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# Quantifying Time Series Periodicity with Interpretable Machine Learning

Climate Systems & Urban Human Mobility

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Cambridge, USA

# Spatiotemporal Data

- Transport & mobility & climate application scenarios



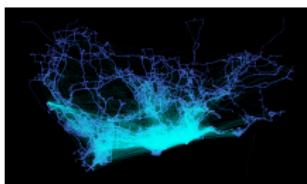
Highway (Portland)



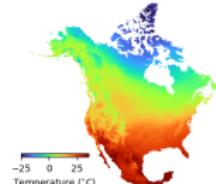
Uber movement (NYC)



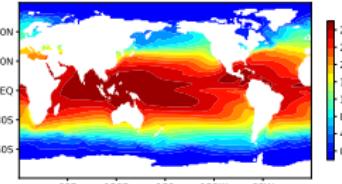
Uber movement (Seattle)



Taxi trajectory (Shenzhen)



Temperature (NA)

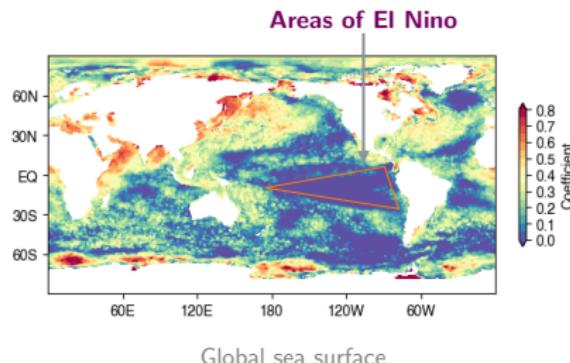
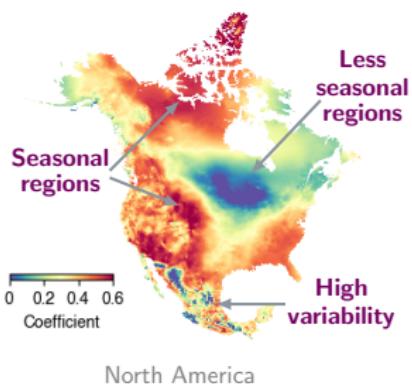


Temperature (sea surface)

- Challenges: Sparsity, high-dimensionality, multi-dimensionality, heavy tails, irregular sampling, and time-varying systems

# Motivation

Yearly temperature seasonality patterns in 2010s

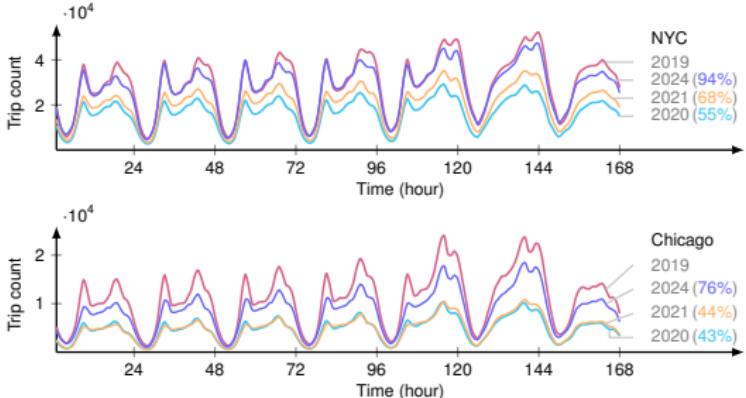
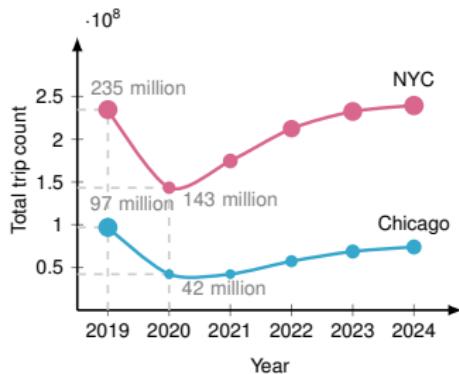


What motivates us most about periodicity?

- ① **Monitoring climate systems:** Empirically measure the periodicity of climate variables (e.g., temperature, precipitation).
- ② **Discovering spatiotemporal patterns:** Identify periodicity pattern shift and special climate events.

# Motivation

## Ridesharing trip data



## What motivate us most about periodicity?

- ① Resilience and stability of systems:** Empirically measure the periodicity and predictability of urban systems.
- ② Optimization of transport systems:** Optimize resources (e.g., public transit, taxi, ridesharing, micromobility) to meet transport demand efficiently.
- ③ Design of sustainable transport & infrastructure:** Implement energy-efficient solutions (e.g., congestion pricing) tailored to peak hours.



## Interpretable Time Series Autoregression



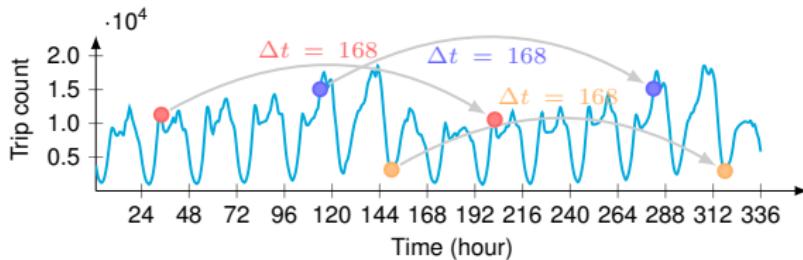
<https://github.com/xinychen/integers>

- Interpretable ML
- $\ell_0$ -norm optimization
- Climate system seasonality
- Sparse autoregression
- Mixed-integer optimization
- Human mobility regularity

# Valorizing Autoregression

- Time series autoregression on  $\textcolor{blue}{x} \in \mathbb{R}^T$  with order  $d \in \mathbb{Z}^+$

$$\boldsymbol{w} := \arg \min_{\boldsymbol{w}} \sum_{t=d+1}^T \left( \textcolor{blue}{x}_t - \sum_{k=1}^d w_k \textcolor{blue}{x}_{t-k} \right)^2$$



Periodicity of hourly rideshare trip time series

- Sparse** coefficient vector  $\mapsto$  **Interpretability?**

$$\underbrace{\boldsymbol{w}}_{\text{sparsity } \|\boldsymbol{w}\|_0 \triangleq 3} = (\underbrace{0.33}_{k=1}, 0, \dots, 0, \underbrace{0.20}_{k=167}, \underbrace{0.46}_{k=168})^\top \in \mathbb{R}^{168}$$

# Sparse Autoregression

- Identify the dominant auto-correlations
  - $\tau \in \mathbb{Z}^+$ : Upper bound of the number of nonzero entries in  $w \in \mathbb{R}^d$

$$\tilde{x} \approx A \begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{pmatrix} \quad \left\| w \right\|_0 \leq \tau$$

$$w := \arg \min_{\|w\|_0 \leq \tau} \sum_{t=d+1}^T \left( x_t - \sum_{k=1}^d w_k x_{t-k} \right)^2$$

$$= \arg \min_{\|w\|_0 \leq \tau} \|\tilde{x} - Aw\|_2^2$$

- $\ell_0$ -norm optimization is NP-hard
- Formulate it as a mixed-integer programming
  - Introduce binary decision variables  $\beta \in \{0, 1\}^d$

$$\min_w \|\tilde{x} - Aw\|_2^2 \quad \iff \quad \min_{w, \beta} \|\tilde{x} - Aw\|_2^2$$

$$\text{s.t. } \underbrace{\|w\|_0 \leq \tau}_{\clubsuit \text{ sparsity of } w} \quad \iff \quad \text{s.t. } \underbrace{-\beta \leq w \leq \beta}_{\text{bounds being either 0 or } \pm 1}, \quad \underbrace{\|\beta\|_1 \leq \tau}_{\clubsuit \text{ sparsity of } \beta}$$

# Sparse Autoregression Done Right

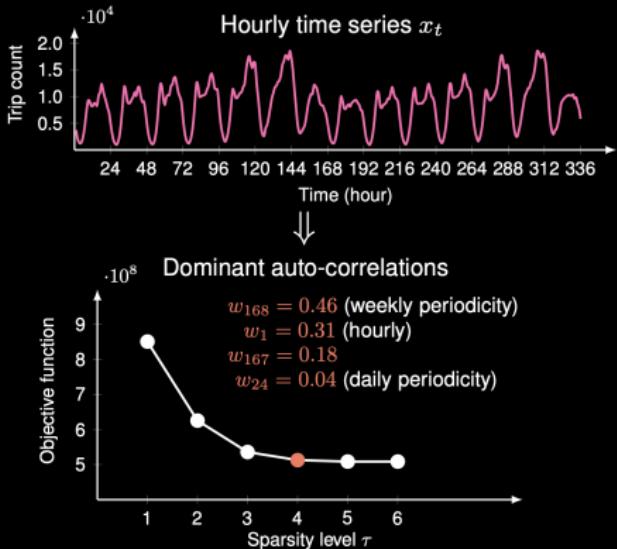
$$\min_{\mathbf{w}, \boldsymbol{\beta}} \underbrace{\sum_{t=d+1}^T \left( x_t - \sum_{k=1}^d w_k x_{t-k} \right)^2}_{\text{Time series autoregression}} \quad \text{s.t. } \underbrace{-\beta_k \leq w_k \leq \beta_k}_{\text{Lower and upper bounds}}, \quad \underbrace{\sum_{k=1}^d \beta_k \leq \tau}_{\clubsuit \text{ Sparsity}} , \quad \underbrace{\beta_k \in \{0, 1\}}_{\text{Binary variable}}$$

- $\mathbf{w} \in \mathbb{R}^d$ : Auto-correlations
- $\boldsymbol{\beta} \in \{0, 1\}^d$ : Sparsity pattern
- $d = 168$ : Autoregression order

```

1 import numpy as np
2 from docplex.mp.model import Model
3
4 def sparse_ar(x, d, tau):
5     model = Model('Sparse Autoregression')
6     T = x.shape[0]
7     w = [model.continuous_var(name = f'w_{k}') for k in range(d)]
8     beta = [model.binary_var(name = f'beta_{k}') for k in range(d)]
9     model.minimize(model.sum((x[t] - model.sum(w[k] * x[t - k - 1]
10                                for k in range(d))) ** 2
11                                for t in range(d, T)))
12     model.add_constraint(model.sum(beta[k] for k in range(d)) <= tau)
13     for k in range(d):
14         model.add_constraint(w[k] <= beta[k])
15         model.add_constraint(w[k] >= -beta[k])
16     solution = model.solve()
17     return np.array(solution.get_values(w))

```



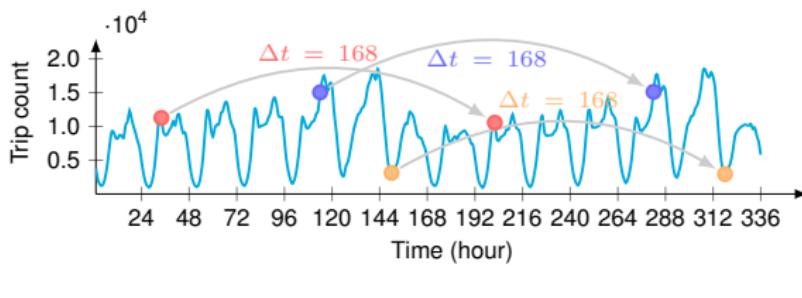
<https://github.com/xinychen/integers>

## Solution Quality → Better Interpretability?

- Sparse autoregression

$$\min_{\mathbf{w} \geq 0} \|\tilde{\mathbf{x}} - \mathbf{A}\mathbf{w}\|_2^2 \quad \text{s.t. } \|\mathbf{w}\|_0 \leq \tau$$

- Subspace pursuit (SP) sometimes fails

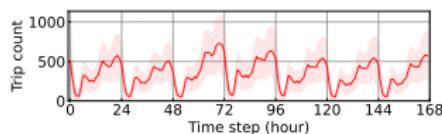
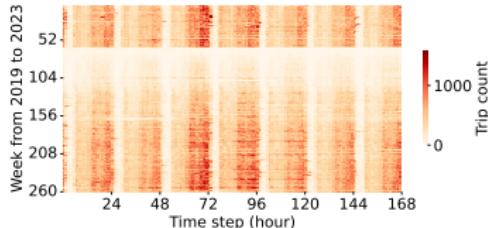


- Exact solution w/ mixed-integer programming (MIP)
- An intuitive example (sparsity  $\tau = 2$ ):

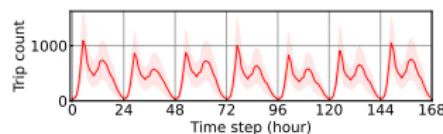
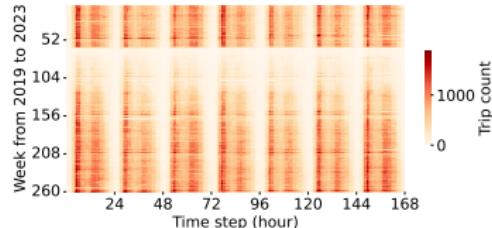
$$\underbrace{\mathbf{w} = (\dots, \underbrace{0.02}_{k=53}, \dots, \underbrace{0.96}_{k=168})^\top}_{\text{obj. } = 8.32 \times 10^7 \text{ (SP)}} \quad \text{vs.} \quad \underbrace{\mathbf{w} = (\underbrace{0.22}_{k=1}, \dots, \underbrace{0.77}_{k=168})^\top}_{\clubsuit \text{ obj. } = 6.25 \times 10^7 \text{ (MIP)}}$$

# John F. Kennedy International Airport

- Daily & weekly periodicity: **dropoff > pickup** trips at JFK airport
  - Pickup trips are relevant to flight delay, baggage claim, and other factors.
  - Dropoff trips to airport are highly related to flight schedules.



Pickup trips from airport



Dropoff trips to airport

- Sparse coefficient vectors (**sparsity  $\tau = 3$** ):

$$\mathbf{w} = (\underbrace{0.31}_{k=1}, \dots, \underbrace{0.28}_{k=24}, \dots, \underbrace{0.41}_{k=168})^\top \quad \text{vs.} \quad \mathbf{w} = (\underbrace{0.18}_{k=1}, \dots, \underbrace{0.35}_{k=24}, \dots, \underbrace{0.47}_{k=168})^\top$$

## High-Dimensional Sparse Autoregression

- On high-dimensional time series with a large  $N$ :

$$\begin{aligned} & \underbrace{\min_{\{\boldsymbol{w}_n\}_{n=1}^N, \boldsymbol{\beta}}}_{(N+1)d \text{ decision var.}} \quad \underbrace{\sum_{n=1}^N \|\tilde{\boldsymbol{x}}_n - \boldsymbol{A}_n \boldsymbol{w}_n\|_2^2}_{\text{multivariate time series}} \\ \text{s.t.} \quad & \underbrace{0 \leq \boldsymbol{w}_n \leq \boldsymbol{\beta},}_{\text{bounds being either 0 or 1}} \quad \underbrace{\|\boldsymbol{\beta}\|_1 \leq \tau,}_{\text{sparsity of } \boldsymbol{\beta}} \quad \boldsymbol{\beta} \in \{0, 1\}^d \end{aligned}$$

- How to handle millions of time series (e.g.,  $N \geq 10^6$ )?

# High-Dimensional Sparse Autoregression

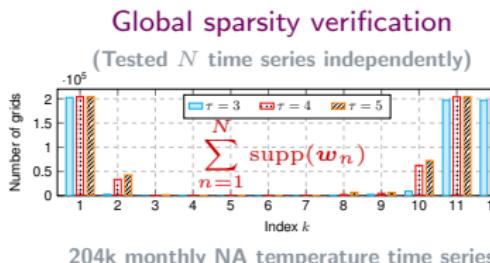
- On high-dimensional time series with a large  $N$ :

$$\begin{aligned}
 & \underbrace{\min_{\{\mathbf{w}_n\}_{n=1}^N, \boldsymbol{\beta}}}_{(N+1)d \text{ decision var.}} \quad \underbrace{\sum_{n=1}^N \|\tilde{\mathbf{x}}_n - \mathbf{A}_n \mathbf{w}_n\|_2^2}_{\text{multivariate time series}} \\
 \text{s.t.} \quad & \underbrace{0 \leq \mathbf{w}_n \leq \boldsymbol{\beta},}_{\text{bounds being either 0 or 1}} \quad \underbrace{\|\boldsymbol{\beta}\|_1 \leq \tau,}_{\text{sparsity of } \boldsymbol{\beta}} \quad \boldsymbol{\beta} \in \{0, 1\}^d
 \end{aligned}$$

- How to handle millions of time series (e.g.,  $N \geq 10^6$ )?
- Two-stage optimization (♣):

① Learn sparsity patterns in  $\boldsymbol{\beta} \in \{0, 1\}^d$

$$\begin{aligned}
 & \min_{\mathbf{w}, \boldsymbol{\beta}} \underbrace{\text{tr}(\mathbf{w} \mathbf{w}^\top \mathbf{P})}_{\text{quadratic}} - \underbrace{2 \mathbf{w}^\top \mathbf{q}}_{\text{linear}} \\
 \text{s.t.} \quad & 0 \leq \mathbf{w} \leq \boldsymbol{\beta}, \quad \|\boldsymbol{\beta}\|_1 \leq \tau
 \end{aligned}$$



② Quadratic programming with index set  $\Omega = \text{supp}(\boldsymbol{\beta})$

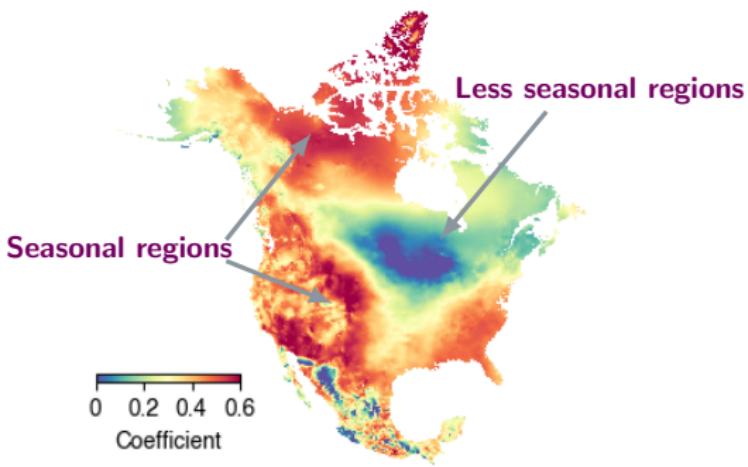
$$\mathbf{w}_n := \arg \min_{\mathbf{w} \geq 0} \|\tilde{\mathbf{x}}_n - \mathbf{A}_n \mathbf{w}\|_2^2 \quad \text{s.t. } w_k = 0, \forall k \notin \Omega$$

## Climate System Seasonality Patterns

(arXiv:2506.22895)

- North America temperature/precipitation     Sea surface temperature
- Climate variable seasonality     Spatiotemporal patterns

## Motivation



Yearly temperature **seasonality** pattern in 2010s

# Understanding Climate Systems

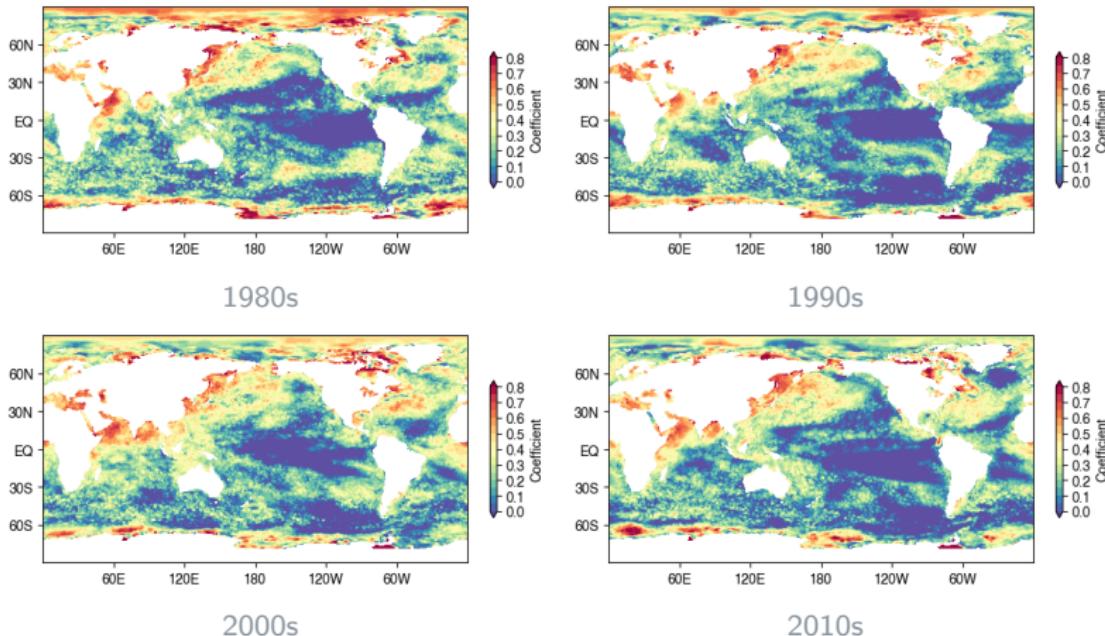
Quantify yearly seasonality by  $\{w_{m,n,\gamma,k}\}$  at index  $k = 12$

$$\min_{\{\mathbf{w}_{m,n,\gamma}\}, \boldsymbol{\beta}} \sum_{m=1}^M \sum_{n=1}^N \sum_{\gamma=1}^{\delta} \|\tilde{\mathbf{x}}_{m,n,\gamma} - \mathbf{A}_{m,n,\gamma} \mathbf{w}_{m,n,\gamma}\|_2^2$$

longitude  
latitude | decade      monthly  
          ↓        ↓        ↓      temperature

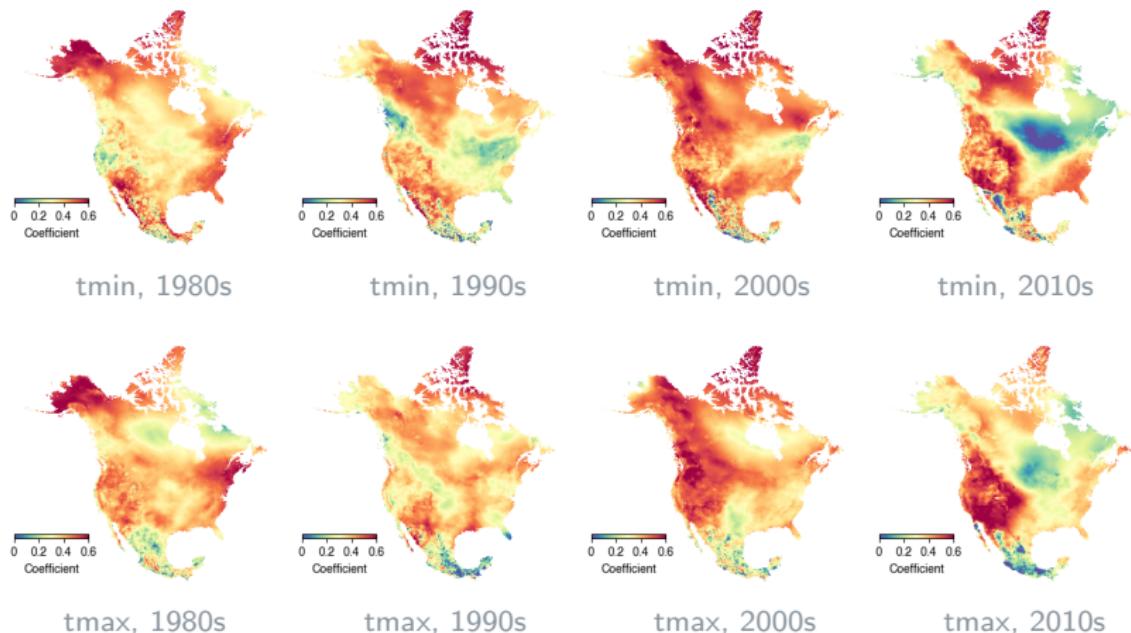
s.t.  $0 \leq \mathbf{w}_{m,n,\gamma} \leq \boldsymbol{\beta}$       sparsity constraint  
 $\|\boldsymbol{\beta}\|_1 \leq \tau$   
 $\boldsymbol{\beta} \in \{0, 1\}^d$       binary decision var.

# Sea Surface Temperature



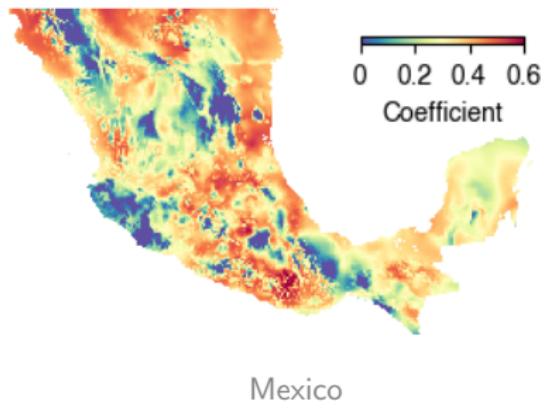
- Identify yearly periodicity at  $k = 12$  from SST data ( $\tau = 3$ )
  - ❶ The areas of El Niño events are less seasonal/predictable
  - ❷ Arctic becomes less seasonal/predictable in the past 20 years

# North America Temperature



- Identify yearly periodicity at  $k = 12$  from temperature data ( $\tau = 3$ )
  - ❶ Stronger yearly seasonality in high-latitude areas
  - ❷ Less seasonal temperature in south areas (e.g., Mexico)
  - ❸ Seasonality patterns in 2000s & 2010s are different from 1980s & 1990s

## North America Temperature



# Human Mobility Regularity

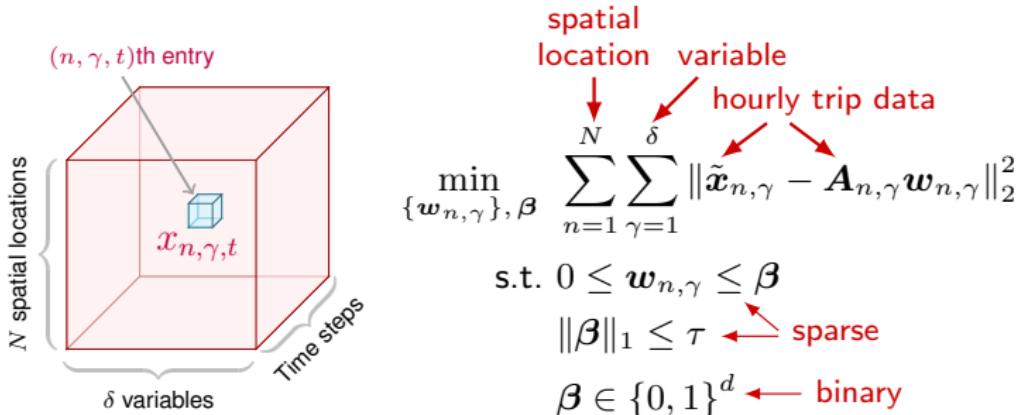
Applications and Case Studies

(arXiv:2508.03747)

- NYC & Chicago ridesharing     Multi-modal mobility regularity
- Hangzhou metro passenger flow     Network resilience

# Envisioning Human Mobility

- Human mobility data

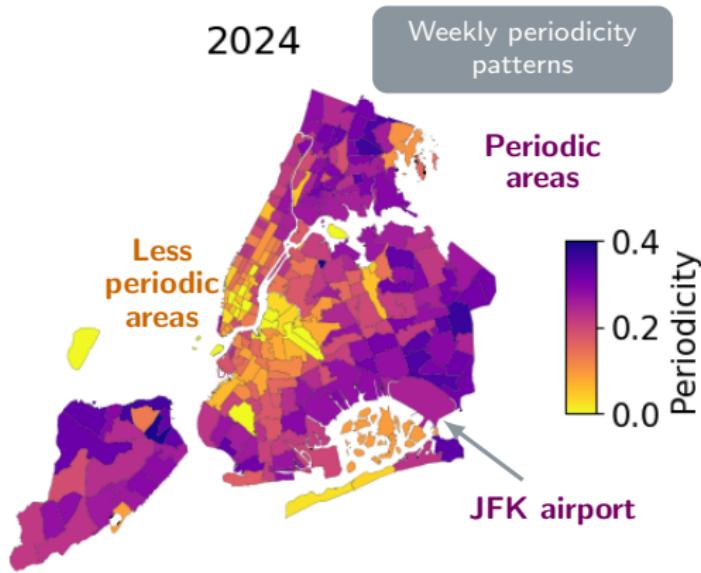


- Quantify **weekly periodicity** by  $\{\mathbf{w}_{n,\gamma,k}\}$  at index  $k = 168$

$$\text{Trip data at } t \approx \sum_{k \in [d]} \text{Coefficients} \times \text{Trip data at } t - k$$

The diagram illustrates the decomposition of trip data. On the left, a grid of pink circles represents "Trip data at  $t$ ". It has a brace indicating "N locations" vertically and "δ variables" horizontally. This is followed by an approximation symbol ( $\approx$ ) and a sum symbol ( $\sum$ ). The sum is over  $k \in [d]$ , where  $d$  is the number of coefficients. The term in the sum consists of two grids: one of blue circles labeled "Coefficients" and one of pink circles labeled "Trip data at  $t - k$ ".

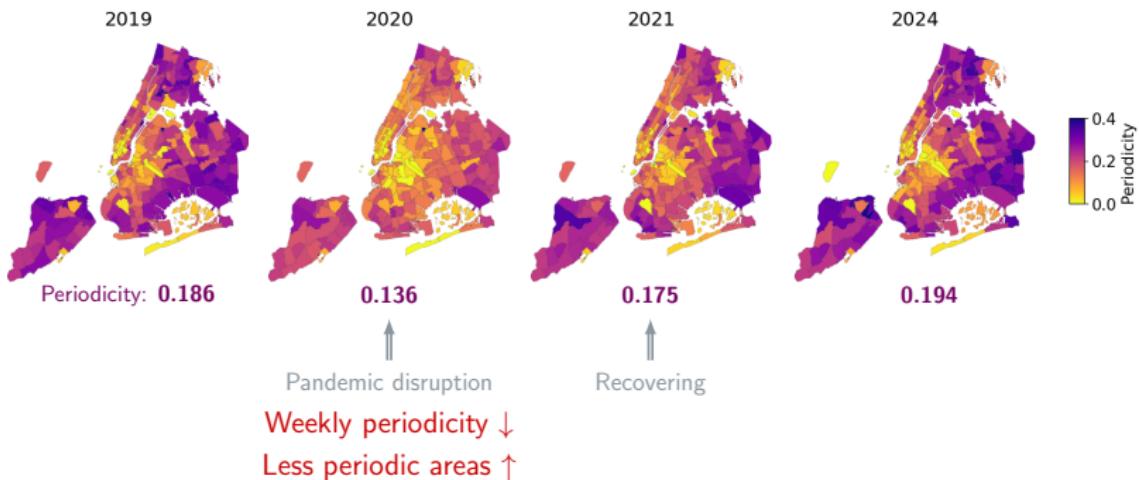
# NYC Ridesharing



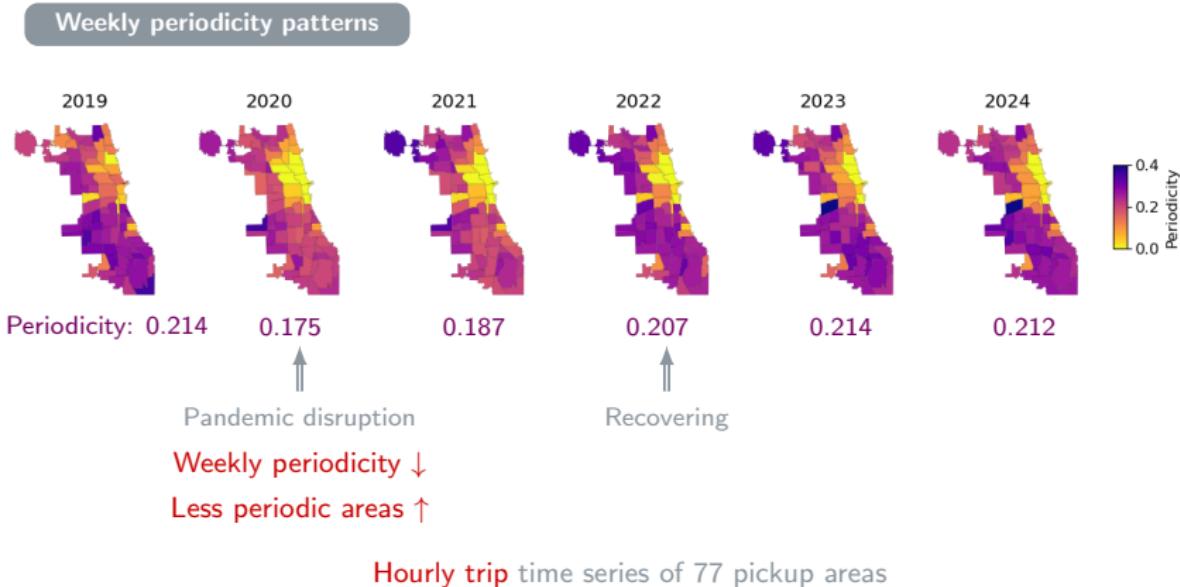
Hourly trip time series of 265 pickup areas

# NYC Ridesharing

## Weekly periodicity patterns

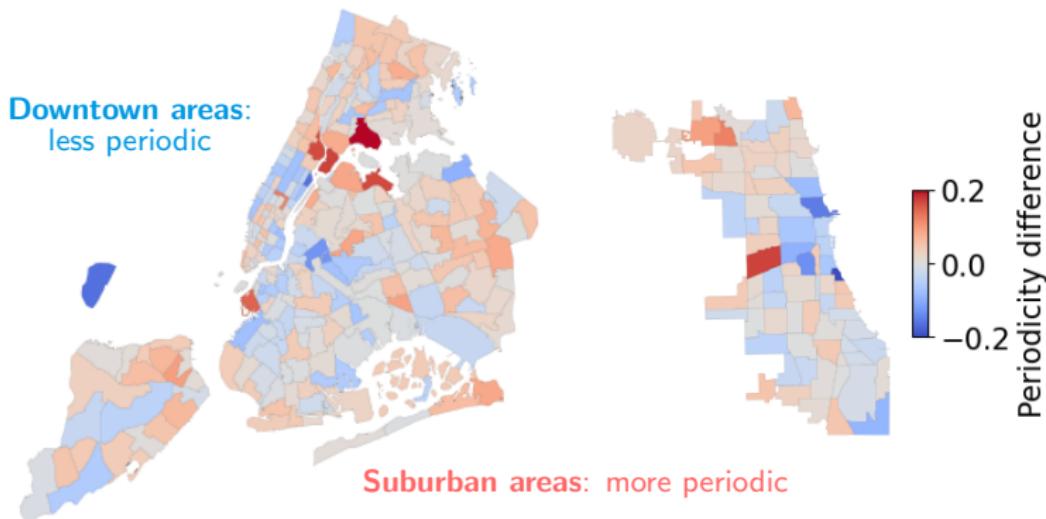


# Chicago Ridesharing

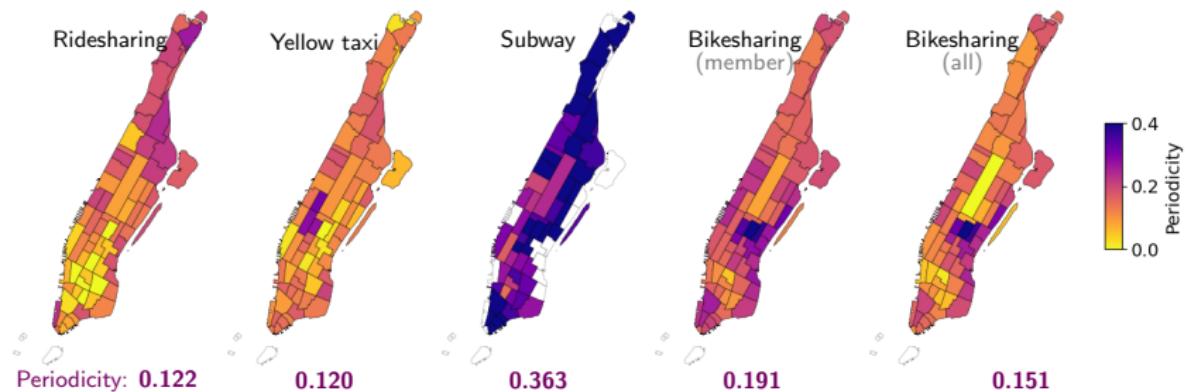


# Post-Pandemic Recovery

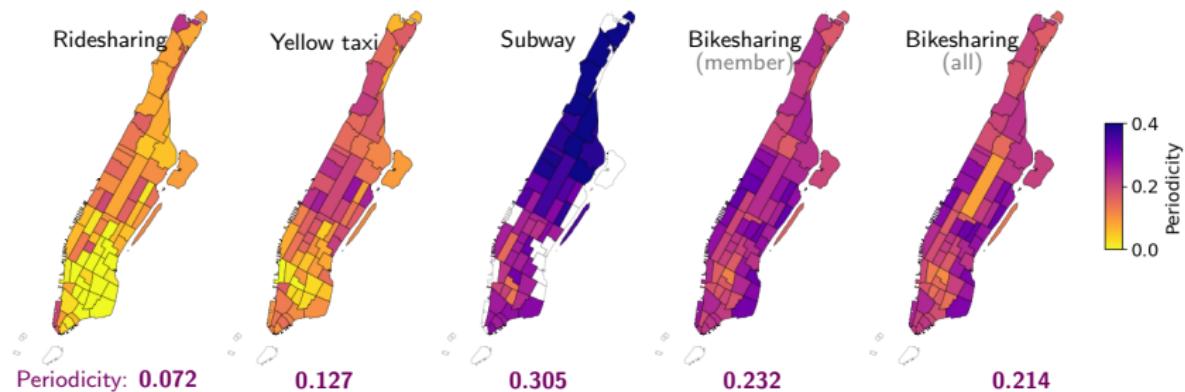
2024's periodicity minus 2019's periodicity



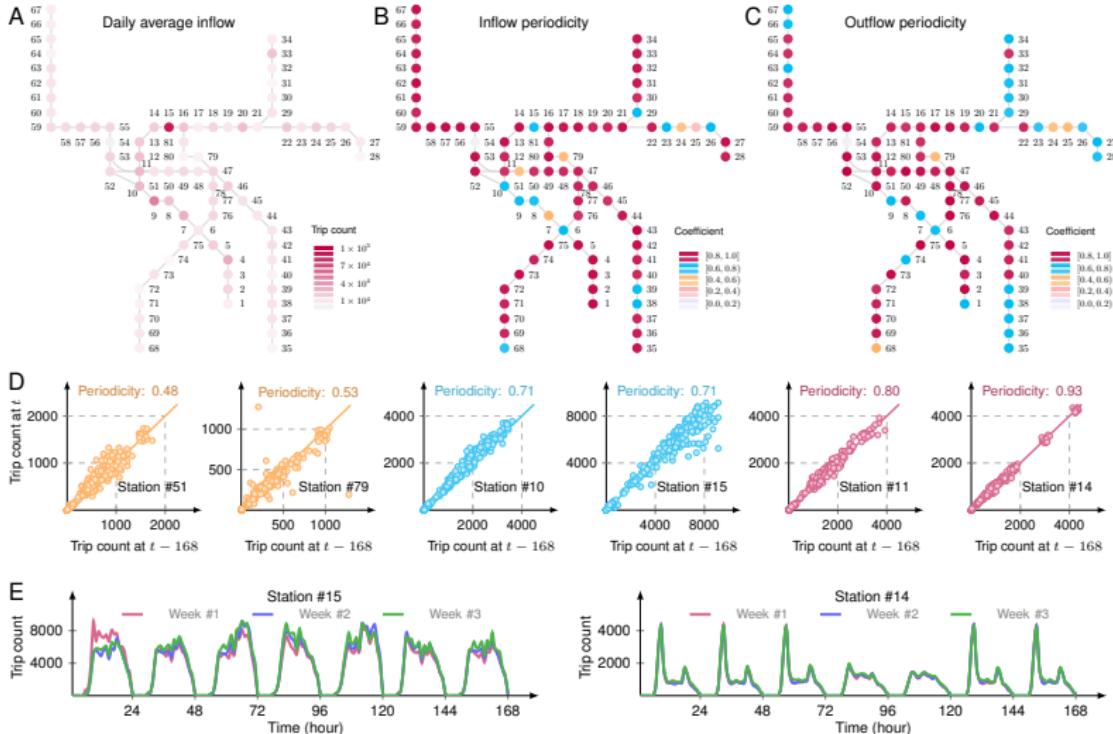
# Weekly Periodicity of Multi-Modal Mobility



# Daily Periodicity of Multi-Modal Mobility



# Hangzhou Metro Passenger Flow





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# Thanks for your attention!

Any Questions?

Slides: <https://xinychen.github.io/slides/intro.pdf>

## About me:

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- ✉ How to reach me: [xinychen@mit.edu](mailto:xinychen@mit.edu)