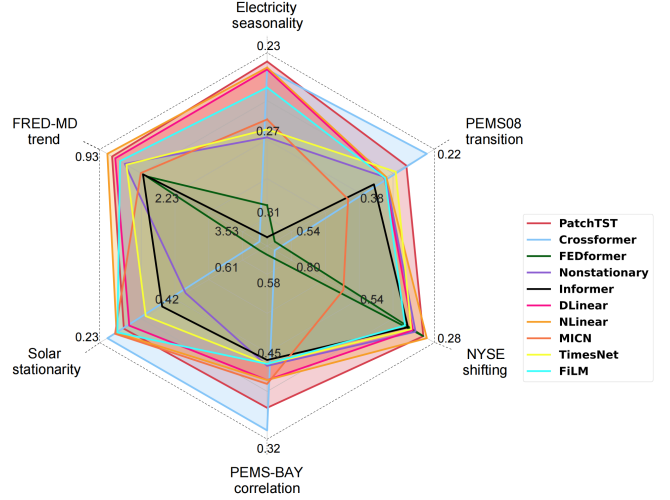


Figure 9: MAE results of methods across six characteristics.

trend. Next, Linear-based methods tend to perform moderately better on datasets with strong trend. Surprisingly, we observe that recent methods not consistently outperform earlier studies, such as Informer, LR, and VAR. This discovery highlights the need for evaluating method performance across diverse datasets. Evaluating methods on relatively few datasets render it difficult to accurately assess their universality and overall performance. Therefore, it is crucial to expand the range of datasets used in evaluations.

5.2.3 Performance on different characteristics. We proceed to study the performance of different deep learning methods with respect

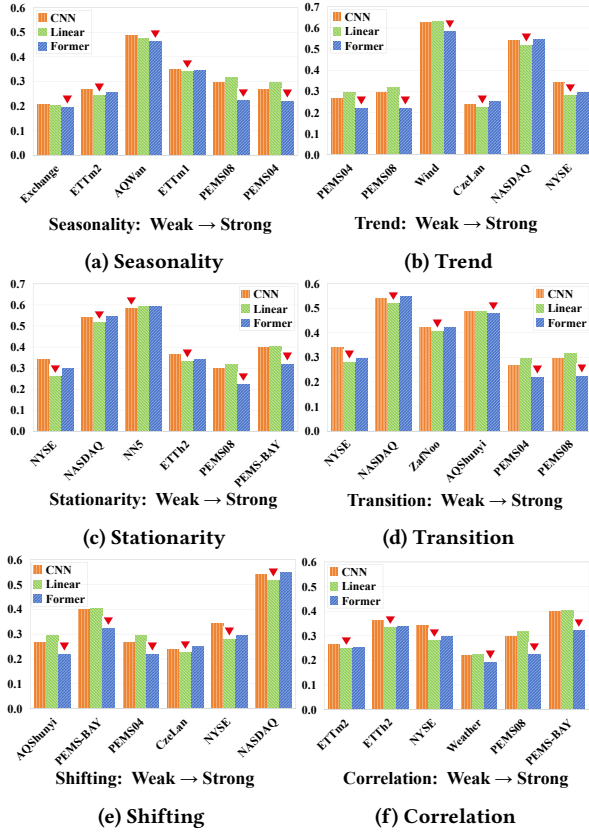


Figure 10: Comparison between Transformer-based, CNN-based, and Linear-based methods. Red triangles indicate methods with the best accuracy (minimum MAE).

to different characteristics. First, we score the multivariate time series with respect to the six characteristics we consider. Then, we select the dataset with the highest score for each characteristic, which are FRED-MD on trend, Electricity on seasonality, PEMS08 on transition, NYSE on shifting, PEMS-BAY on correlation, and Solar on stationarity. Next, we show the best MAE results for the methods in a radar figure. We use a forecasting horizon of 24 for FRED-MD and NYSE and of 96 for other datasets—see Figure 9. We see that no deep learning method excels on all datasets. In particular, Crossformer demonstrates exceptional performance on datasets where transition is highly pronounced (PEMS08), the data is most stationary (Solar), and the data is most correlated (PEMS-BAY). However, Crossformer’s performance is noticeably inferior to other methods on time series with other characteristics. Next, PatchTST achieves optimal performance on datasets with strong seasonality (Electricity). Similarly, NLinear delivers outstanding results on time series with the most significant trend (FRED-MD) and severe drift (NYSE). Both PatchTST and NLinear perform well consistently, without any notably poor outcomes.

These observations indicate that various deep learning methods have varying abilities on datasets with different characteristics.

5.3 Hints to Method Design

5.3.1 Transformers vs. linear methods. To study the impact of different data characteristics on these two types of methods, we consider

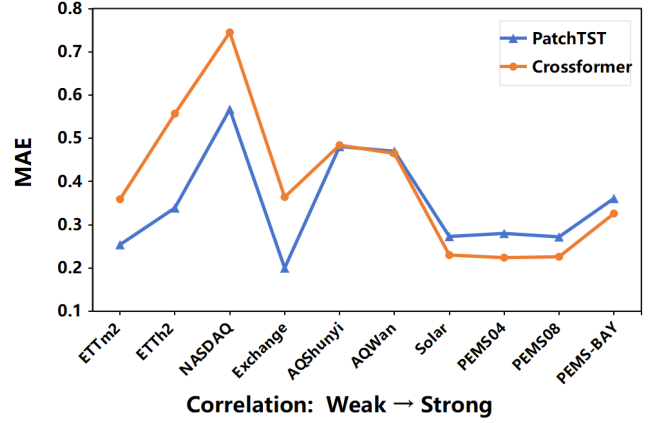


Figure 11: Method performance for varying correlation within datasets.

the best MAE results obtained by CNN, Linear and Transformer. We use a forecasting horizon of 24 for NASDAQ, NYSE, and NN5 and of 96 for other datasets—see Figure 10. We choose CNN as a reference to gain a more comprehensive understanding of the performance of Transformer and Linear methods. We have the following observations. First, each method exhibits distinct advantages on datasets with different characteristics. Second, Linear-based methods excel when the dataset shows an increasing trend or significant shifts. This can be attributed to the linear modeling capabilities of the Linear model, making it well-suited for capturing linear trends and shifts. Third, Transformer-based methods outperform Linear-based methods on datasets exhibiting marked seasonality, stationarity, and nonlinear patterns, as well as more pronounced patterns or strong internal similarities. This superiority may stem from the enhanced nonlinear modeling capabilities of Transformer-based methods, enabling them to flexibly adapt to complex time series patterns and intrinsic correlations.

Therefore, the observed phenomenon underscores the inherent differences between Transformer-based and Linear-based methods at addressing diverse characteristics of time series. To achieve optimal performance, we recommend selecting the appropriate method based on the characteristics of the relevant time series, allowing the method to fully leverage its strengths.

5.3.2 Channel independence vs. channel dependence. In multivariate datasets, variables are occasionally referred to as channels. To study the impact of channel dependency in multivariate time series, we compare PatchTST and Crossformer on ten datasets with dependencies ranging from weak to strong. We report the MAE for forecasting horizon F is 96 in Figure 11. We observe that as the correlations within a dataset increase, the performance of Crossformer gradually surpasses that of PatchTST, suggesting that it is better to consider channel dependencies when correlations are strong. However, when correlations among variables are not pronounced, PatchTST that does not consider channel dependencies is better.

This observation indicates that introducing consideration for dependencies between channels can significantly improve the performance of multivariate time series prediction, especially on datasets with strong correlations, when compared to methods that assume

Table 7: Multivariate forecasting results I.

Model	PatchTST	Crossformer	FEDformer	Informer	Triformer	DLinear	NLinear	MICN	TimesNet	TCN	FiLM	RNN	LR	VAR
Metrics	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse	mae mse mae mse
PEMS04	96	<u>0.280</u> <u>0.161</u> 0.224 0.112	0.565 0.573 0.304 0.189 0.325 0.218	0.296 0.196 0.294 0.202	0.318 0.199 <u>0.266</u> <u>0.159</u>	0.291 0.168	0.297 0.204	0.916 1.318	0.539 0.572	0.3130.192				
	192	<u>0.290</u> <u>0.178</u> 0.236 0.134	0.624 0.655 0.335 0.229 0.353 0.257	0.310 0.213 0.305 0.223	0.380 0.290 <u>0.282</u> <u>0.179</u>	0.303 0.188	0.307 0.219	0.933 1.359	0.588 0.666	0.3360.216				
	336	<u>0.302</u> <u>0.193</u> 0.286 0.190	0.920 1.365 0.323 0.217 0.347 0.250	0.327 0.235 0.324 0.245	0.453 0.384 0.269 0.169	0.336 0.237	0.327 0.243	0.939 1.373	0.601 0.698	0.3620.245				
	720	<u>0.338</u> <u>0.233</u> 0.331 0.235	0.728 0.873 0.391 0.310 0.375 0.284	0.395 0.327 0.396 0.350	0.629 0.677 0.286 0.187	0.354 0.246	0.386 0.322	0.938 1.372	0.658 0.831	0.4090.298				
PEMS-BAY	96	<u>0.361</u> <u>0.567</u> 0.326 0.492	0.540 0.815 0.435 0.844 0.472 0.785	0.404 <u>0.628</u> 0.404 0.642	0.398 0.664 0.429 0.908 0.680 1.300	0.429 0.660	0.659 1.198	1.192 2.934	0.5160.761					
	192	<u>0.382</u> <u>0.619</u> 0.336 0.490	0.583 0.872 0.461 0.912 0.500 0.854	0.419 <u>0.666</u> 0.420 0.687	0.429 0.727 0.448 0.997 0.710 1.327	0.404 0.677	0.659 1.201	1.176 2.776	0.5450.863					
	336	<u>0.403</u> <u>0.670</u> 0.342 0.529	0.609 1.026 0.447 0.834 0.477 0.805	0.439 <u>0.710</u> 0.438 0.735	0.481 0.919 0.429 0.893 0.573 1.040	0.421 0.726	0.660 1.204	1.071 2.310	0.5810.966					
	720	<u>0.448</u> 0.795 0.494 0.850	0.659 1.124 0.498 1.005 0.519 0.900	0.508 <u>0.872</u> 0.516 0.929	0.596 1.105 0.447 0.962 0.544 1.089	0.482 0.895	0.660 1.210	0.959 1.844	0.6171.082					
METR-LA	96	0.629 1.058 <u>0.633</u> 1.232	0.770 1.335 0.664 1.375 0.640 1.048	0.658 1.009 0.650 <u>1.044</u>	0.685 1.256 <u>0.640</u> 1.323 0.716 1.409	0.682 1.282	0.774 1.668	1.968 7.219	0.7061.100					
	192	<u>0.676</u> <u>1.177</u> 0.663 1.312	0.887 1.645 0.707 1.554 0.714 1.222	0.716 1.148 0.720 1.218	0.701 1.359 <u>0.681</u> 1.490 0.860 1.715	0.733 1.223	0.784 1.727	1.955 6.797	0.7541.276					
	336	<u>0.733</u> <u>1.300</u> <u>0.711</u> 1.367	0.840 1.687 <u>0.721</u> 1.615 0.735 <u>1.286</u>	0.742 1.241 0.758 1.339	0.741 1.390 0.688 1.502 0.899 1.811	0.745 1.323	0.791 1.765	1.762 5.511	0.8761.375					
	720	<u>0.779</u> <u>1.466</u> <u>0.773</u> 1.516	0.962 2.018 0.805 1.878 0.782 <u>1.437</u>	0.793 1.415 0.874 1.656	0.780 1.486 0.784 1.801 0.854 1.898	0.825 1.574	0.809 1.849	1.382 3.472	0.8171.478					
PEMS08	96	<u>0.272</u> <u>0.163</u> 0.226 0.119	0.568 0.623 0.345 0.247 0.329 0.226	0.321 0.241 0.317 0.259	0.403 0.310 <u>0.296</u> <u>0.213</u>	0.393 0.299	0.320 0.252	0.879 1.071	4.198 78.523	0.3630.267				
	192	<u>0.295</u> <u>0.201</u> 0.259 0.151	0.690 0.782 0.409 0.351 0.365 0.279	0.342 0.273 0.338 0.300	0.408 0.346 <u>0.321</u> <u>0.264</u>	0.393 0.289	0.341 0.290	0.880 1.072	4.969 90.307	0.4350.393				
	336	<u>0.311</u> <u>0.225</u> 0.276 0.180	0.859 1.256 0.386 0.342 0.365 0.287	0.362 0.299 0.358 0.325	0.438 0.358 <u>0.315</u> <u>0.264</u>	0.446 0.394	0.360 0.309	0.880 1.074	9.553 297.857	0.4740.467				
	720	<u>0.347</u> <u>0.264</u> 0.332 0.254	0.706 0.843 0.467 0.461 0.398 0.330	0.429 0.378 0.426 0.403	0.641 0.732 <u>0.343</u> <u>0.311</u>	0.470 0.466	0.413 0.365	0.883 1.080	311.450 8.7e+5	0.5560.591				
Traffic	96	0.2710.379 <u>0.282</u> 0.514	0.365 0.593 0.371 0.664 0.323 0.589	0.282 <u>0.410</u> <u>0.279</u> <u>0.410</u>	0.295 0.494 0.313 0.600 0.606 1.139	0.284 0.411	1.604 5.834	0.548 0.799	1.0562.355					
	192	<u>0.277</u> 0.394 0.273 0.501	0.375 0.614 0.396 0.724 0.325 0.597	0.288 <u>0.423</u> <u>0.284</u> <u>0.423</u>	0.301 0.521 0.328 0.619 0.559 1.040	<u>0.283</u> <u>0.406</u>	2.120 8.563	0.551 0.794	0.8691.751					
	336	<u>0.281</u> 0.404 0.279 0.507	0.373 0.609 0.435 0.796 0.332 0.617	0.296 0.436 0.291 0.436	0.309 0.552 0.330 0.627 0.540 1.006	<u>0.298</u> <u>0.425</u>	2.405 10.153	0.552 0.802	0.7521.397					
	720	<u>0.302</u> 0.442 0.301 0.571	0.394 0.646 0.453 0.823 0.350 0.650	0.315 <u>0.466</u> <u>0.308</u> <u>0.464</u>	0.328 0.569 0.342 0.659 0.626 1.063	0.370 0.523	2.644 11.596	0.568 0.837	0.6441.113					
Solar	96	0.273 <u>0.190</u> 0.230 0.166	0.530 0.509 0.373 0.338 0.279 0.225	0.287 0.216 <u>0.254</u> <u>0.222</u>	<u>0.250</u> <u>0.193</u> 0.330 0.285 0.265 0.206	0.256 0.225	2.271 6.661	0.365 0.235	0.5930.556					
	192	0.302 0.204 0.251 <u>0.214</u>	0.500 0.474 0.391 0.375 0.295 0.250	0.305 0.244 <u>0.269</u> <u>0.252</u>	<u>0.270</u> <u>0.225</u> 0.342 0.309 0.347 0.304	0.276 0.266	2.258 6.457	0.369 0.253	0.6860.668					
	336	<u>0.293</u> <u>0.212</u> 0.260 0.203	0.439 0.338 0.416 0.417 0.298 0.261	0.319 0.263 <u>0.282</u> <u>0.273</u>	0.301 <u>0.250</u> 0.365 0.335 0.306 0.279	0.299 0.308	2.291 6.604	0.402 0.291	0.7240.710					
	720	0.310 0.221 0.721 0.735	0.459 0.365 0.407 0.390 <u>0.292</u> <u>0.258</u>	0.324 <u>0.264</u> <u>0.282</u> 0.273	0.362 0.323 0.355 0.346 0.269 0.296	0.300 0.310	2.321 6.743	0.452 0.333	0.7510.738					
ETTh1	96	0.343 0.290 0.361 0.310	0.465 0.467 0.424 0.430 0.384 0.342	0.343 <u>0.299</u> <u>0.343</u> <u>0.301</u>	0.349 0.303 0.398 0.377 0.643 0.700	<u>0.343</u> 0.301	0.908 2.087	0.393 0.359	0.6780.889					
	192	0.368 0.329 0.402 0.363	0.536 0.524 0.610 0.479 0.550 0.415 0.389	0.364 <u>0.334</u> <u>0.365</u> <u>0.337</u>	0.368 0.335 0.411 0.405 0.616 0.698	<u>0.365</u> 0.339	1.121 2.961	0.442 0.434	0.7621.031					
	336	0.390 0.360 0.430 0.408	0.544 0.618 0.529 0.654 0.446 0.427	0.384 <u>0.365</u> <u>0.384</u> <u>0.371</u>	0.388 0.366 0.437 0.443 0.764 0.900	<u>0.384</u> 0.373	1.394 4.439	0.488 0.503	0.8031.093					
	720	0.422 <u>0.416</u> 0.637 0.777	0.551 0.615 0.578 0.714 0.484 0.488	<u>0.415</u> <u>0.418</u> <u>0.415</u> 0.426	0.423 0.409 0.464 0.495 0.779 0.979	0.414 0.423	1.594 5.515	0.568 0.632	0.8261.111					
Weather	96	0.196 <u>0.149</u> <u>0.212</u> 0.146	0.292 0.223 0.255 0.218 0.231 0.168	0.230 0.170 0.222 0.179	0.232 0.172 <u>0.219</u> 0.170 0.332 0.262	0.229 0.178	0.545 0.543	0.293 0.201	0.4010.360					
	192	0.240 <u>0.193</u> <u>0.261</u> 0.195	0.322 0.252 0.306 0.269 0.279 0.216	0.267 0.212 0.262 0.218	0.270 0.214 0.264 0.222 0.447 0.420	0.263 0.218	0.545 0.544	0.330 0.240	0.4530.413					
	336	0.281 <u>0.244</u> 0.325 0.268	0.371 0.327 0.340 0.320 0.322 0.271	0.305 <u>0.257</u> <u>0.296</u> <u>0.266</u>	0.309 <u>0.259</u> 0.310 0.293 0.496 0.509	<u>0.295</u> 0.266	0.548 0.549	0.379 0.303	0.4910.459					
	720	0.332 <u>0.314</u> 0.380 0.330	0.419 0.424 0.390 0.392 0.379 0.358	0.356 <u>0.318</u> <u>0.344</u> <u>0.334</u>	<u>0.342</u> 0.308 0.355 0.360 0.474 0.499	<u>0.340</u> 0.332	0.548 0.549	0.447 0.396	0.5390.529					
ILI	24	0.835 1.840 1.096 2.981	1.020 2.400 1.151 2.738 1.728 6.044	1.031 2.208 <u>0.919</u> <u>1.998</u>	1.020 2.279 <u>0.926</u> <u>2.009</u>	1.419 4.194	1.011 2.454	3.125 15.131	14.244 560.589	1.0122.429				
	36	0.845 1.724 1.162 3.295	1.005 2.410 1.145 2.890 1.762 6.226	<u>0.981</u> <u>2.032</u> <u>0.916</u> <u>1.920</u>	1.085 2.451 0.997 2.552 1.514 4.999	1.016 2.412	3.133 15.196	20.263 1252.09	1.0812.851					
	48	0.863 1.762 1.230 3.586	1.033 2.592 1.136 2.742 1.764 6.230	1.063 2.209 <u>0.924</u> <u>1.895</u>	1.077 2.440 <u>0.919</u> <u>1.956</u>	1.458 4.636	1.040 2.398	3.152 15.340	38.509 7473.60	1.1303.060				
	60	0.894 1.752 1.256 3.693	1.070 2.539 1.139 2.825 1.828 6.596	1.086 2.292 <u>0.947</u> <u>1.964</u>	1.009 2.305 <u>0.962</u> <u>2.178</u>	1.639 5.676	0.969 2.227	3.203 15.704	68.997 2.5e+4	1.1523.151				
Electricity	96	0.233 <u>0.133</u> <u>0.237</u> <u>0.135</u>	0.302 0.186 0.321 0.214 0.285 0.185	0.237 <u>0.140</u> <u>0.236</u> 0.141	0.262 0.156 0.267 0.164 0.433 0.371	0.246 0.154	1.651 4.368	0.946 1.641	0.3590.264					
	192	<u>0.248</u> 0.150 <u>0.262</u> 0.160	0.315 0.201 0.350 0.245 0.297 0.196	<u>0.250</u> <u>0.154</u> 0.248 <u>0.155</u>	0.285 0.173 0.280 0.180 0.435 0.371	0.261 0.168	1.657 4.392	0.985 1.738	0.3700.282					
	336	<u>0.267</u> 0.168 0.282 0.182	0.330 0.218 0.393 0.294 0.315 0.215	<u>0.268</u> <u>0.169</u> 0.264 <u>0.171</u>	0.296 0.184 0.292 0.190 0.442 0.371	0.284 0.189	1.663 4.415	1.004 1.796	0.3800.296					
	720	0.295 0.202 0.337 0.246	0.350 0.241 0.393 0.306 0.348 0.265	<u>0.301</u> <u>0.204</u> <u>0.297</u> 0.210	0.311 <u>0.203</u> 0.307 0.209 0.468 0.420	0.340 0.249	1.670 4.445	1.039 1						

Table 8: Multivariate forecasting results II.

Model	PatchTST	Crossformer	FEDformer	Informer	Triformer	DLinear	NLinear	MICN	TimesNet	TCN	FILM	RNN	LR	VAR
Metrics	mae	mse	mae	mse	mae	mse	mae	mse	mae	mse	mae	mse	mae	mse
AQShunyi	0.481	0.648	0.484	0.652	0.525	0.706	0.542	0.754	0.492	0.651	0.486	0.658	0.550	0.807
192	0.501	0.690	0.499	0.674	0.531	0.729	0.536	0.759	0.512	0.691	0.504	0.705	0.750	1.147
336	0.515	0.711	0.515	0.704	0.569	0.824	0.560	0.837	0.529	0.716	0.517	0.725	0.754	1.161
720	0.538	0.770	0.518	0.747	0.561	0.794	0.543	0.777	0.549	0.789	0.544	0.787	0.755	1.172
AQWan	0.470	0.745	0.465	0.750	0.508	0.796	0.522	0.901	0.481	0.756	0.475	0.758	0.475	0.766
192	0.491	0.792	0.479	0.762	0.517	0.825	0.521	0.833	0.519	0.821	0.490	0.779	0.521	0.842
336	0.503	0.819	0.504	0.802	0.537	0.863	0.525	0.847	0.525	0.826	0.505	0.814	0.544	0.900
720	0.533	0.890	0.511	0.830	0.552	0.907	0.532	0.883	0.548	0.891	0.538	0.830	0.536	0.906
NN5	0.612	0.755	0.591	0.741	0.618	0.785	0.949	1.362	0.593	0.750	0.646	0.836	0.651	0.846
24	0.595	0.694	0.589	0.703	0.606	0.727	0.945	1.342	0.577	0.690	0.639	0.790	0.702	0.883
36	0.585	0.667	0.575	0.669	0.607	0.725	0.942	1.337	0.573	0.665	0.632	0.761	0.741	0.969
60	0.582	0.653	0.587	0.683	0.615	0.726	0.946	1.334	0.574	0.658	0.629	0.748	0.747	0.969
WiKe2000	1.023	457.187	1.707	637.822	3.745	681.415	1.569	1219.935	2.028	641.407	1.354	515.430	1.240	643.931
24	1.115	511.946	1.818	691.940	3.233	716.180	1.647	1291.983	2.080	694.272	1.613	773.376	1.381	1040.933
36	1.179	531.902	1.899	718.072	3.026	748.497	1.724	1342.577	2.130	719.606	1.623	786.374	1.577	1448.341
60	1.244	554.829	1.920	730.350	2.953	786.667	1.800	1459.240	2.152	731.595	1.672	814.153	1.239	515.910
Wind	0.652	0.889	0.590	0.784	0.697	1.030	0.674	0.953	0.612	0.845	0.632	0.881	0.640	0.923
192	0.747	1.076	0.698	0.965	0.807	1.275	0.764	1.147	0.692	1.028	0.715	1.034	0.734	1.081
336	0.809	1.209	0.755	1.073	0.864	1.307	0.825	1.310	0.749	1.139	0.779	1.159	0.805	1.228
720	0.851	1.304	0.803	1.191	0.890	1.402	0.864	1.323	0.783	1.169	0.815	1.233	0.852	1.328
ZafNoo	0.426	0.444	0.419	0.432	0.441	0.475	0.473	0.541	0.420	0.442	0.411	0.434	0.410	0.446
192	0.456	0.498	0.449	0.479	0.479	0.544	0.575	0.708	0.448	0.493	0.444	0.484	0.447	0.503
336	0.480	0.530	0.469	0.521	0.517	0.595	0.661	0.851	0.467	0.523	0.464	0.518	0.470	0.544
720	0.499	0.574	0.483	0.543	0.560	0.697	0.699	0.876	0.494	0.563	0.486	0.548	0.504	0.595
CzeLan	0.251	0.183	0.443	0.581	0.310	0.231	0.305	0.250	0.519	0.818	0.289	0.211	0.229	0.178
192	0.271	0.208	0.503	0.705	0.339	0.268	0.337	0.295	0.589	0.962	0.323	0.252	0.252	0.210
336	0.302	0.243	0.596	0.971	0.361	0.298	0.361	0.335	0.659	1.161	0.366	0.317	0.280	0.243
720	0.335	0.273	0.762	1.566	0.446	0.416	0.416	0.384	0.741	1.496	0.392	0.358	0.337	0.284
Covid-19	0.042	1.052	2.297	1768.4320	0.177	2.125	0.079	2.642	2.395	1768.993	0.240	9.587	0.070	1.139
24	0.051	1.398	2.394	1770.6950	0.177	2.463	0.087	3.064	2.432	1769.541	0.173	5.333	0.091	1.582
36	0.060	1.814	2.465	1773.2210	0.192	2.847	0.097	3.698	2.481	1770.224	0.246	9.598	0.099	1.932
60	0.068	2.265	2.427	1772.8350	0.212	3.275	0.106	4.232	2.533	1773.691	0.297	7.778	0.127	2.682
NASDAQ	0.567	0.649	0.745	1.149	0.547	0.627	0.744	1.110	0.330	2.727	0.666	0.830	0.522	0.566
24	0.682	0.821	0.885	1.414	0.659	0.885	0.895	1.399	1.534	3.387	0.862	1.356	0.656	0.827
36	0.793	1.169	1.136	2.108	0.786	1.139	0.864	1.296	1.551	3.412	0.990	1.817	0.757	1.106
60	0.828	1.268	1.230	2.336	0.783	1.251	0.834	1.171	1.528	3.287	1.037	2.011	0.792	1.204
NYSE	0.296	0.226	0.848	0.825	0.297	0.194	0.353	0.280	1.258	2.353	0.335	0.247	0.283	0.193
24	0.375	0.365	0.904	0.942	0.377	0.322	0.417	0.411	1.552	3.381	0.472	0.457	0.360	0.321
36	0.450	0.523	0.962	1.064	0.457	0.477	0.500	0.571	1.737	4.266	0.603	0.709	0.438	0.464
60	0.586	0.771	0.937	1.121	0.557	0.636	0.615	0.782	1.847	4.701	0.696	0.914	0.522	0.631
FRED-MD	1.014	35.777	3.618	380.703	1.623	66.090	1.559	69.980	5.046	395.884	1.070	37.898	0.931	32.125
24	1.345	61.034	3.960	396.700	1.863	94.359	1.867	102.875	5.175	411.328	1.477	71.047	1.258	58.332
36	1.667	93.482	4.110	412.674	2.135	129.798	2.147	138.049	5.234	423.926	2.002	118.579	1.609	82.184
60	2.011	133.444	4.189	420.936	2.435	173.616	2.461	185.188	5.299	432.464	2.221	156.844	1.882	109.625

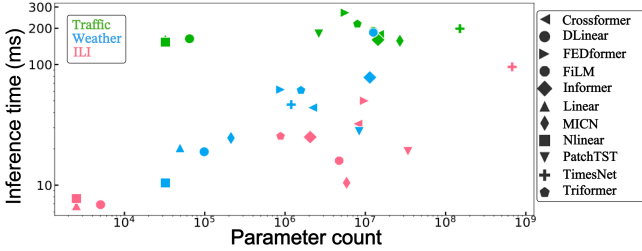


Figure 12: Comparison of parameter counts and inference time for deep learning methods.

the horizontal axis represents the number of parameters on a logarithmic scale and the vertical axis represents the inference time per sample (window in the test dataset) in milliseconds, which is also on a logarithmic scale. The reported parameter counts and inference times refer to the method’s best performance on the dataset. We observe a general upward trend in the inference time as the number of parameters increases, which is intuitive. When considering the running time and number of parameters, Linear-based methods outperform CNN-based and Transformer-based methods. Further, CNN-based methods tend to have a larger number of parameters. Among the Transformer-based methods, we can also observe that PatchTST demonstrates a notable advantage over Triformer and Crossformer in terms of running time.

6 CONCLUSIONS

We present the TFB time series forecasting benchmark that addresses three issues to enable comprehensive and reliable comparison of TSF methods. *To alleviate the insufficient data domains problem*, TFB includes datasets from a total of 10 different domains, covering traffic, electricity, energy, environment, nature, economics, stock, banking, health, and web. We also include a time series characteristics analysis to ensure that selected datasets are well distributed across different characteristics. *To remove the bias on traditional methods*, TFB covers a diverse range of methods, including statistical learning, machine learning, and deep learning methods, accompanied by a variety of evaluation strategies and metrics. Thus, TFB can evaluate the performance of different methods comprehensively. *To address the inconsistent and inflexible pipelines problem*, TFB offers a new flexible and scalable pipeline, eliminating biases and providing a better basis for performance comparison. Overall, TFB is a more comprehensive and fair benchmark that aims to promote the development of new TSF methods.

ACKNOWLEDGMENTS

This work was partially supported by National Natural Science Foundation of China (62372179), Independent Research Fund Denmark under agreement 8048-00038B, and Huawei Cloud Algorithm Innovation Lab.

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