2023-02-10

Graphical analysis I

Time-space diagrams

Cathy Wu

1.041/1.200 Transportation: Foundations and Methods

References

1. Readings: Chap 1. of Prof. Carlos Daganzo’s book Fundamentals of Transportation and Traffic Operations (2007)

2. Prof. Nikolas Geroliminis’ lecture Fundamentals of Traffic Operations and Control, Spring 2010 EPFL

3. Chap 7 of Prof. Michael Meyer and Prof. Eric Miller’s book Urban Transportation Planning (2001)

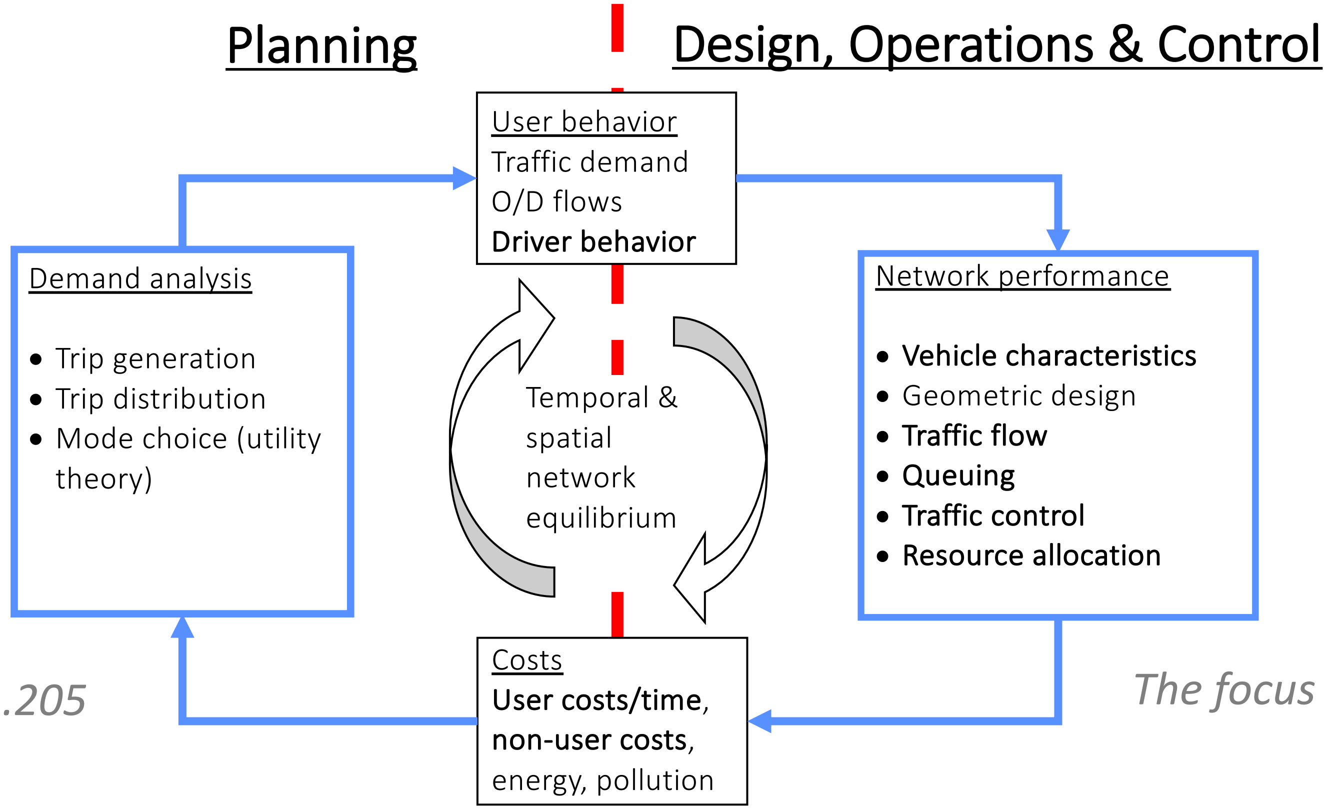
4. Some slides adapted from Profs. Carolina Osorio and Dan Work.

Outline

1. Big picture of transportation engineering
2. Time-space diagrams
3. From sensors to data to trajectories to time-space diagrams

Overview: Transportation Engineering

“Demand”



“Supply”

See 1.202, 1.205

The focus of this course!

Given the transportation demand, what is the performance of the transportation network?

Outline

1. Big picture of transportation engineering
2. **Time-space diagrams**
   a. Applications and traffic system design: road, air, rail, transit
   b. Exercise: Waterway capacity problem
3. From sensors to data to trajectories to time-space diagrams

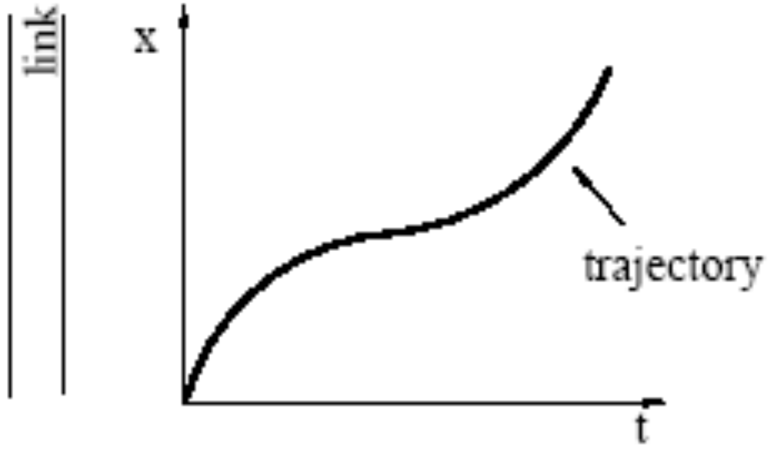
Today's key takeaway

Graphs are your friend.

To analyze temporal phenomena, first translate time into space.

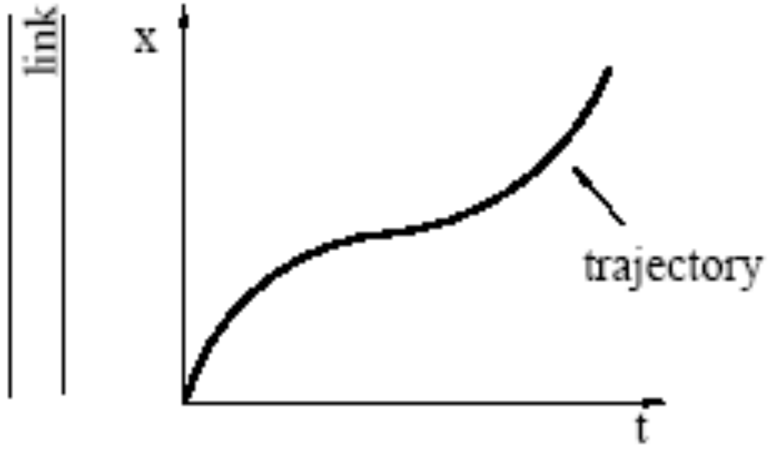
Time-space diagrams: overview

- Transportation systems have many moving parts – how do you summarize and analyze the system?
- Time-space diagrams are a simple yet very useful technique for analyzing the performance of interacting vehicles in a transportation system
- Used to
  - solve design problems of future infrastructure,
  - or diagnose problems in existing systems.
- For more complex scenarios (e.g. high number of vehicles interacting), a (t, x) diagram can serve as the basis for more detailed analysis (e.g. simulation)



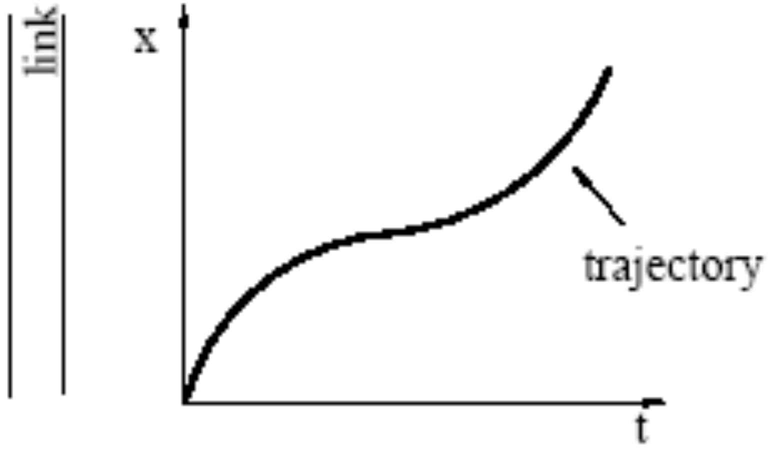
Time–Space Diagrams

- Vehicles are typically constrained to a one-dimension channel (road link, water way, airport landing strip)
  - We can analyze their 1-dimension movement by plotting distance vs time
  - Pick a point on vehicle (e.g., front bumper) to represent its location;
- Trajectories: curves in the time-space diagram that define a single position for every moment of time, denoted x(t).



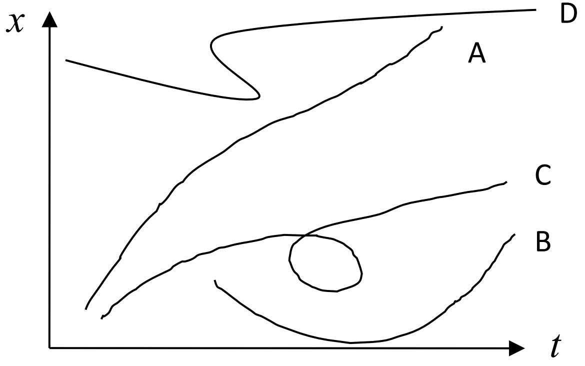
Time–Space Diagrams

- Time-space diagrams are "complete". They offer a lot of valuable information in a condensed manner. Why do we say this?
  - Keep this in mind for next lecture.
- Recall from basic physics
  - first derivative, slope, dx/dt (velocity)
  - second derivative, d2x/dt2 (acceleration)

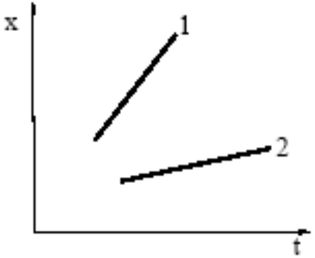


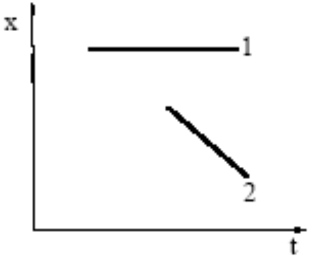
Interpreting time space diagrams

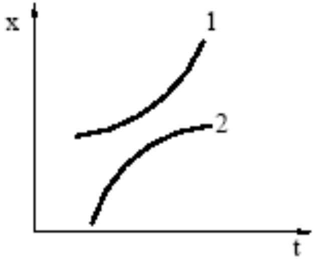
- Which are possible vehicle trajectories?



- Describe the vehicle motion





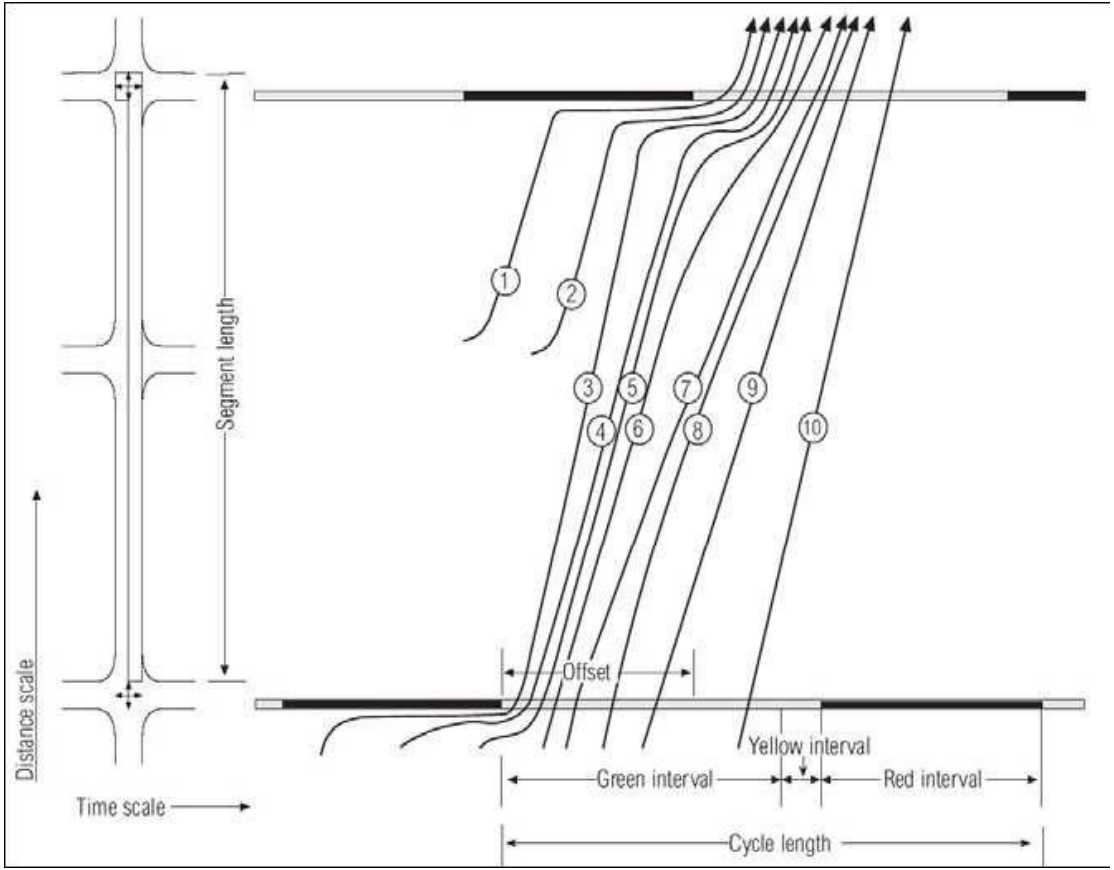


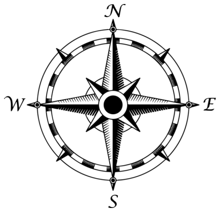
Outline

1. Big picture of transportation engineering
2. **Time-space diagrams**
   a. **Applications and traffic system design: road, air, rail, transit**
   b. Exercise: Waterway capacity problem
3. From sensors to data to trajectories to time-space diagrams

Signalized intersections

- Two intersections with signals and an intermediate cross street with a stop sign

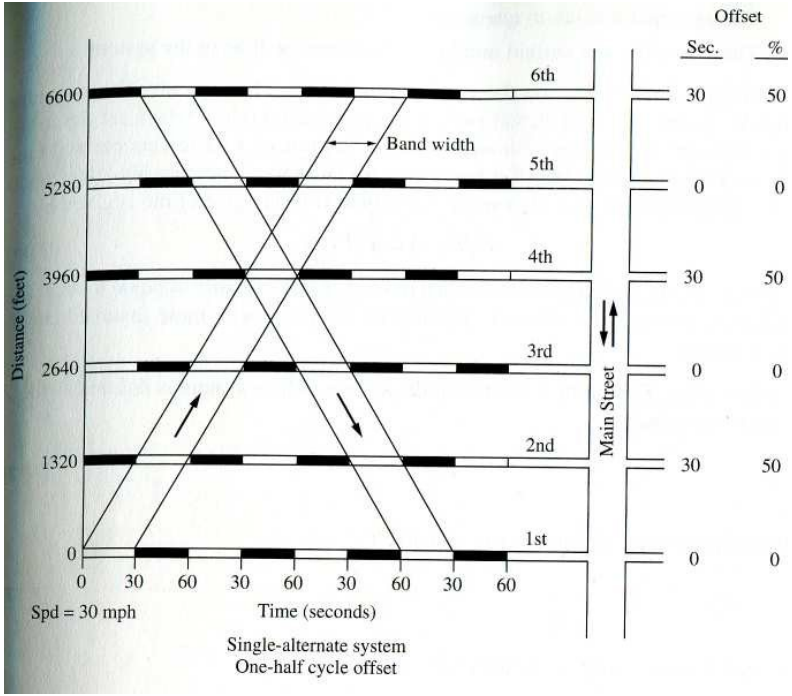


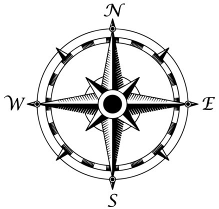


Wu

Signal timing design

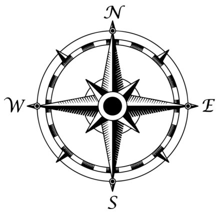
- Fixed-time control analysis

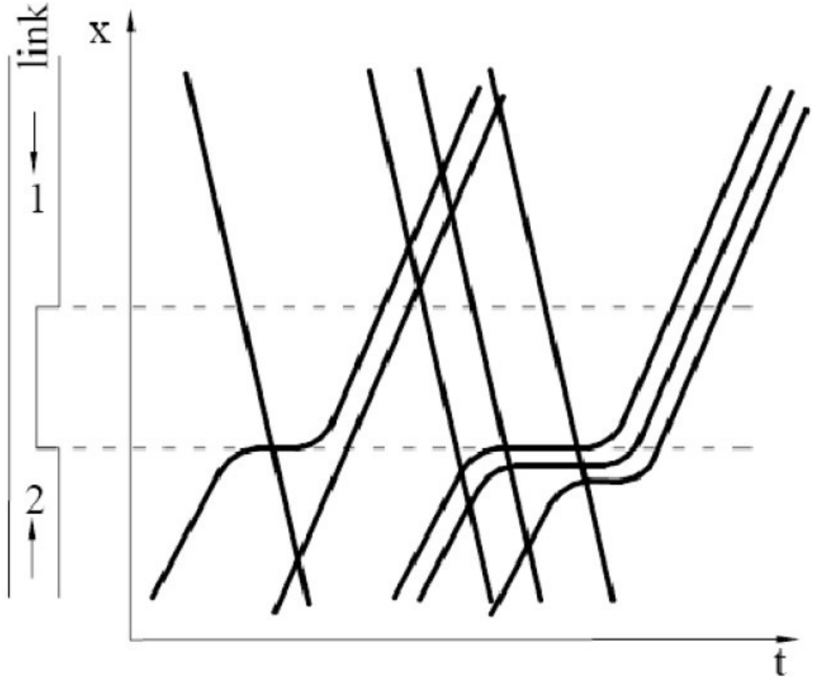




From Meyer and Miller (2001)

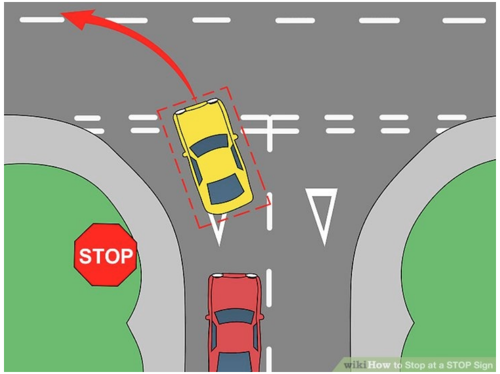
Lane reduction

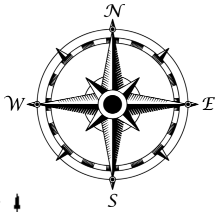


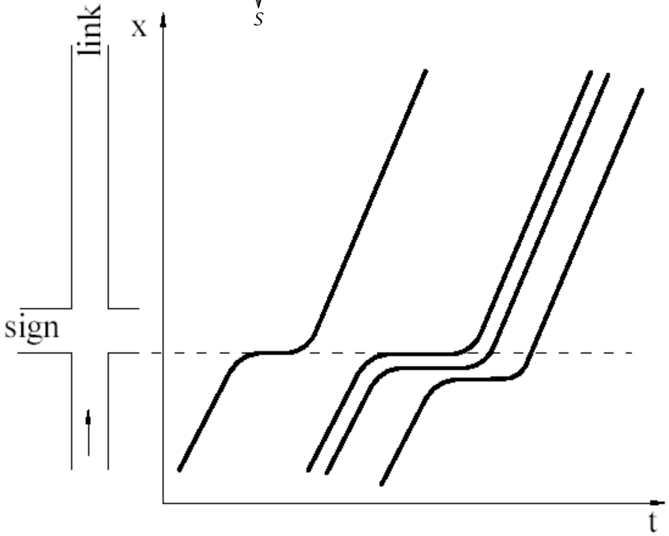


Trajectories reveal a lot of information

- Intersection with stop sign
  - All vehicles must stop before crossing the intersection



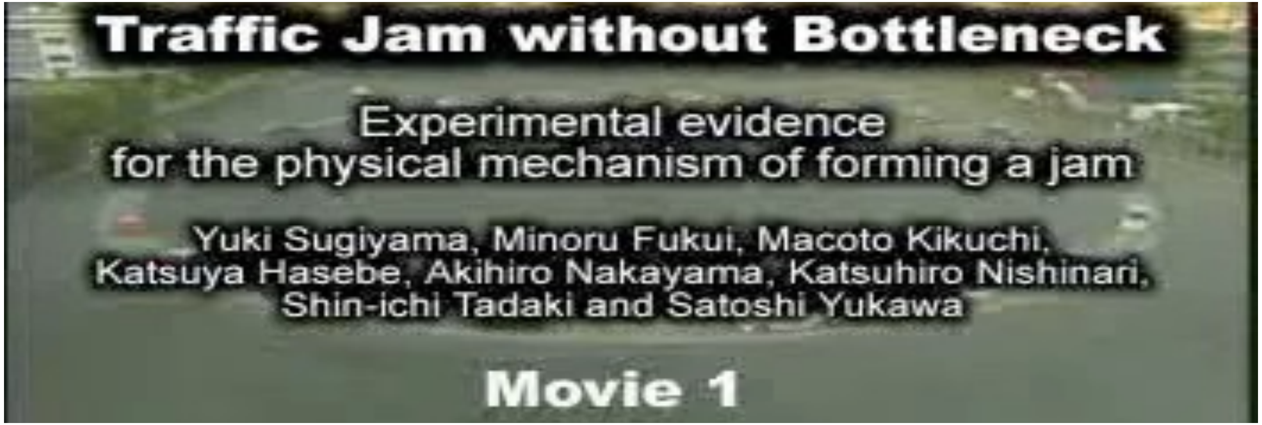




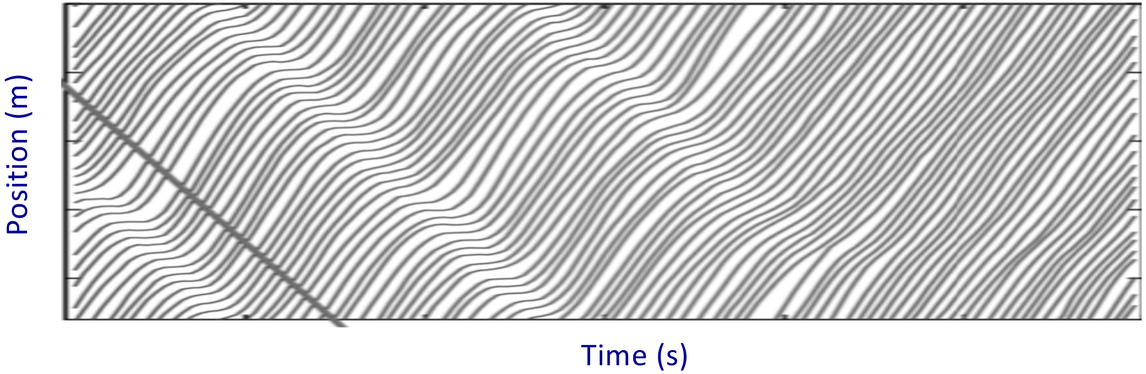
- Any violations of the law?

What’s an alternative to graphical analysis?

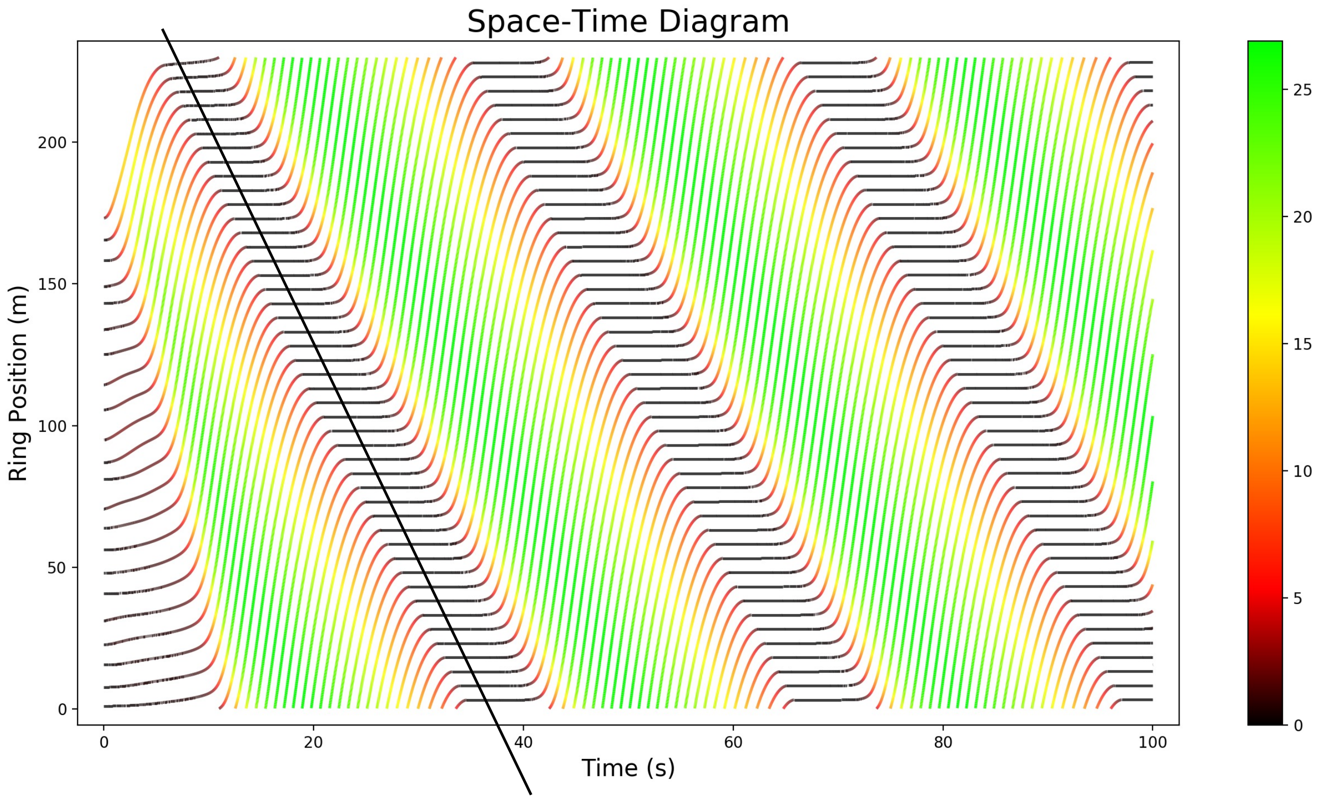
Trajectories also show traffic waves



Vehicle trajectories (Sugiyama et al. 2008)



Trajectories also show traffic waves

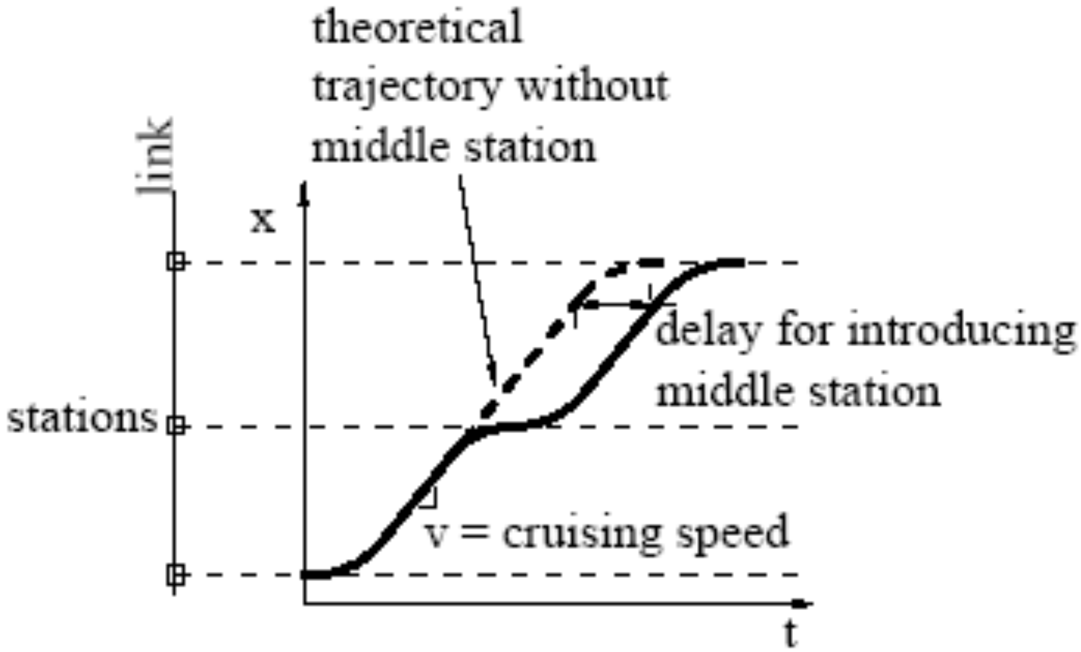


Rate of backwards wave propagation

Wu, et al. IEEE T-RO, 2021.

Transit station placement

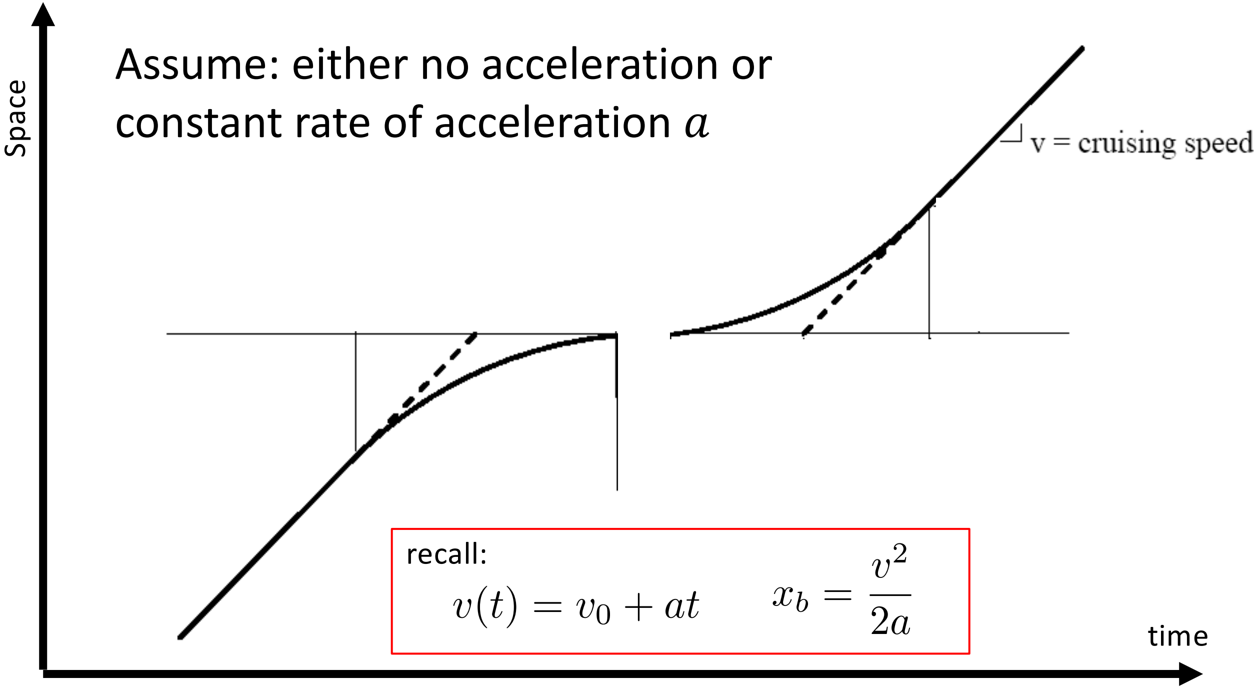
- Stations for a transit vehicle (bus)



- Note that if the distance between stations is not long enough the vehicle can't reach its cruising speed

Transit station placement

- Delay: The additional travel time experienced by a driver, passenger or pedestrian due to circumstances that impede the desirable movement of traffic. It is measured as the time difference between actual travel time and free-flow travel time.



Assume: either no acceleration or constant rate of acceleration a

recall:

$$v(t) = v_0 + at \qquad x_b = \frac{v^2}{2a}$$

Time-space diagram – In a nutshell

- Analyze performance of multiple vehicles along a shared path
- (t, x)-diagram is useful to examine or coordinate the schedules of various vehicles that interact while traveling on the same path, to operate the system as efficiently as possible.
- Generally, they enable us to estimate/analyze:
  - Headway between operations at various transportation facilities
  - Capacity of transportation systems
  - Level of service
  - Exclusive rights-of-way, shared rights-of-way

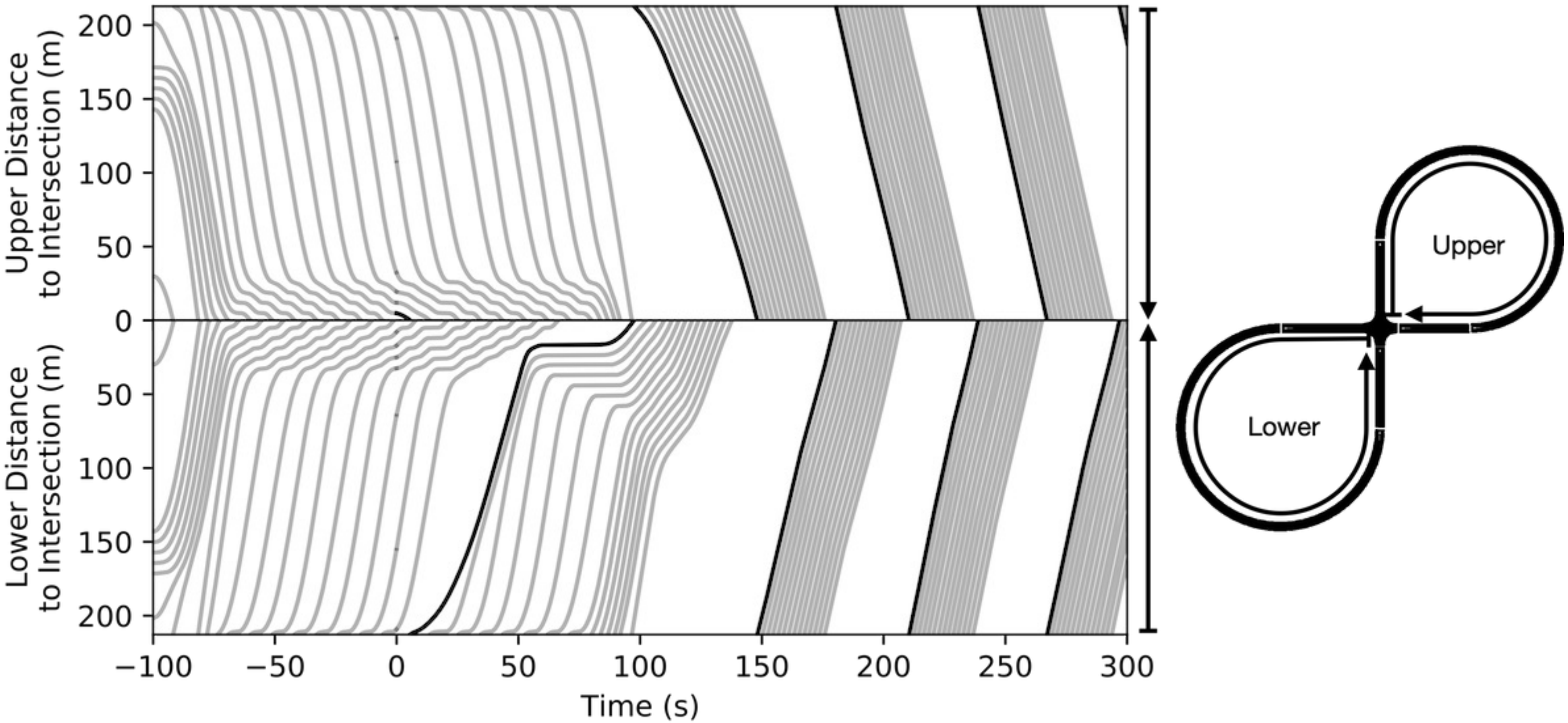
More applications (for inspiration)

Extra credit: Find a creative use of time-space diagrams.

- Scheduling problems:
  - Road: traffic signal coordination on two-way arterial streets
  - Rail: scheduling of freight (slow) and passenger (fast) trains along a single-track railroad line with passing allowed at pre-determined sidings
  - Air: airplanes with various gliding speeds sharing a landing approach path subject to minimum spacing requirements
  - Transit: determination of the maximum safe service frequency at a rapid transit station
- Network design problems:
  - Highway traffic: determine the length of acceleration lanes on on-ramps
  - Air transportation: determine the runway length
  - Public transportation:
    - Determine the minimum spacing between stations, such that the vehicles (e.g. trains) can achieve their maximum operating speed (or cruising speed).
    - What is the additional delay incurred by introducing a new station/stop?

Examples from our research

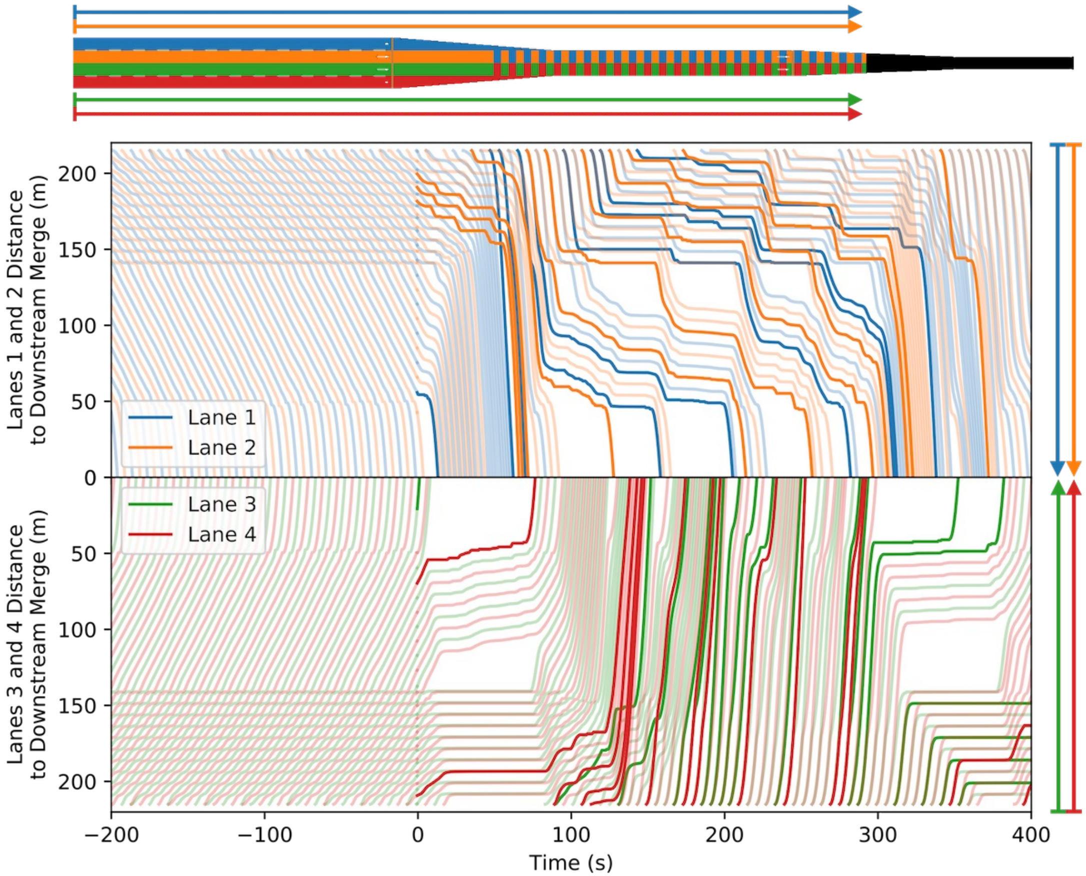
- Visualizing junctions



Yan, Kreidieh, Vinitsky, Bayen, **Wu**. Unified Automatic Control of Vehicular Systems with Reinforcement Learning. T-ASE (2022)

Examples from our research

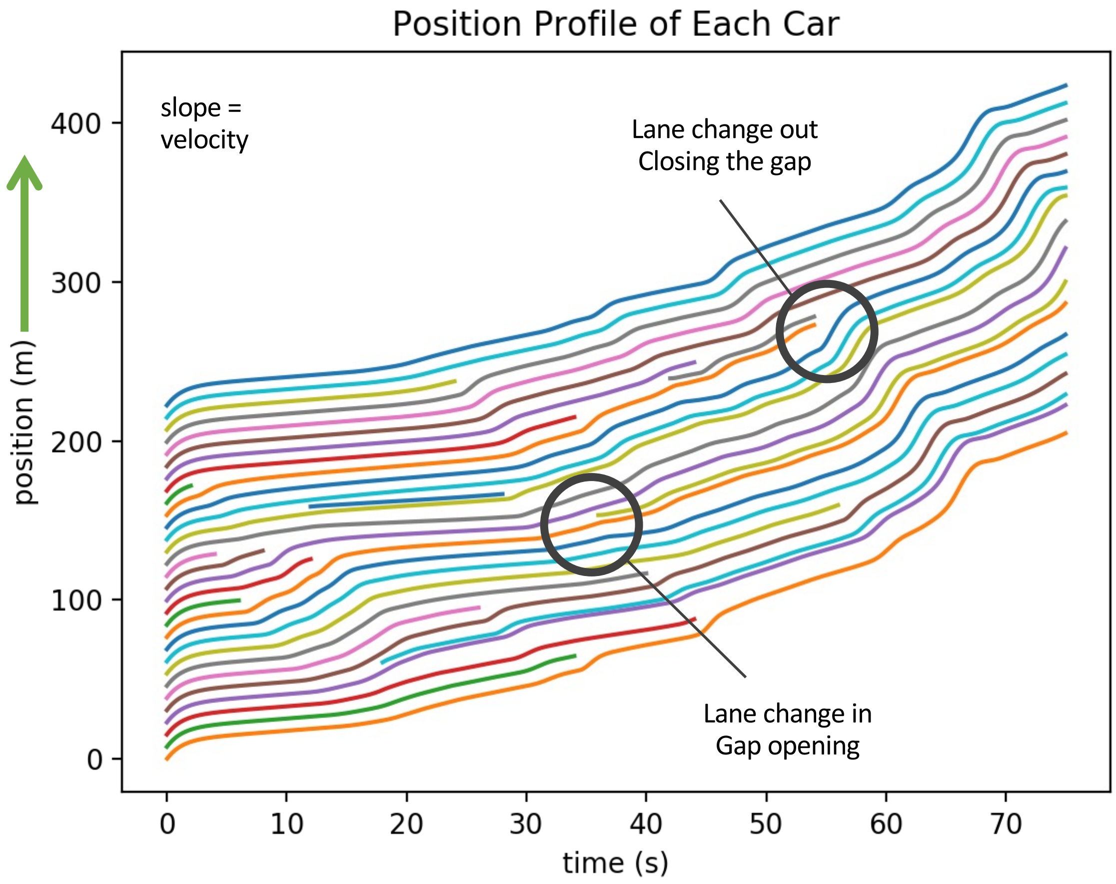
- Multiple lanes in a highway bottleneck



Yan, Kreidieh, Vinitsky, Bayen, **Wu**. Unified Automatic Control of Vehicular Systems with Reinforcement Learning. T-ASE (2022)

Examples from our research

- Lane changing

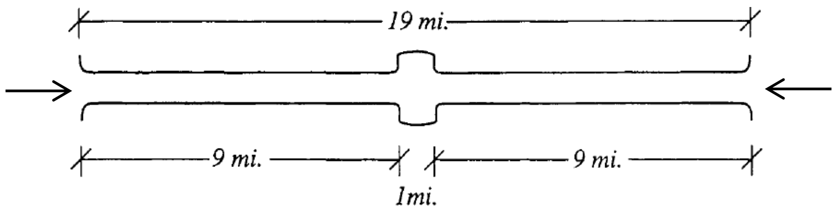


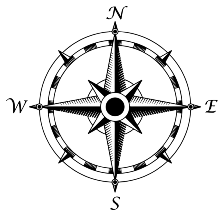
Wu, Cathy, Eugene Vinitsky, Aboudy Kreidieh, and Alexandre Bayen. "Multi-lane reduction: A stochastic single-lane model for lane changing." IEEE ITSC, 2017.

Outline

1. Big picture of transportation engineering
2. **Time-space diagrams**
    a. Applications and traffic system design: road, air, rail, transit
    b. **Exercise: Waterway capacity problem**
3. From sensors to data to trajectories to time-space diagrams

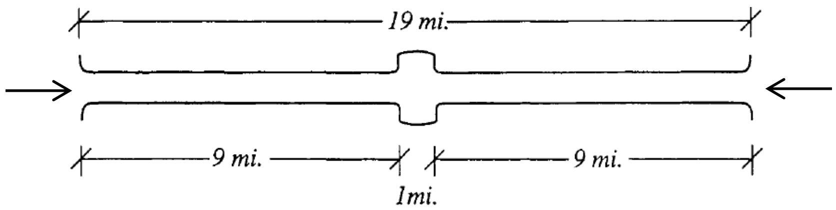
Waterway capacity Problem

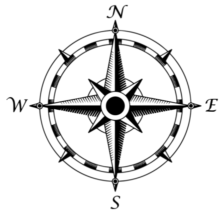




- Evaluation/design of a waterway. From Daganzo (2007).
- Waterway with an intermediate siding for ship crossings
- Similar problems arise in connection with temporary lane closures on two-lane bi-directional roads and in two-way railroad scheduling on a single-track line
- The waterway is wide enough for 1 ship only, except in the central siding which is wide enough for 2 ships
- Westbound ships travel full of cargo and are thus given high priority by the canal authority over the eastbound ships which travel empty

Waterway capacity Problem





- Ships can travel at an average speed of 6 miles/hour
- Ships must be spaced at least 0.5 miles apart while moving in the waterway and 0.25 miles apart while stopped in the siding
- Westbound ships travel in 4 ship convoys which are regularly scheduled every 3.5 hours and do not stop at the siding.
- Eastbound ships must allow a 5-minute clearance from westbound ships when using the one-way sections. We do this to take into account that ships do not accelerate instantaneously.
- Reminder: Westbound ships have priority over eastbound ships.
- For an 8-hour period, determine
  - The maximum daily traffic of eastbound ships
  - The maximum daily traffic of eastbound ships if the siding is expanded by one mile on both sides to a total of three miles.


The Cause of 2021's Shortages

Outline

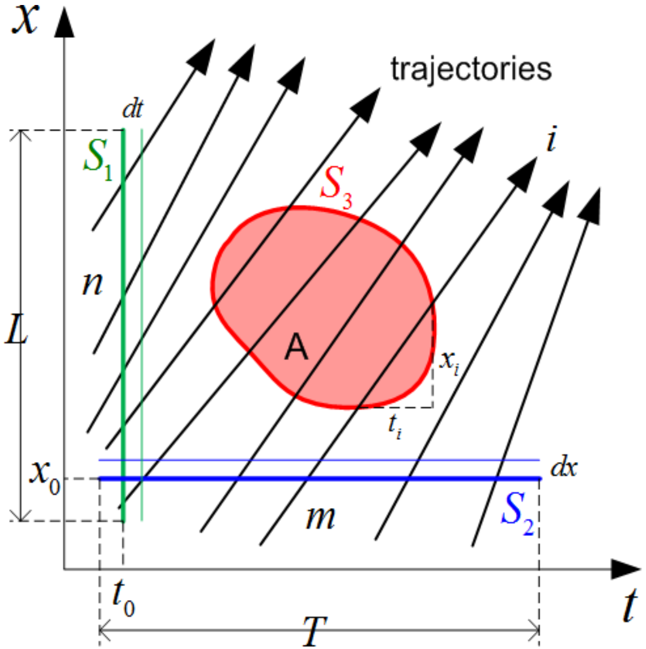
1. Big picture of transportation engineering
2. Time-space diagrams
   a. Applications and traffic system design: road, air, rail, transit
   b. Exercise: Waterway capacity problem
3. **From sensors to data to trajectories to time-space diagrams**

Trajectory measurements

- In principle, trajectories may be derived from vehicle kinematics (solving ordinary differential equations).
- In practice, need to partially measure and then estimate full trajectories.

- **Three types of measurements:**
  - S1-aerial surveys, such as aerial photograph
  - S2-stationary observers, such as loop detectors
  - S3-moving observers, such as driver logs

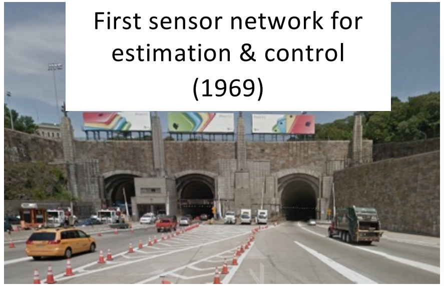
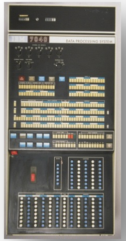
When trajectory data are available, they are the **most** appropriate.

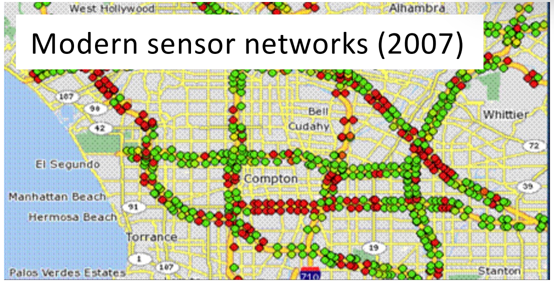


Slide adapted from Prof. Zhengbing He

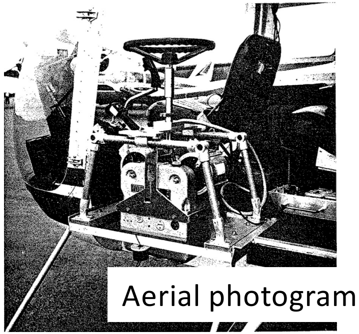
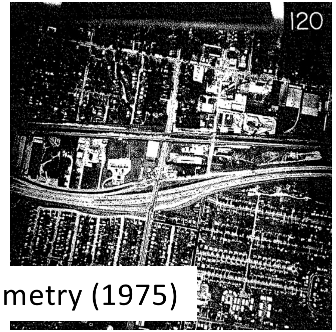
How traffic has been measured over time


Traffic via video camera (1935)



First sensor network for estimation & control (1969)



Modern sensor networks (2007)

Aerial photogrammetry (1975)


Mobile phone based monitoring (2008)

[Greenshields 1935; Treiterer 1975; Gazis et al. 1970; PeMS 2007; Herrera et al. 2010]

Wu

Today’s sensing technologies

loops

video

GPS

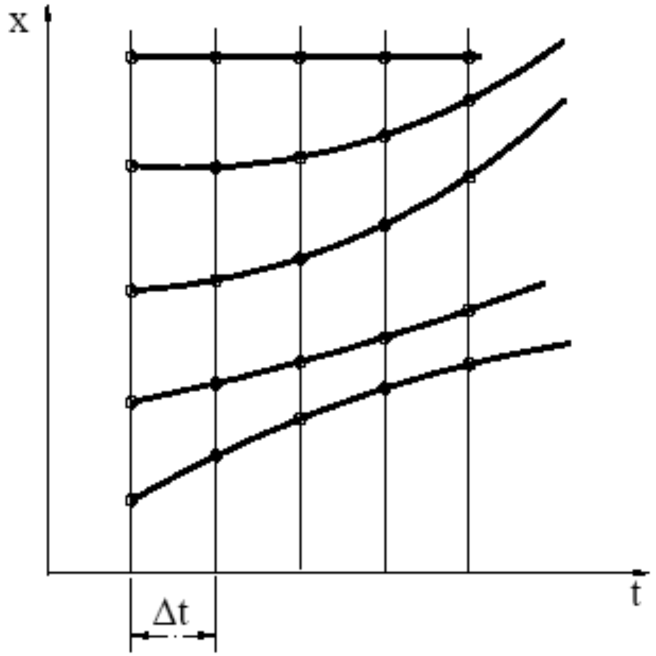
magnetometer

radar

RFID

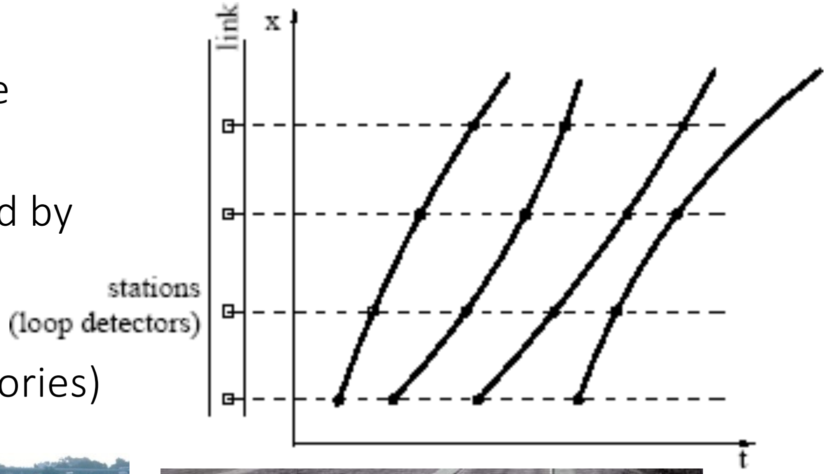
Aerial Surveys (e.g., overhead cameras)

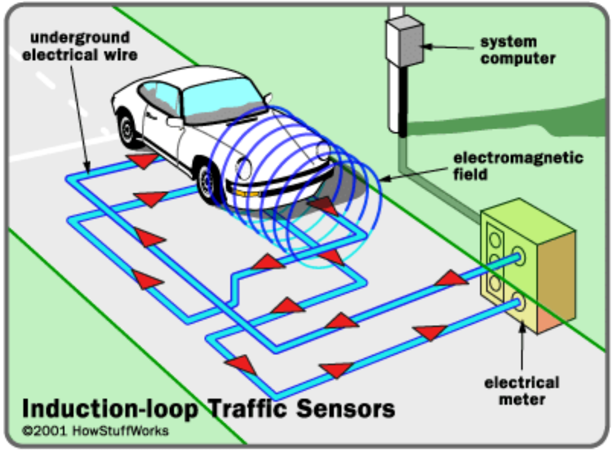
- Take consecutive photographs to the same road segment
- Place them next to each other, separated by the time interval between shots
- Draw lines across the different pictures following the location of the individual vehicles (these are the trajectories)

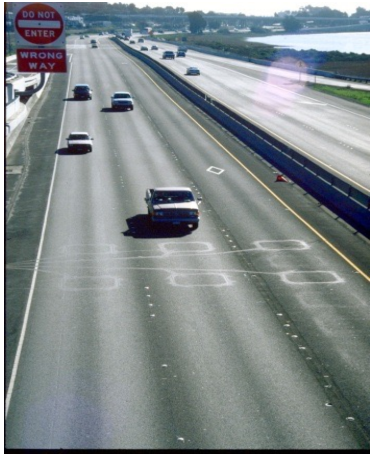


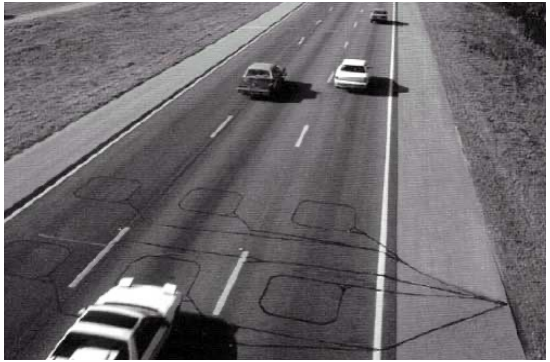
Stationary observers (e.g., loop detectors)

- Measure the time at which every vehicle passes the observers
- Place them next to each other, separated by the distance intervals
- Draw lines following the time of the individual vehicles (these are the trajectories)



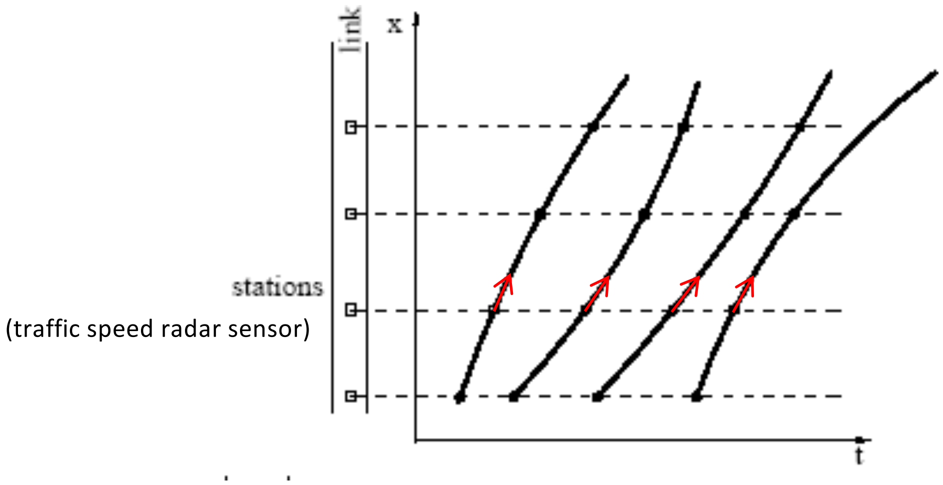






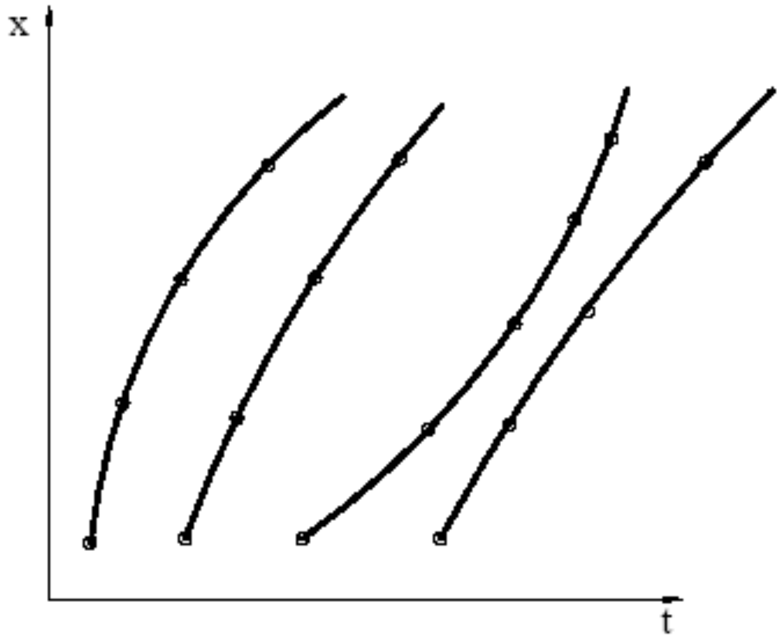
Stationary observers

- Measuring vehicle speed instead of vehicle counts



Moving observers: driver logs (e.g., GPS)

- Drivers record the time and location along their trip
- Plot the corresponding points
- Draw lines following the points corresponding to the individual vehicles (these are the trajectories)



Trajectories - Development

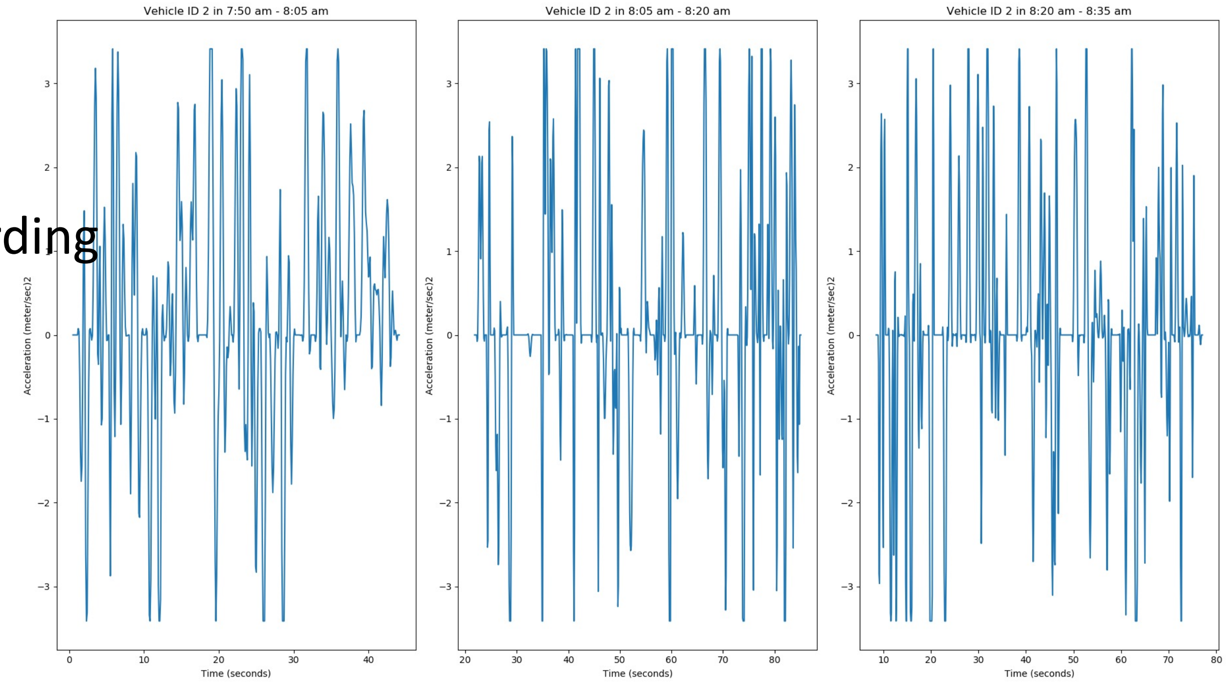
- Full trajectories may be constructed based on interpolation methods
  - Consider when observations are collected at discrete times (every 5 seconds, 5 minutes, etc.)
  - E.g. cameras, transit systems where only times at stations are observed

- Trajectories may also be derived from models (based on vehicle and guideway attributes).

Real trajectory datasets you can download

NGSIM US 101 (2005)

- https://ops.fhwa.dot.gov/trafficanalysistools/ngsim.htm
- Canonical dataset for traffic modeling
- Vehicle trajectories from 8 mounted cameras
- 45 minutes of recording
- Data quality issues



NGSIM US-101 Dataset Smoothing, 2019. https://github.com/Rim-El-Ballouli/NGSIM-US-101-trajectory-dataset-smoothing

HighD dataset (2018)

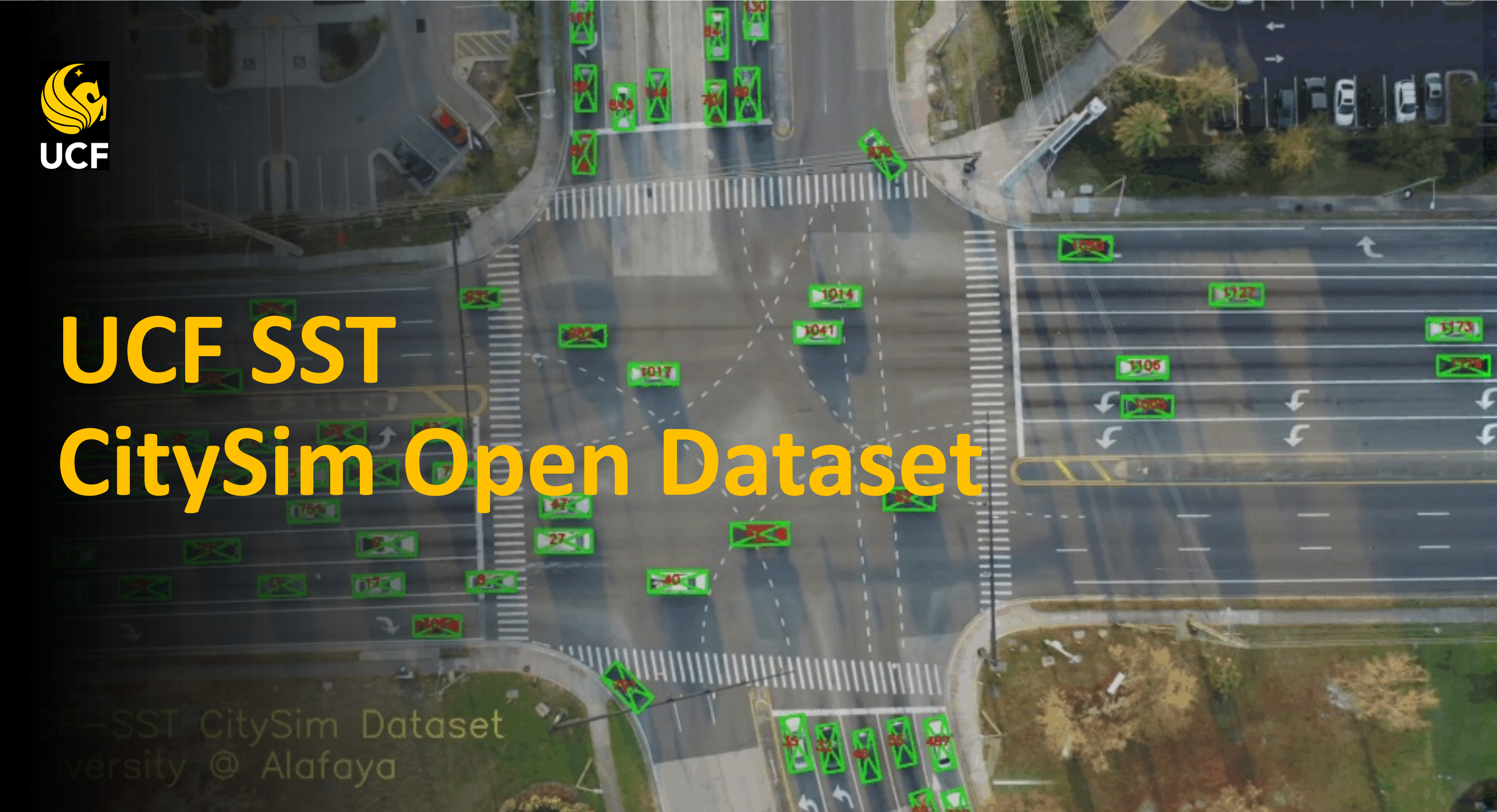
Drone-captured trajectories
16.5 hours of recording

[https://www.highd-dataset.com]

Krajewski, et al. The highD Dataset: A Drone Dataset of Naturalistic Vehicle Trajectories on German Highways for Validation of Highly Automated Driving Systems. ITSC, 2018.

UCF

UCF SST CitySim Open Dataset



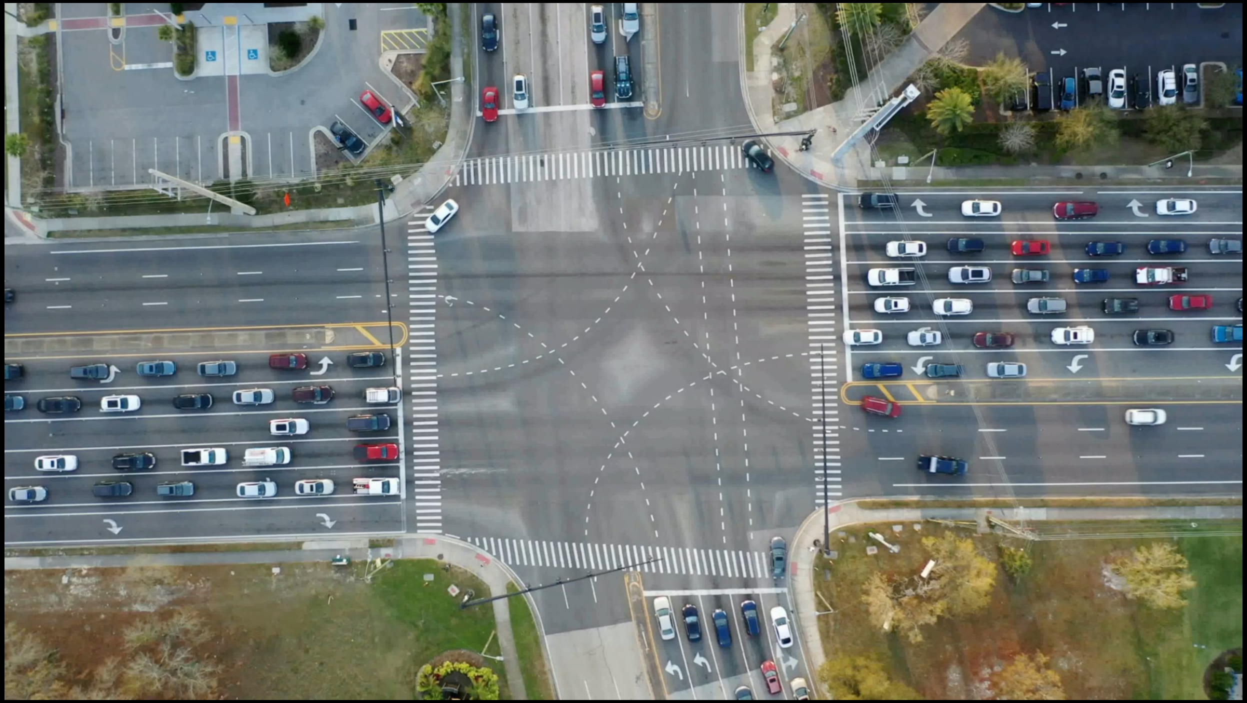
Zheng, Abdel-Aty, Yue, Abdelraouf, Wang, Mahmoud, “CitySim: A Drone-Based Vehicle Trajectory Dataset for Safety Oriented Research and Digital Twins.” arXiv, 2022.

CitySim: A Drone-Based Vehicle Trajectory Dataset for Safety Oriented Research and Digital Twins

Mission: facilitating traffic safety-based research and digital twining

Meta Info:

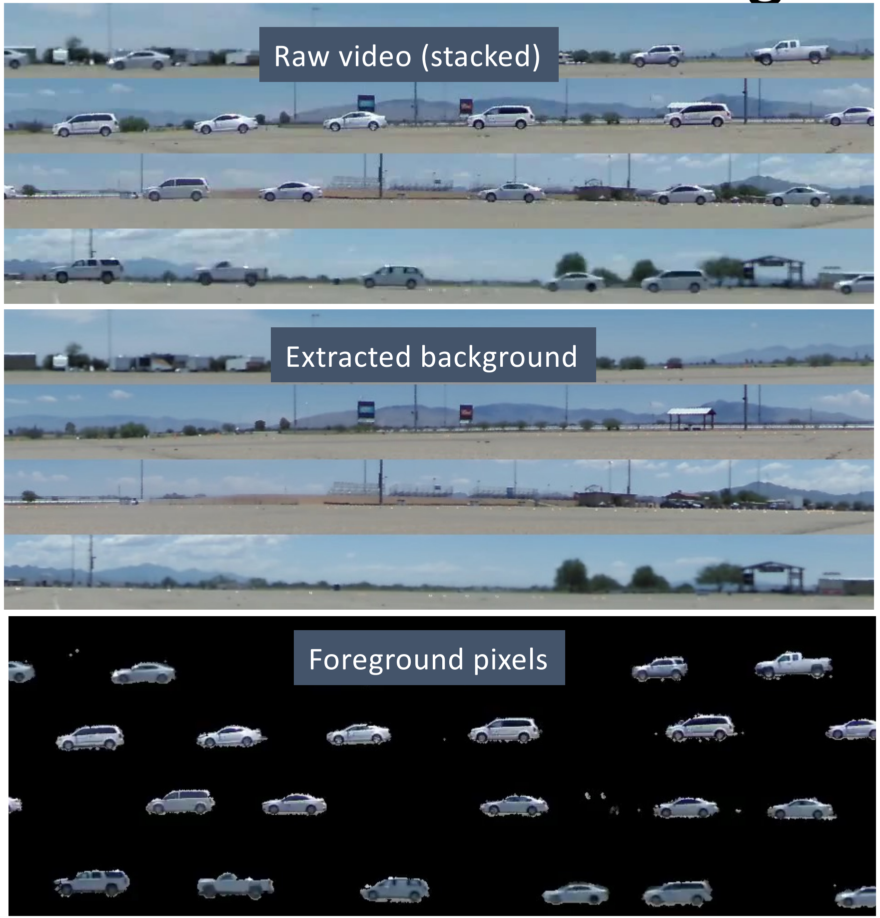
- 12 locations:
    - freeway basic segments,
    - weaving segments,
    - merge/diverge segments,
    - signalized intersections,
    - non-signalized intersections
- 1140-minutes record duration (19 hours)
    - peak hours
    - Over 2 million frames
- First to provide vehicle rotated bounding boxes GPS trajectory
- Dense conflicts:
    - rear-end,
    - lane change,
    - merging/diverging conflicts, etc.
- High-fidelity digital twin 3D maps
- GIS road network file
- Matched signal timing, crash reports at the locations



Zheng, Abdel-Aty, Yue, Abdelraouf, Wang, Mahmoud, "CitySim: A Drone-Based Vehicle Trajectory Dataset for Safety Oriented Research and Digital Twins." arXiv, 2022.

Conceptual overview of camera based tracking

- Step 1. Identify Foreground
  - Filter moving pixels
  - estimate static background image
  - Subtract background to find vehicle pixels

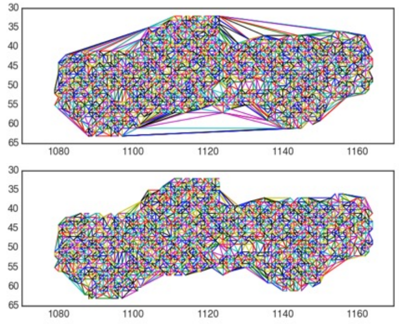


[Stern, et al 2017]

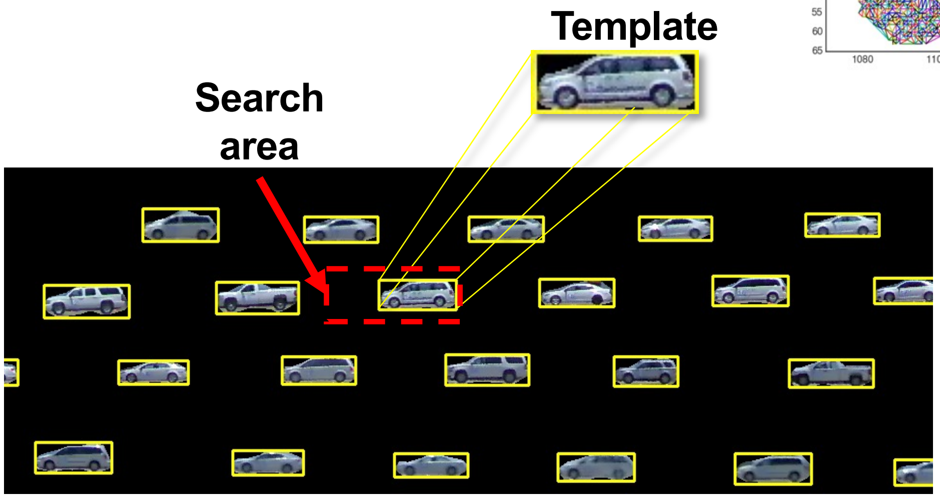
Conceptual overview of camera based tracking

- Step 2. Cluster foreground pixels
  - Construct a template for each vehicle

Template refinement
from pixel cluster



- Step 3: Tracking
  - Match template frame by frame



Conceptual overview of camera based tracking

- Position Accuracy: 10 cm error; matched with human annotated data
- Velocity Accuracy: 0.14 m/s error; matched with Odometer data