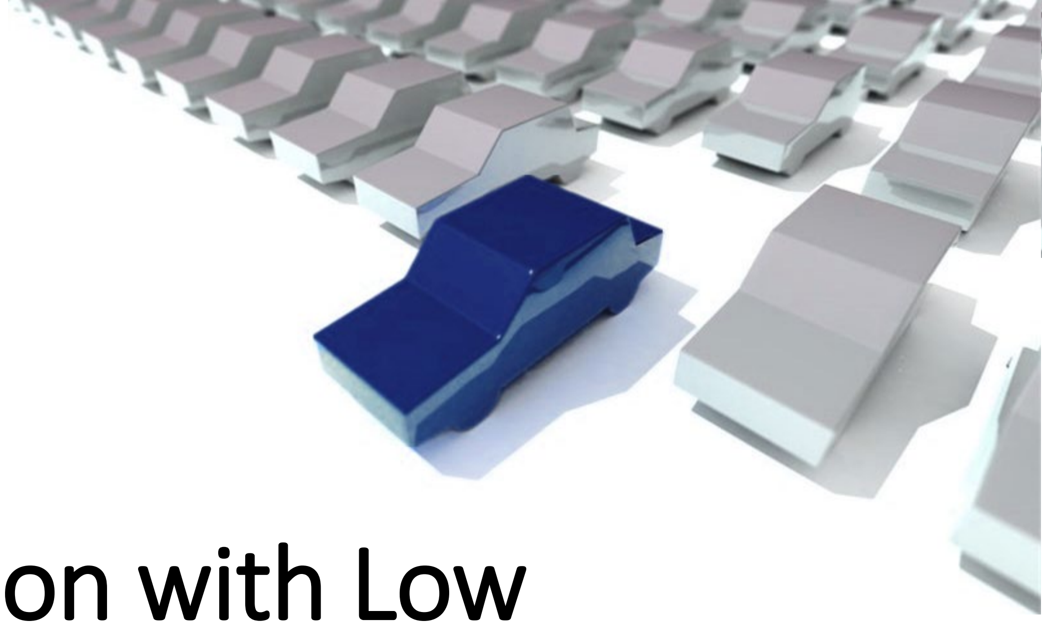

Traffic Signal Optimization with Low Penetration Vehicle Trajectory Data

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Project Team

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Collaboration between Academia, Private Industry, and Government

Data

Research & Development

Implementation

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Traffic signals in urban traffic networks

- Traffic light optimization: cost-efficient without changing physical infrastructure
  - Reduces congestion and energy consumption
- One of the main bottlenecks is ***data collection***
  - High cost of vehicle detection systems
- A large proportion of 320,000 signalized intersections in US are controlled by fixed-time traffic signals
  - Many traffic signals are not regularly optimized in response to changing traffic demand

We present a large-scale traffic signal re-timing system that uses a small percentage of vehicle trajectory data as the only input without reliance on any detectors.

Systems and Technology	C+
Infrastructure	B-
Business Processes	
Design	C+
Operations	C+
Maintenance	C+
Management	C
Workforce	C+
Management and Administration / Leadership	
Culture	C+
Organization	C+
Collaboration	C+
Performance	C
OVERALL GRADE	C+

National traffic signal report card

Reference: "Traffic Signal Benchmarking and State of the Practice Report," National Operation Center of Excellence, 2019.

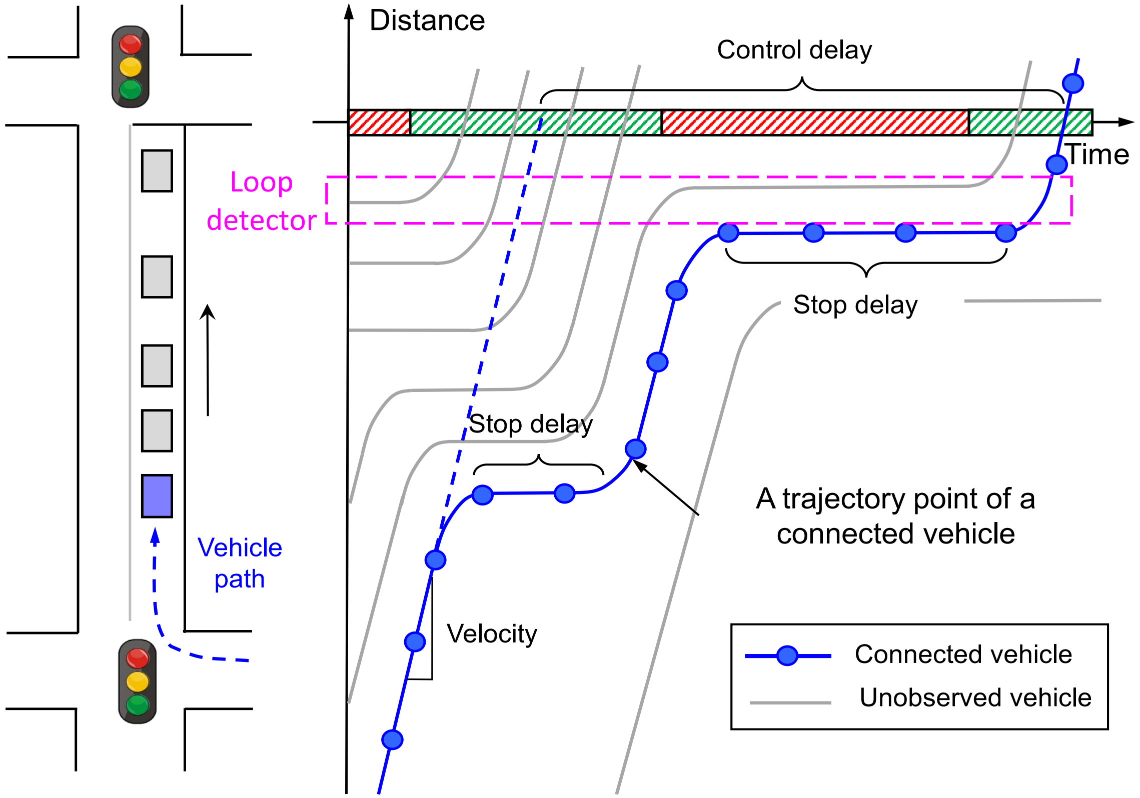
Detector data vs. vehicle trajectory data

❑ Detector data

- Limited installation
- Mainly detect the presence of vehicles
- Complete information (traffic counts, occupancy, etc.) at specific locations

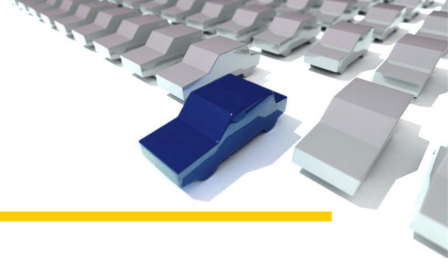
❑ Vehicle trajectory data

- Available at almost every intersection, particularly with a large traffic volume
- Large coverage cross the spatial-temporal space
- Enriched information including delay, number of stops, and vehicle path
- The main limitation of vehicle trajectory data is the sparse and incomplete observation caused by the low penetration rate

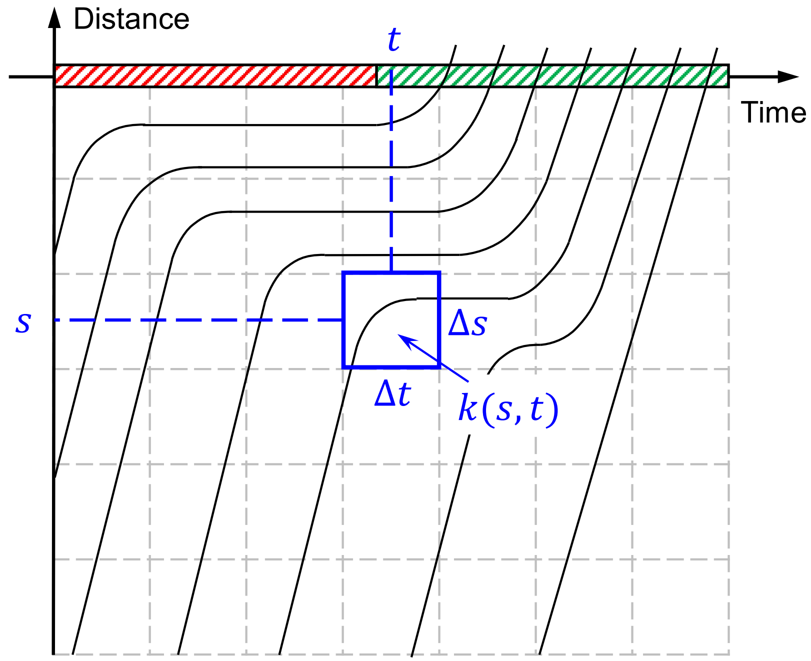


Most existing literature assume high penetration rates, so there are few traffic flow models suitable for current vehicle trajectory penetration rates.

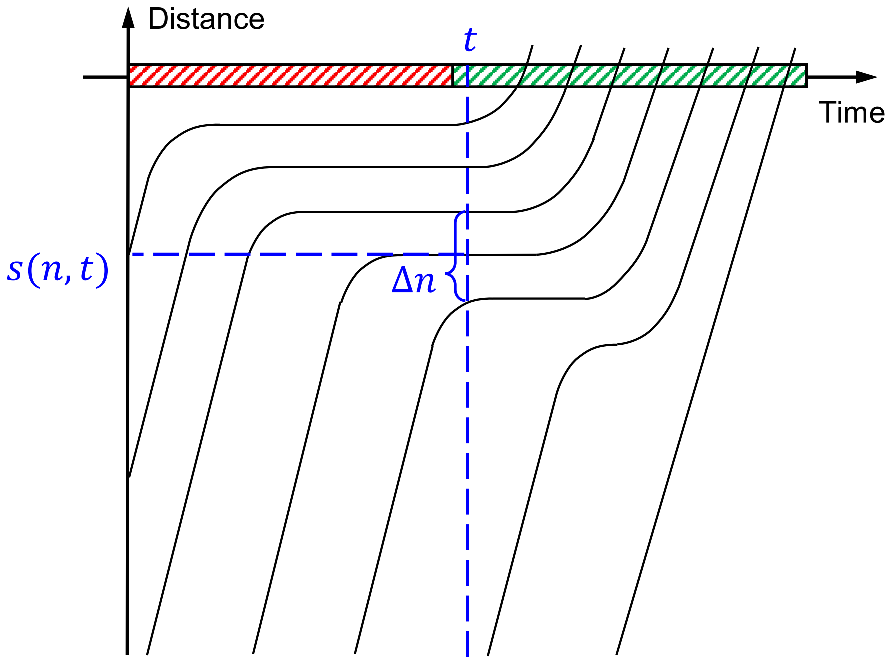
Obstacles in existing traffic flow models



❑ Eulerian representation



❑ Lagrangian representation



Main obstacles

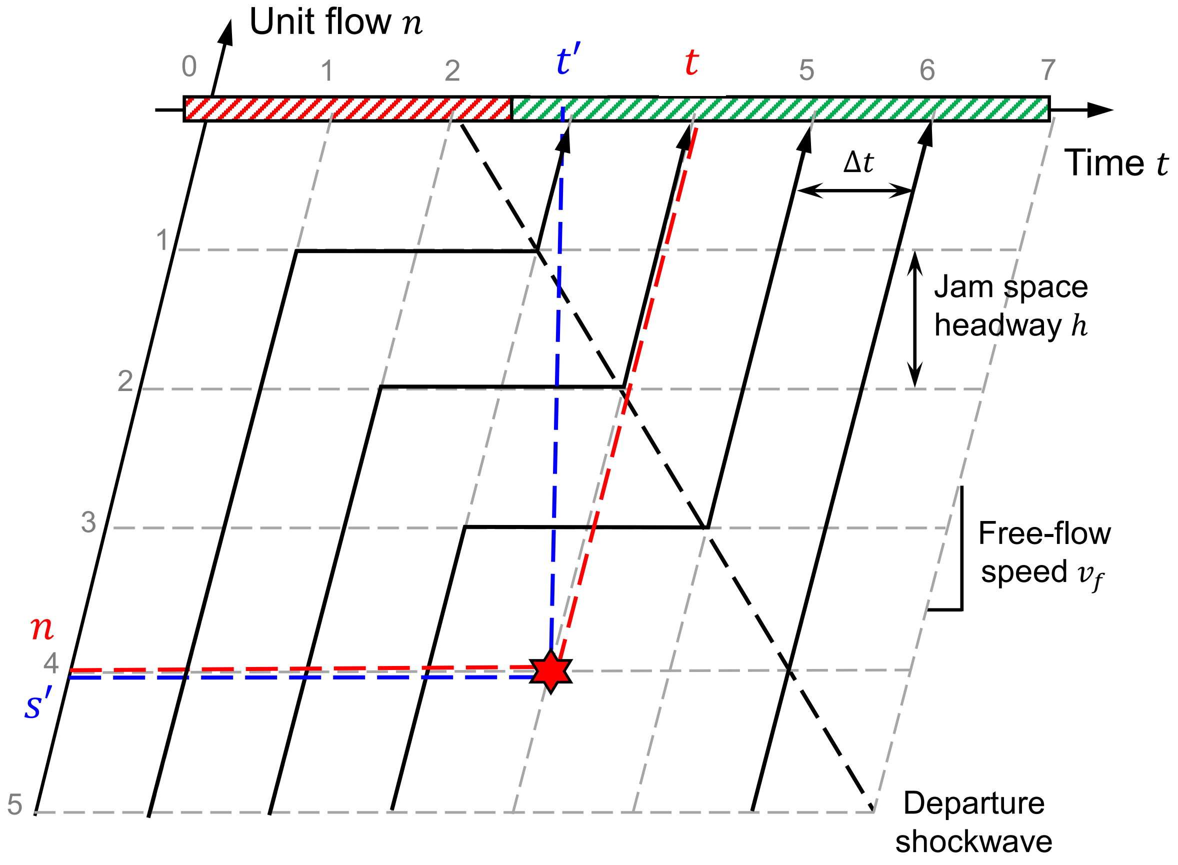
- Low penetration rate trajectory does not directly provide traffic measurements in either representations
- Complicated with high dimensions, particularly extended to stochastic settings

Our proposed model

Main representation	Density $k(s,t)$	Location $s(n,t)$	Queue length $X(t)$
Dimension at each time	# of cells for each time	# of vehicles / Δn	1

Newellian coordinates

❑ Establishment of Newellian coordinates



Vehicles only travel on the grid of the Newellian coordinates

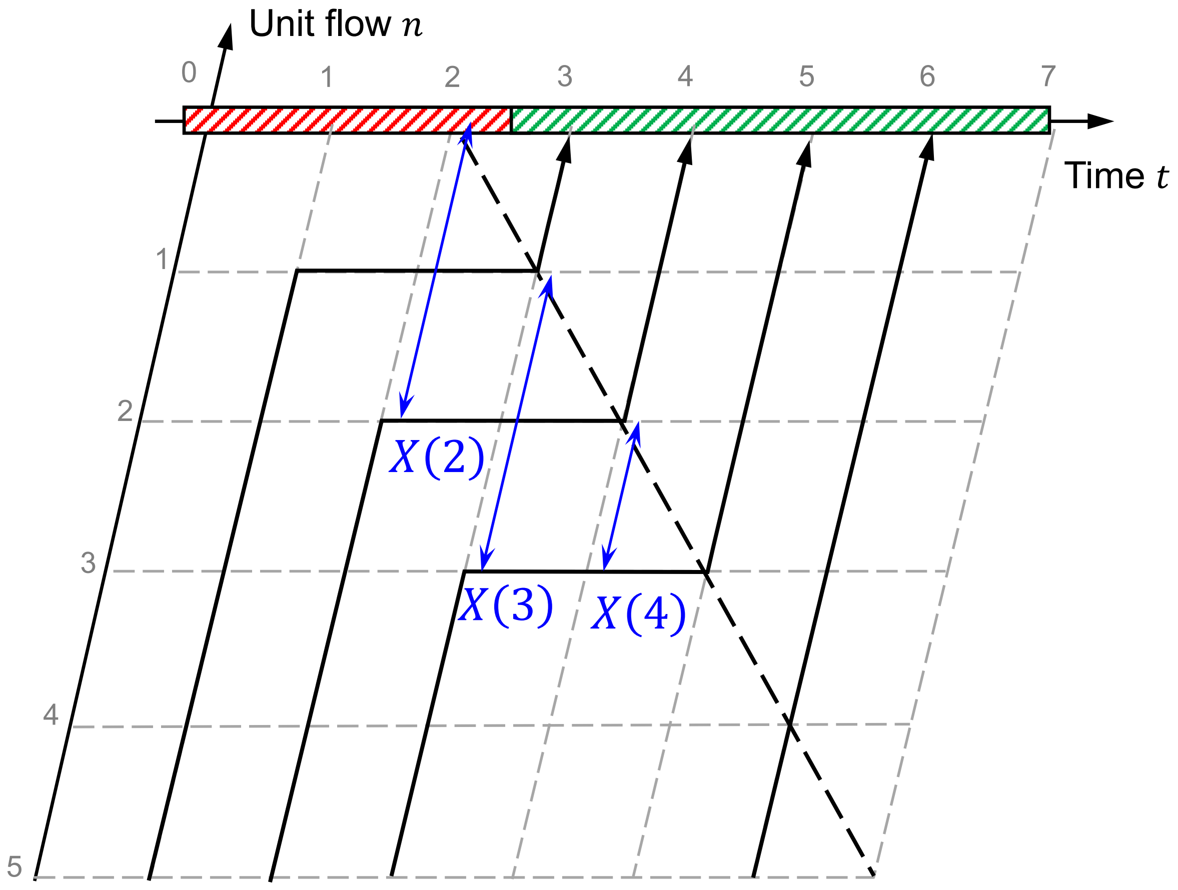
- ***Assumption***: All vehicle trajectories follow a uniform deterministic Newell's car-following model. Vehicles only have stop state & free flow state
- ***Discrete approximation***: traffic flow comes in binary (0 or Δu) for each time

$$\Delta u = q^m z \Delta t \qquad h = \frac{\Delta u \cdot h_0}{z} = q^m h_0 \Delta t$$

Notation	Meaning
Δu	Unit traffic flow
q^m	Saturation flow rate
z	Number of lanes
Δt	Time interval
h	Jam space headway (per Δu)
h_0	Jam space headway (per vehicle)

Point-queue representation

- Vehicle trajectories can be projected to a point-queue representation



Time t	$A(t)$	$X(t)$	$B(t)$
1	1	1	0
2	1	2	0
3	1	2	1
4	0	1	1
5	0	0	1
6	1	0	1
7	0	0	0

- $A(t), B(t)$: arrival & departure at time t
- $X(t)$: number of stopped vehicles right after time t

$$\boxed{X(t) = X(t-1) + A(t) - B(t)}$$

Probabilistic time-space (PTS) diagram

❑ Stochastic point-queue model and PTS diagram

$$X(t) = X(t-1) + A(t) - B(t) = X'(t) - B(t)$$

1) Stochastic arrival (Bernoulli distribution each time)

$$A(t) \sim \text{Bernoulli}\big(a(t)\big) \qquad \mathbb{P}(A(t) = 1) = a(t)$$

(A Poisson process when $\Delta t \to 0$)

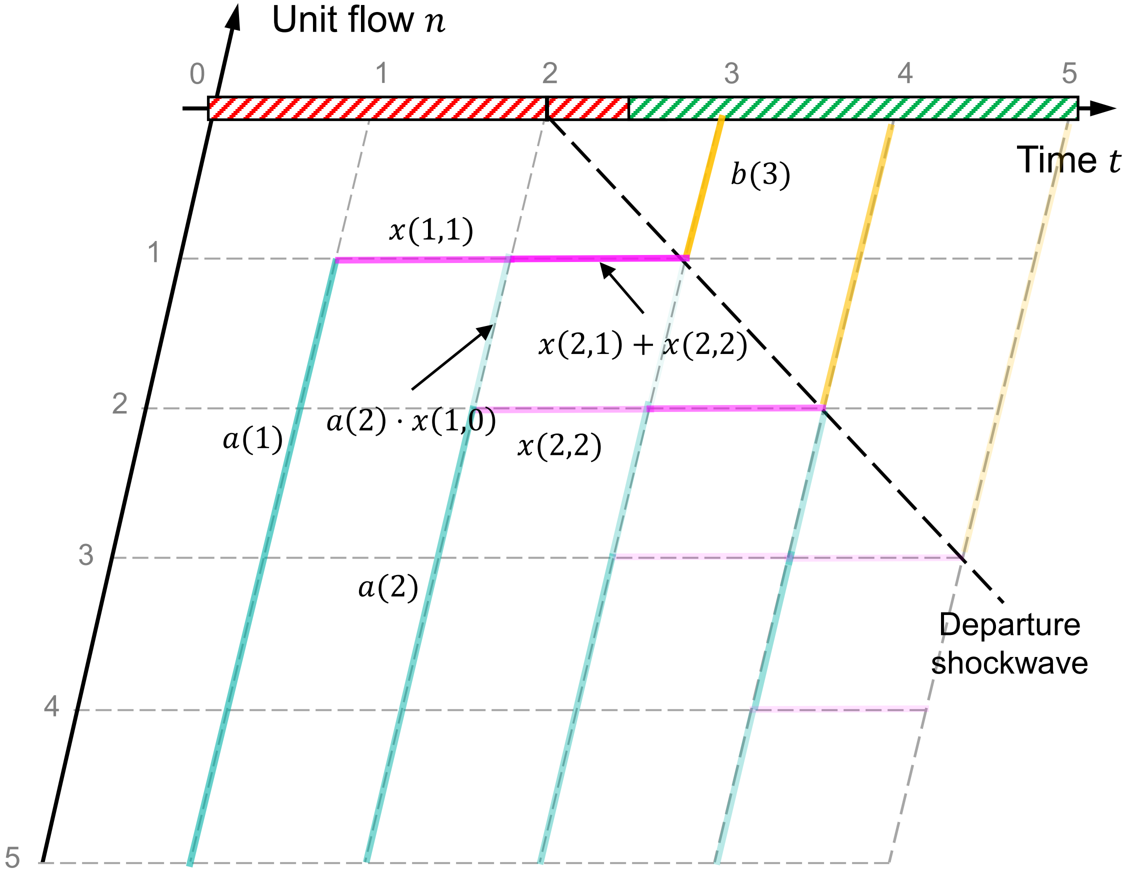
2) Deterministic departure controlled by traffic signal

$$\mathbb{P}(B(t) = 1) = b(t) = \mathbb{P}(X(t) \geq 1 \,\&\, S(t) = 1)$$

Time	Arrival probability	Queue length distribution					Departure probability
		0	1	2	3	…	
1	$a(1)$	$x(1,0)$	$x(1,1)$	$x(1,2)$	$x(1,3)$	…	$b(1)$
2	$a(2)$	$x(2,0)$	$x(2,1)$	$x(2,2)$	$x(2,3)$	…	$b(2)$

$x(i,j)$: probability that queue is j at time i ($\mathbb{P}(X(i) = j)$)

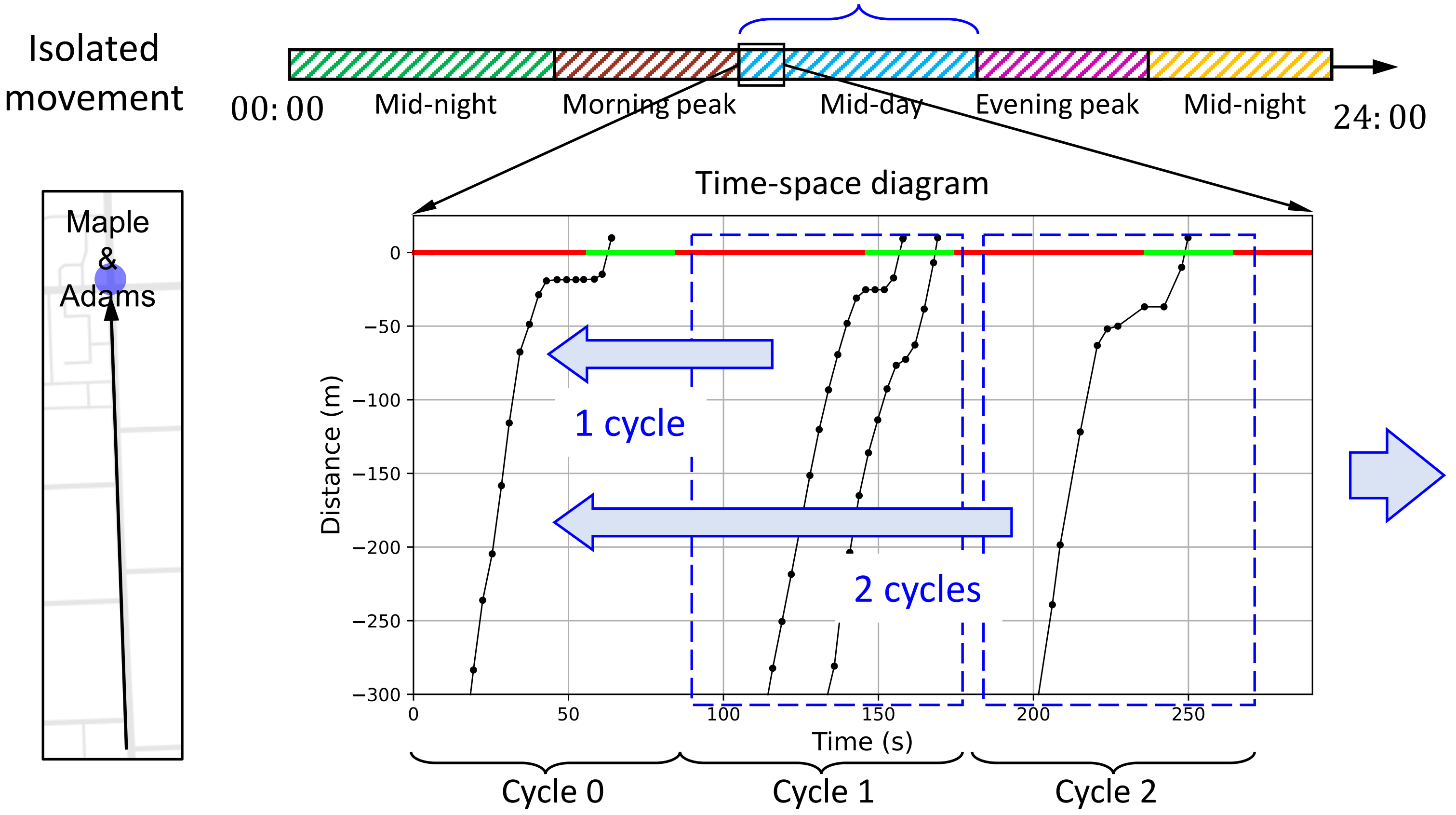
Spatial-temporal distribution of vehicle trajectories

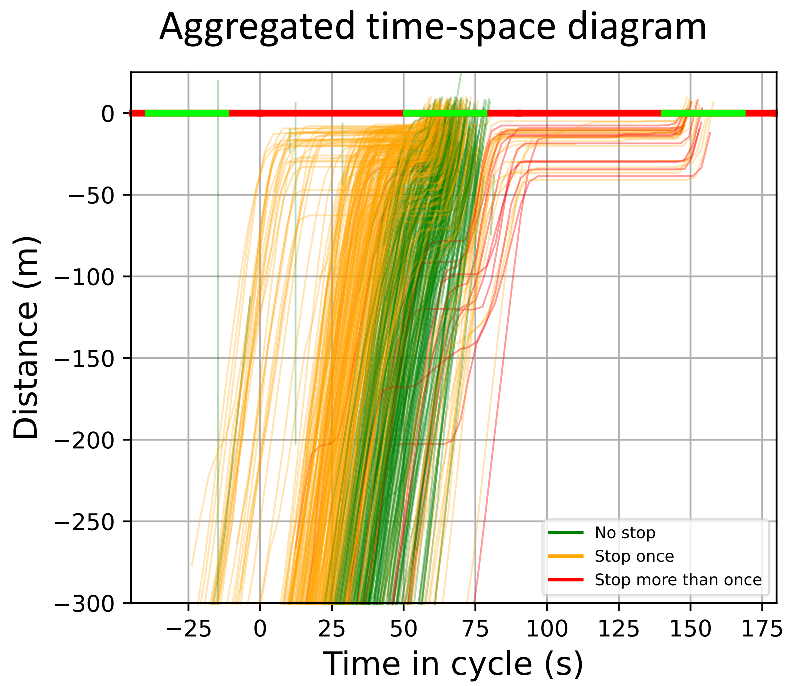


Trajectory aggregation

Traffic signal parameters & traffic demand are **stationary** within the same time of day (TOD)

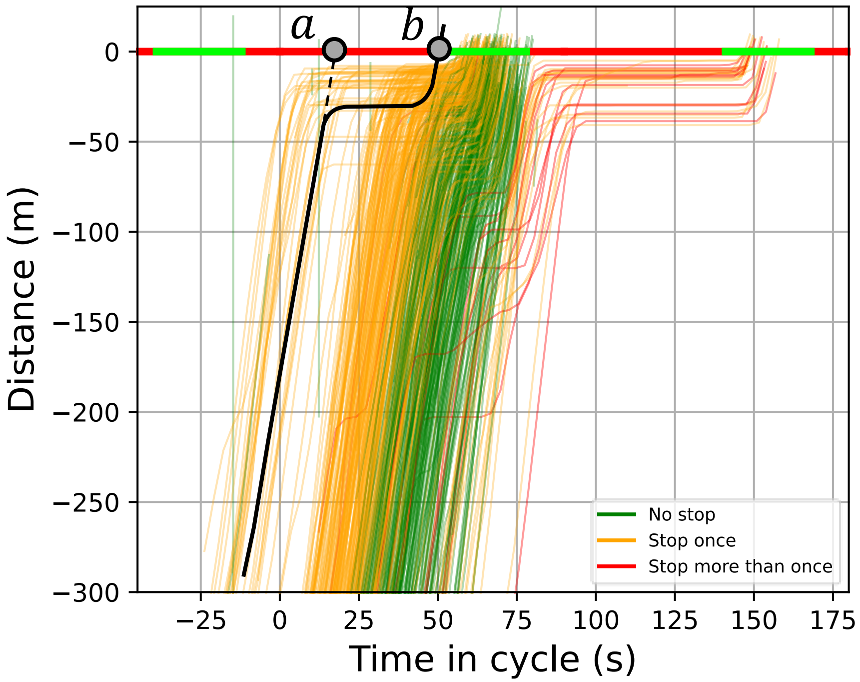
Average (recurrent) traffic state of the movement



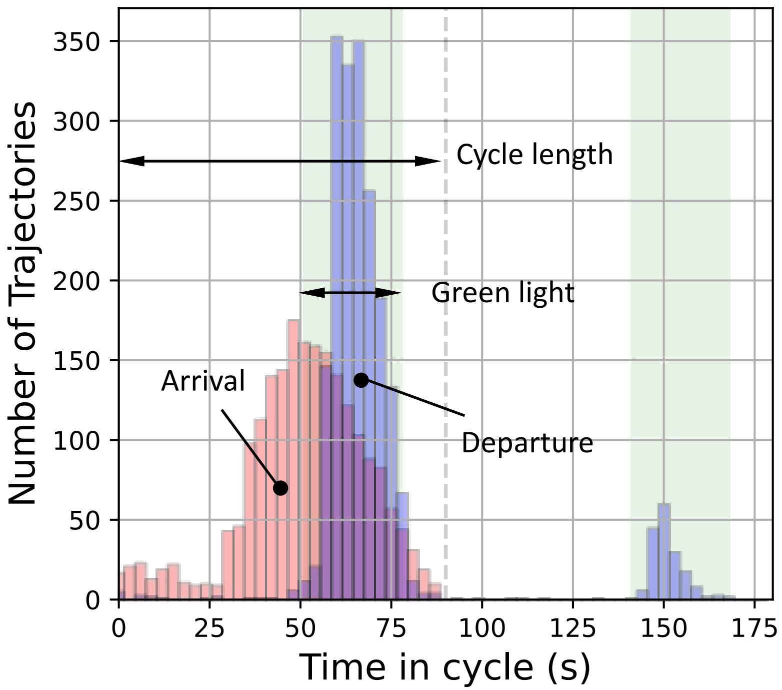


Penetration rate & arrival rate estimation

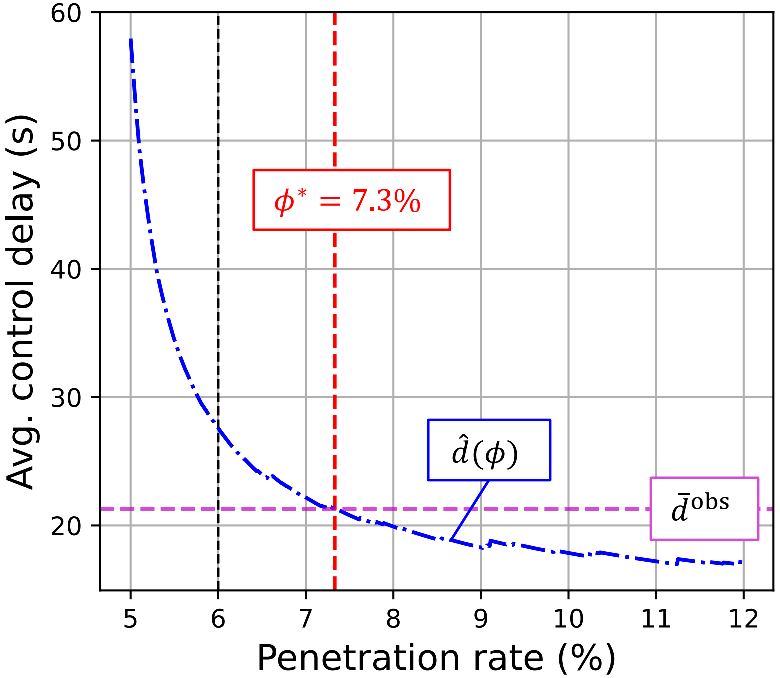
Aggregated time-space diagram



Arrival/departure histogram



Penetration rate estimation



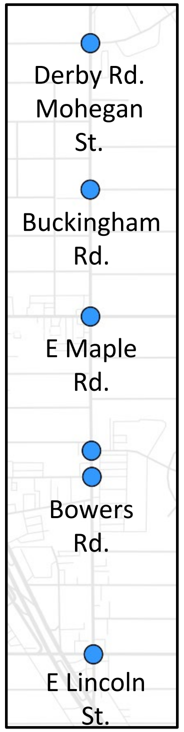
$$\text{Estimated arrival probability} = \frac{\text{Observed \# of arrival per cycle}}{\text{Penetration rate}}$$

Penetration rate ↑ ⇒ estimated arrival ↓ ⇒ estimated average delay ↓

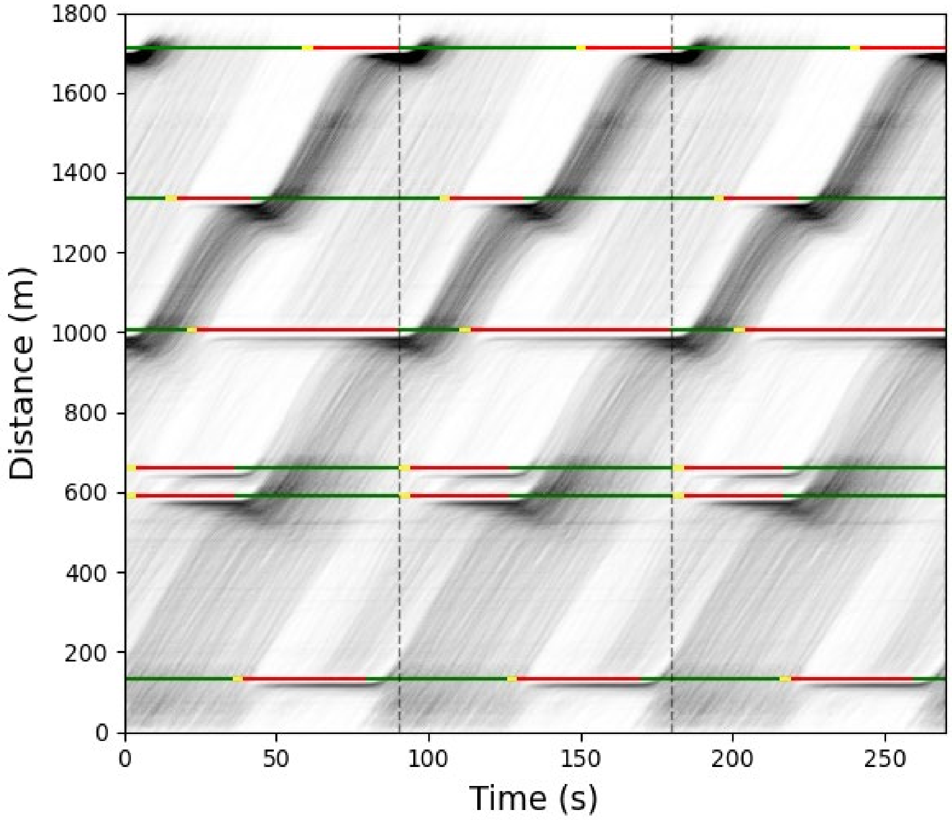
Penetration rate can be estimated under which the model-estimated average delay is equivalent to the observed average delay

Model calibration for a corridor

- The estimation method can also be applied to a corridor

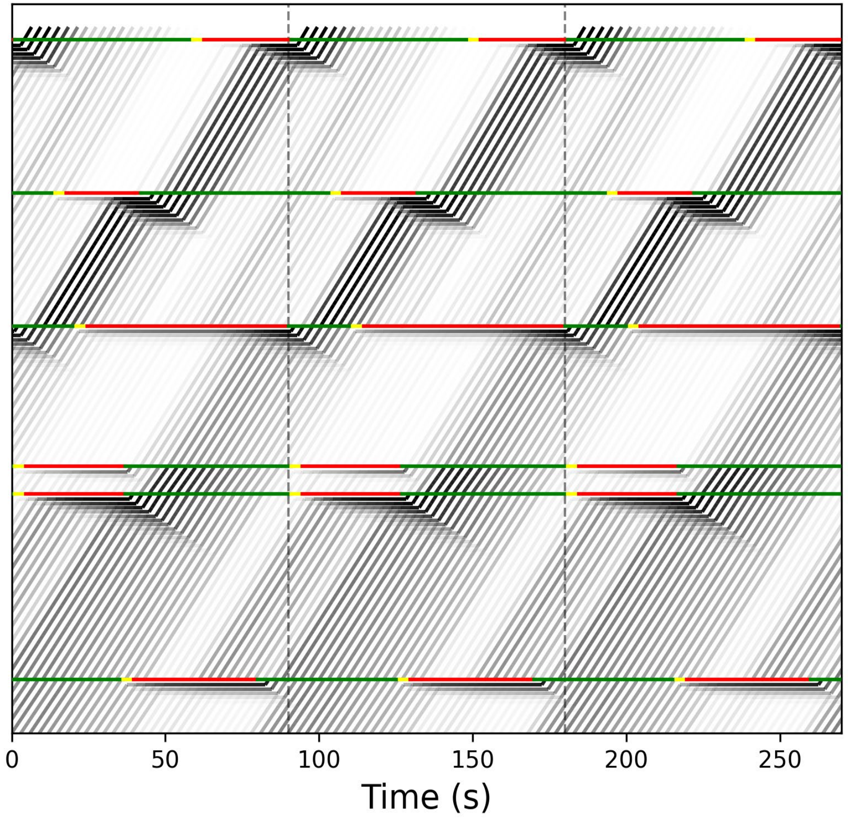


Aggregated time-space diagram



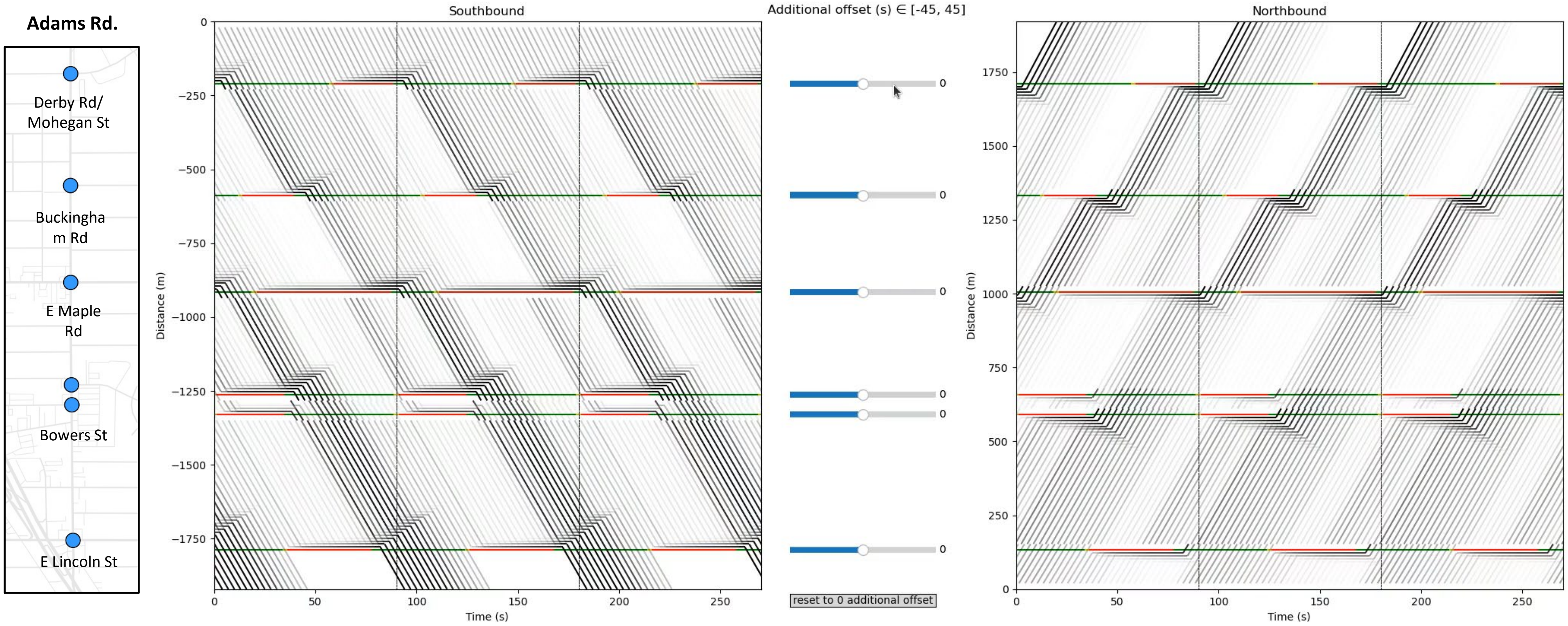
(Three weeks' data, weekdays only, 10:00-15:00)

Calibrated probabilistic time-space diagram



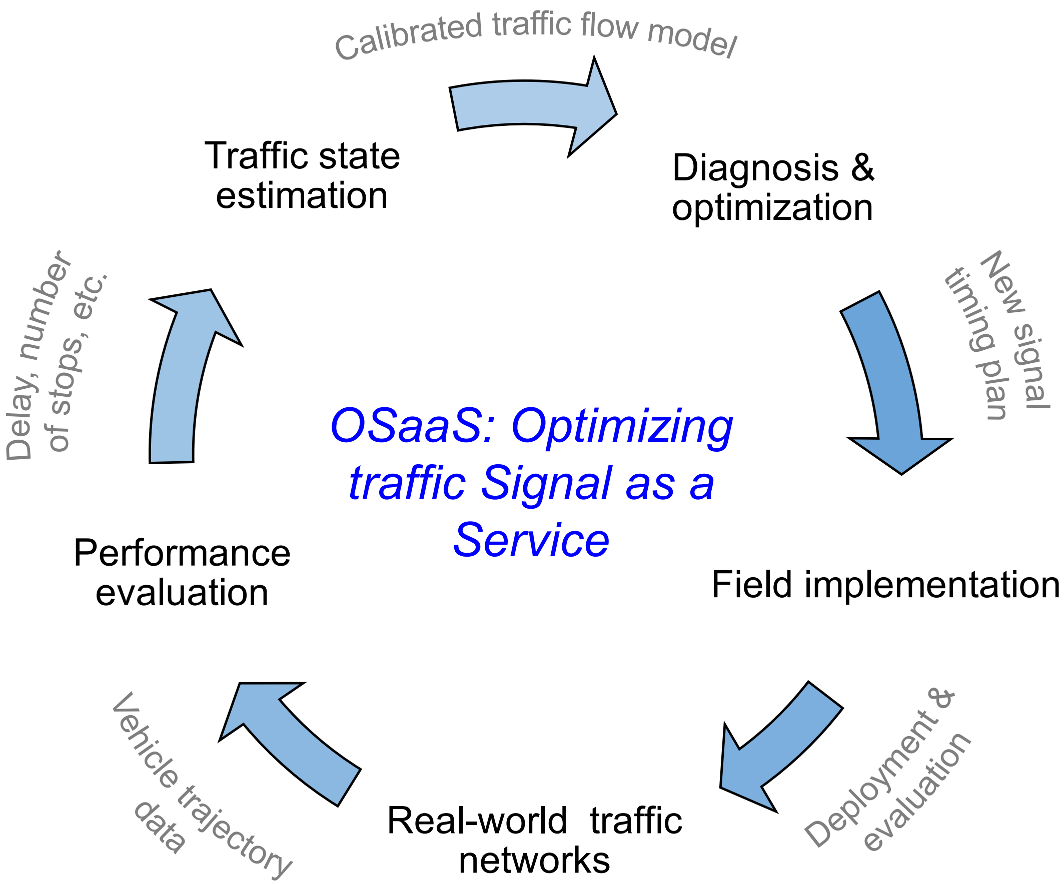
Traffic signal diagnosis & optimization based on the calibrated traffic flow model

- ❑ The calibrated traffic flow model can be used to predict what will happen if the signal timing plan is changed



OSaaS system overview

- OSaaS: Optimizing traffic Signals as a Service

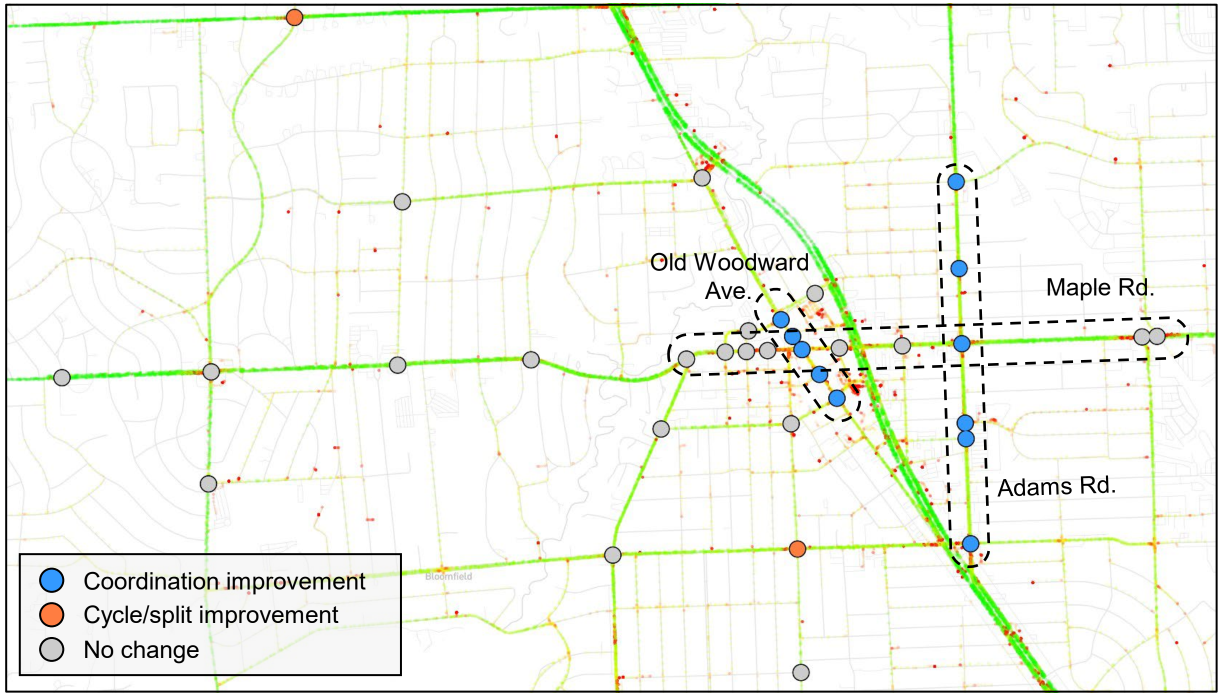


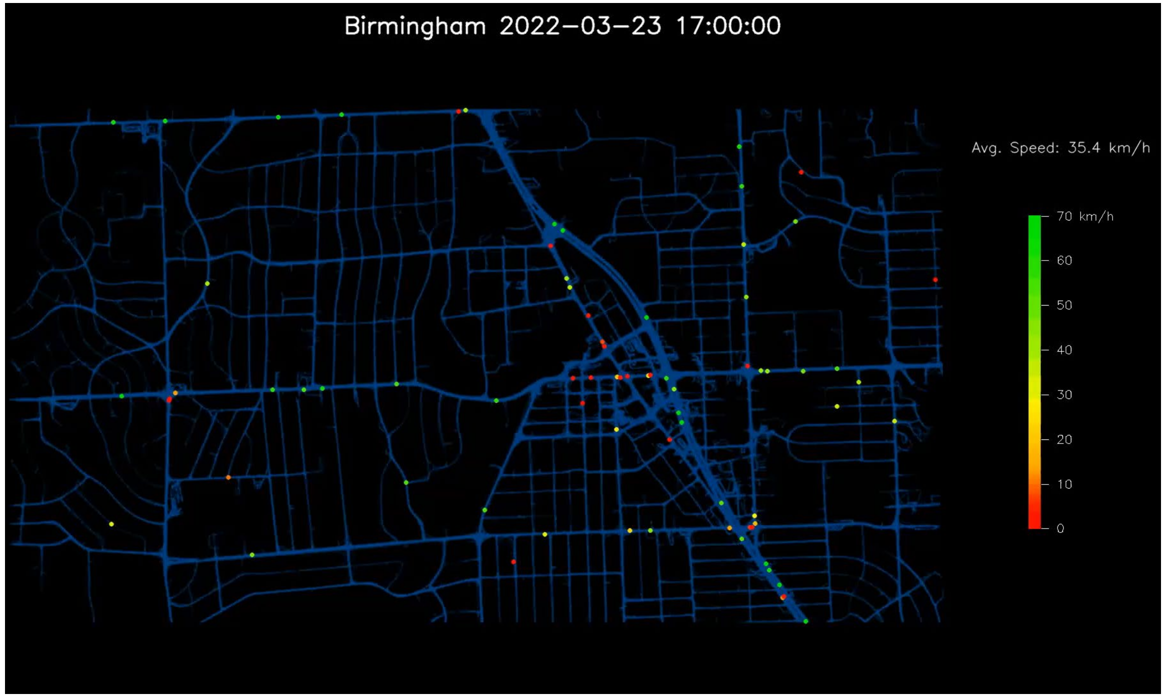
Systematic methods for traffic signal re-timing based on the probabilistic time-space diagram built from vehicle trajectory data

- Without relying on any detector-based data, OSaaS is a closed loop iteration traffic signal re-timing system that only utilizes vehicle trajectory data as the input

Field test at the City of Birmingham

- Performance evaluation, diagnosis, and optimization for 34 signalized intersections
  - Three corridors and some isolated intersections
- Most of these signalized intersections are not equipped with any vehicle detectors, so the proposed system provided previously unavailable opportunities.



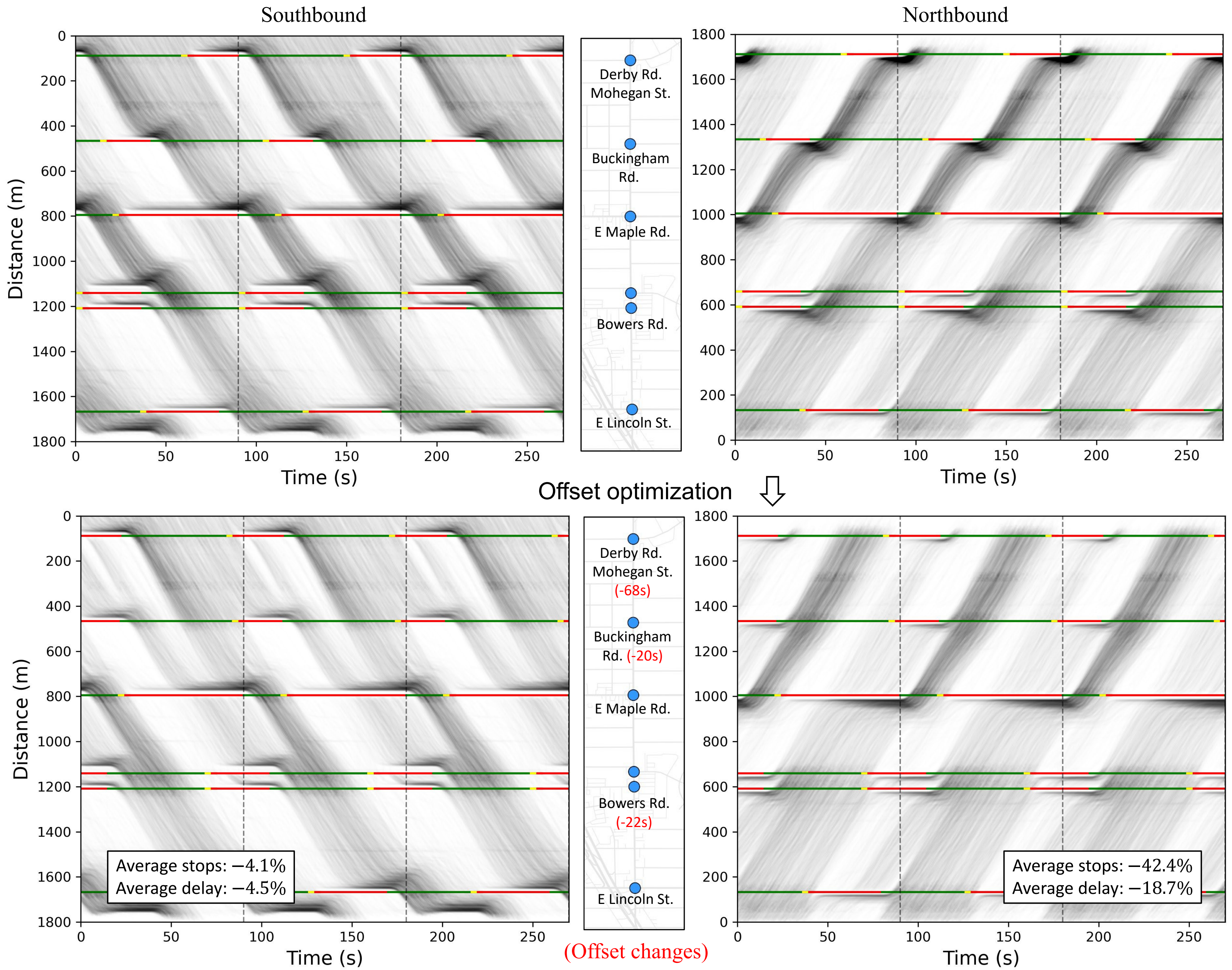


Demonstration of the vehicle trajectory data

Before-and-after comparison for Adams Rd.

Before optimization
(2022 March 9th -27th , Weekdays, Mid-day)

After optimization
(2022 April 4th -22nd , Weekdays, Mid-day)



Before-and-after comparison for Adams Rd.

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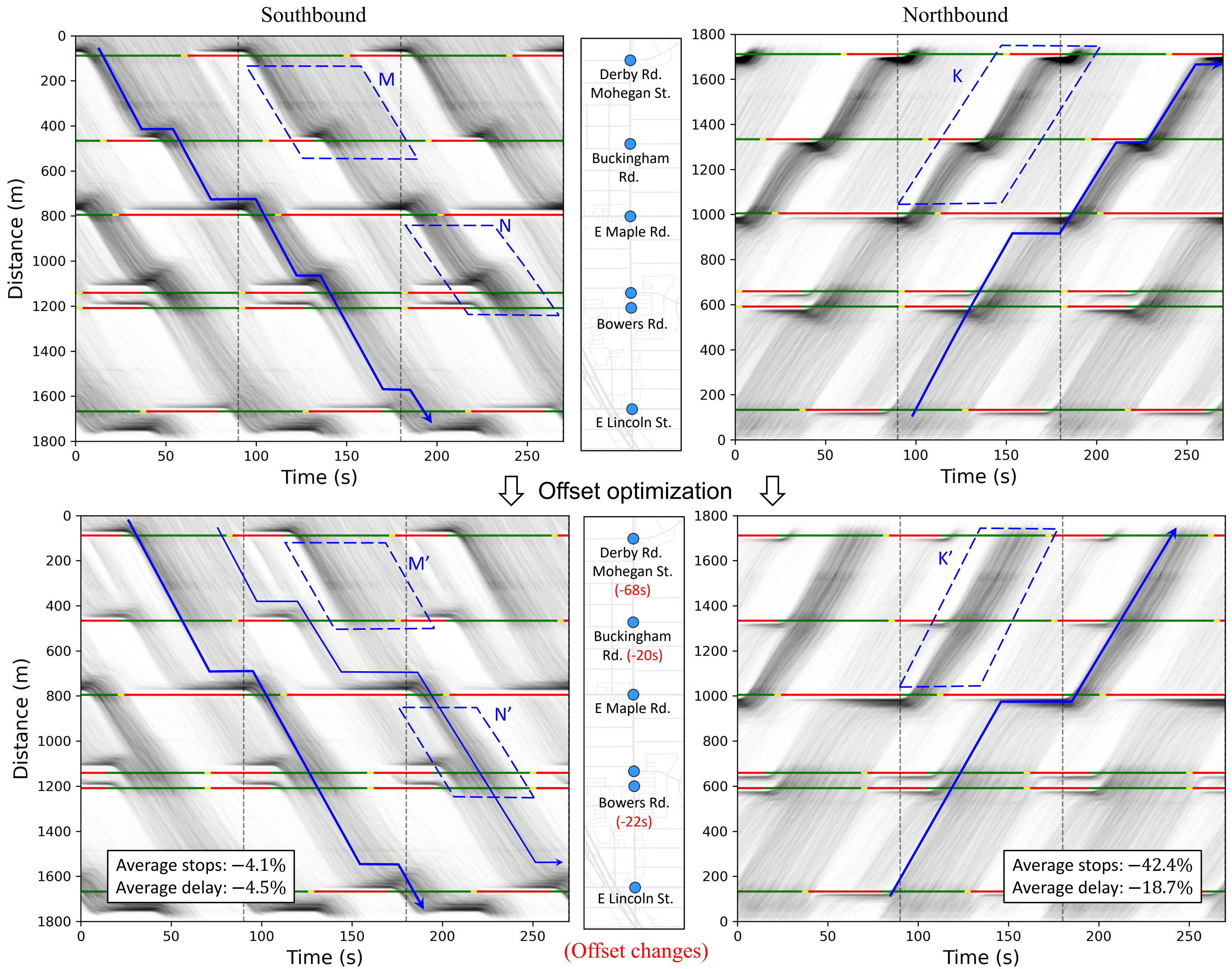

Conclusion

- We present a large-scale traffic signal re-timing system that uses a small percentage of vehicle trajectories as the only input without reliance on any detectors.
- We develop the probabilistic time-space diagram, which establishes the connection between a stochastic point-queue model and vehicle trajectories under the proposed Newellian coordinates.
- This model enables us to reconstruct the recurrent spatial-temporal traffic state by aggregating sufficient historical data.
- Optimization algorithms are developed to update traffic signal parameters for intersections with optimality gaps.
- A real-world citywide test of the system demonstrated that it decreased the delay and number of stops at signalized intersections by up to 20% and 40%, respectively.
- This system provides a scalable, sustainable, and efficient solution to traffic light optimization and can potentially be applied to every fixed-time signalized intersection in the world.

Publication

Wang, X., Jerome, Z., Wang, Z., Zhang, C., Shen, S., Kumar, V., Bai, F., Krajewski, P., Deneau, D., Jaward, A., Jones, R., Piotrowicz, G. & Liu, H. X. Traffic light optimization with low penetration rate vehicle trajectory data. *Nature communications*. (Accepted)

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