Heterogeneity-Informed Meta-Parameter Learning for Spatiotemporal Time Series Forecasting

KDD2024 BARCELONA, SPAIN

Zheng Dong[1,*], Renhe Jiang[2,*], Haotian Gao[2], Hangchen Liu[1], Jinliang Deng[3], Qingsong Wen[4], Xuan Song[5,1,†]

[1]Southern University of Science and Technology, [2]The University of Tokyo
[3]Hong Kong University of Science and Technology, [4]Squirrel AI, [5]Jilin University

Contributions

1. We propose a novel **Heterogeneity-Informed Meta-Parameter Learning** scheme for spatiotemporal forecasting.
2. It not only captures but explicitly leverages spatiotemporal heterogeneity to **inform** the learning of spatiotemporal-specific model parameters from **meta-parameter** pools.
3. We develop a forecasting model **HimNet** that achieves SOTA performance and superior **interpretability**.

Introduction

■ **Spatial Heterogeneity:**

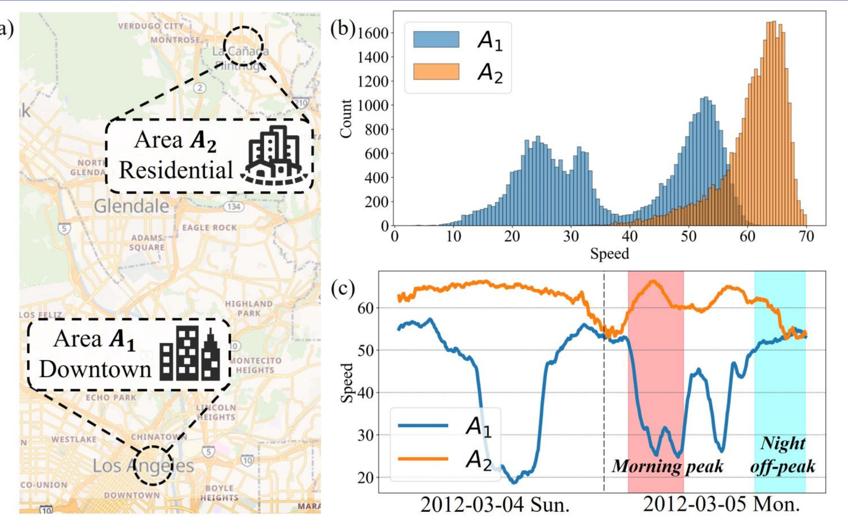
- **Different locations** + same time = different patterns

  e.g. different traffic speed distribution of A_1 and A_2

■ **Temporal Heterogeneity:**

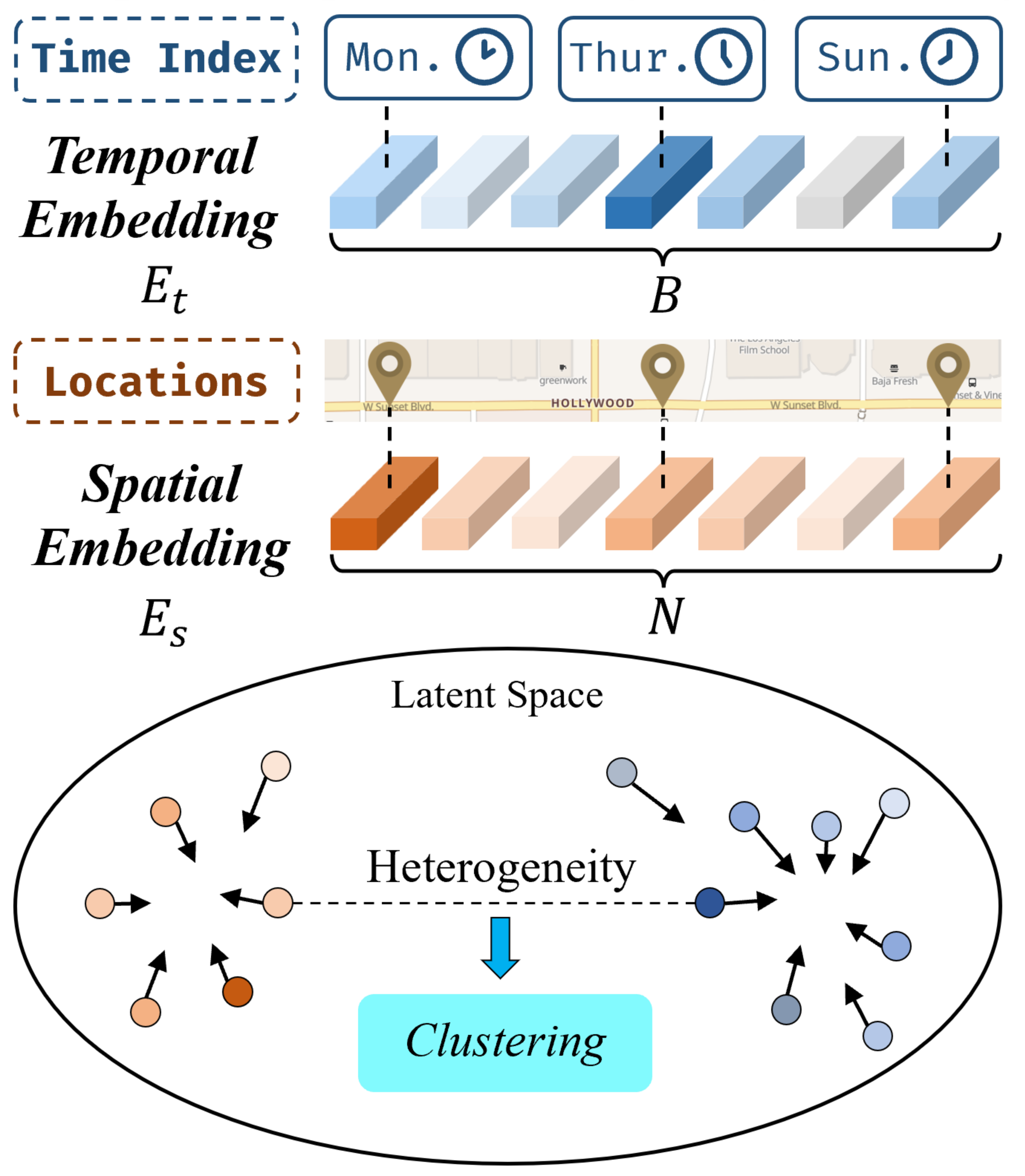
- Same location + **different times** = different patterns

  e.g. different speed patterns between Sun. and Mon.

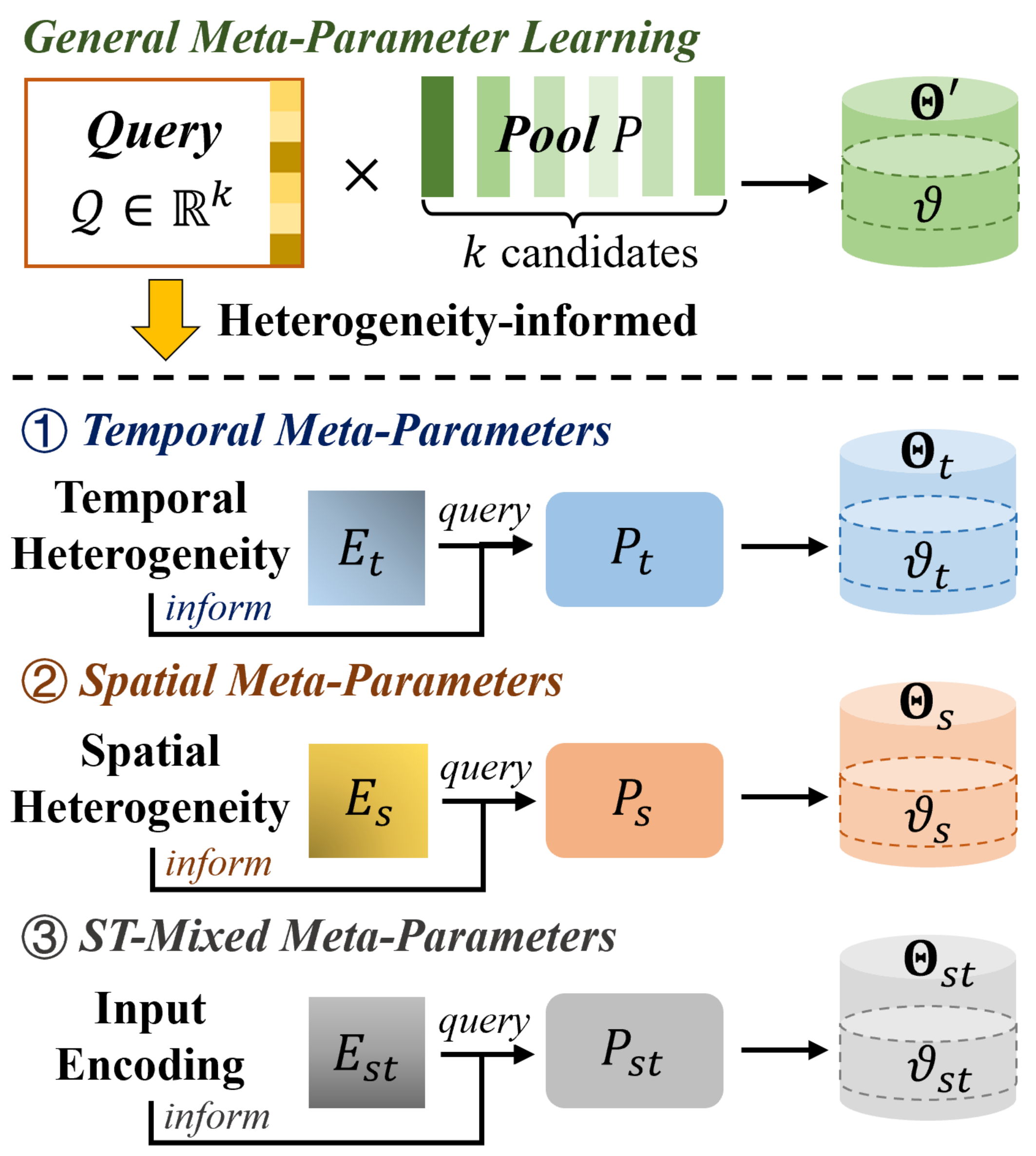


Methodology: Heterogeneity-Informed Meta-Parameter Learning

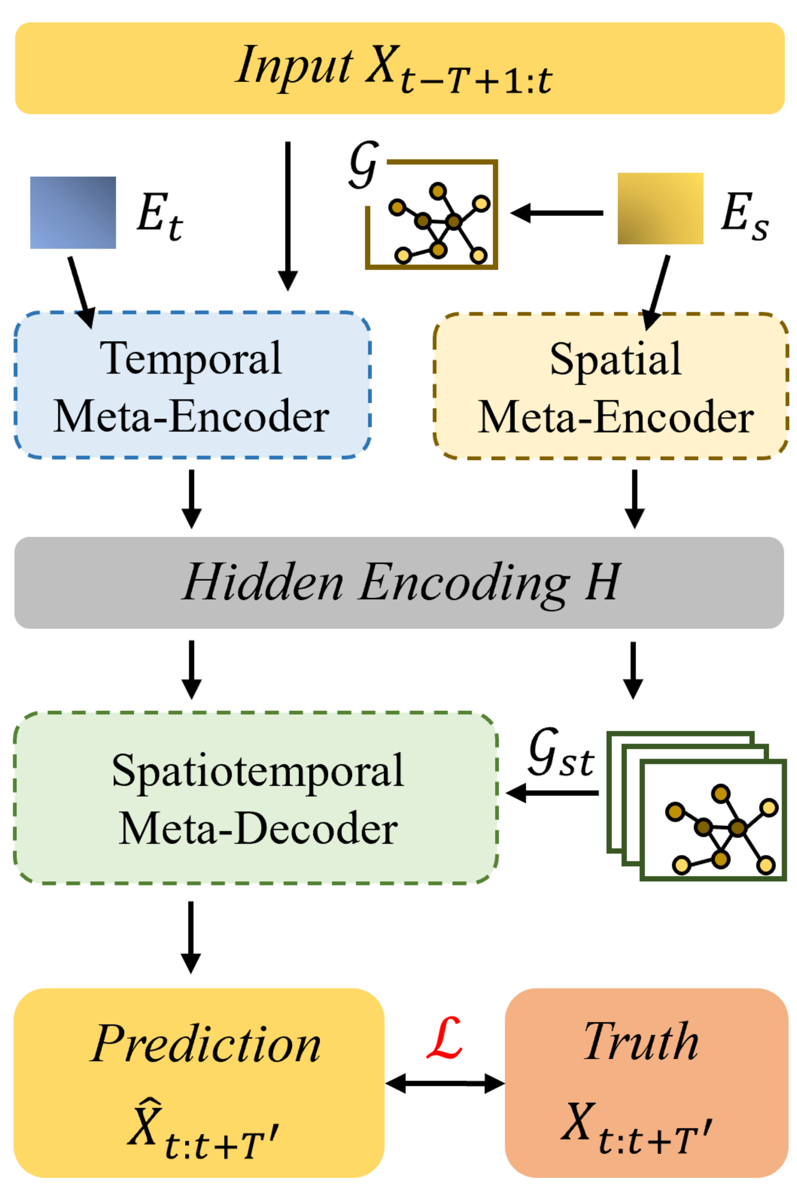
(a) Spatiotemporal Heterogeneity Modeling



(b) Spatiotemporal Meta-Parameter Learning



(c) HimNet Architecture



■ **Modeling Heterogeneity**

- The **clustering** view
- Hetero. of ST data → Hetero. of embeddings

■ **Learning Meta-Parameter**

- Meta-parameter pool

  $P = [\vartheta_1, \vartheta_2, \dots, \vartheta_k]$

- General formulation

  $\vartheta = QP = \sum Q_i \vartheta_i$

- *Spatial*/*Temporal*/*ST-Mixed*

  $\vartheta_{\{s,t,st\}} = E_{\{s,t,st\}} P_{\{s,t,st\}}$

  E_{st}: encoding of input X

■ **Heterogeneity-Informed ST Meta-Network**

- GCRU-based architecture
- Parameters are dynamically generated on each input via Meta-Parameter Learning

Experiments

■ Forecasting Performance on METRLA, PEMSBAY, and PEMS04/07/08

Dataset		Metric	HI	GRU	STGCN	DCRNN	GWNet	AGCRN	GTS	STNorm	STID	ST-WA	PDFormer	MegaCRN	HimNet
METRLA	Step 3 15 min	MAE	6.80	3.07	2.75	2.67	2.69	2.85	2.75	2.81	2.82	2.89	2.83	2.65	**2.60**
		RMSE	14.21	6.09	5.29	5.16	5.15	5.53	5.27	5.57	5.53	5.62	5.45	5.08	**5.02**
		MAPE	16.72%	8.14%	7.10%	6.86%	6.99%	7.63%	7.12%	7.40%	7.75%	7.66%	7.77%	6.73%	**6.70%**
	Step 6 30 min	MAE	6.80	3.77	3.15	3.12	3.08	3.20	3.14	3.18	3.19	3.25	3.20	3.04	**2.95**
		RMSE	14.21	7.69	6.35	6.27	6.20	6.52	6.33	6.59	6.57	6.61	6.46	6.18	**6.06**
		MAPE	16.72%	10.71%	8.62%	8.42%	8.47%	9.00%	8.62%	8.47%	9.39%	9.22%	9.19%	8.22%	**8.11%**
	Step 12 60 min	MAE	6.80	4.88	3.60	3.54	3.51	3.59	3.59	3.57	3.55	3.68	3.62	3.51	**3.37**
		RMSE	14.21	9.75	7.43	7.47	7.28	7.45	7.44	7.51	7.55	7.59	7.47	7.39	**7.22**
		MAPE	16.71%	14.91%	10.35%	10.32%	9.96%	10.47%	10.25%	10.24%	10.95%	10.78%	10.91%	10.01%	**9.79%**
PEMSBAY	Step 3 15 min	MAE	3.05	1.44	1.36	1.31	1.30	1.35	1.37	1.33	1.31	1.37	1.32	1.28	**1.27**
		RMSE	7.03	3.15	2.88	2.76	2.73	2.88	2.92	2.82	2.79	2.88	2.83	2.71	**2.68**
		MAPE	6.85%	3.01%	2.86%	2.73%	2.71%	2.91%	2.85%	2.76%	2.78%	2.86%	2.78%	2.67%	**2.64%**
	Step 6 30 min	MAE	3.05	1.97	1.70	1.65	1.63	1.67	1.72	1.65	1.64	1.70	1.64	1.60	**1.57**
		RMSE	7.03	4.60	3.84	3.75	3.73	3.82	3.86	3.77	3.73	3.81	3.79	3.69	**3.60**
		MAPE	6.84%	4.45%	3.79%	3.71%	3.73%	3.81%	3.88%	3.66%	3.73%	3.81%	3.71%	3.60%	**3.52%**
	Step 12 60 min	MAE	3.05	2.70	2.02	1.97	1.99	1.94	2.06	1.92	1.91	2.00	1.91	1.90	**1.84**
		RMSE	7.01	6.28	4.63	4.60	4.60	4.50	4.60	4.45	4.42	4.52	4.43	4.49	**4.32**
		MAPE	6.83%	6.72%	4.72%	4.68%	4.71%	4.55%	4.88%	4.46%	4.55%	4.63%	4.51%	4.53%	**4.33%**
PEMS04	Average	MAE	42.35	25.55	19.57	19.63	18.53	19.38	20.96	18.96	18.38	19.06	18.36	18.72	**18.14**
		RMSE	61.66	39.71	31.38	31.26	29.92	31.25	32.95	30.98	29.95	31.02	30.03	30.53	**29.88**
		MAPE	29.92%	17.35%	13.44%	13.59%	12.89%	13.40%	14.66%	12.69%	12.04%	12.52%	12.00%	12.77%	**12.00%**
PEMS07	Average	MAE	49.29	26.74	21.74	21.16	20.47	20.57	22.15	20.50	19.61	20.74	19.97	19.83	**19.21**
		RMSE	71.34	42.78	35.27	34.14	33.47	34.40	35.10	34.66	32.79	34.05	32.95	32.91	**32.75**
		MAPE	22.75%	11.58%	9.24%	9.02%	8.61%	8.74%	9.38%	8.75%	8.30%	8.77%	8.55%	8.36%	**8.03%**
PEMS08	Average	MAE	34.66	19.36	16.08	15.22	14.40	15.32	16.49	15.41	14.21	15.41	13.58	14.75	**13.57**
		RMSE	50.45	31.20	25.39	24.17	23.39	24.41	26.08	24.77	23.28	24.62	23.41	23.73	**23.22**
		MAPE	21.63%	12.43%	10.60%	10.21%	9.21%	10.03%	10.54%	9.76%	9.27%	9.94%	9.05%	9.48%	**8.98%**

- **HimNet** achieves SOTA performance on **5 benchmarks** against **12 baselines**

■ Ablation Study: Average Prediction MAE

Model	METRLA	PEMSBAY	PEMS04	PEMS07	PEMS08
w/o E_t	2.94	1.53	18.35	22.00	14.14
w/o E_s	3.49	1.74	21.30	19.26	14.79
w/o E_{st}	3.07	1.55	18.55	19.77	13.61
w/o TMP	2.94	1.54	18.65	19.58	14.44
w/o SMP	3.53	1.75	21.41	22.26	14.07
w/o STMP	3.01	1.57	18.65	19.86	13.72
HimNet	**2.92**	**1.51**	**18.14**	**19.21**	**13.57**

- **w/o *E***: replaces embedding with a static matrix of all ones, thus removing heterogeneity modeling
- **w/o MP**: removes meta-parameters by downgrading to randomly initialized parameters

Contact Us

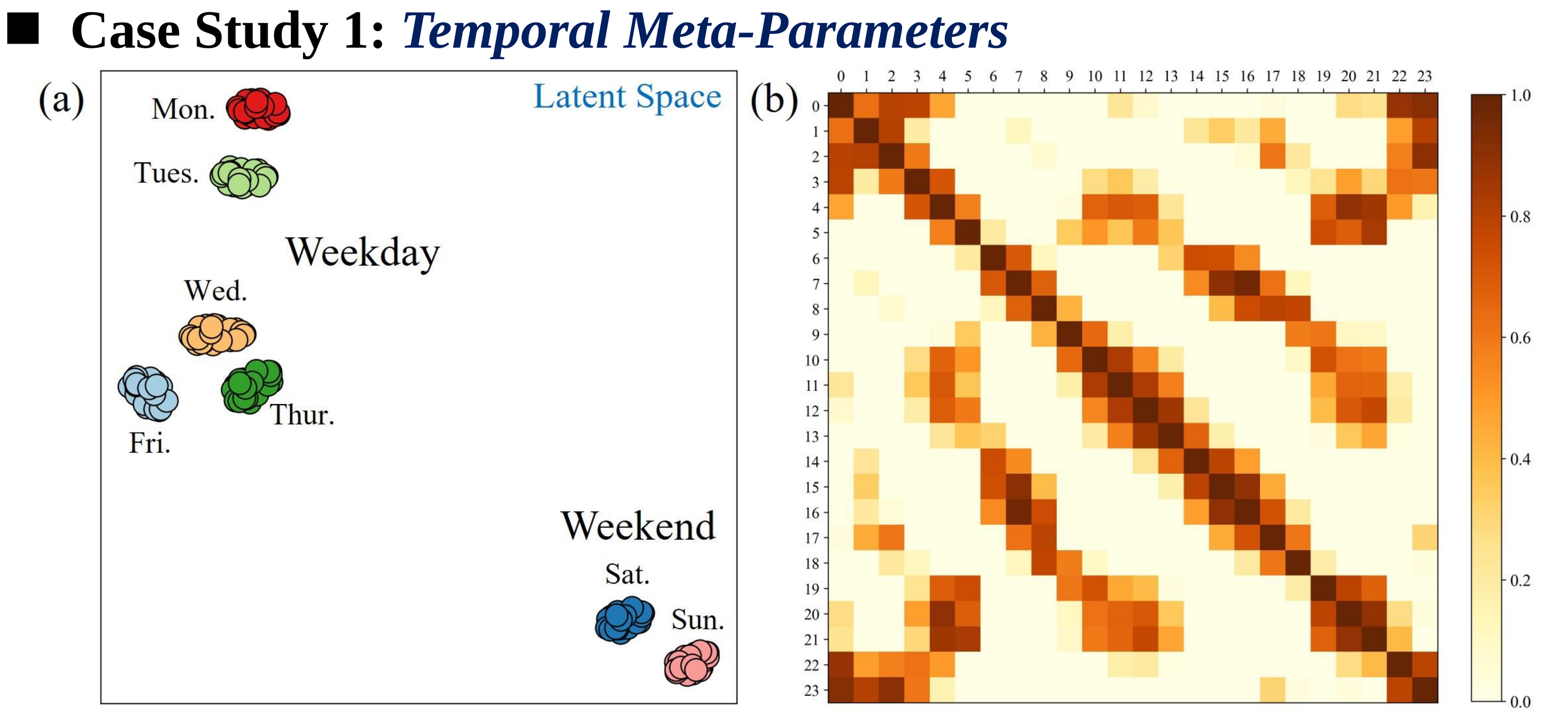
GitHub **WeChat**

■ Efficiency Comparison

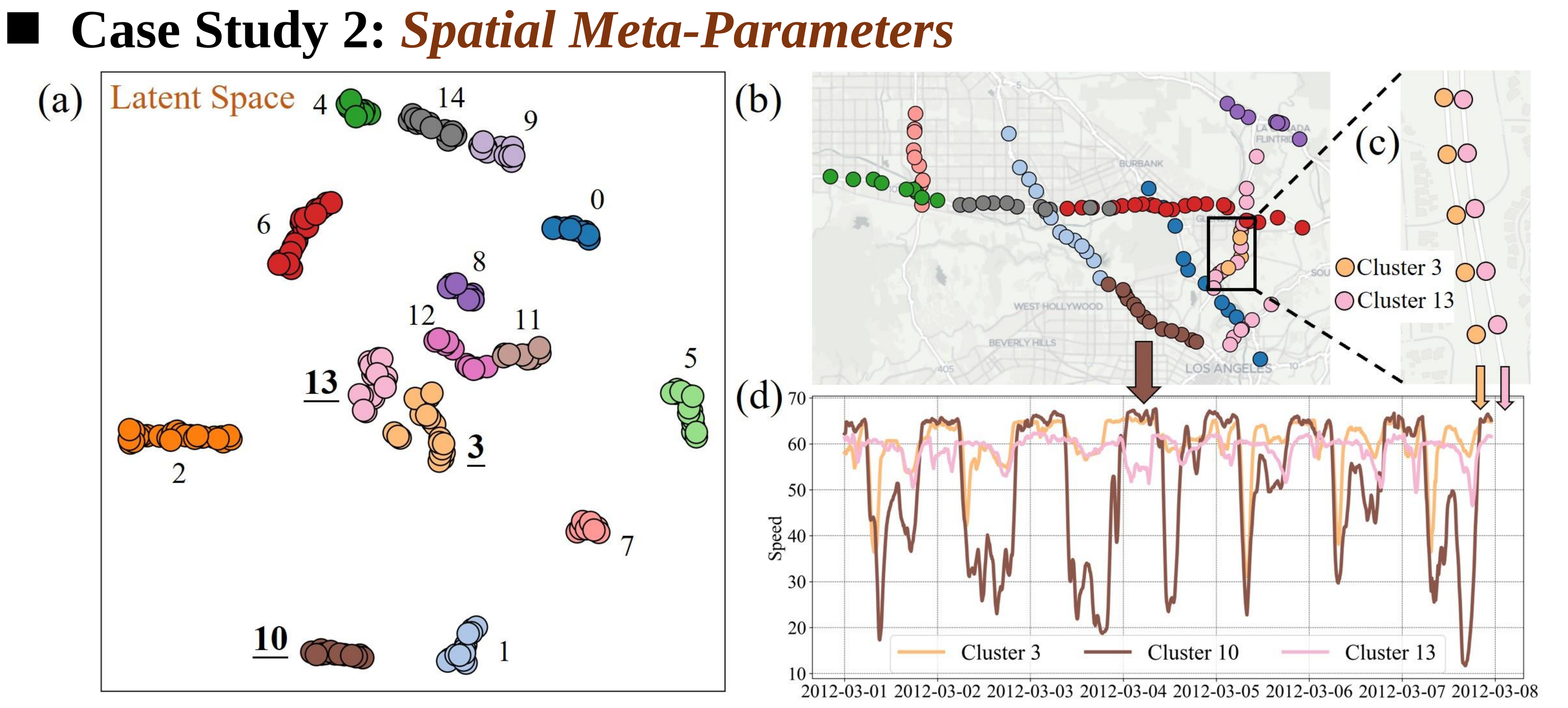
Model	#Params	Time / Batch	Time / Epoch	Mem Usage
STID [51]	118K	8ms	12s	1420MB
STGCN [64]	246K	23ms	34s	1650MB
GWNet [60]	309K	40ms	60s	1994MB
STNorm [11]	224K	39ms	59s	1818MB
DCRNN [36]	372K	189ms	284s	2134MB
AGCRN [2]	752K	54ms	82s	2492MB
GTS [49]	38.5M	114ms	171s	4096MB
MegaCRN [28]	389K	89ms	134s	1962MB
ST-WA [8]	375K	135ms	203s	2668MB
PDFormer [26]	531K	173ms	260s	6938MB
HimNet-Θ'	10.9B	N/A	N/A	N/A
HimNet	1251K	97ms	144s	6056MB

Interpretability

■ Case Study 1: *Temporal Meta-Parameters*



■ Case Study 2: *Spatial Meta-Parameters*



■ Case Study 3: *ST-Mixed Meta-Parameters*