Open-Source Dynamic Traffic Assignment Package DTALite: GMNS based Multi-Resolution Modeling

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Arizona State University

Prepared for Short Course on
Modelling transportation supply and demand-supply interactions
30th June — 2nd July 2022
Organized by
The Department of Civil Engineering
Indian Institute of Technology (IIT), Madras, India

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Evolution of Simulation/Digital Twins

Computer-driven *Simulation* **(1960)**

Computer-driven Simulation (1985)

AutoCAD becomes a de facto tool in nearly all engineering and design

Simulation-driven System Design (2000)

NASA & USAF papers on digital twins (2011)

Source: chesky - stock.adobe.com

Digital Twins (2015)

Gartner lists digital twins as a top 10 tech trend (2017)

Source: www.esri.com/en-us/digital-twin/overview

Questions to be Addressed

1. How to practically build a prototype of Digital Twin system for smart cities and communities? How to encourage collaboration from different software developers, researchers and planners/engineers

2. How to leverage the open-source model and open data to enable decision intelligence?

3. How to build a high-fidelity multimodal simulator that mirrors the physical world with complex interactions?

4. How to bridge the gap in multiresolution modeling: From micro to macro, from macro to micro mesh network.

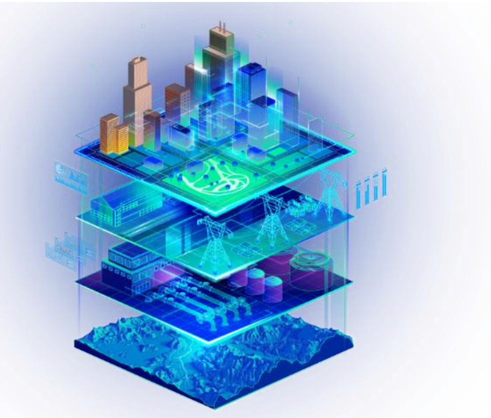
Outline/Main Research Line

I. Open Network Data Specification

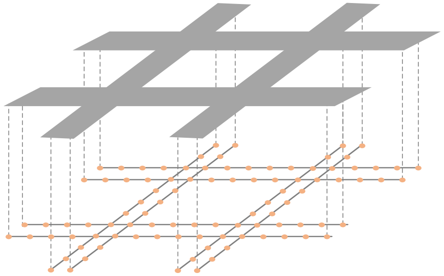
Outline/Main Research Line

I. **Open Network Data Specification**

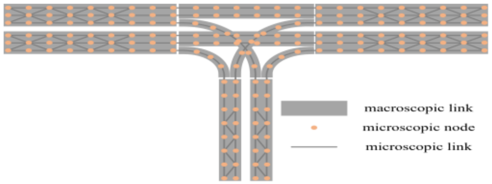
II. **Open-Source Tools**



Macroscopic Layer



Microscopic Mesh Layer

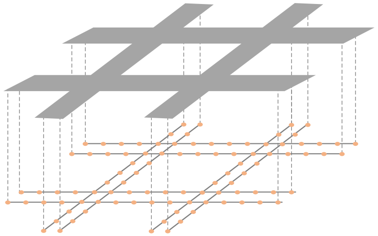


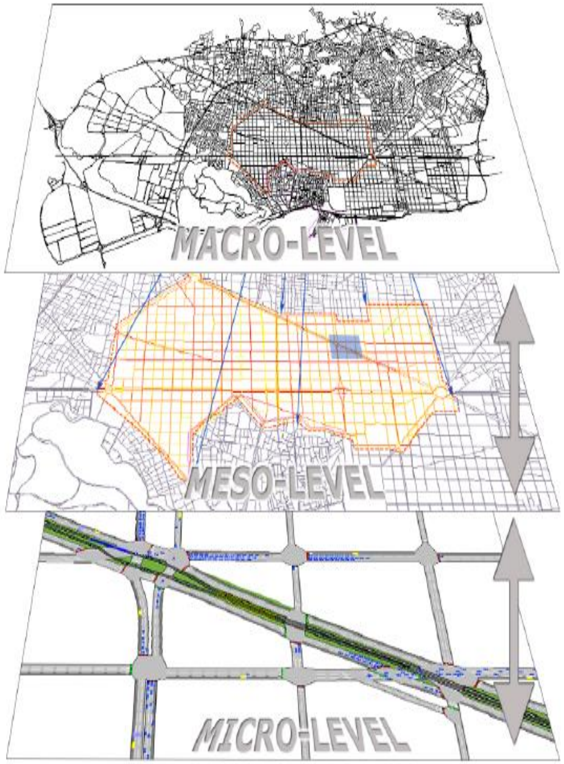
Outline/3 Parts/DTA

I. **Open Data Specification**

II. **Open-Source Tools**

III. **Supply-side Analytical Models for Large Scale System**



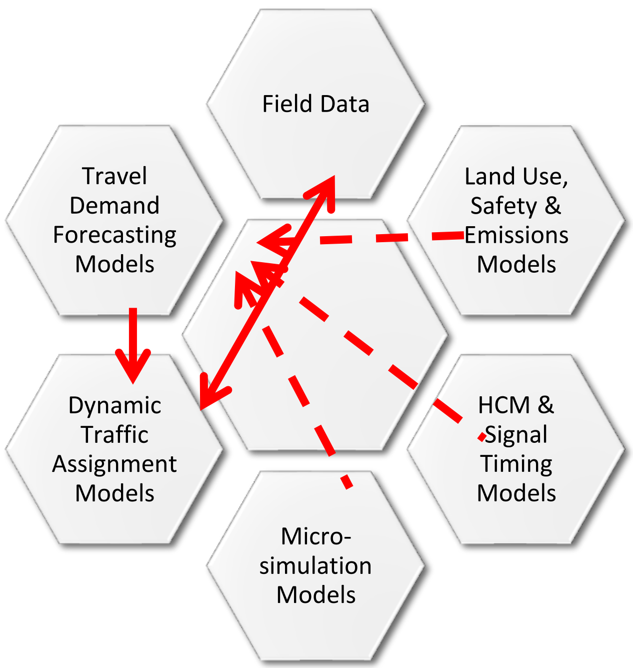


Part I: Open Network Data Specification

I. **Open Data Specification**

Critical Challenges for Transportation Analysis Modeling and Simulation (AMS) Data Hub

Ad Hoc Connection



Systematic Coupling

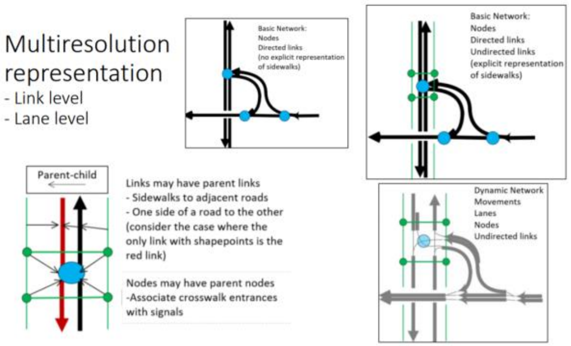
AMS Data Hub for Transportation Planning Applications

Introducing
General Modeling Network Specification (GMNS)

The objective of the GMNS is to provide **a common human and machine-readable format** for sharing routable road network files.

The project is overseen by a project management group, with MPO, city, industry, academic and US DOT participation.

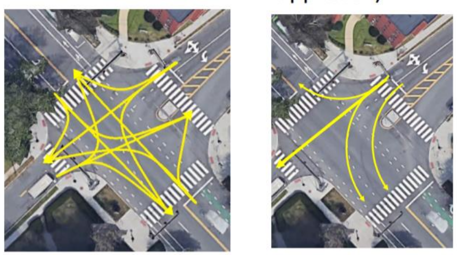
github.com/zephyr-data-specs/GMNS



Source: Volpe Center GMNS team
Scott.Smith@dot.gov
Ian.Berg@dot.gov

Movements at an intersection

- Link Level
- Lane Level (for the northeast approach)



Permitted movements may also be time-of-day specific

- Movement attributes
  - Node
  - Inbound link and lane(s)
  - Outbound link and lane(s)
  - Type of Movement
    - left, right, thru, merge, uturn
  - Type of control
    - no_control, yield, stop, stop_2_way, stop_4_way, signal
  - Optionally
    - Right-turn-on-red
    - Penalty
    - Capacity
    - Pct Green Time

Governance

This project is overseen by a board-approved Project Management Group (PMG) as follows:

- Joe Castiglione, SFCTA (chair, board representative)
- Michael Mahut, INRO
- Wu Sun, SANDAG
- Guy Rousseau, ARC
- Chetan Joshi, PTV
- Jeff Frkonja, Portland Metro
- Scott Smith, Volpe
- Natalia Ruiz Juri, University of Texas Center for Transportation Research
- Song Gao, UMass Amherst

GMNS Format

Basic Data Elements

- node
- link
- geometry
- zone

name	node_id	osm_node.	osm_highw	zone_id	ctrl_type	node_type	activity_typ	is_boundar	x_coord	y_coord	main_node	poi_id	notes
	0	41459438			0				-111.928	33.4245			
	1	41520512			0				-111.944	33.42547			
	2	41520515			0				-111.944	33.42432			
	3	41520518			0				-111.944	33.42318			
	4	41520521	traffic_signals		1				-111.944	33.42189			
	5	41520523			0				-111.944	33.42064			
	6	41520525			0				-111.944	33.42035			
	7	41520528			0				-111.944	33.4194			
	8	41520531			0				-111.944	33.41892			
	9	41520533			0				-111.944	33.41778			

node.csv

name	link_id	osm_way_i	from_node	to_node_ic	dir_flag	length	lanes	free_speed	capacity	link_type_n	link_type	geometry	allowed_us	from_biwa
South Farn	0	5590095	13	14	1	81.57798	1	25		residential	6	LINESTRIN	auto	1
South Farn	1	5590095	14	13	1	81.57798	1	25		residential	6	LINESTRIN	auto	1
South Farn	2	5590095	14	15	1	80.16146	1	25		residential	6	LINESTRIN	auto	1
South Farn	3	5590095	15	14	1	80.16146	1	25		residential	6	LINESTRIN	auto	1
South Farn	4	5590095	15	16	1	240.2824	1	25		residential	6	LINESTRIN	auto	1
South Farn	5	5590095	16	15	1	240.2824	1	25		residential	6	LINESTRIN	auto	1
South Farn	6	5590095	16	17	1	84.15426	1	25		residential	6	LINESTRIN	auto	1
South Farn	7	5590095	17	16	1	84.15426	1	25		residential	6	LINESTRIN	auto	1
South Farn	8	5590095	17	18	1	83.10715	1	25		residential	6	LINESTRIN	auto	1
South Farn	9	5590095	18	17	1	83.10715	1	25		residential	6	LINESTRIN	auto	1

link.csv

[1] https://github.com/zephyr-data-specs/GMNS

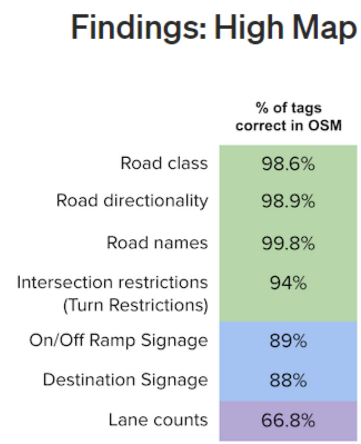
OpenStreetMap

OpenStreetMap (OSM) is a free, open-source, editable map website that can provide free downloads. osm2gmns, as a data conversion tool, can directly convert the OSM map data to node and link network files in GMNS format. Users can convert and model drivable, walkable, railway, or aeroway networks with a single line of Python code.

OpenStreet Map Server

Raw Network Data

Standard Network Data
GMNS format[1]



We found that core features of OpenStreetMap roads are correct more than 95% of the time relative to what exists in the real world. Data critical to safe navigation, such as left turn restrictions, are correct more than 85% of the time. Nationwide, these estimates are precise to within 5% sampling uncertainty. The regional uncertainty varies more based on region-level dynamics, visible in the figures at the end of this post.

https://eng.lyft.com/how-lyft-discovered-openstreetmap-is-the-freshest-map-for-rideshare-a7a41bf92ec

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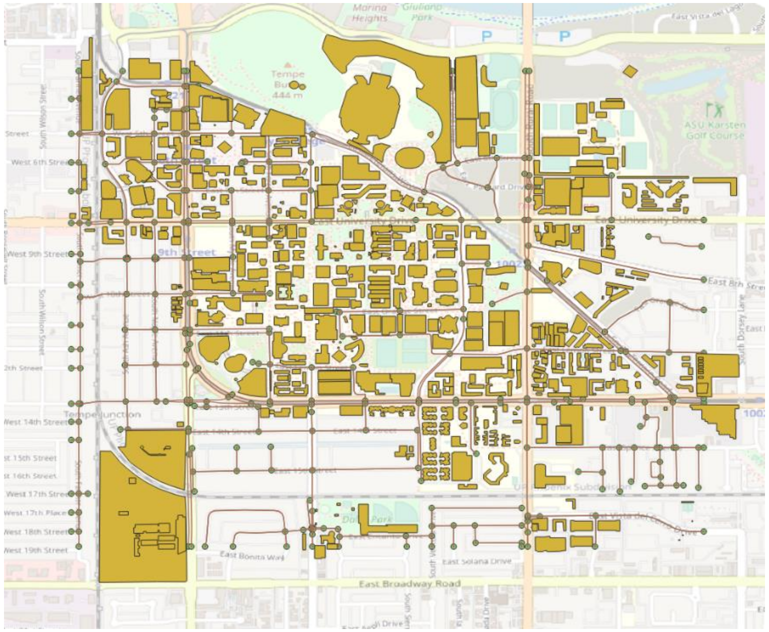
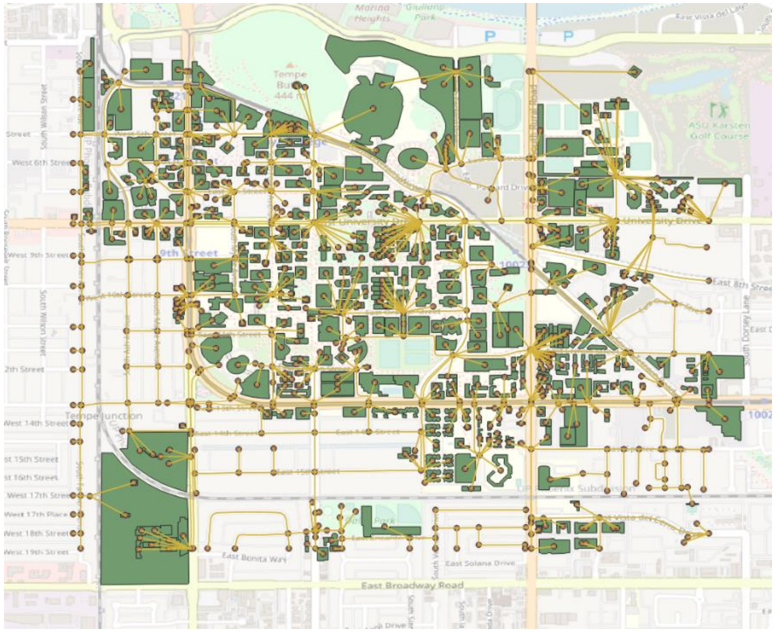
POIs, Activity Locations and Network



Network with POIs

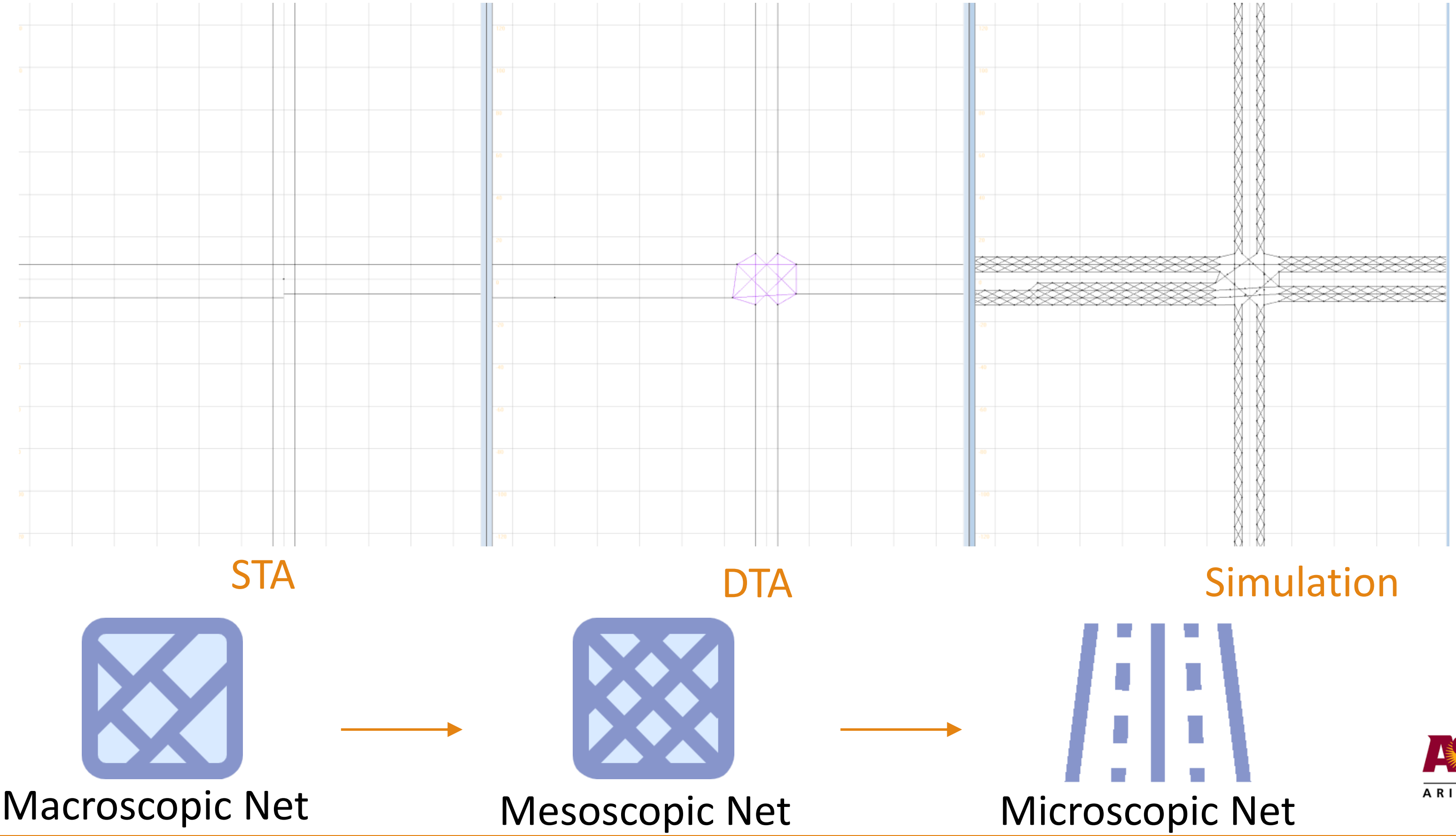


Connect POIs with network

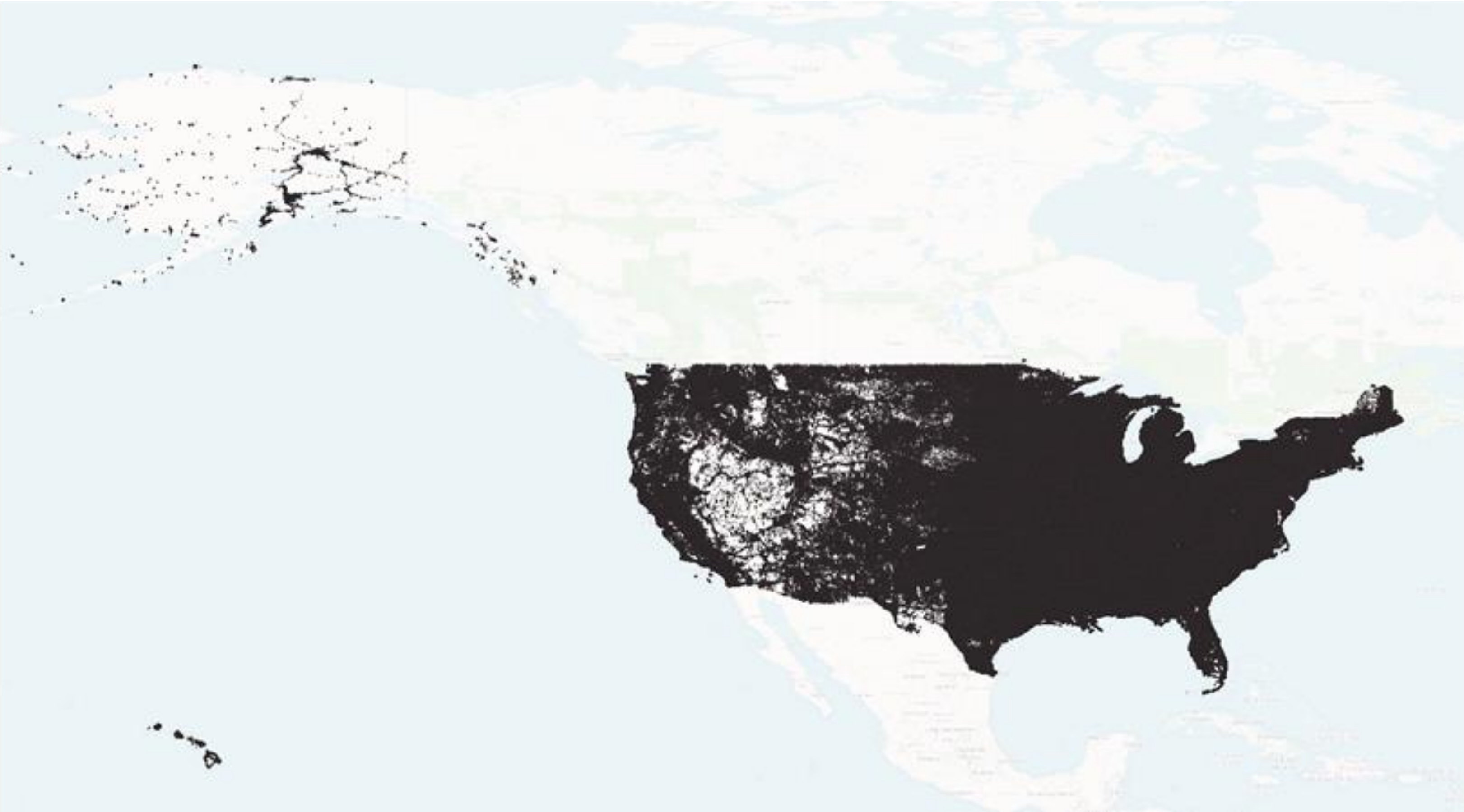
More sample networks
https://osm2gmns.readthedocs.io/en/latest/sample-net.html

Multi-resolution Network

For any given networks that meet the GMNS standard, net2cell helps users automatically generate hybrid (macroscopic, mesoscopic and microscopic) transportation networks to accommodate different modelling needs.



Multi-resolution Network



Using ASU research computing facilities, we are able to produce the entire U.S. driving network from OpenStreetMap with 20 million nodes.

https://github.com/asu-trans-ai-lab/asu-trans-ai-lab.github.io

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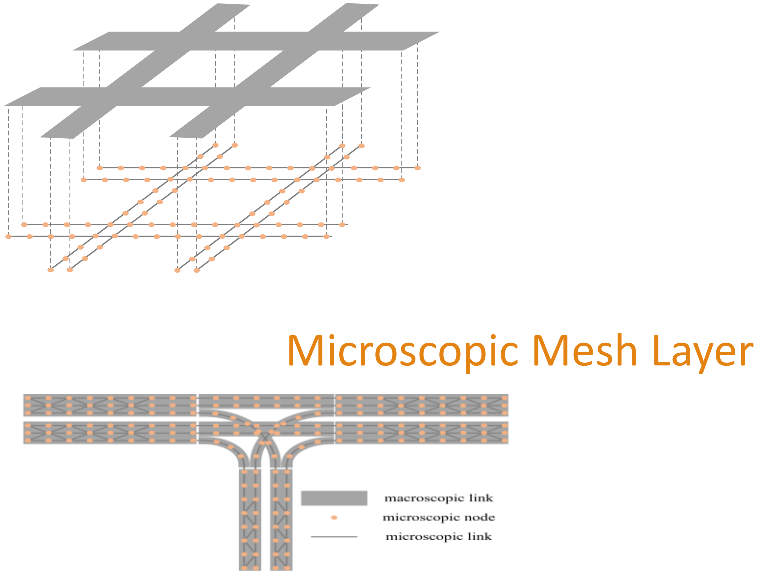
Part II: Open-Source Tools

I. Open Data Specification

II. Open-Source Tools

Macroscopic Layer

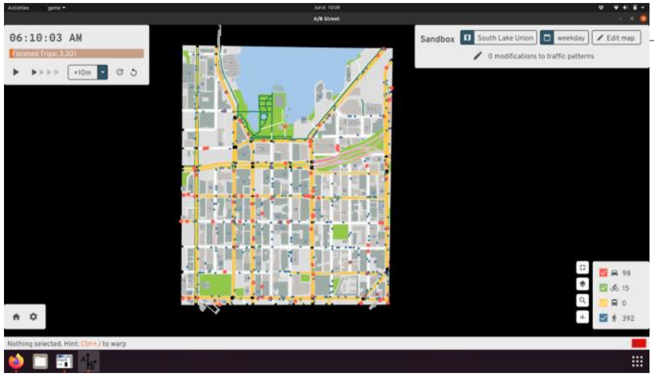


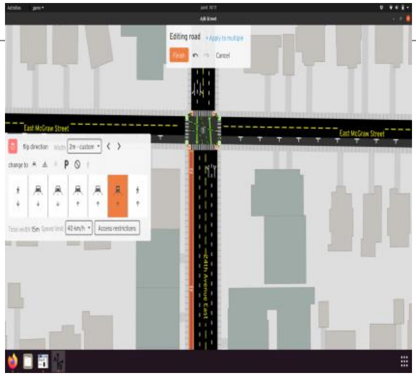
(a) Smart Planning, Digital Twins, & Open Data

A/B STREET

DUSTIN CARLINO, MICHAEL KIRK, & YUWEN LI

HTTPS://DOCS.GOOGLE.COM/PRESENTATION/D/1TT6OENTUH_Q-WPIC8AUX67HBOCPTJ7YWNKZN-X6NY8W/EDIT?USP=SHARING





Carlino, Dustin, Stephen D. Boyles, and Peter Stone. "Auction-based autonomous intersection management." *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*. IEEE, 2013.

(b) Network Data Set: OSM2GMNS

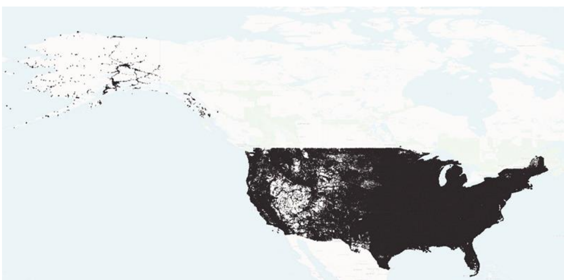
OpenStreetMap (OSM) is an open-source map website providing free download.

OSM2GMNS can convert the OSM map data to multi-resolution routable network files in GMNS format. Users can convert and model drivable, walkable, railway, or aeroway networks with a few lines of Python code.

osm2gmns 0.5.2

`pip install osm2gmns`

https://pypi.org/project/osm2gmns/

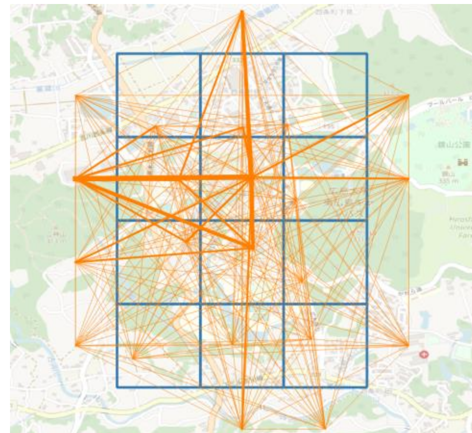


PyPI link	https://pypi.org/project/osm2gmns
Total downloads	46,148
Total downloads - 30 days	2,747
Total downloads - 7 days	538

Jiawei (Jay) Lu
PhD. student at Arizona State University

(c) Demand Generation: Grid2Demand

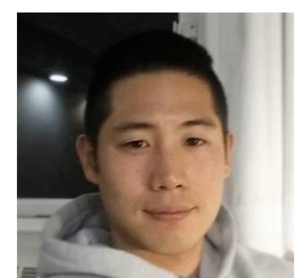
Grid zones can be automatically generated by a given number of grid cells or cell's width and height in meters.



Advantages:

- ◆ Compared with traditional TAZs like census tracts, grid zones could reduce spatial biases.
- ◆ Trip generation directly comes from activity nodes, which is aggregated in grid zones.
- ◆ Cell size is flexible to satisfy multi-resolution models.
- ◆ Open-source quick transportation demand generation tool grid2demand – YouTube
- ◆ Developers: Anjun Li, Entai Wang and Taehooie Kim

Census tract
Grid cell



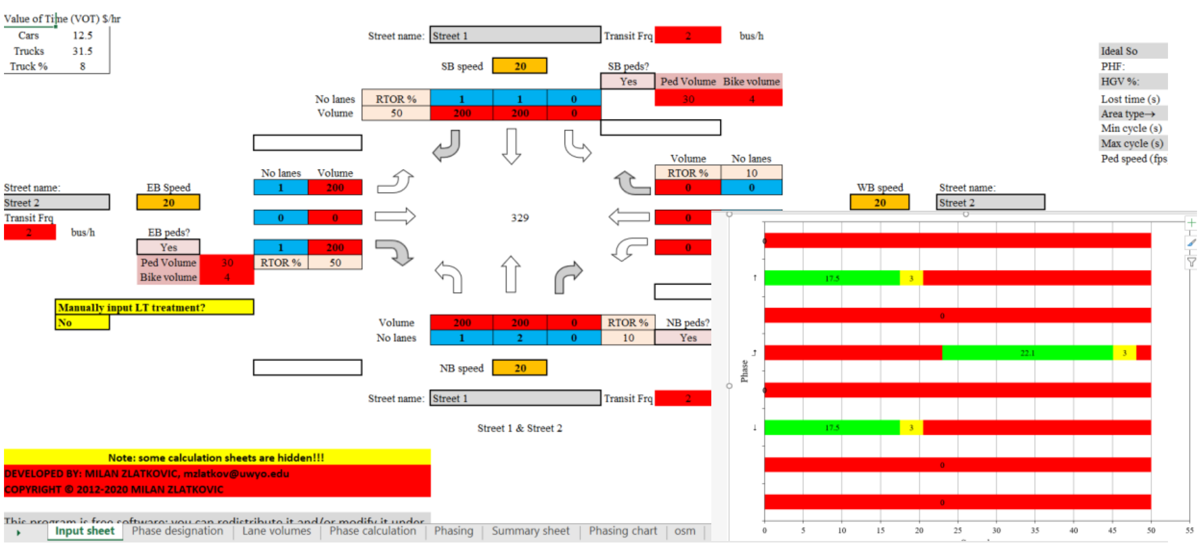
(d) Sigma-X: Excel-based computational engine for signalized intersections,

https://github.com/milan1981/Sigma-X

Excel->GMNS, Synchro UTDF -> GMNS

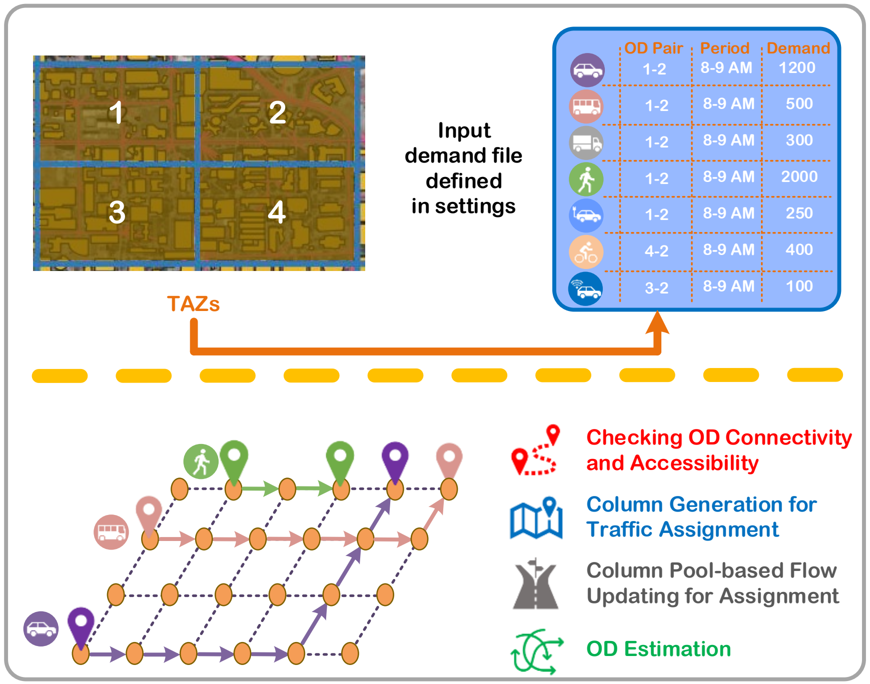
Contributor: Prof. Milan Zlatkovic

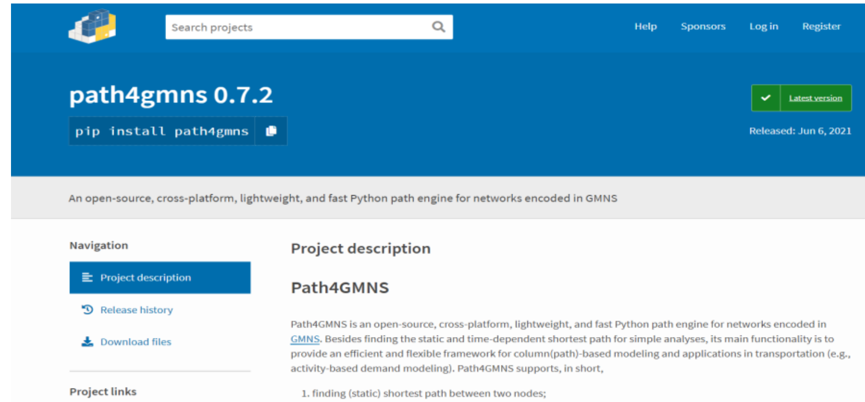
http://www.uwyo.edu/civil/faculty_staff/faculty/milan-zlatkovic/index.html



Python Package: https://github.com/asu-trans-ai-lab/signal4gmns

(e) Path4GMNS





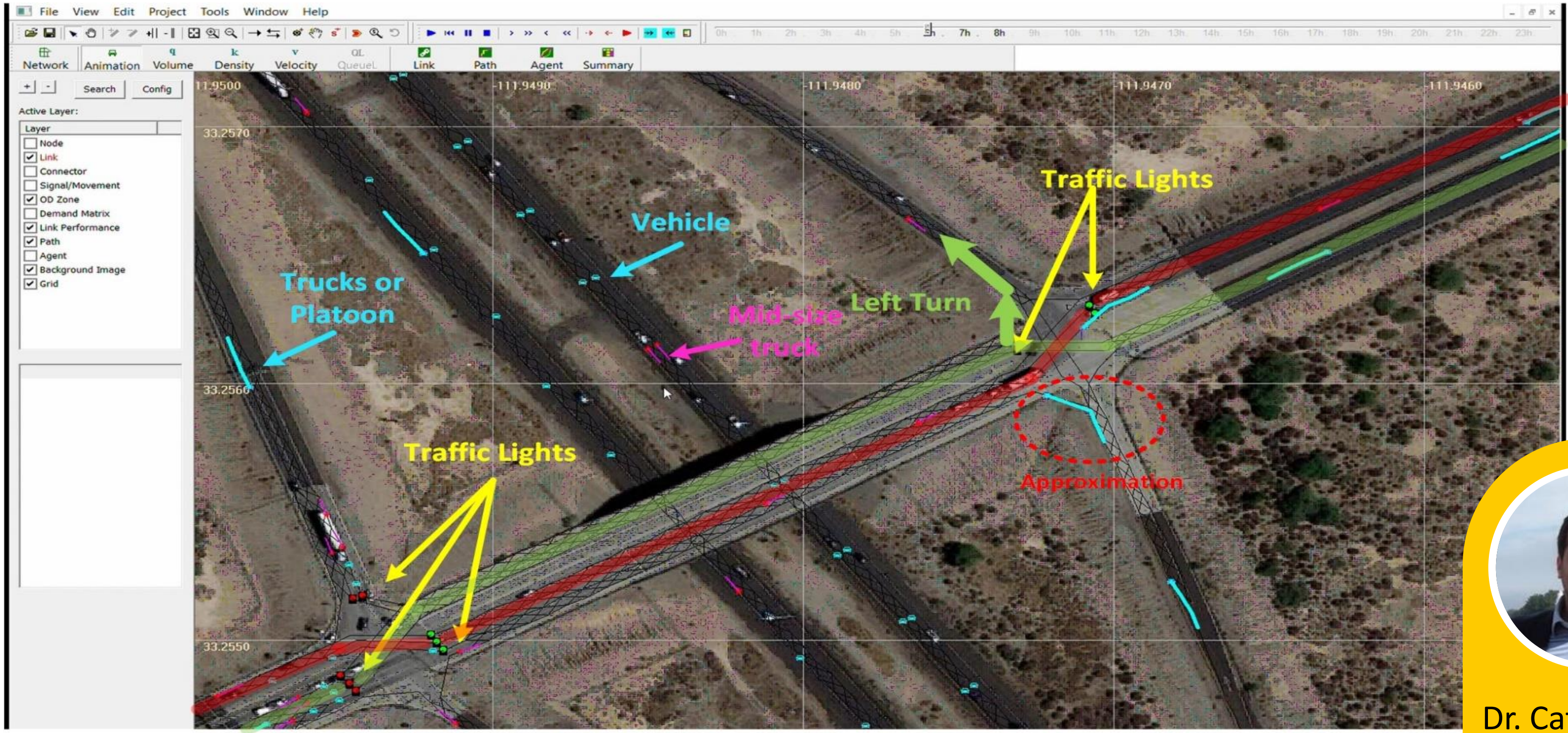
PyPI link	https://pypi.org/project/path4gmns
Total downloads	16,865
Total downloads - 30 days	812
Total downloads - 7 days	201

Dr. Peiheng Li

Operations Research Analyst at Norfolk Southern Corporation

ASU Graduate Ph.D. (2017)

(f) DLSim: Deep Learning Based Traffic Simulation



Dr. Cafer Avci

Simulation Engine

(g) GTFS2GMNS

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Cafer Avci
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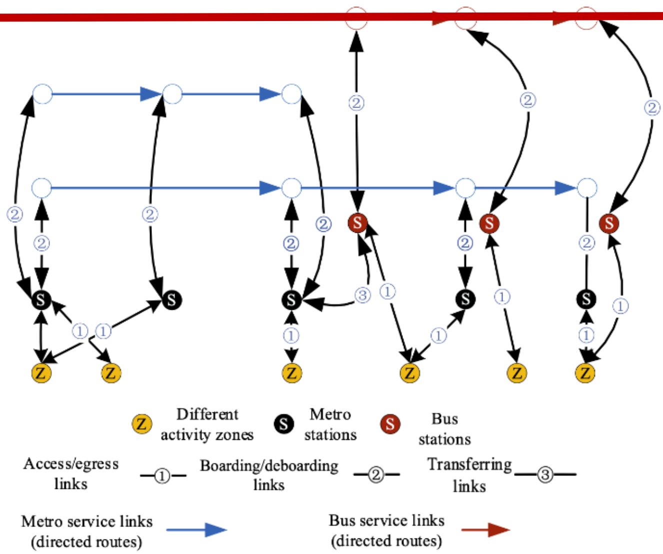
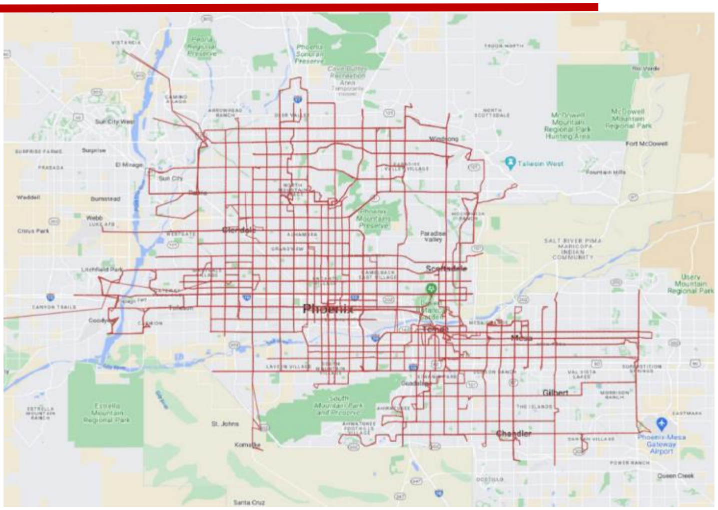
Xuesong (Simon) Zhou
xzhou74@asu.edu



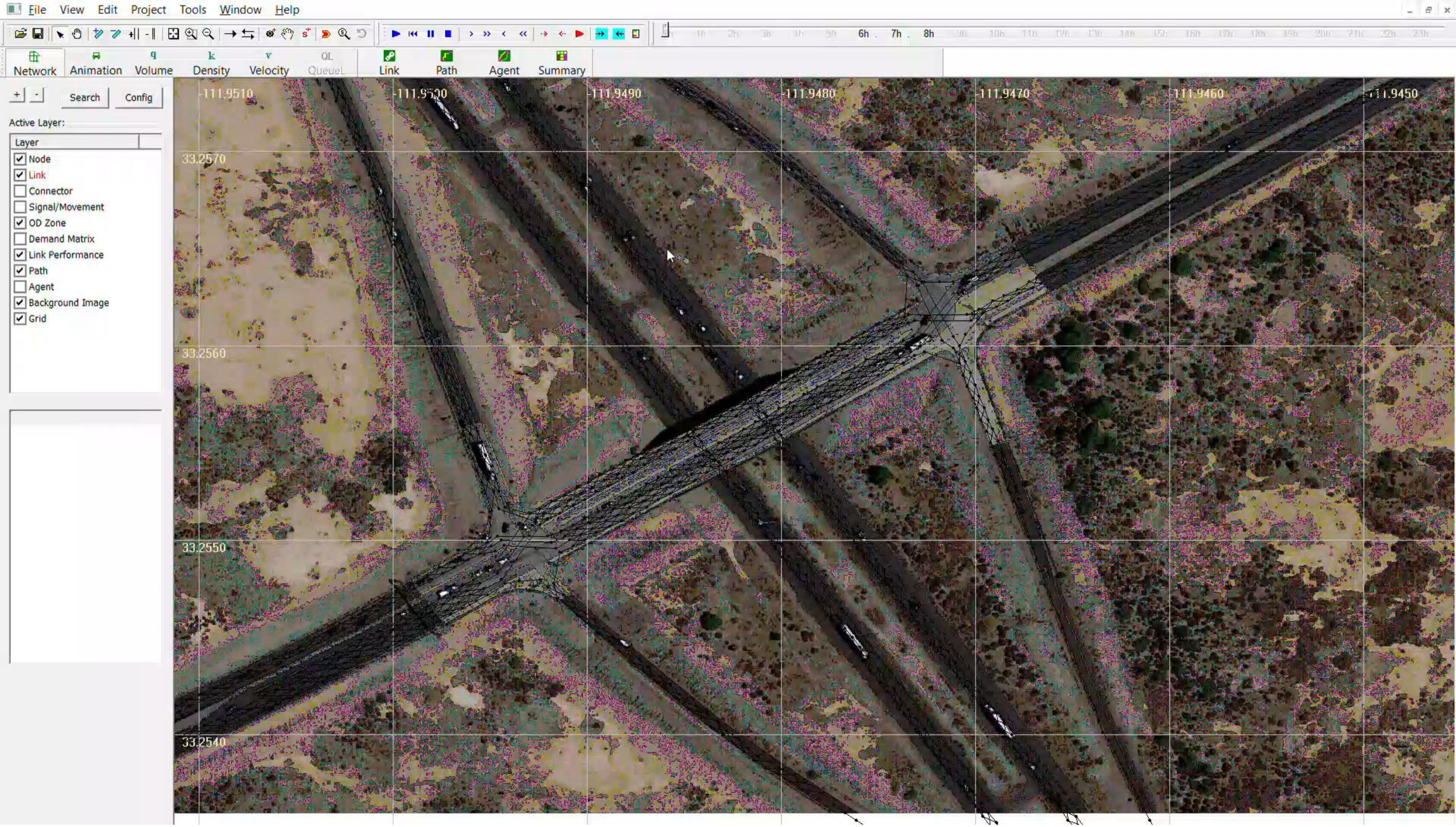


gtfs2gmns is an open-source Python code that enables users to conveniently construct any multi-modal transit network from General Transit Feed Specification (GTFS).

Fang (Alicia) Tang at ASU, Xianting (Alice) Huang at CMU

DLSIM

Sample Simulation of DDI



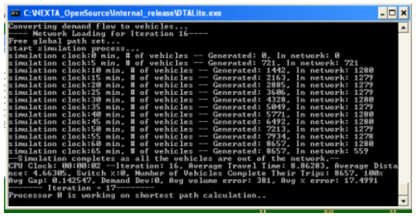
(h) DTALite and NeXTA

NEXTA: front-end GUI (C++)

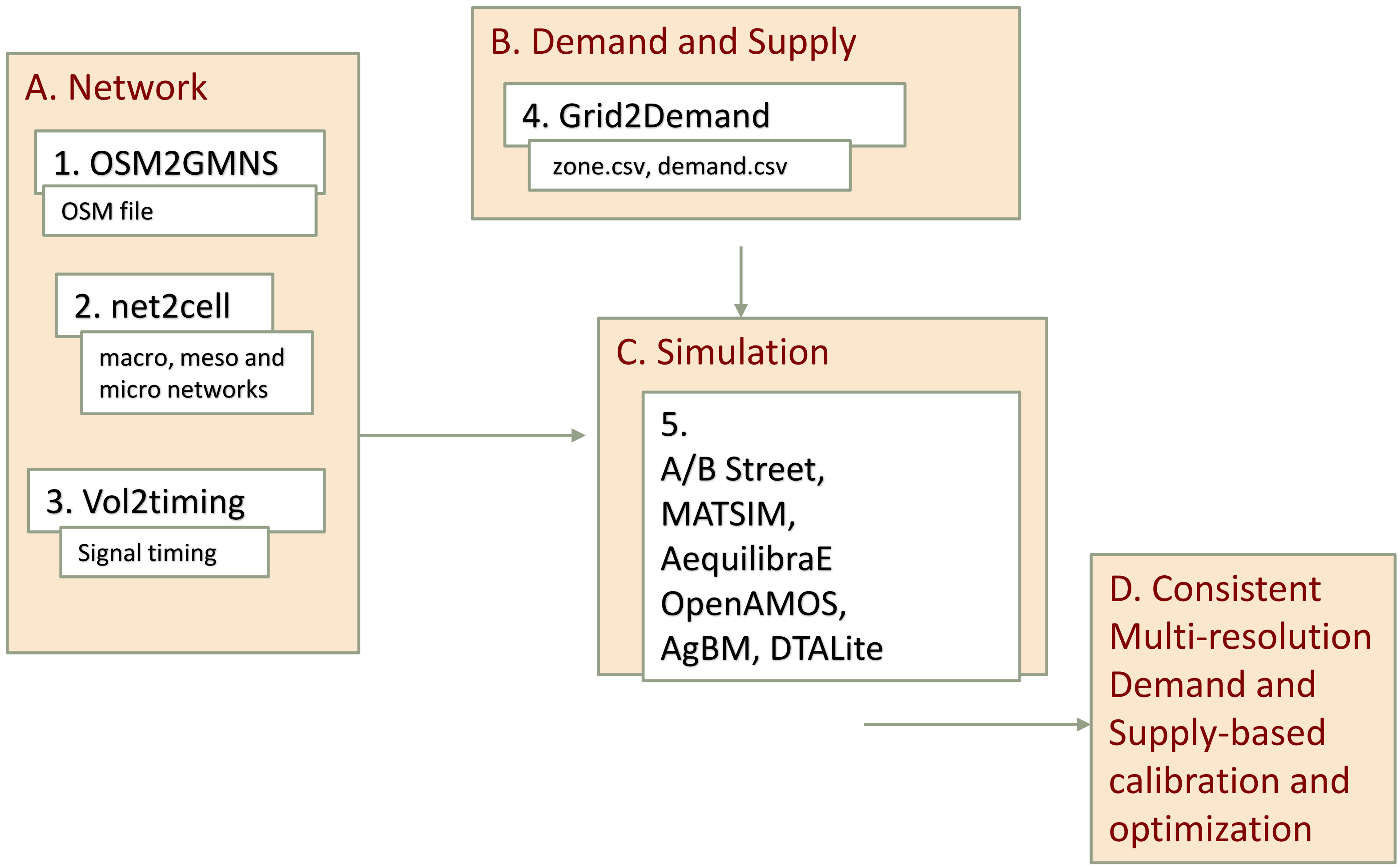
- Version 2: GUI for TRANSIMS and DYNASMART
- Version 3: GNU Open-source data hub

DTALite: Open-source computational engine (C++)

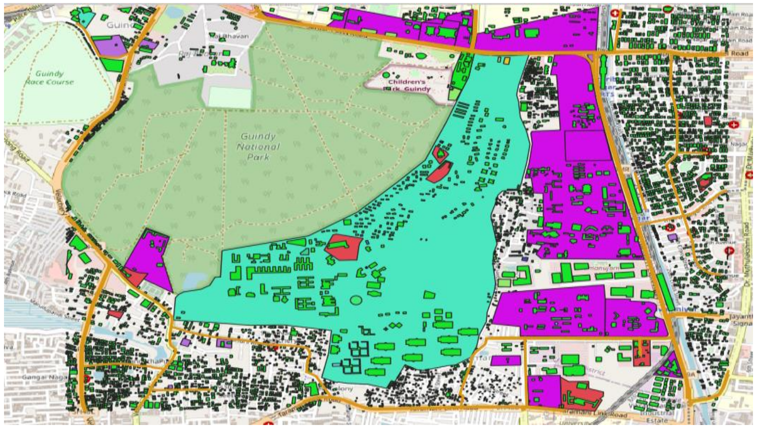
- Light-weight and agent-based DTA



Long-term Goal: Integrate Network, Demand and Supply Elements



Case study of Indian Institute of Technology (IIT), Madras, India



https://github.com/asu-trans-ai-lab/gmns_education_data_sets/tree/main/Universities/Asia/India/IIT%20Madras

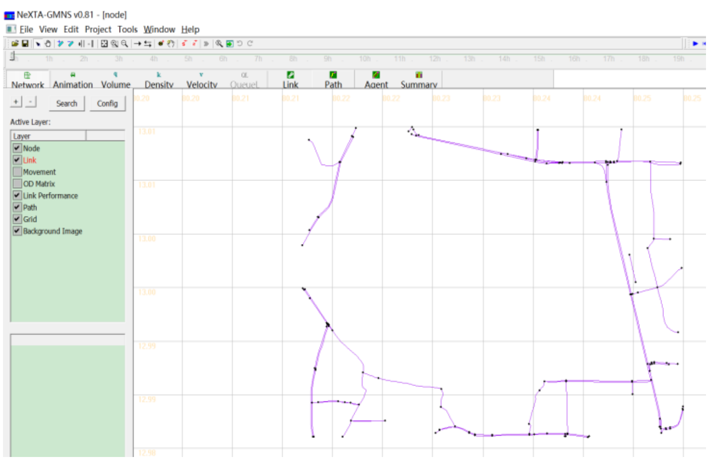
Step 1: Open-Source Network Visualization

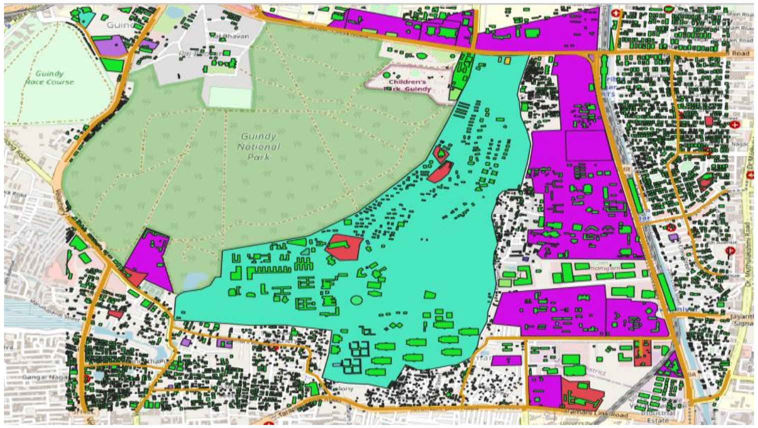
NEXTA: front-end Graphical User Interface GUI (C++) NEXTA.exe

https://github.com/xzhou99/NeXTA-GMNS

QGIS: a free, open source, cross platform (lin/win/mac) geographical information system (GIS)

https://qgis.org/en/site/forusers/download.html





More sample networks

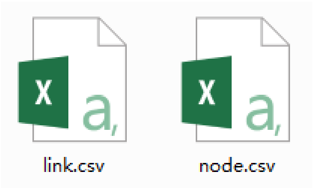
https://osm2gmns.readthedocs.io/en/latest/sample-net.html

Step 2: Open-source MRM Tools: osm2gmns

Some examples

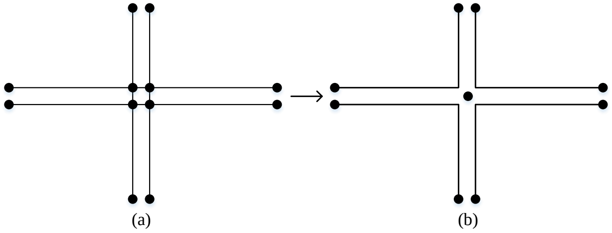
Download OSM data

https://osm2gmns.readthedocs.io/en/latest/quick-start.html



Get a network in GMNS format

```
>>> import osm2gmns as og
>>> net = og.getNetFromOSMFile(‘map.osm’)
>>> og.outputNetToCSV(net)
```



Consolidate Intersections

```
>>> og.consolidateComplexIntersections(net)
```

Generate movements at intersections

```
>>> og.generateMovements(net)
```

Network Types and POI

```
>>> net = og.getNetFromOSMFile(‘map.osm', network_type=('auto’,’bike’,’walk'))

>>> net = og.getNetFromOSMFile('map.osm', POIs=True)

>>> og.connectPOIWithNet(net)
```

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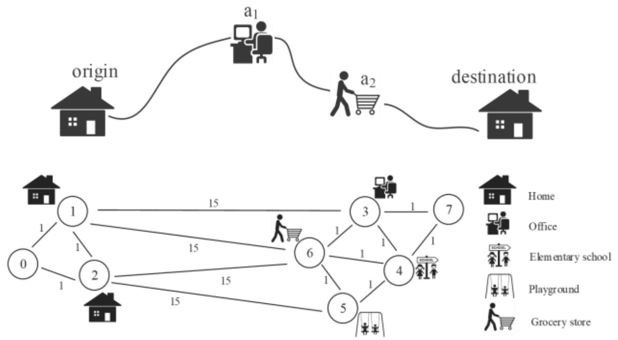
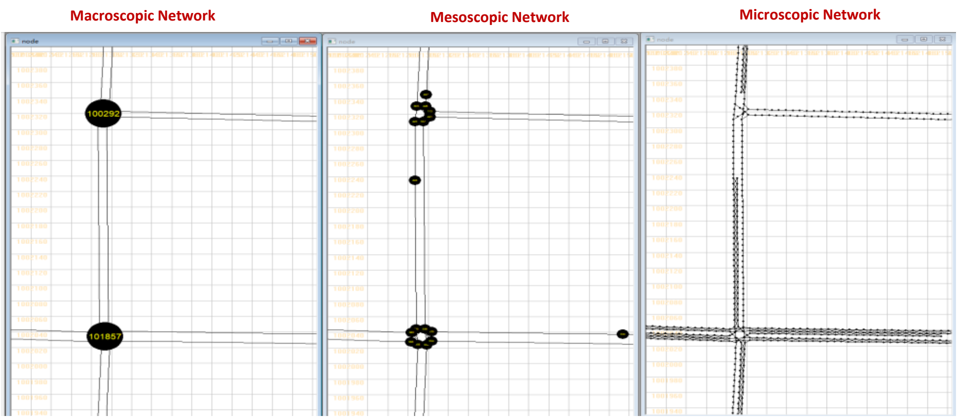
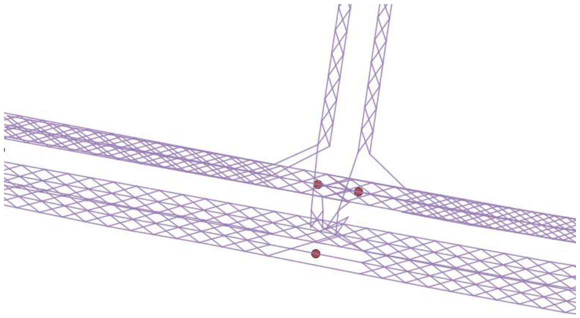
Step 3: Multi-Resolution Network Generation

Open-source tool for creating cell-based (microscopic) and mesoscopic networks





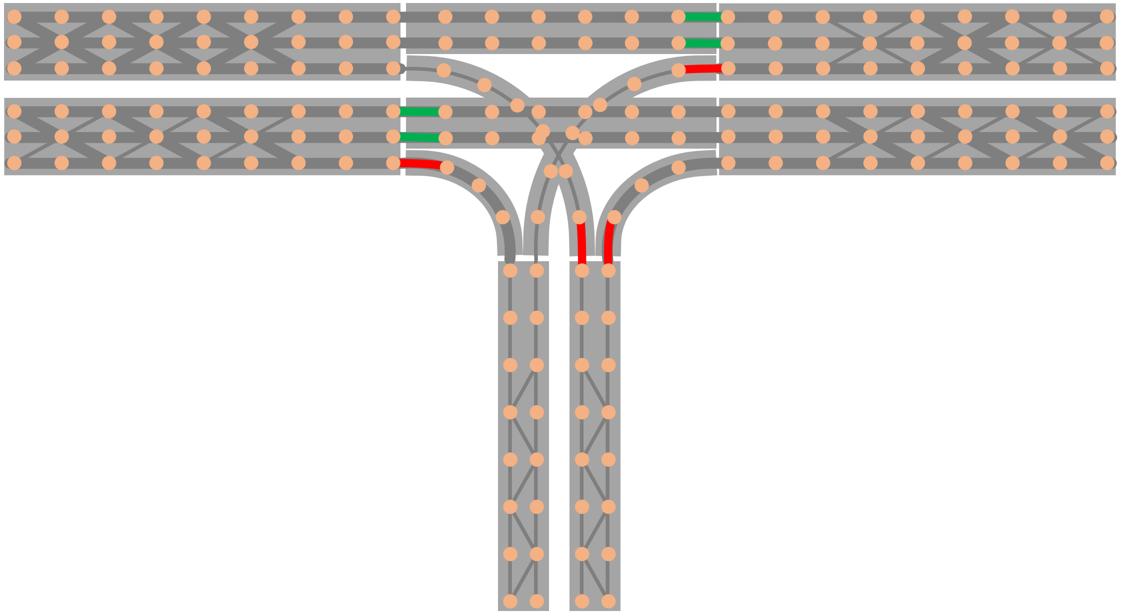
- mesonet
- micronet
- link.csv
- map.pbf
- movement.csv
- mrm.qgz
- node.csv
- poi.csv



Step 4: Signal Timing Generation Tool

Signal4gmns download: https://pypi.org/project/signal4gmns/

Signal Control Logic



- ❑ Map signal timing data on microscopic cells to simulate signal control
- ❑ Make it extremely efficient for signal optimization modeling after introducing expanded space-time network

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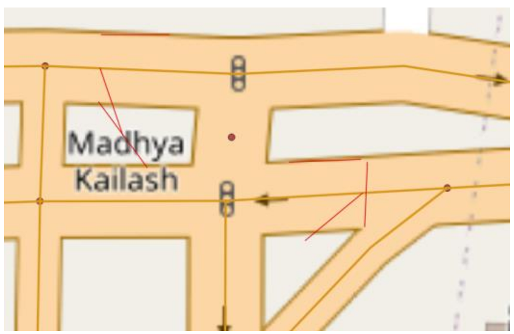
Step 4: Signal Timing Generation Tool

Signal4gmns download: https://pypi.org/project/signal4gmns/

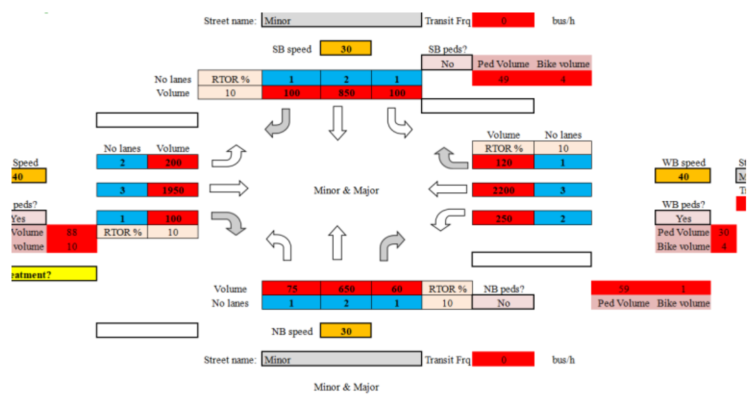
Excel-based and Python based

https://github.com/milan1981/Sigma-X

HCM-based computational engine for signalized intersections

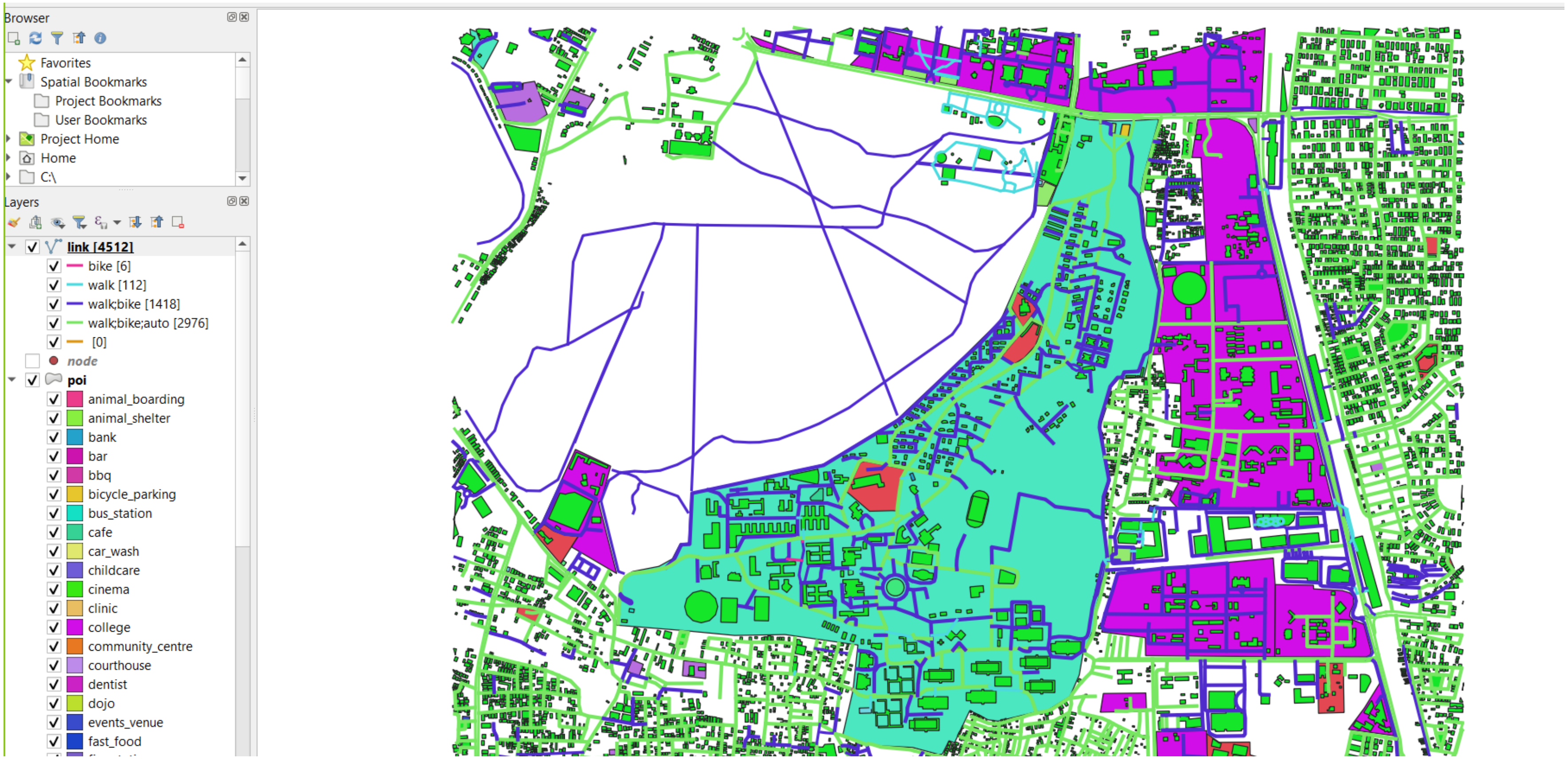


- signal_movement_setting.csv
- signal_node_setting.csv
- signal_phase_mvmt.csv
- signal_timing_phase.csv
- timing.csv



Step 5: Demand Generation

Grid2Demand download: https://pypi.org/project/grid2demand/

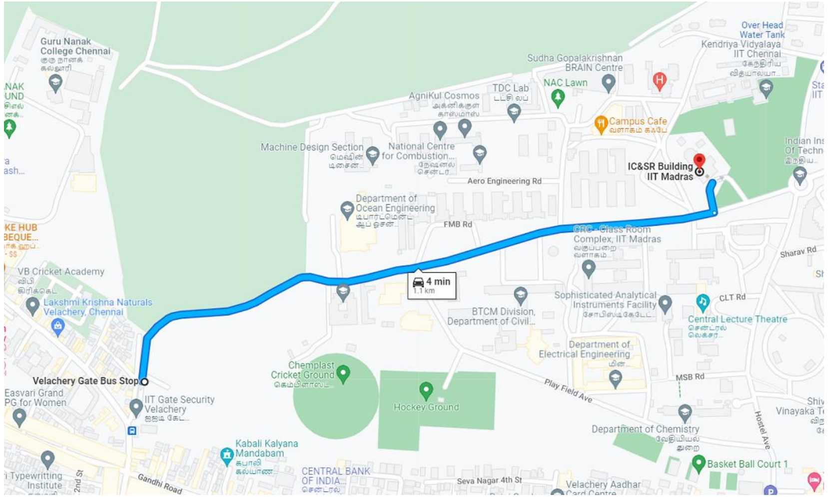


Step 5: Demand Generation

Grid zones can be automatically generated by a given number of grid cells or cell's width and height in meters.

Advantages:

- Compared with traditional TAZs like census tracts, grid zones could reduce spatial biases.
- Trip generation directly comes from activity nodes, which is aggregated in grid zones.
- Cell size is flexible to satisfy multi-resolution models.
- [Open-source quick transportation demand generation tool grid2demand – YouTube]



Origin: Velachery Gate Bus Stop, Anna Garden

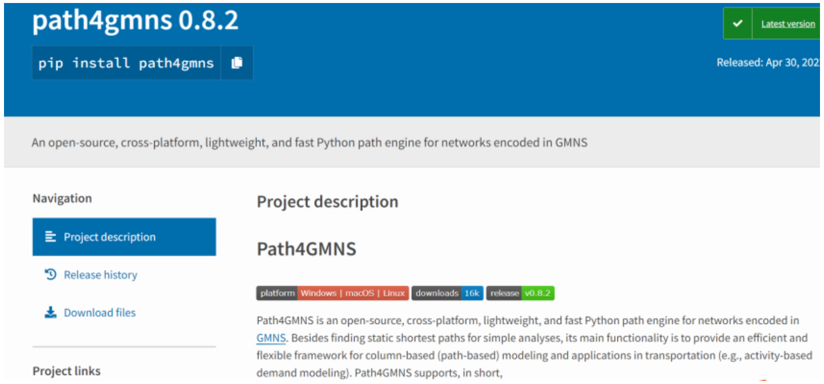
Destination:

Step 6: Shortest Path for GMNS

Path4GMNS download: https://pypi.org/project/path4gmns/

Path4GMNS is an open-source, cross-platform, lightweight, and fast Python path engine for networks encoded in GMNS. Besides finding static shortest paths for simple analyses, its main functionality is to provide an efficient and flexible framework for column-based (path-based) modeling and applications in transportation (e.g., activity-based demand modeling). Path4GMNS supports, in short,

- finding (static) shortest path between two nodes,
- constructing shortest paths for all individual agents,
- performing path-based User-Equilibrium (UE) traffic assignment,
- evaluating multimodal accessibility.



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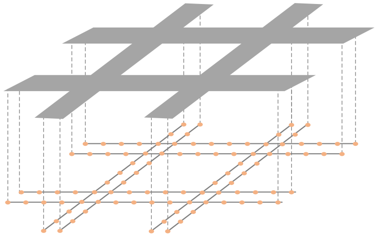
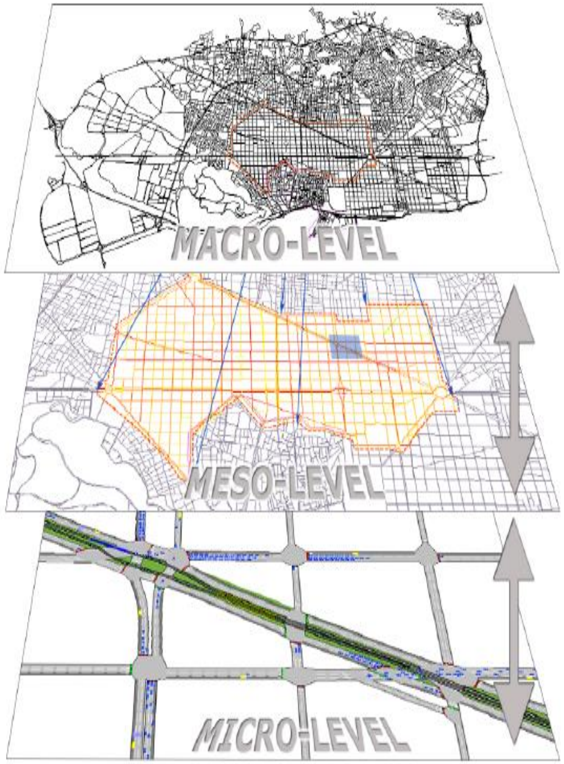
Outline

I. Open Data Specification

***II.* Open-Source Tools**

III. Supply-side Models for Large Scale System





Motivations

- Existing technical barriers (based on DTA user survey, TRB network modeling committee, 2009)
  - Require too many input data: 47%
  - Take too long to run: 35%
  - Model is unclear: 35%

- Our goals
  - Simplified data input from traffic assignment
  - Use parallel computing capability, simplified routing and simulation
  - Open-source Visualization: Seeing is believing
  - Excel Tools: Start from basics

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Part III: Keywords on Supply-side Models

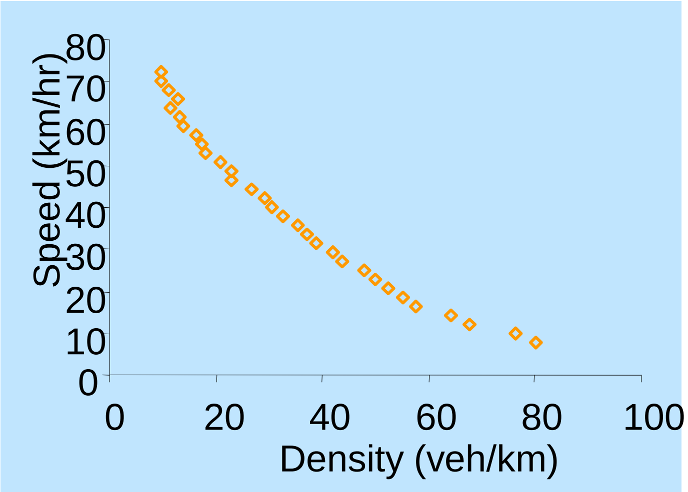
A. Macroscopic traffic stream models

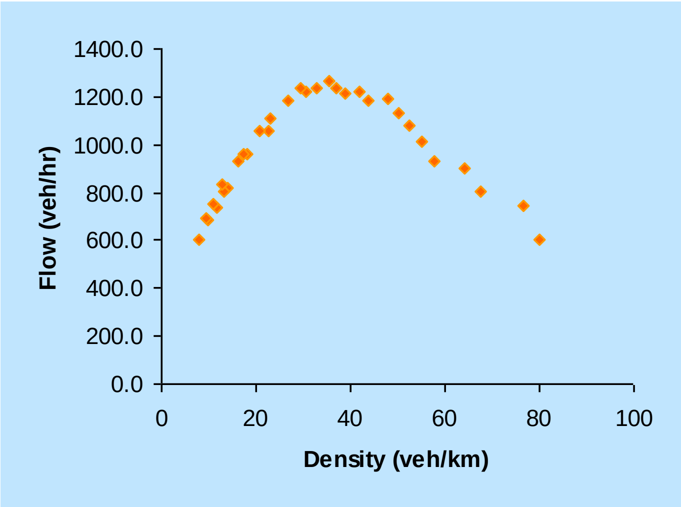
B. Simulation model for traffic Bottlenecks (Kinematic wave)

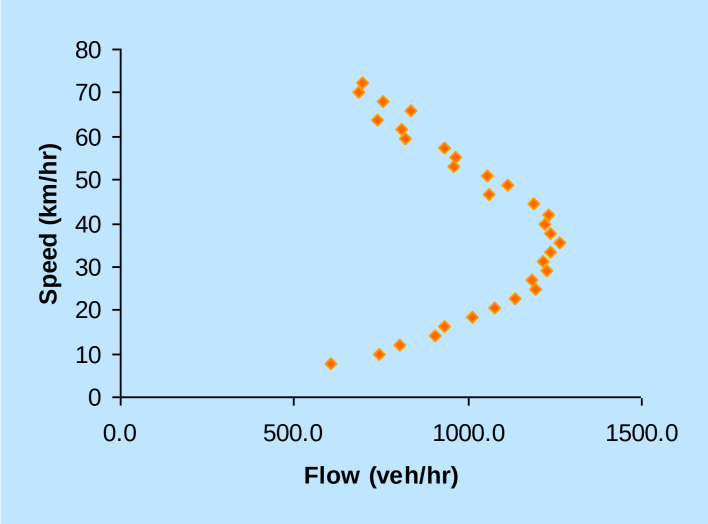
C. Continuous-time fluid-based approximation for describing queue dynamics

D. Queue-based volume-Delay function: QVDF

A.1: Field Data (Holland Tunnel, Eddie 63)







A.2: Single-regime models

- *Greenberg's model* →

$$u = u_m \ln(k_j / k)$$

- *Underwood's model* →

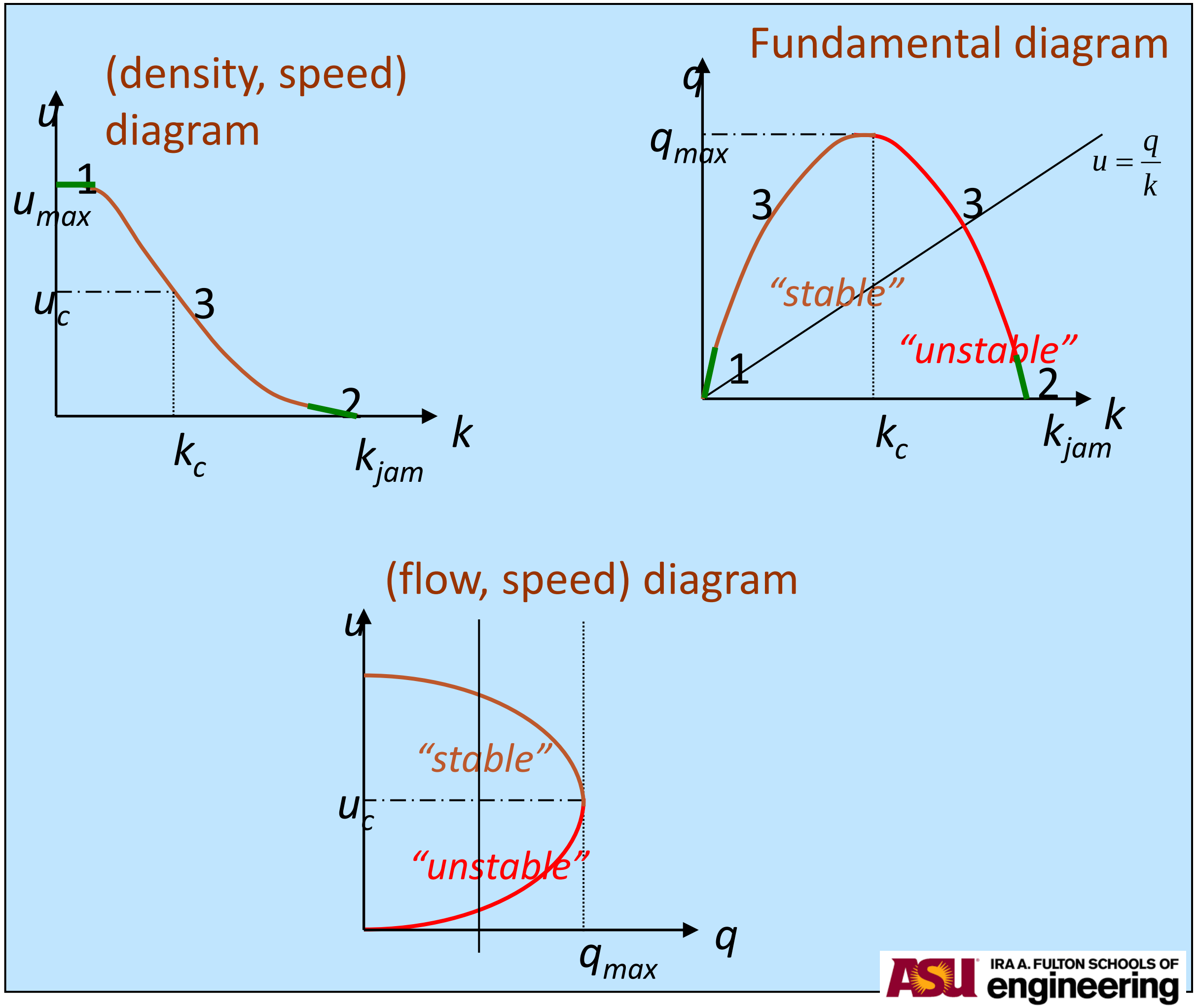
$$u = u_f e^{-k / k_m}$$

u_f, k_j, k_m, parameters to be calibrated

A.3: Multi-regime Relationships

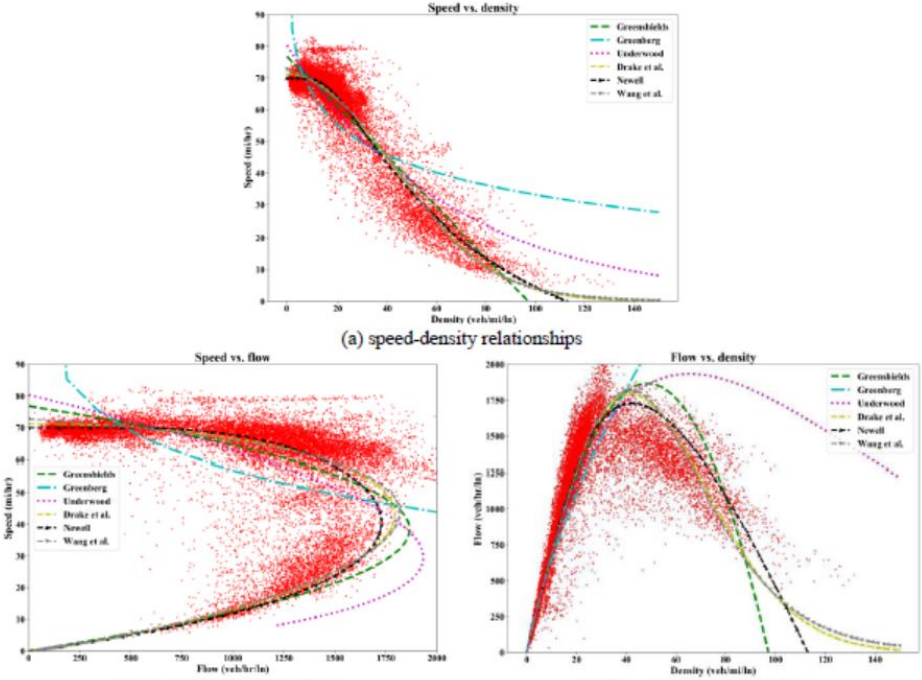
Structure

- *Single regime:* same functional form under all traffic conditions
- *Multiple regime*: different models for different traffic conditions



A.4: Nonlinear Single-regime Traffic Flow Models

Single-regime models	Functional form	Parameters
Greenshields et al. (1935)	$v = v_f \cdot (1 - k/k_{jam})$	v_f, k_{jam}
Greenberg (1959)	$v = v_c \cdot \ln(k_{jam}/k)$	v_c, k_{jam}
Underwood (1961)	$v = v_f \cdot \exp(-k/k_c)$	v_f, k_c
Newell (1961)	$v = v_f \cdot \left[1 - \exp\left(-\frac{\lambda}{v_f} \cdot \left(\frac{1}{k} - \frac{1}{k_{jam}}\right)\right)\right]$	v_f, k_{jam}, λ
Drake et al. (1967)	$v = v_f \cdot \exp\left[-(k/k_c)^2/2\right]$	v_f, k_c
Pipes (1967)	$v = v_f \cdot \left(1 - (k/k_{jam})^m\right)$	v_f, k_{jam}, m
Drew (1968)	$v = v_f \cdot \left[1 - (k/k_{jam})^{\frac{m+1}{2}}\right]$	v_f, k_{jam}, m
Ardekani and Herman (1987)	$v = v_f \cdot (1 - f_{s,\min})^{m+1} \cdot \left[1 - (k/k_{jam})^l\right]^{m+1}$	$v_f, k_{jam}, f_{s,\min}, m, l$
Kerner and Konhäuser (1994)	$v = v_f \cdot \left[\frac{1}{1 + \exp((k/k_c - 0.25)/0.06)} - 3.72 \times 10^{-6}\right]$	v_f, k_c
Castillo and Benítez (1995a)	$v = v_f \cdot \left[1 - \exp\left(\frac{\lvert C_j \rvert}{v_f} \cdot \left(1 - \frac{k_{jam}}{k}\right)\right)\right]$	$v_f, k_{jam}, \lvert C_j \rvert$
Jayakrishnan et al.	$v = v \ldots + (v \ldots - v \ldots) \cdot (1 - k/k \ldots)^m$	$v \ldots, v \ldots, k \ldots, m$
Van Aerde (1995)	$k = \frac{1}{c_1 + \frac{c_2}{v_f - v} + c_3 v}$	v_f, c_1, c_2, c_3
MacNicholas (2011)	$v = v_f \cdot \left(\frac{k_{jam}^m - k^m}{k_{jam}^m - c \cdot k^m}\right)$	v_f, k_{jam}, m, c
3PL model in Wang et al. (2011)	$v = \frac{v_f}{1 + \exp[(k - k_c)/\theta]}$	v_f, k_c, θ
Ni et al. (2016)	$k = \frac{1}{(\gamma v^2 + \tau v + l)[1 - \ln(1 - v/v_f)]}$	v_f, γ, τ, l
This paper	$v = \frac{v_f}{\left[1 + (k/k_c)^m\right]^{2/m}}$	v_f, k_c, m



(a) speed-density relationships
(b) speed-flow relationships
(c) flow-density relationships

Cheng, Q., Liu, Z., Lin, Y., & Zhou, X. S. (2021). An s-shaped three-parameter (S3) traffic stream model with consistent car following relationship. *Transportation Research Part B: Methodological*, *153*, 246-271.

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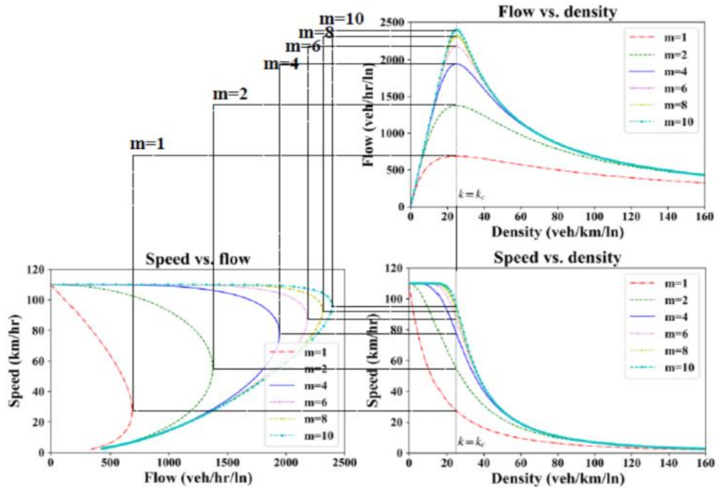
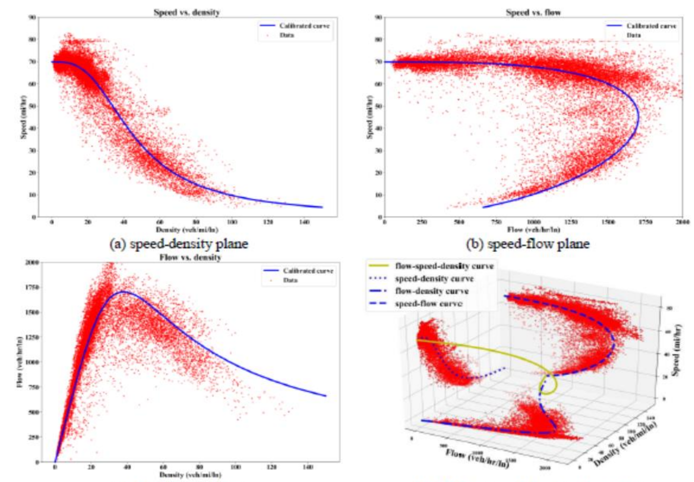
A.5: S3 Model

3 parameter: Vf, Kcritical, m: flow maximizing inertia factor

Parsimony and interpretability





(a) speed-density plane (b) speed-flow plane (c) flow-density plane (d) 3D flow-speed-density relationship

Advantages:

1. With only three parameters to cover **both light-traffic and jam conditions**.
2. Propose a three-dimensional (3D) traffic flow model with the **3D surface connecting the flow, speed, and density simultaneously.**

[An s-shaped three-parameter (S3) traffic stream model with consistent car following relationship – ScienceDirect]

Cheng, Q., Liu, Z., Lin, Y., & Zhou, X. S. (2021). An s-shaped three-parameter (S3) traffic stream model with consistent car following relationship. *Transportation Research Part B: Methodological*, *153*, 246-271.

A.6: S-shaped Three-parameter (S3) Fundamental Diagram

$$v = \frac{v_f}{\left[1+\left(k/k_c\right)^m\right]^l} \qquad q = \frac{k \cdot v_f}{\left[1+\left(k/k_c\right)^m\right]^l}$$

where v_f is the free flow speed, k_c is the critical density which can result in a maximal traffic flow rate, and m and l represent the flow maximization ratio (FMR) to be determined.

$q(k)$ is continuously differentiable. When $k=k_c$, we have $q=q_{max}$.

$$\left.\begin{array}{l} \dfrac{dq}{dk} = \dfrac{v_f}{\left[1+\left(k/k_c\right)^m\right]^l} - \dfrac{k \cdot v_f}{k_c} \cdot \dfrac{l \cdot m \cdot \left(k/k_c\right)^{m-1}}{\left[1+\left(k/k_c\right)^m\right]^{l+1}} \\ \left.\dfrac{dq}{dk}\right|_{k=k_c} = 0 \Rightarrow \dfrac{v_f}{2^l} - v_f \cdot \dfrac{l \cdot m}{2^{l+1}} = 0 \Rightarrow l = \dfrac{2}{m} \end{array}\right\} \Rightarrow \begin{cases} v = \dfrac{v_f}{\left[1+\left(k/k_c\right)^m\right]^{2/m}} \\ q = \dfrac{k \cdot v_f}{\left[1+\left(k/k_c\right)^m\right]^{2/m}} \end{cases}$$

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A.7: S-shaped Three-parameter (S3) Fundamental Diagram

Averaged maximal flow rate (or capacity):

$$k = k_c \Rightarrow q_{\max} = \frac{k_c \cdot v_f}{2^{2/m}}$$

Explanation of the **flow-maximization** parameter *m*:

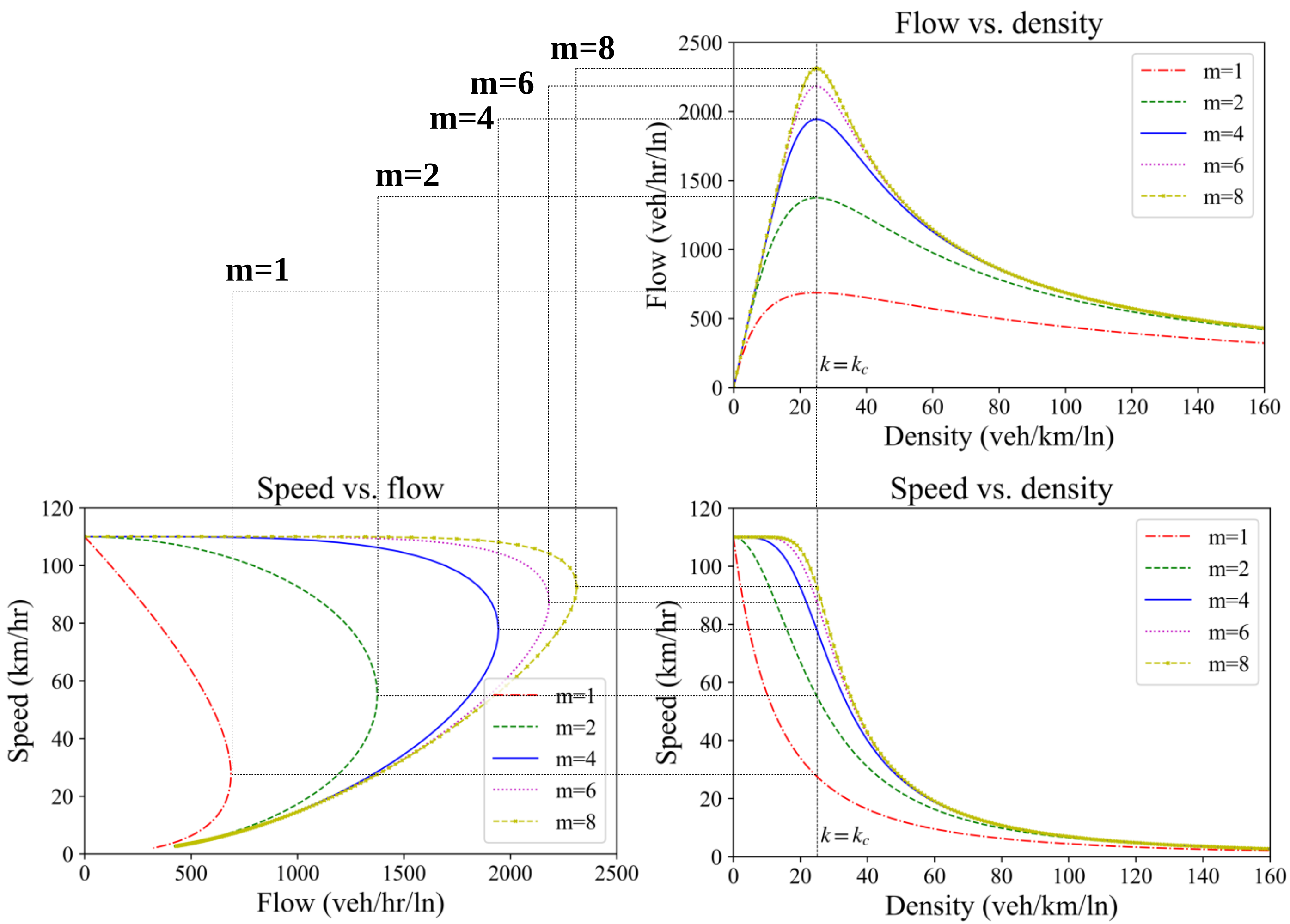
$$v_c = \frac{v_f}{\left[1+\left(k_c/k_c\right)^m\right]^{2/m}} \Rightarrow v_c = \frac{v_f}{2^{2/m}} \Rightarrow m = \frac{2\ln 2}{\ln\left(v_f/v_c\right)}$$

where v_c is the speed at the critical density.

A.8: S-shaped Three-parameter (S3) Fundamental Diagram

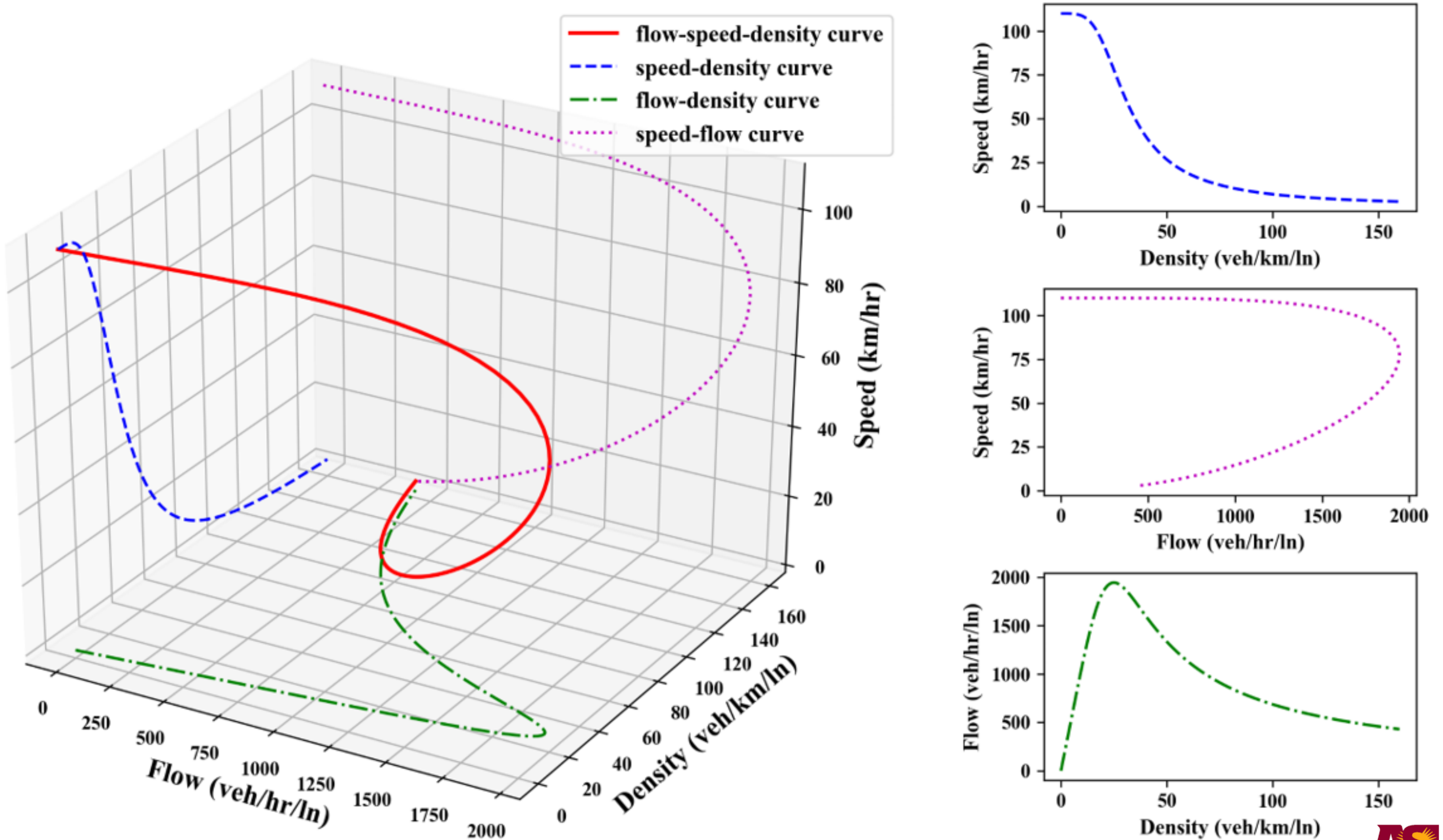
Discuss

Projections to the 2D planes:



A.9: S-shaped Three-parameter (S3) Fundamental Diagram

3D Space when m=4



A.10: Deriving Macro-to-Micro Car-following Models

Macroscopic speed-density

$$v = \frac{v_f}{\left[1+\left(k/k_c\right)^m\right]^{2/m}}$$

$$\Leftrightarrow$$

Microscopic car-following

$$a_n(t+\tau_n) = \frac{\alpha \cdot \Delta x_n(t) \cdot \Delta v_n(t)}{\left[1+\left(\beta \cdot \Delta x_n(t)\right)^m\right]^{1+\frac{2}{m}}}$$

FoC	Speed-density function	Car-following model	Connection
$m=1$	$v=\frac{v_f}{\left[1+\left(k/k_c\right)\right]^2}$	$a=\frac{\alpha\cdot\Delta x}{\left[1+\left(\beta\cdot\Delta x\right)\right]^3}\cdot\Delta v$	
$m=2$	$v=\frac{v_f}{\left[1+\left(k/k_c\right)^2\right]}$	$a=\frac{\alpha\cdot\Delta x}{\left[1+\left(\beta\cdot\Delta x\right)^2\right]^2}\cdot\Delta v$	
$m=3$	$v=\frac{v_f}{\left[1+\left(k/k_c\right)^3\right]^{2/3}}$	$a=\frac{\alpha\cdot\Delta x}{\left[1+\left(\beta\cdot\Delta x\right)^3\right]^{5/3}}\cdot\Delta v$	$\alpha=2v_f\beta^2$ $\beta=k_c$
$m=4$	$v=\frac{v_f}{\sqrt{1+\left(k/k_c\right)^4}}$	$a=\frac{\alpha\cdot\Delta x}{\left[1+\left(\beta\cdot\Delta x\right)^4\right]^{3/2}}\cdot\Delta v$	
$m=5$	$v=\frac{v_f}{\left[1+\left(k/k_c\right)^5\right]^{2/5}}$	$a=\frac{\alpha\cdot\Delta x}{\left[1+\left(\beta\cdot\Delta x\right)^5\right]^{7/5}}\cdot\Delta v$	
$m=6$	$v=\frac{v_f}{\left[1+\left(k/k_c\right)^6\right]^{1/3}}$	$a=\frac{\alpha\cdot\Delta x}{\left[1+\left(\beta\cdot\Delta x\right)^6\right]^{4/3}}\cdot\Delta v$	

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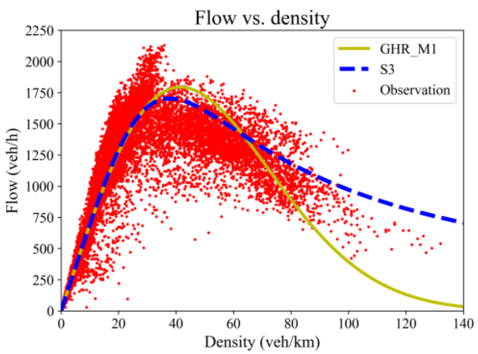
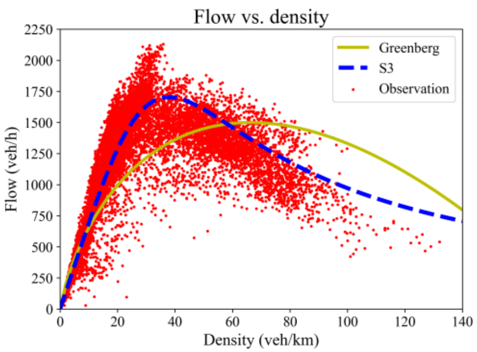
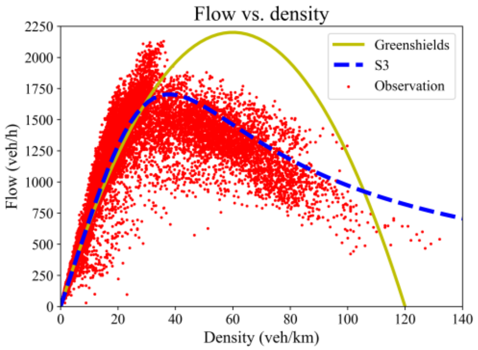
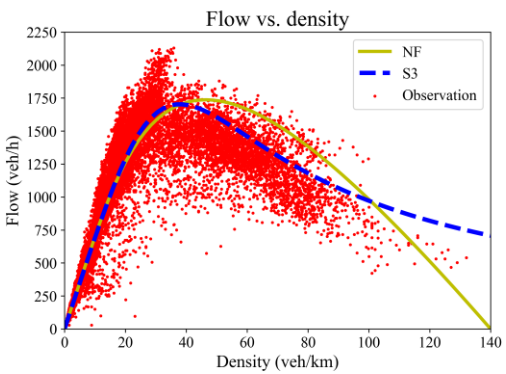
A.11: Model calibration

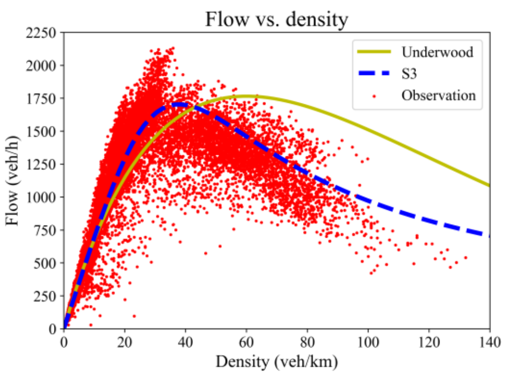
Flow vs. Density





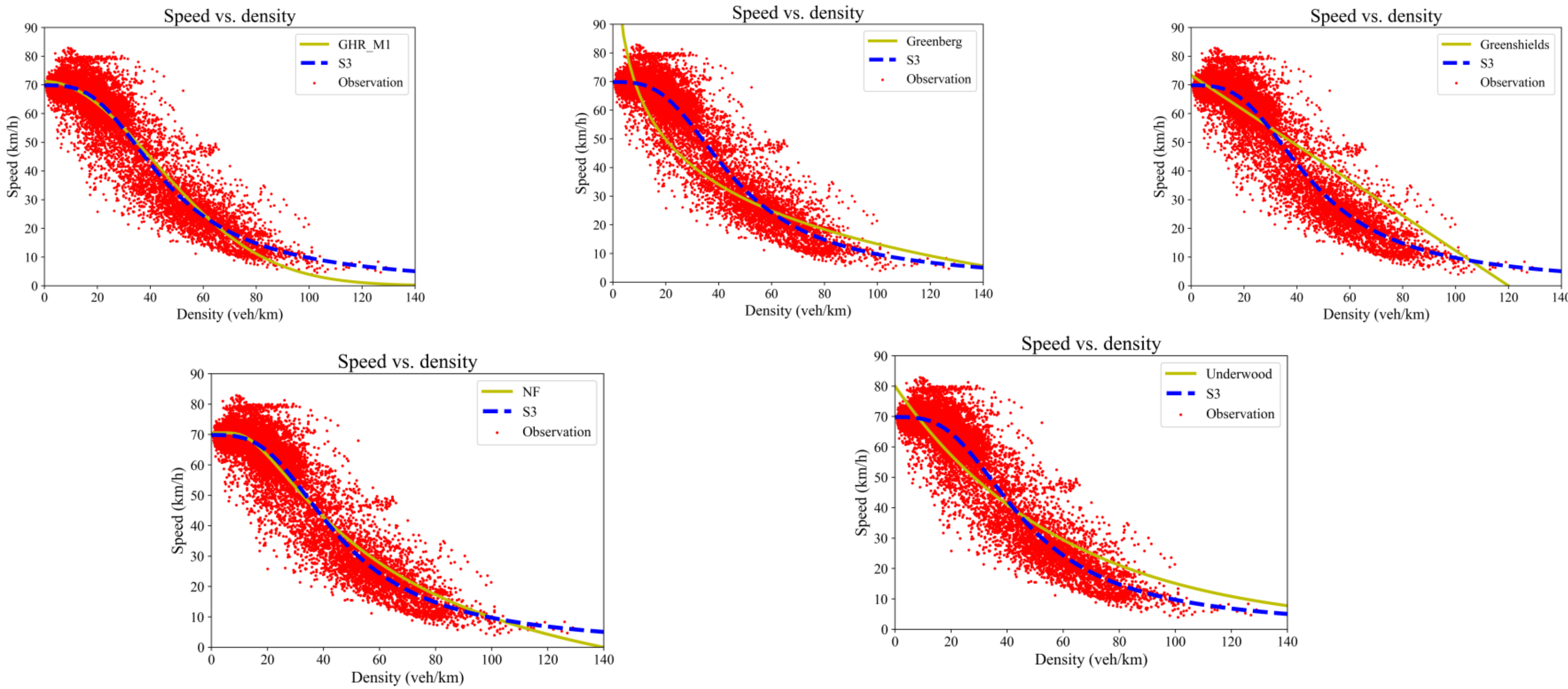






A.11: Model calibration

Speed vs. Density



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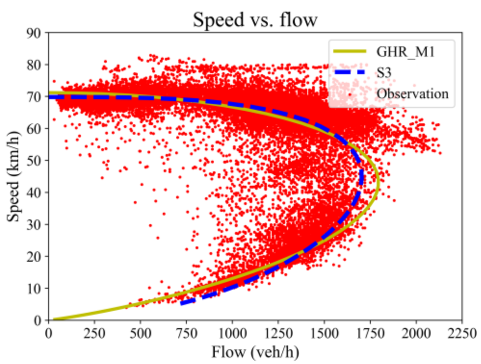
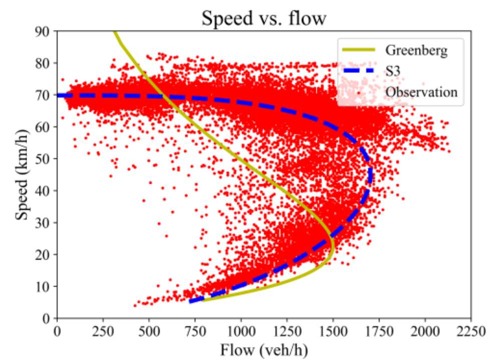
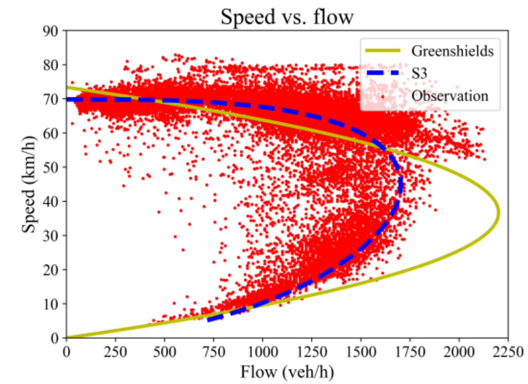
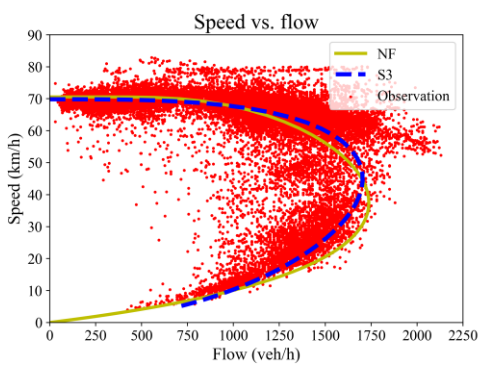
A.11: Model calibration

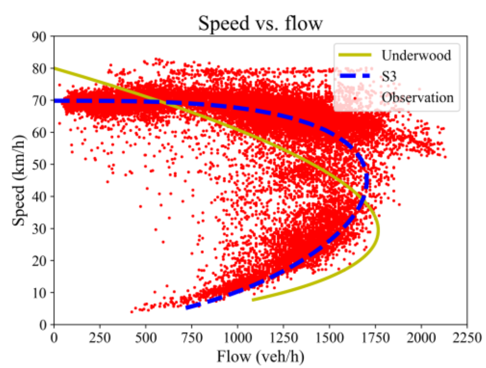
Flow vs. Speed











Comparison of MRE on the estimated speed with only speed information in the objective function

Literature	Density range (veh/mi)											
	0~10	10~20	20~30	30~40	40~50	50~60	60~70	70~80	80~90	90~100	>100	Avg	Std
GS	3.59%	6.69%	9.43%	22.30%	40.92%	53.27%	60.08%	78.51%	76.80%	55.59%	69.70%	43.35%	28.46%
GB	22.34%	17.09%	25.32%	23.93%	19.32%	18.07%	23.32%	36.90%	43.60%	48.46%	62.35%	30.97%	14.82%
UW	7.22%	9.02%	14.51%	18.99%	23.94%	28.24%	34.01%	52.19%	60.34%	65.41%	86.86%	36.43%	26.12%
NW	2.96%	5.10%	9.00%	18.82%	25.00%	25.68%	26.92%	35.73%	34.36%	25.27%	33.74%	22.05%	11.68%
DK	3.15%	5.20%	8.41%	20.02%	26.53%	22.62%	21.29%	24.31%	29.83%	49.23%	65.00%	25.05%	18.44%
PP: M1	6.15%	7.37%	10.96%	20.33%	35.52%	46.74%	54.96%	76.71%	81.98%	73.35%	68.49%	43.87%	29.32%
PP: M2	6.76%	6.43%	10.76%	19.26%	28.93%	32.63%	33.58%	41.93%	36.43%	22.31%	41.67%	25.52%	13.27%
DR	6.15%	7.37%	10.96%	20.33%	35.52%	46.74%	54.96%	76.71%	81.98%	73.35%	68.49%	43.87%	29.32%
KK	3.65%	5.34%	8.46%	20.42%	27.41%	22.73%	21.23%	24.79%	31.82%	49.92%	62.19%	25.27%	17.92%
JA	6.76%	6.43%	10.76%	19.26%	28.93%	32.63%	33.58%	41.93%	36.43%	22.31%	41.67%	25.52%	13.27%
VA	220.45 %	22.06%	26.10%	24.76%	17.60%	13.02%	13.17%	12.22%	10.32%	11.20%	10.97%	34.72%	61.87%
MN	2.81%	5.11%	8.28%	19.33%	23.61%	20.44%	21.18%	24.80%	22.87%	24.95%	28.02%	18.31%	8.71%
3PL	3.65%	5.34%	8.46%	20.42%	27.41%	22.73%	21.23%	24.79%	31.82%	49.92%	62.19%	25.27%	17.92%
4PL	3.18%	5.21%	8.24%	20.01%	24.16%	19.59%	21.15%	24.64%	23.51%	24.69%	54.18%	20.78%	13.70%
5PL	2.71%	5.13%	8.20%	18.68%	21.59%	19.45%	21.51%	28.18%	29.45%	29.67%	49.13%	21.25%	13.22%
S3 model	2.71%	5.11%	8.22%	18.96%	22.26%	19.66%	21.28%	26.54%	25.31%	22.49%	26.48%	18.09%	8.64%

Discussion: Under different density ranges, S3 model has the least avg and std error in terms of MRE

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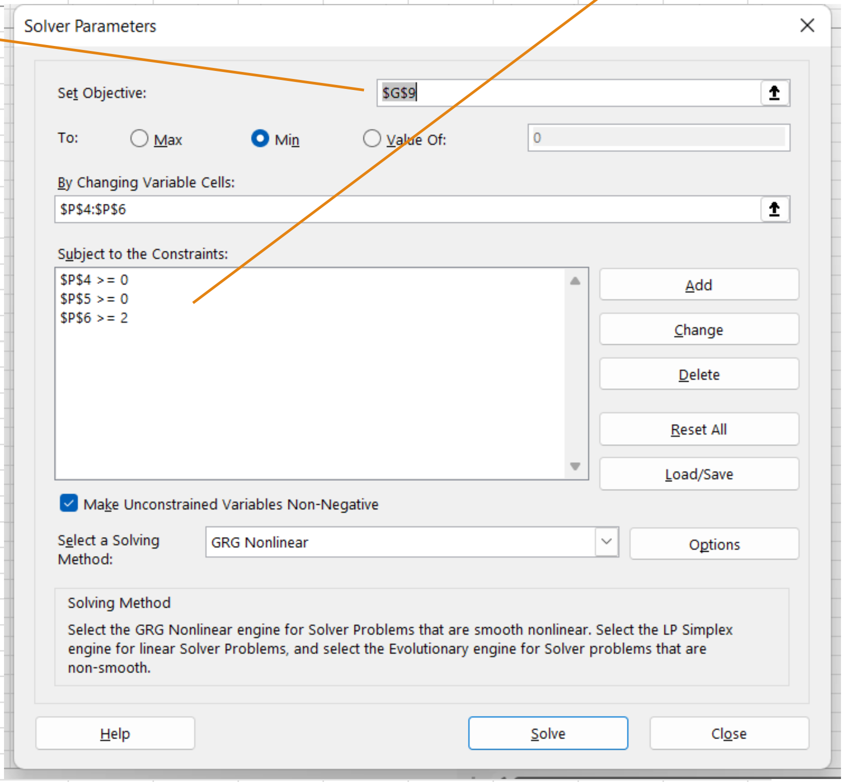
Case study: Excel-based Traffic Stream Model Calibration

S3 : $v = \dfrac{v_f}{[1+(k/k_c)^m]^{2/m}}$ Objective: $\min Z_1' = \sum_{i=1}^{P}\left[\left(v_i - \hat{v}(k_i; v_f, k_c, m)\right)^2 + \delta \cdot \left(q_i - \hat{q}(k_i; v_f, k_c, m)\right)^2\right]$ δ: 0.00134

OUTPUT	
vf:	70.5336
kc:	35.0671
m:	3.40583

Observed			Theoretical		Error	Obj Value
Flow	Speed	Density	Flow	Speed		
1680	60.7	24.40	1481.47	60.716	52.6496351	1230936.449
924	66.2	12.00	833.774	69.4812	21.6404085	
1580	29.2	56.40	1382.934	24.5201	73.7769602	
439	71.0	6.57	462.5015	70.396	1.10264558	
1380	45.2	23.80	1460.811	61.3786	270.470518	
1440	68.4	20.00	1301.039	65.052	37.0037623	
706	71.0	8.53	598.8052	70.1999	15.9893961	
1580	59.8	18.50	1225.19	66.2265	209.46309	
1660	35.4	45.30	1559.594	34.4281	14.4113336	
636	71.6	9.86	690.0934	69.9892	6.50337328	
1260	70.1	18.20	1209.24	66.4417	16.8246976	
993	59.9	15.50	1055.326	68.0856	72.1921909	
156	70.9	2.03	143.1782	70.5311	0.35567789	
1200	62.9	20.00	1301.039	65.052	18.2679192	
1500	34.3	36.80	1643.097	44.6494	134.462495	
237	66.9	3.25	229.1935	70.5211	13.1937032	
1310	65.7	20.20	1310.638	64.8831	0.66790272	
1110	67.5	14.50	994.1831	68.5643	19.0506072	
996	70.0	14.10	969.1944	68.7372	2.55451044	
1460	47.4	34.40	1645.835	47.844	46.3283191	
900	66.6	11.40	793.9759	69.647	24.300087	
1480	62.0	22.50	1411.683	62.7415	6.78424635	
1680	37.5	40.00	1622.444	40.5611	13.7954116	
855	10.2	76.10	1094.488	14.3822	94.1048219	
221	72.1	3.10	218.6212	70.523	2.49462433	
423	65.7	6.76	475.7821	70.382	25.6422562	
789	68.6	10.80	753.7754	69.794	3.08310185	
1200	42.1	24.20	1474.726	60.9391	455.729716	
1680	65.7	29.40	1603.991	54.5575	131.872677	
543	66.8	8.76	614.6758	70.1685	18.2091618	
1400	69.4	16.70	1125.907	67.4196	104.276419	



CLICK ME https://github.com/asu-trans-ai-lab/Traffic-Flow-Fundamental-Diagram/tree/main/Traffic_Model_Calibration%20S3

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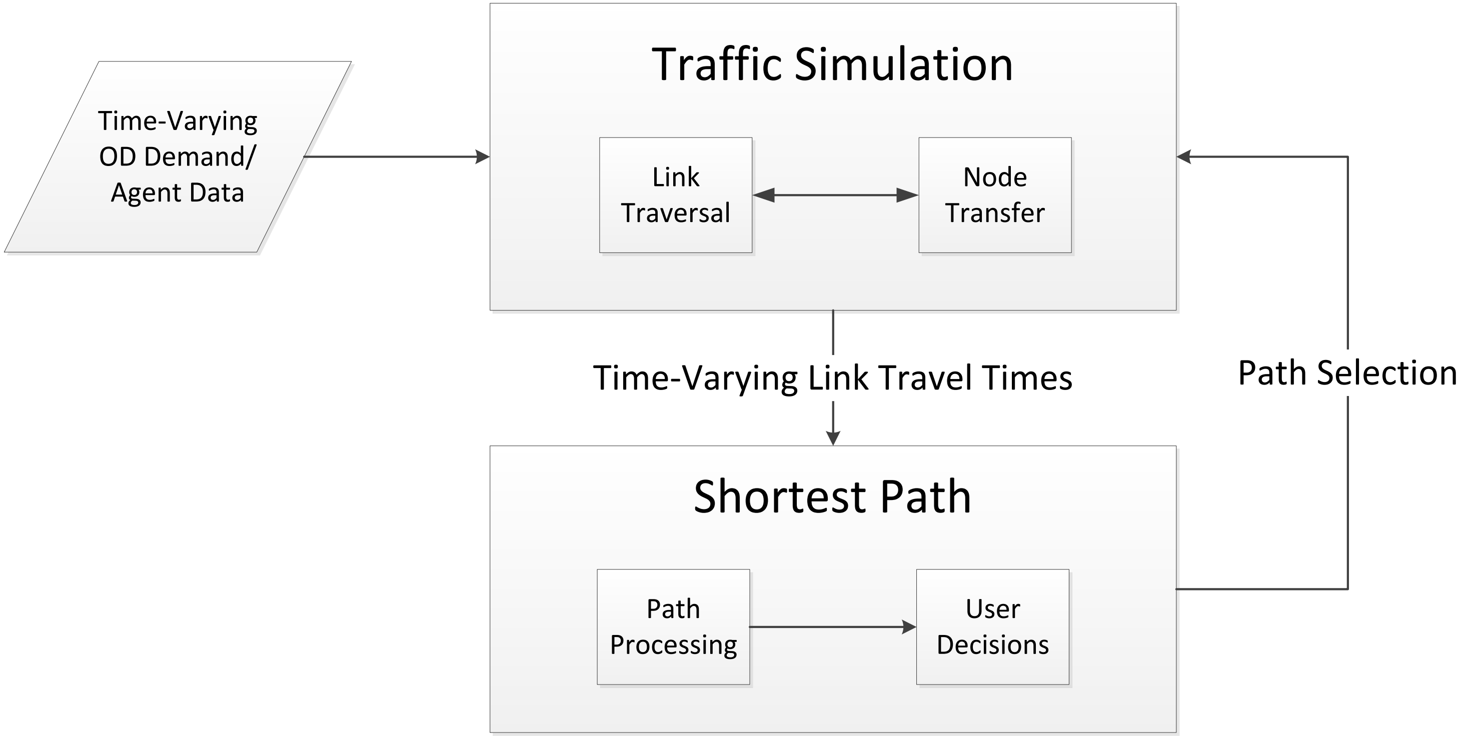
Case study: Python-based Traffic Stream Model Calibration

```python
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from math import sqrt
from sklearn.metrics import mean_squared_error, r2_score
plt.rcParams.update({'figure.max_open_warning': 0})
plt.rc('font',family='Times New Roman')
plt.rcParams['mathtext.fontset']='stix'


class fundamental_diagram_model():

    def __init__(self, observed_flow, observed_density, observed_speed):
        self.observed_flow = observed_flow
        self.observed_density = observed_density
        self.observed_speed = observed_speed

    def S3(self, beta):
        vf, kc, foc = beta
        estimated_speed = vf/np.power(1 + np.power((self.observed_density/kc), foc), 2/foc)
        f_obj = np.mean(np.power(estimated_speed - self.observed_speed, 2))
        return f_obj

class first_order_derivative():

    def __init__(self, observed_flow, observed_density, observed_speed):
        self.observed_flow = observed_flow
        self.observed_density = observed_density
        self.observed_speed = observed_speed

    def S3(self, beta):
        vf, kc, foc = beta
        intermediate_variable = np.power(self.observed_density/kc, foc)
        first_order_derivative_1 = 2*np.mean((vf/np.power(1 + intermediate_variable, 2/foc) - self.observed_speed) / np
        first_order_derivative_2 = 2*np.mean((vf/np.power(1 + intermediate_variable, 2/foc) - self.observed_speed) * 2 
        first_order_derivative_3 = 2*np.mean((vf/np.power(1 + intermediate_variable, 2/foc) - self.observed_speed) * 2 
        first_order_derivative = np.asarray([first_order_derivative_1, first_order_derivative_2, first_order_derivative_
        return first_order_derivative

class estimated_value():

    def __init__(self, observed_flow, observed_density, observed_speed):
        self.observed_flow = observed_flow
        self.observed_density = observed_density
        self.observed_speed = observed_speed
```

B: Bottleneck based Traffic Simulation



B.1 Traffic Flow Theoretical Foundation: LWR Equations

Hyperbolic system of conservation laws

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = g(x,t)$$

where q, k are flow and density, respectively, and g(·) is the net vehicle generation rate.

Traffic flow model

- Speed (or flow) of traffic is a function of density only
- E.g. Greenshields model: $V = V_{free}(1 - k/K_{jam})$

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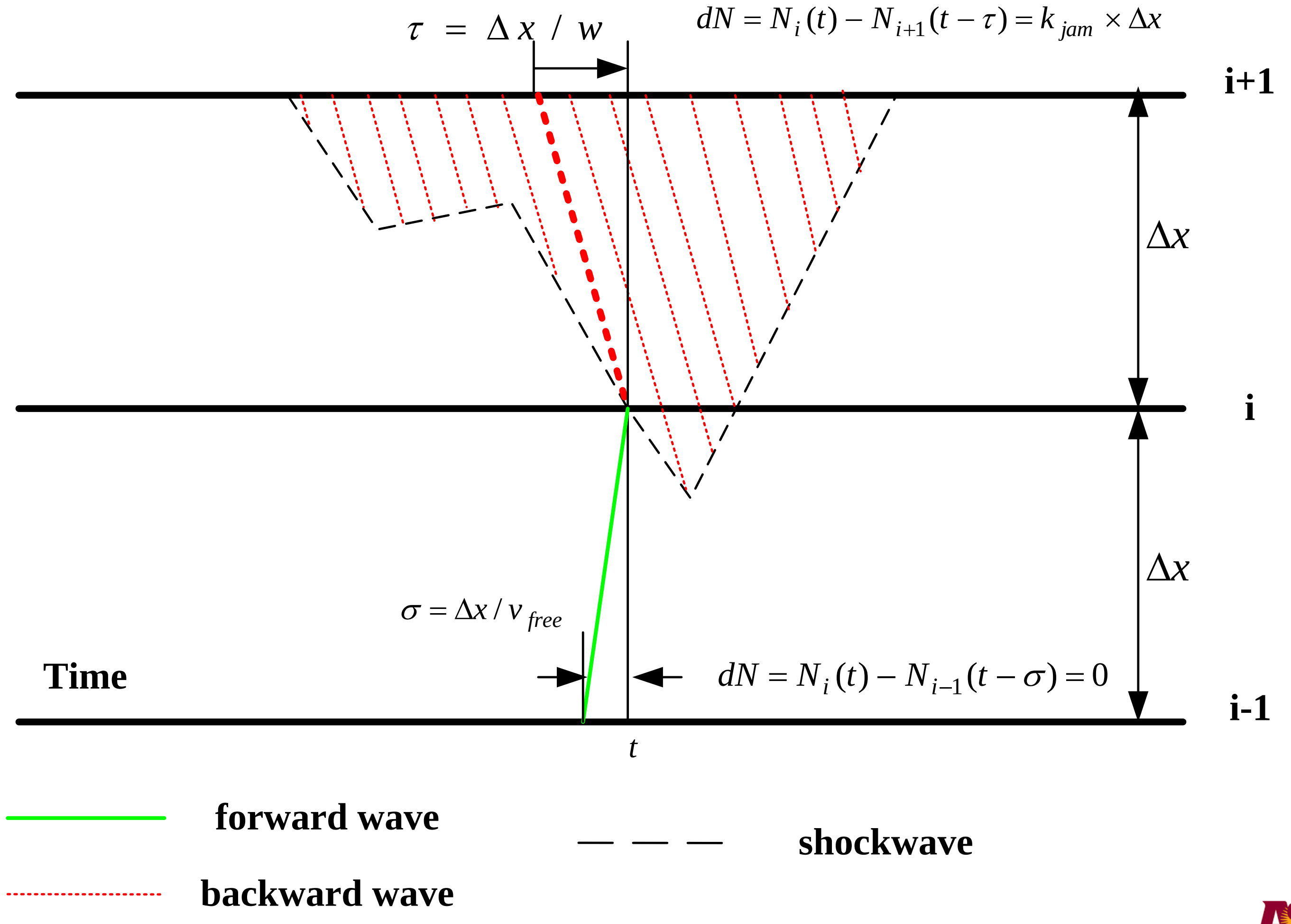
B.2: Illustration of N-Curve Computation For Tracking Queue Spillback



B.3: Numerical Calculation Scheme Based on Link Flow/Density (Used in CTM)

Notation

- Δt = length of simulation interval (e.g. 1 sec, 6 sec)
- Δx = cell length (e.g. 0.5 mile)
- $k_{i,t}$, $v_{i,t}$ =the prevailing density and mean speed in cell i during the t^{th} time step
- $q_{i,t}$ = transfer flow rate from section i to cell i+1 during the t^{th} time interval [t, t+Δt].

Computation Procedure

- Step 1: Calculate prevailing speed $v_{i,t}$ according to a traffic flow model
- Step 2: Calculate flow ready to move from cell i-1 to section i: $v_{i,t} \times k_{i,t}$
- Step 3: Calculate transfer flow from section i to cell i+1

$$q_{i,t} = \text{Min}\,\{ v_{i,t} \times k_{i,t} , q_{max\ i+1,t} \}$$

- Step 4: Update prevailing density at cell i

$$k_{i,t+1} = k_{i,t} + (q_{i-1,t} - q_{i,t}) \times \Delta t / \Delta x$$

Issue: transfer flow $q_{i,t}$ is an explicit function of the occupancy at the current cell, other than the downstream capacity

- Transferred flow exceeds the spatial storage capacity at the next cell

B.4: Link Transmission Model

along the corridor, and $N(x, t)$ is the cumulative flow count at location x and time t of a link. The change of $N(x, t)$ along a characteristic line (wave) is represented as follows:

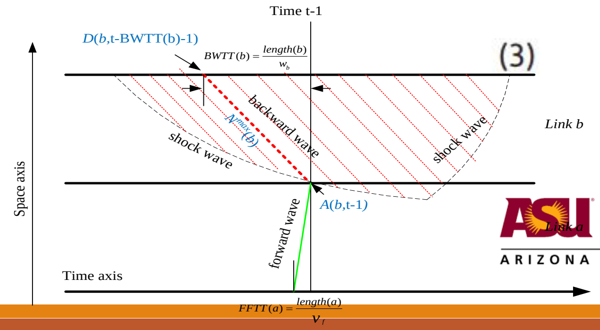
$$dN(x,t) = \frac{\partial N}{\partial x}dx + \frac{\partial N}{\partial t}dt = qdt - kdx \tag{1}$$

A wave represents the propagation of a change in flow and density along the roadway, and the wave speed is the slope of the characteristics line $w = \frac{\partial q}{\partial k} = \frac{dx}{dt}$. Along the movement of a wave, we substitute $dt = \frac{dx}{w}$ into the above equation, so that we can link the difference of cumulative flow counts together through

$$dN(x,t) = qdt - kdx = \left(-k + \frac{q}{w}\right)dx \tag{2}$$

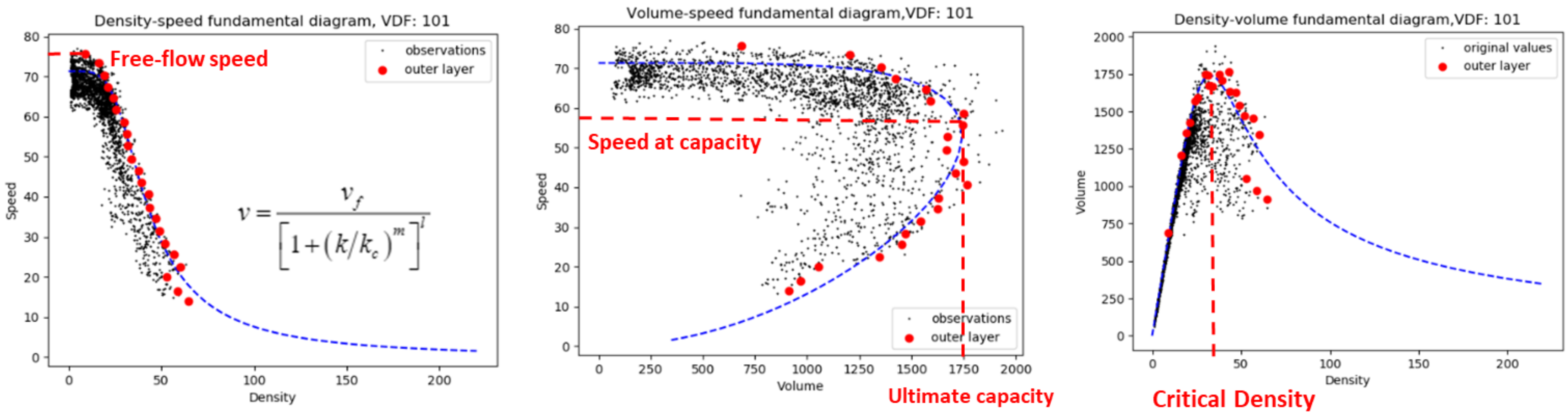
For the triangular-shaped flow–density relationship with constant forward and backward wave speeds, it is easy to verify that, when the speed of the forward wave is v_f, the general cumulative flow count updating formula reduces to $-k + \frac{q}{v_f} = -k + k = 0$. Under congested traffic conditions with a constant backward wave speed w_b, we have $-k + \frac{q}{w_b} = -k_{jam}$, and this equation can be rewritten as:

$$dN = \left(-k + \frac{q}{w_b}\right)dx = -k_{jam}(a) \times \text{length}(a) \times \text{nlanes}(a) \tag{3}$$



B.5: Derivation of the Queued Demand

Supply side (traffic stream model calibration):



$$c = v_{\max} = \frac{k_c u_f}{2^{\frac{2}{m}}}$$

Calibrated fundamental diagram , Freeway, CBD area

https://www.researchgate.net/publication/341104050_An_s-shaped_three-dimensional_S3_traffic_stream_model_with_consistent_car_following_relationship

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B.6: Dynamic Traffic Assignment (DTA)

Existing simulation-based DTA models

- Integration (Vertical queue)
- DynaSMART (Link density function, vertical queue)
- DynaMIT (Link density function, moving queue)
- VISTA (Cell Transmission Model)
- Vissum (Car following)
- Transsims (Cellular Automata)
- Transmodeler (Car following)
- DTALite (Simplified kinematic wave model)

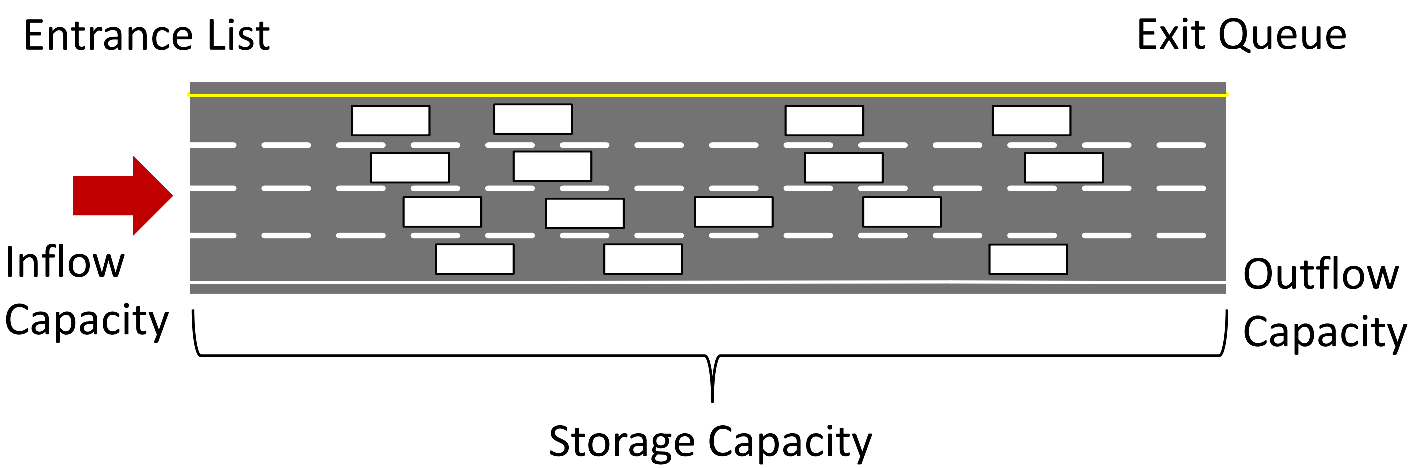
B9: Describing Traffic Congestion Propagation using Simulation Models

Newell’s simplified kinematic wave model

Outflow capacity

Inflow capacity

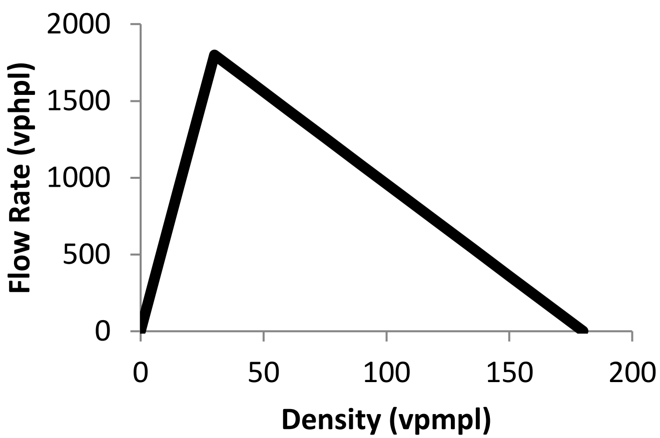
Storage capacity

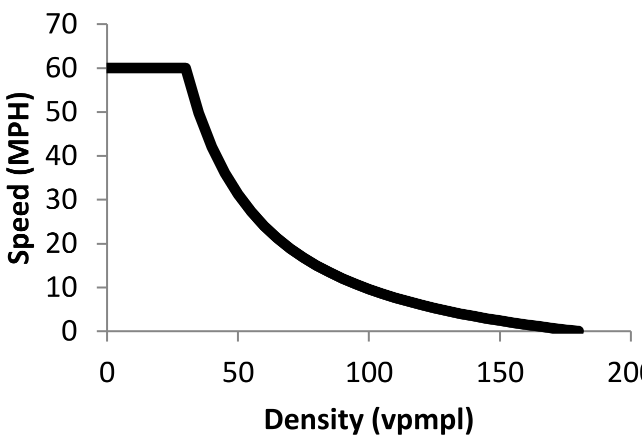


B.10: Bottleneck-based Traffic Simulation Models

Newell's simplified kinematic wave model

- Triangular flow-density relationship
- Free flow speed, jam density, backward wave speed





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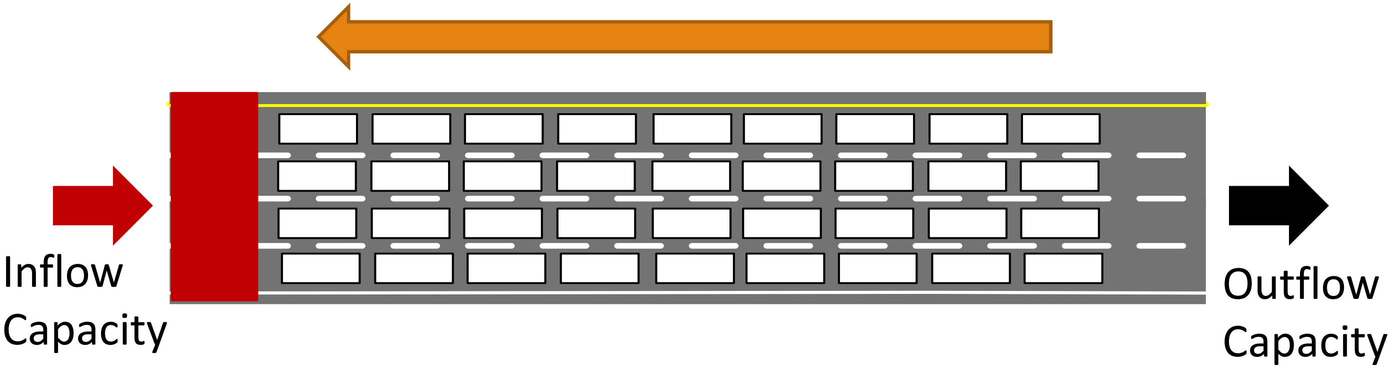
B.11: Bottleneck-based Traffic Simulation Models

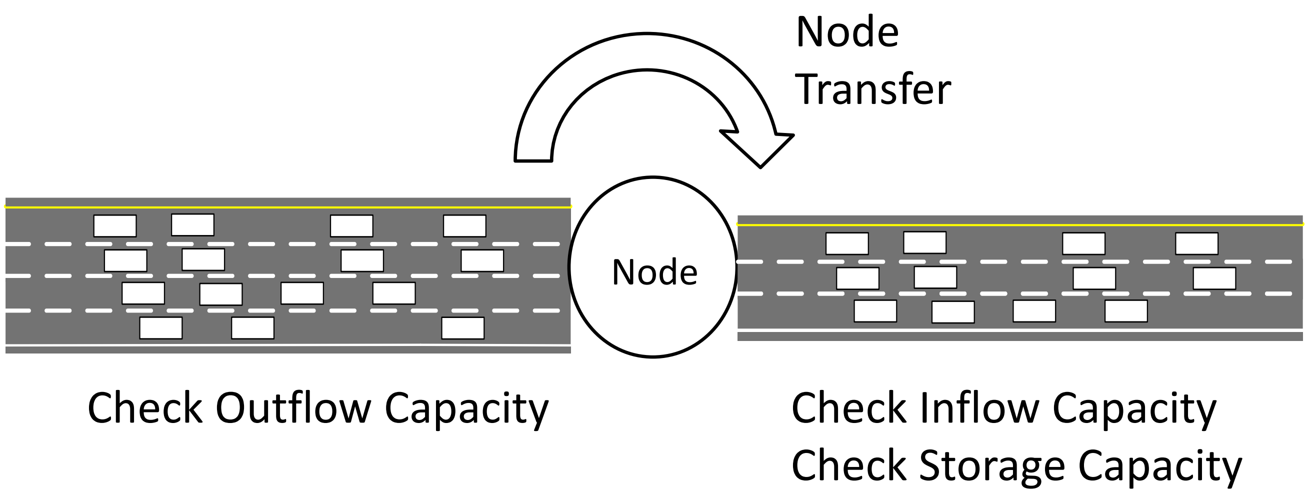
Queue propagation

- Inflow capacity = outflow capacity



B.12: Bottleneck-based Traffic Simulation Models

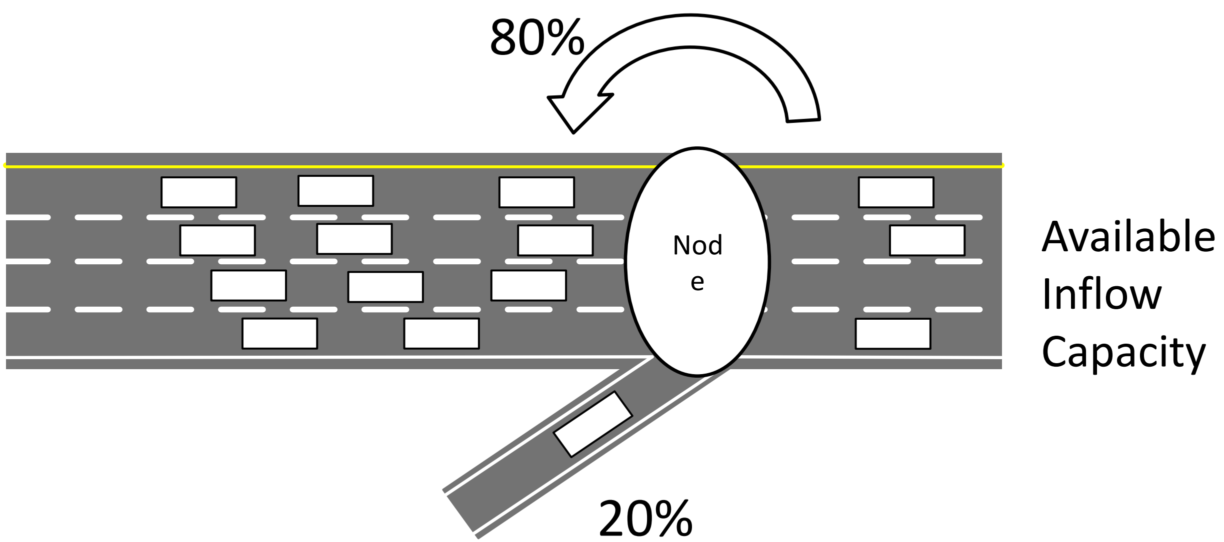
Node transfer



B.13: Bottleneck-based Traffic Simulation Models

Merge Models

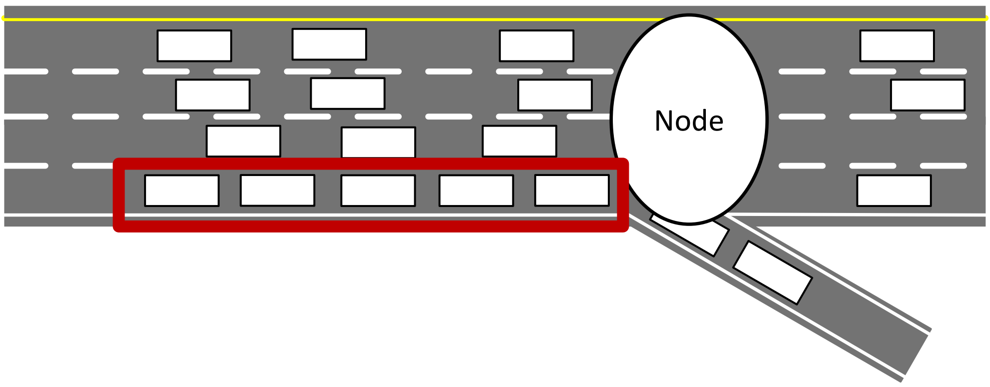
- Distribute inflow capacity to upstream links
- Lane & demand-based methods



B.14: Bottleneck-based Traffic Simulation Models

Diverge Models

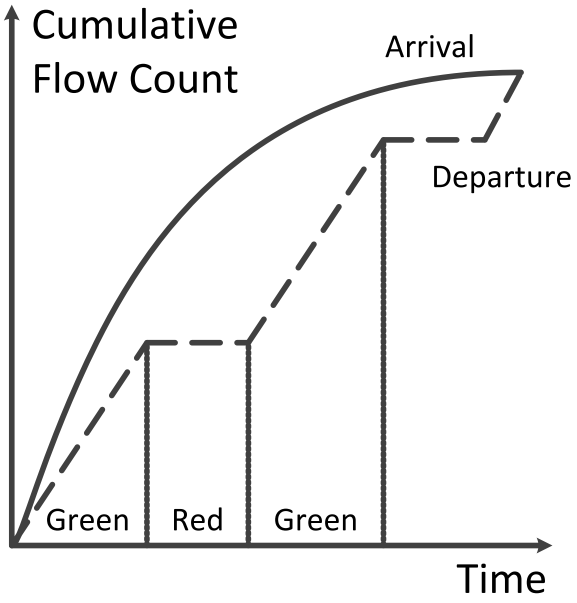
- Different conditions by lane
- First-In-First-Out (FIFO) constraint
- Relaxation to prevent extreme bottlenecks



B.15: Multiple Traffic Simulation Models

Signalized Intersections

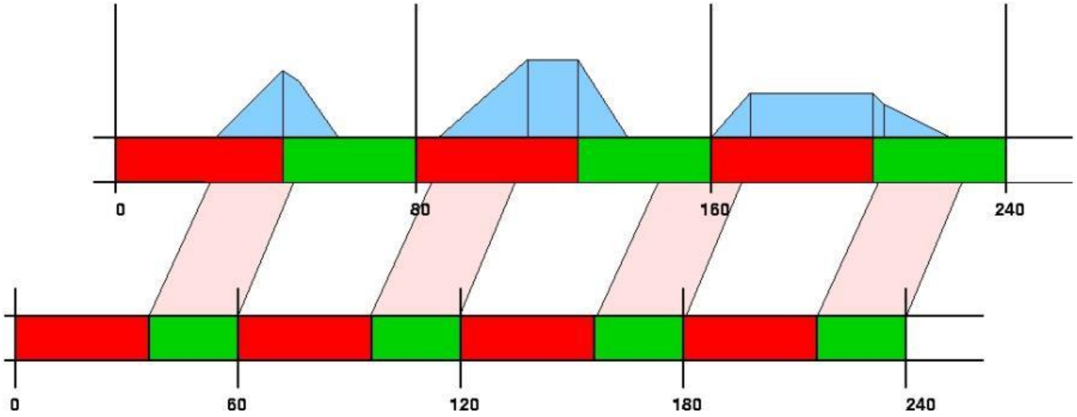
- Effective green time, saturation flow rate, movement-based capacity
- Relaxed inflow constraints



B.16: Multiple Traffic Simulation Models

Signal Timing & Hourly Capacity

- Input: Average hourly capacity, cycle time, offset at node
- Output: Effective green time per cycle(capacity/saturation flow rates)



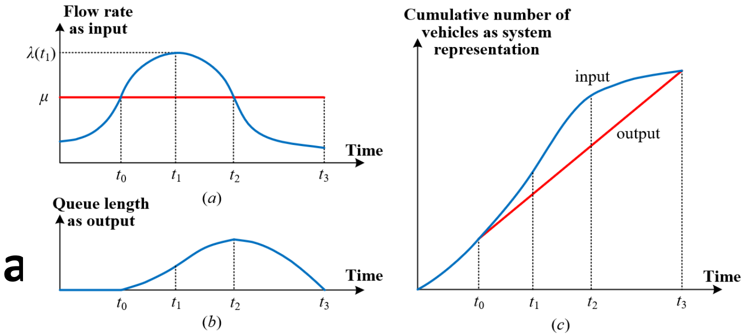
C: Continuous-time Fluid based Queuing Model

Typical Operations Questions about Traffic Dynamics:

How long will people have to wait to turn left from a driveway?

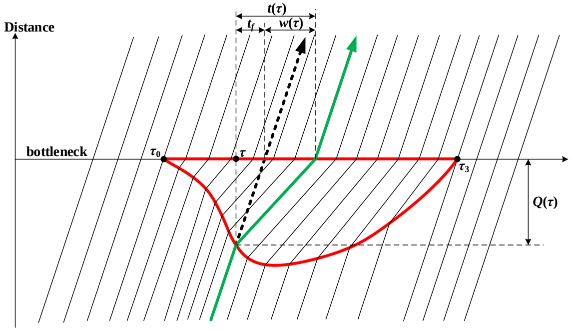
How much delay will people face at this signal?

What is the “**capacity**” or “queue-discharge rate” of a freeway?

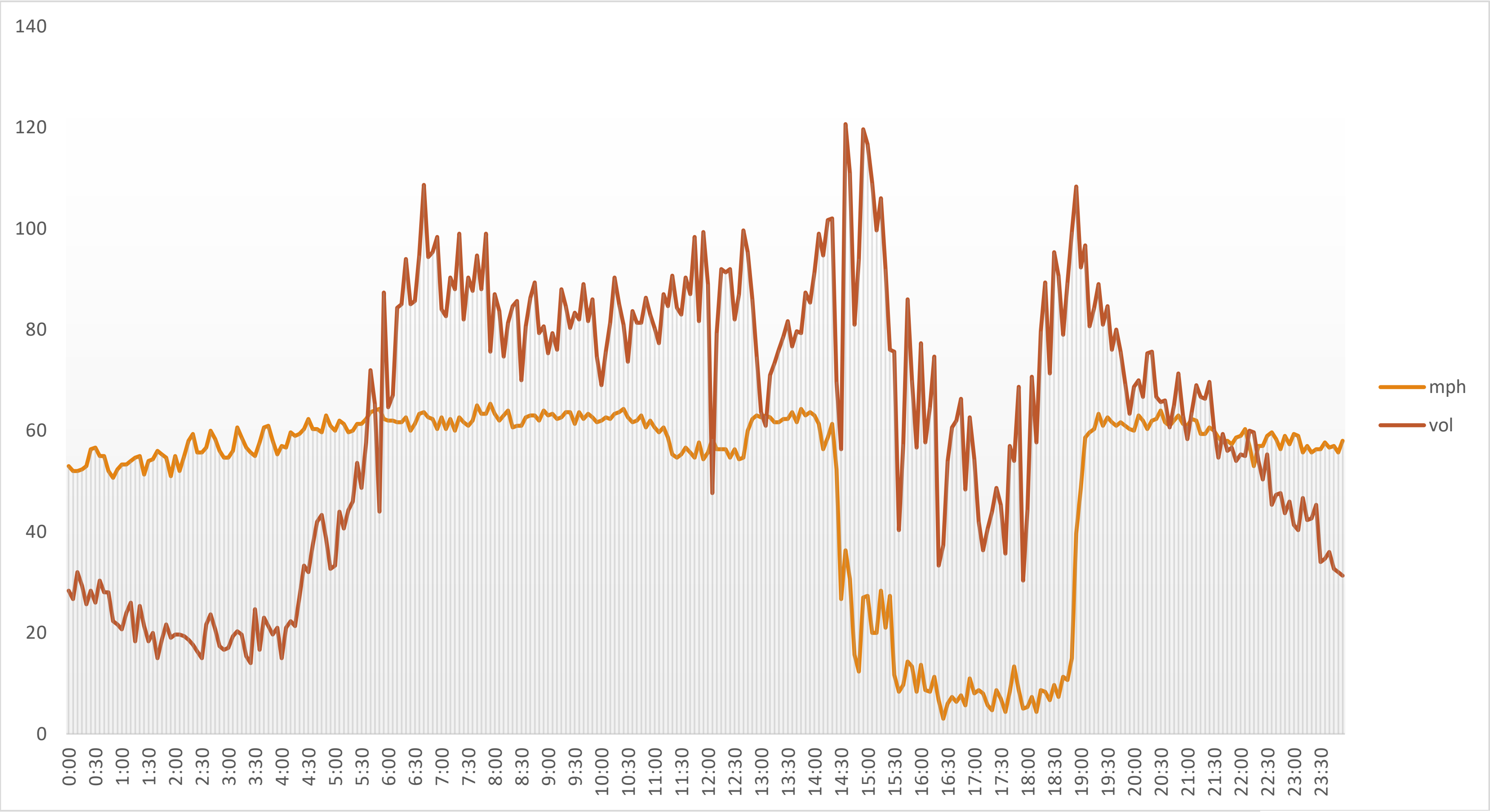


Proposed Models: Fluid Queue /PAQ Polynomial Arrival Queue

- Applications of Queueing Theory
- By G. F. Newell
- Chapter 2: Deterministic fluid approximation – single server



C.1: Understand Volume vs. Speed Profile



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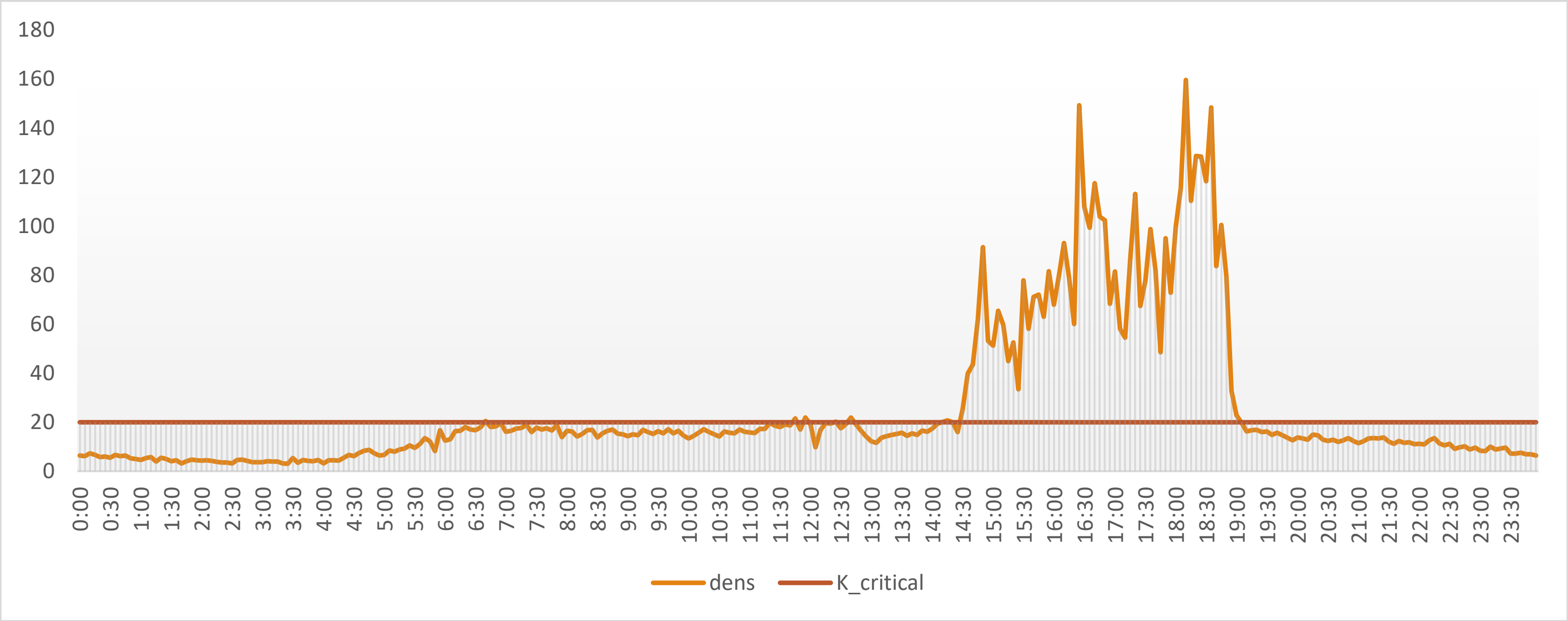
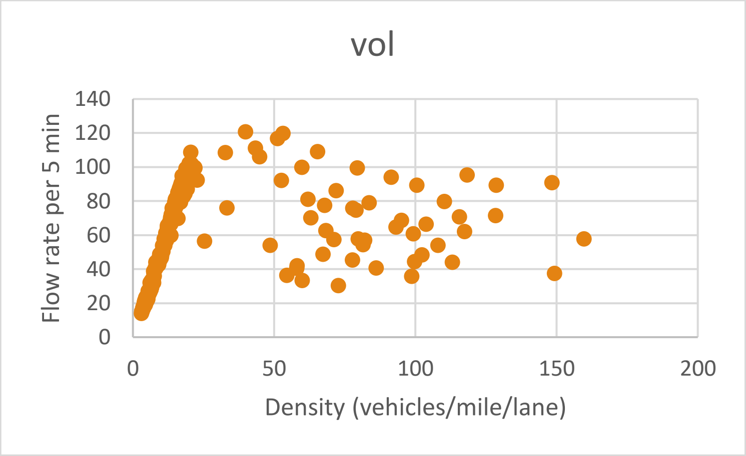
C.2: Understand Density vs. Volume Profile





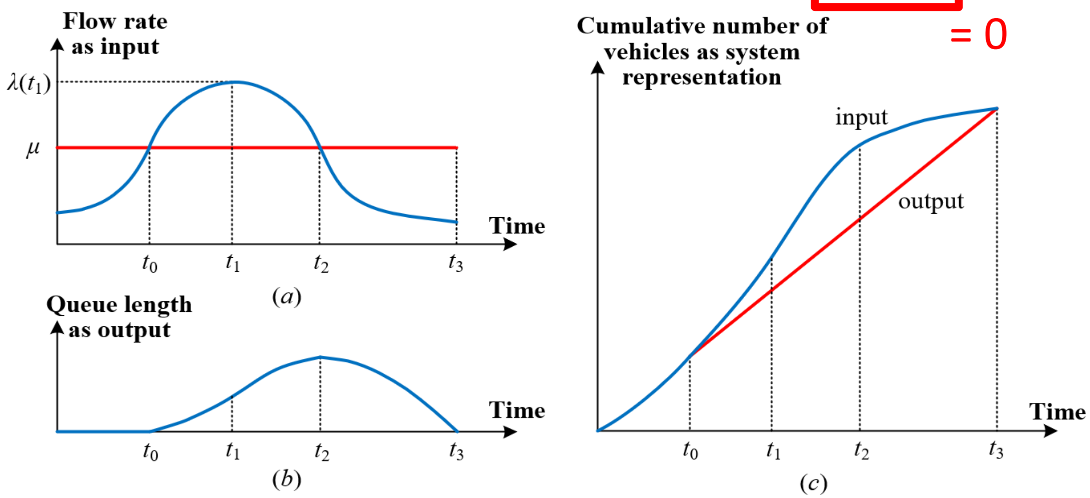
C.3: Assumption

Newell (1982)

- Assumption: quadratic inflow rate $\lambda(t) = \lambda(t_1) + \boxed{\lambda'(t_1)} \cdot (t - t_1) + \boxed{\frac{\lambda''(t_1)}{2}} (t - t_1)^2$

= 0

= $-\rho$



$\lambda(t)$: inflow rate at time t

t_0: start time of congestion period

t_1: time index with maximum inflow rate

t_2: time index with maximum queue length

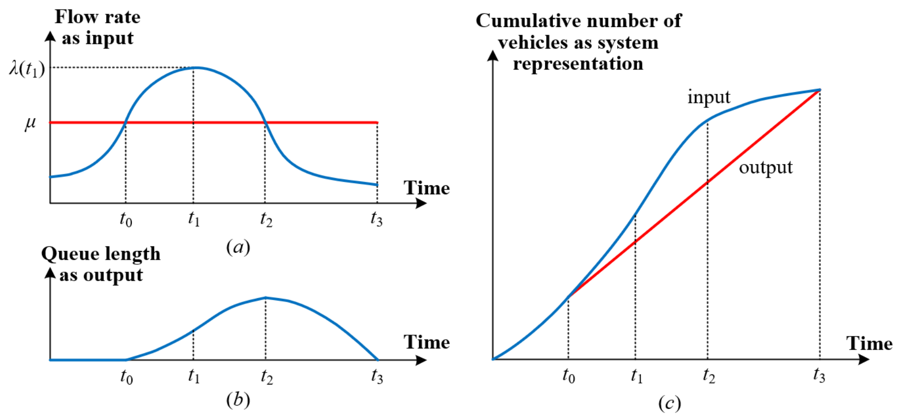
t_3: end time of congestion period

μ: discharge rate (or capacity)

C.4: Factored Form of Net Flow

Newell (1982)

- $\lambda(t) = \lambda(t_1) - \rho(t - t_1)^2$



$\because \mu = \lambda(t_0) = \lambda(t_2)$ $\quad\therefore \mu = \lambda(t_1) - \rho(t_0 - t_1)^2 = \lambda(t_1) - \rho(t_2 - t_1)^2$

$$\therefore t_0 = t_1 - \left[\frac{\lambda(t_1) - \mu}{\rho}\right]^{1/2} \qquad t_2 = t_1 + \left[\frac{\lambda(t_1) - \mu}{\rho}\right]^{1/2}$$

➢ Factored form of : $\lambda(t) - \mu$ $\quad \lambda(t) - \mu = \rho(t - t_0)(t_2 - t)$

C.5: Closed Form of Queue Length(t) as boundary points of t0 and t3

Newell (1982)

- Queue length: $A(t) - D(t)$

$$Q(t) = A(t) - D(t) = \int_{t_0}^{t} [\lambda(\tau) - \mu]\, d\tau$$

$$= \int_{t_0}^{t} [\rho(\tau - t_0)(t_2 - \tau)]\, d\tau$$

$$= \rho(t - t_0)^2 \left[\frac{t_2 - t_0}{2} - \frac{t - t_0}{3}\right]$$

$$\boxed{Q(t) = \frac{\rho}{3}(t - t_0)^2(t_3 - t)}$$

- Maximum queue length at time t_2:

$$Q(t_2) = \frac{\rho}{6}(t_2 - t_0)^3 = \frac{4[\lambda(t_1) - \mu]^{3/2}}{3\rho^{1/2}}$$

- Queue dissipating time t_3:

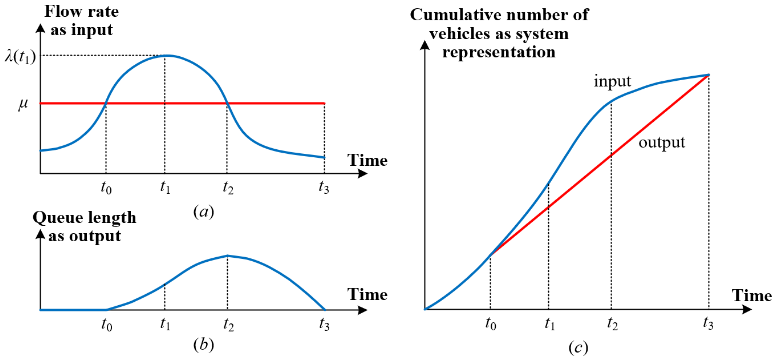
$$t_3 = t_0 + \frac{3}{2}(t_2 - t_0) = t_0 + 3(t_1 - t_0)$$

C.6: Closed Form of Avg Waiting Time

Newell (1982)

- Total delay: W

$$W = \int_{t_0}^{t_3} Q(\tau)\, d\tau = \frac{\rho}{36}(t_3 - t_0)^4 = \frac{9[\lambda(t_1) - \mu]^2}{4\rho}$$



- Average delay:

$$w = \frac{W}{d_3 - d_0} = \frac{\rho}{36} \cdot \frac{P^4}{D} = \frac{\rho}{36\mu} \cdot \left(\frac{D}{\mu}\right)^3$$

$$\boxed{\mu = \frac{d_3 - d_0}{t_3 - t_0} = \frac{D}{P}}$$

- Average travel time function:

$$t = t_f + w = t_f \left[1 + \frac{\rho}{36\mu \cdot t_f} \cdot \left(\frac{D}{\mu}\right)^3\right]$$

Only two parameters: ρ, μ

C.7: Recap of Problem Statement

Closed-form solution of delays
Key Parameters:

- $\lambda(t)$: inflow rate at time t
- t_0: start time of congestion period
- t_1: time index with maximum inflow rate
- t_2: time index with maximum queue length
- t_3: end time of congestion period
- μ: discharge rate (or capacity)

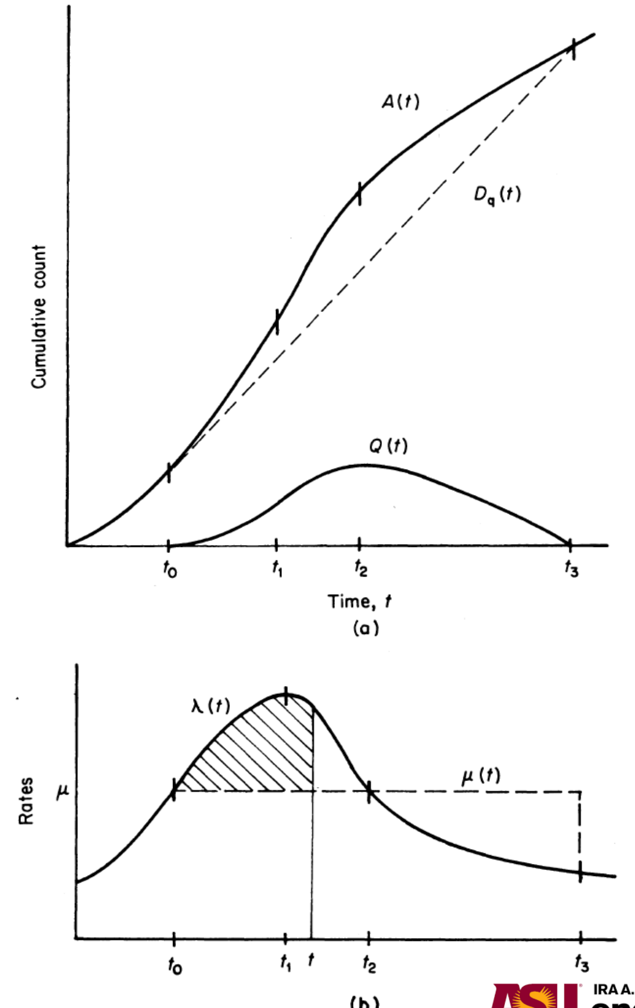


Figure 2.3 *Graphical construction of queue*

C.8: Understand Time-dependent Queue

The queue at any time $t_0 < t < t_3$ is obtained by substitution of (2.4a) into (2.2),

$$Q(t) = \beta(t-t_0)^2\left[\frac{(t_2-t_0)}{2} - \frac{(t-t_0)}{3}\right]. \qquad (2.5)$$

$$\lambda(t) - \mu = \beta(t-t_0)(t_2-t)$$
$$= \beta[-t^2 - t_0 t_2 + (t_0+t_2)t]$$

$$Q(t) = \int_{t_0}^{t}[\lambda(\tau) - \mu]\mathrm{d}\tau$$
$$= \int_{t_0}^{t}[\beta(\tau-t_0)(t_2-\tau)]\mathrm{d}\tau$$
$$= -\beta\int_{t_0}^{t}\tau^2\mathrm{d}\tau + \beta(t_0+t_2)\int_{t_0}^{t}\tau\mathrm{d}\tau$$
$$= -\frac{\beta}{3}[t^3 - t_0^3] + \frac{1}{2}\beta(t_0+t_2)(t^2-t_0^2)$$

The length of the queue at time t

$$Q(t) = A(t) - D_q(t) = \int_{t_0}^{t}[\lambda(\tau) - \mu(\tau)]\,\mathrm{d}\tau \qquad (2.2)$$

$$\mu = \lambda(t_1) - \beta(t_0 - t_1)^2,$$
$$t_0 = t_1 - \left[\frac{\lambda(t_1)-\mu}{\beta}\right]^{1/2},$$
$$t_2 = t_1 + \left[\frac{\lambda(t_1)-\mu}{\beta}\right]^{1/2}. \qquad (2.4)$$

It is convenient now to write $\lambda(t) - \mu$ in the factored form

$$\lambda(t) - \mu = \beta(t-t_0)(t_2-t). \qquad (2.4a)$$

C.9: Average Delay $\bar{w}$

Average delay $\bar{w}$

$$\bar{w} = \frac{W}{\mu(t_3 - t_0)} = \frac{1}{\mu}\cdot\frac{\beta}{36}(t_3 - t_0)^3 = \frac{9[\lambda(t_1) - \mu]^2}{4\beta\mu(t_3 - t_0)}$$

$$W = \int_{t_0}^{t_3} Q(\tau)\mathrm{d}\tau$$
$$= \frac{\beta}{36}(t_3 - t_0)^4$$
$$= \frac{9[\lambda(t_1) - \mu]^2}{4\beta}$$

Average travel time calculation

$$\begin{aligned} tt &= t_f + \bar{w} \\ &= t_f + \frac{1}{\mu}\cdot\frac{\beta}{36}(t_3 - t_0)^3 \\ &= t_f + \frac{1}{\mu}\cdot\frac{\beta}{36}\left(\frac{D}{\mu}\right)^3 \\ &= t_f\left[1 + \frac{1}{t_f}\cdot\frac{1}{\mu}\cdot\frac{\beta}{36}\left(\frac{D}{\mu}\right)^3\right] \end{aligned}$$

$$t_3 - t_0 = P$$
$$\mu P = D$$
$$(t_3 - t_0)^3 = \left(\frac{D}{\mu}\right)^3$$

Quadratic form	$\lambda(t) = -\xi(t - t_0)(t - t_2) + \mu,\ \xi > 0$	$tt = t_f\cdot\left[1 + \frac{\xi}{36\mu\cdot t_f}\cdot\left(\frac{D}{\mu}\right)^3\right]$

$$\lambda(t) - \mu = -\beta(t - t_0)(t - t_2)$$
$$= \beta(t - t_0)(t_2 - t)$$

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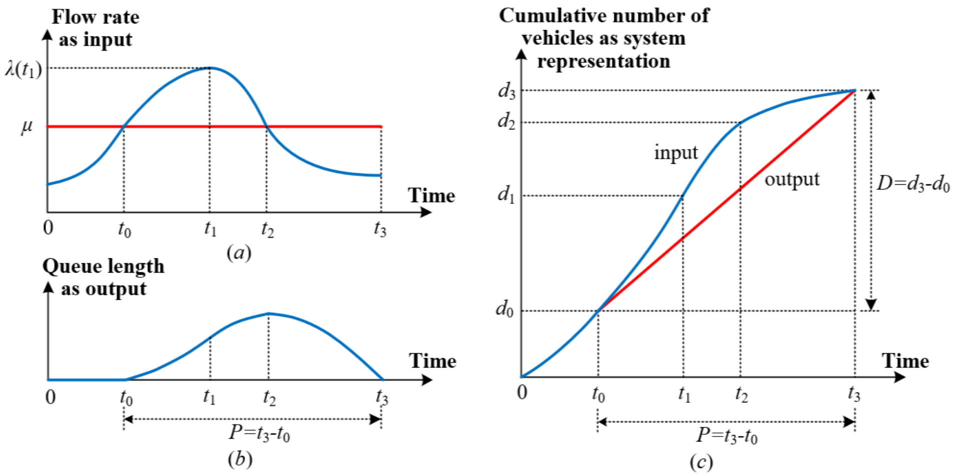
C.10: Cubic Arrival Rate Function

$$\lambda(t) = \lambda(t_1) + \boxed{\lambda'(t_1)}(t - t_1) + \frac{1}{2}\boxed{\lambda''(t_1)}(t - t_1)^2 + \frac{1}{6}\boxed{\lambda'''(t_1)}(t - t_1)^3$$

= 0 = -γ_1 = -γ_2



$\lambda(t)$: inflow rate at time t

t_0: start time of congestion period

t_1: time index with maximum inflow rate

t_2: time index with maximum queue length

t_3: end time of congestion period

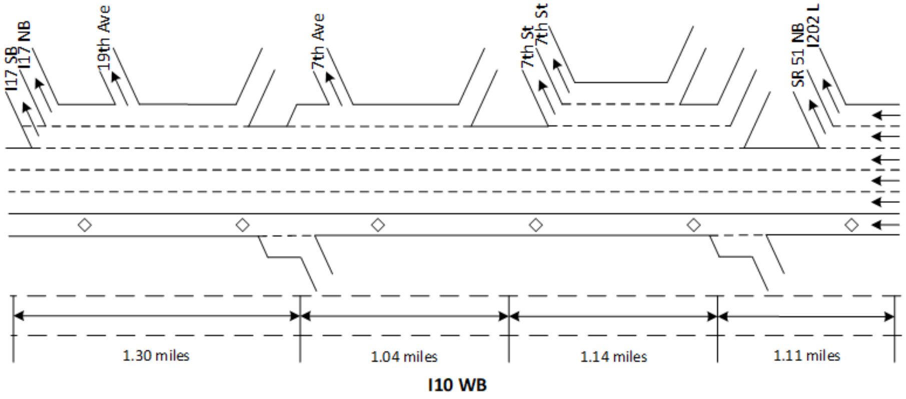
μ: discharge rate (or capacity)

Cheng, Qixiu, Zhiyuan Liu, Jifu Guo, Xin Wu, Ram Pendyala, Baloka Belezamo, and Xuesong Simon Zhou. "Estimating key traffic state parameters through parsimonious spatial queue models." *Transportation Research Part C: Emerging Technologies* 137 (2022): 103596.

Case study: PAQ Approximation in Phoenix

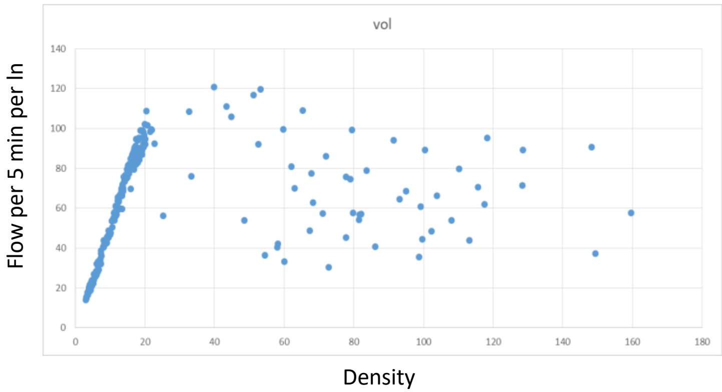
Test set: The traffic data are collected from I-10 freeway corridor (Jan 5th 2016)

Detector	Description
Loop detectors	**78, 84, 137, 139**
Location	I-10 freeway corridor, Westbound direction
Traffic data collected	Speed (mph) and volume (vehicle/5 minutes)
Traffic data collection period	Date: January 5th, 2016 Interval: 5 minutes (from 00:00 to 23:55)

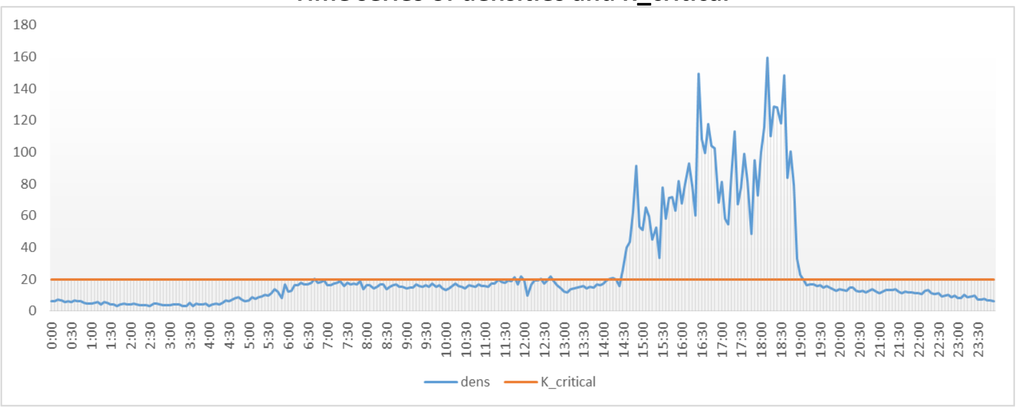


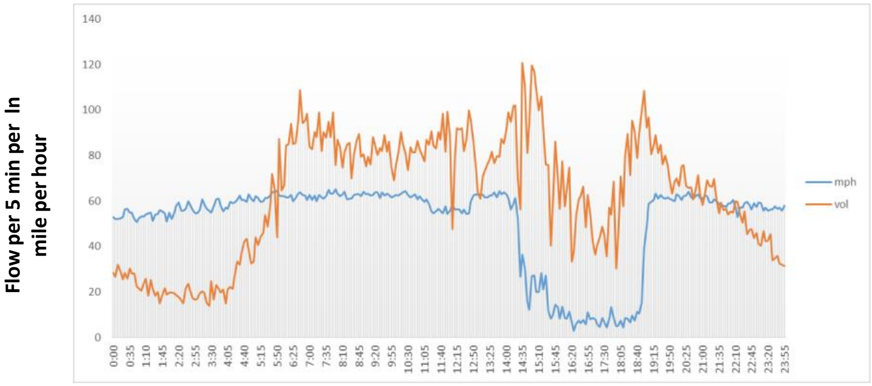
Calibration results： sensor 137

Q-K curve



Time series of densities and K_critical





INPUT			
t0	14:30	14.50	
t3	19:00	19.00	
m	0.58		In our paper, this is a parameter to be calibrated. Here we treat it a constant which equals 7/12.
t2	17:07	17.13	t2 = t0 + m*(t3-t0)
t_bar	20:30	20.50	t_bar = t0 + [3*(t3-t0) - 4*(t2-t0)]/(4-6*m)
n	3		# of lanes immediately downstream the bottleneck
v_f	53	mile/hr	
v_mu	13	mile/hr	
delta_t	5	minutes	

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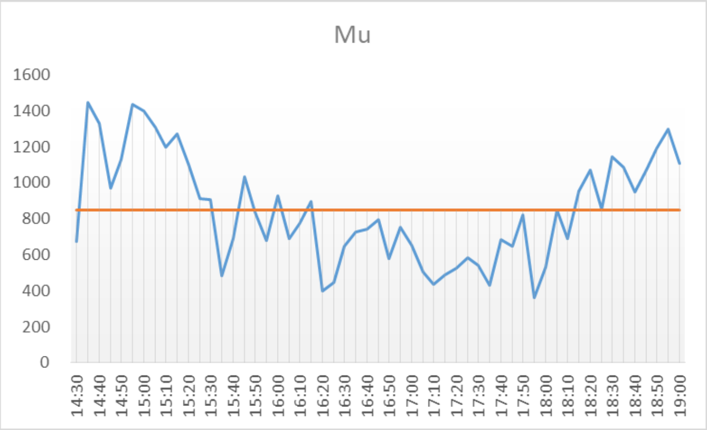
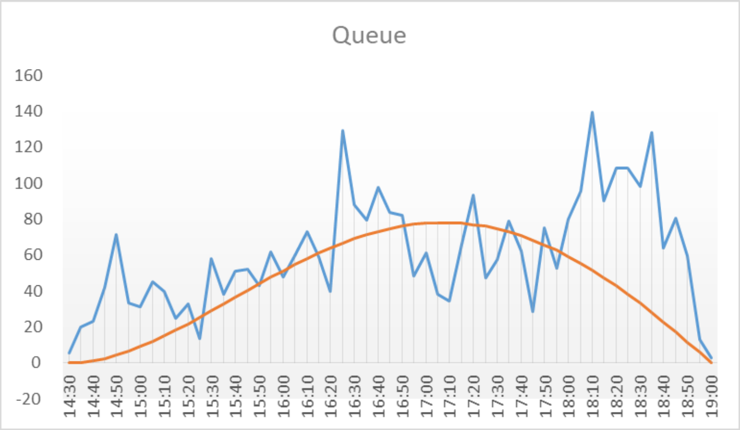
Calibration results： sensor 137

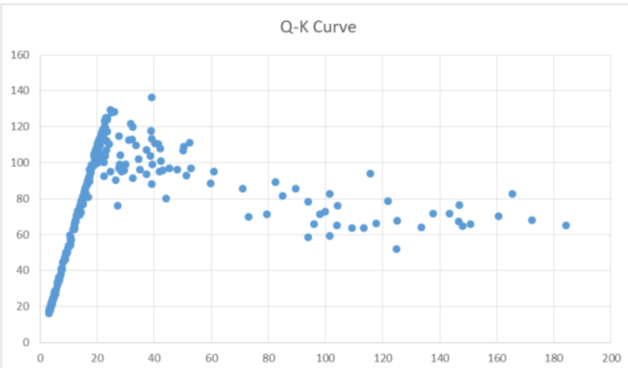




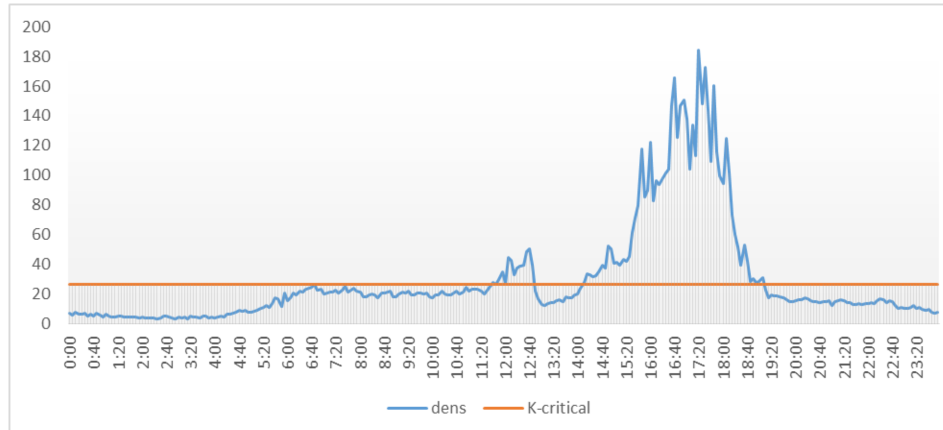
OUTPUT		
mu	849	veh/hr/ln
gamma	4.147966	veh/hr^4

Calibration results: sensor 78

Flow per 5 min per ln

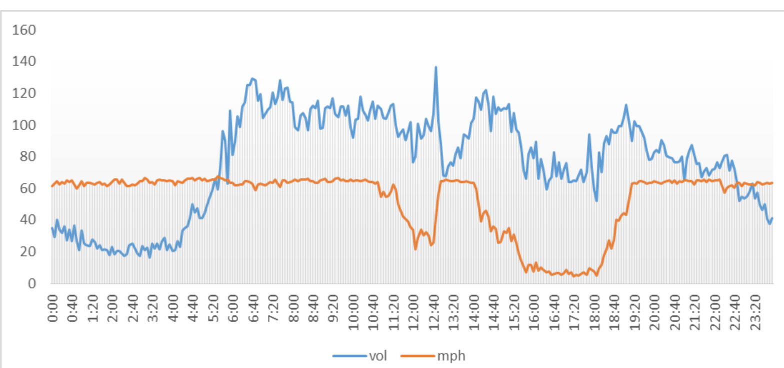


Time series of densities and K_critical



Time series of speed and flow

Flow per 5 min per ln
mile per hour



INPUT			
t0	14:10	14.17	
t3	19:05	19.08	
m	0.58		In our paper, this is a parameter to be calibrated. Here we treat it a constant which equals 7/12.
t2	17:02	17.03	t2 = t0 + m*(t3-t0)
t_bar	20:43	20.72	t_bar = t0 + [3*(t3-t0) - 4*(t2-t0)]/(4-6*m)
n	4		# of lanes immediately downstream the bottleneck
v_f	53	mile/hr	
v_mu	19	mile/hr	
delta_t	5	minutes	

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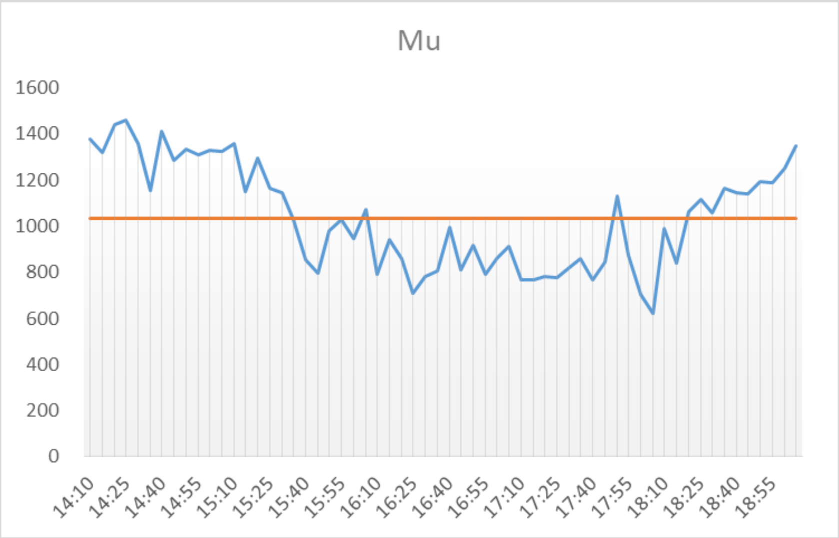
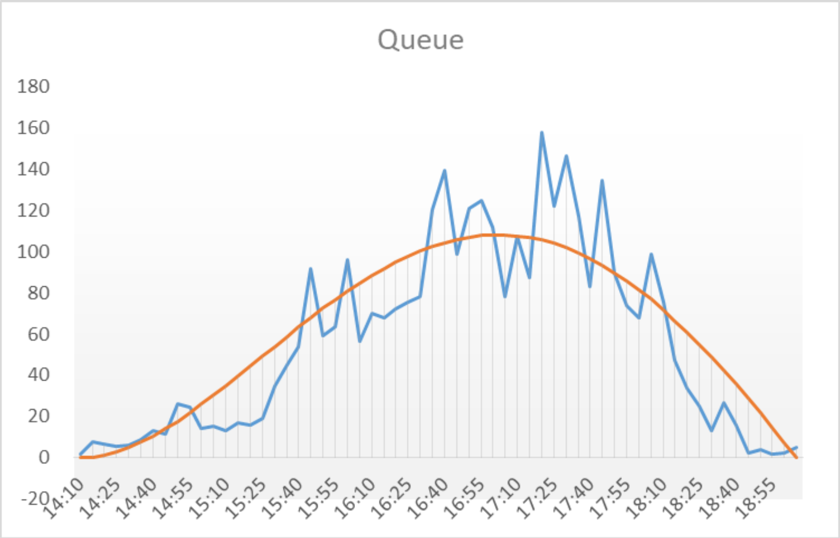
Calibration results： sensor 78





OUTPUT		
mu	1033	veh/hr/ln
gamma	3.42798	veh/hr^4

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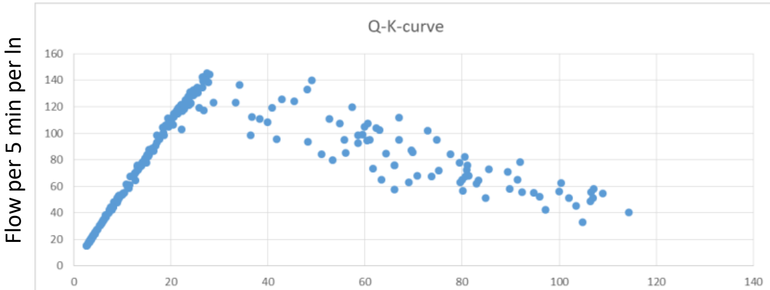
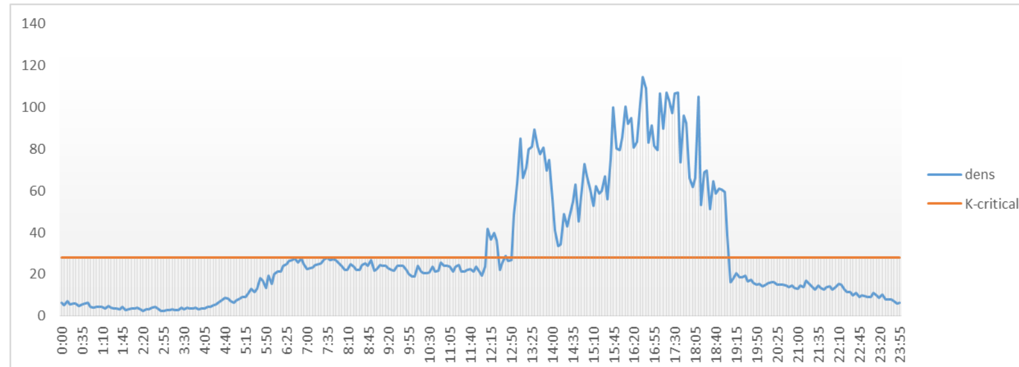
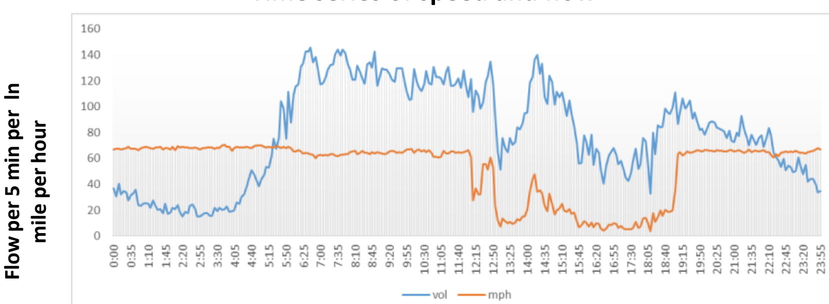
Calibration results： sensor 84



Time series of densities and K_critical



Time series of speed and flow



INPUT			
t0	14:10	14.17	
t3	19:00	19.00	
m	0.58		In our paper, this is a parameter to be calibrated. Here we treat it a constant which equals 7/12.
t2	16:59	16.99	t2 = t0 + m*(t3-t0)
t_bar	20:36	20.61	t_bar = t0 + [3*(t3-t0) - 4*(t2-t0)]/(4-6*m)
n	4		# of lanes immediately downstream the bottleneck
v_f	53	mile/hr	
v_mu	16	mile/hr	
delta_t	5	minutes	

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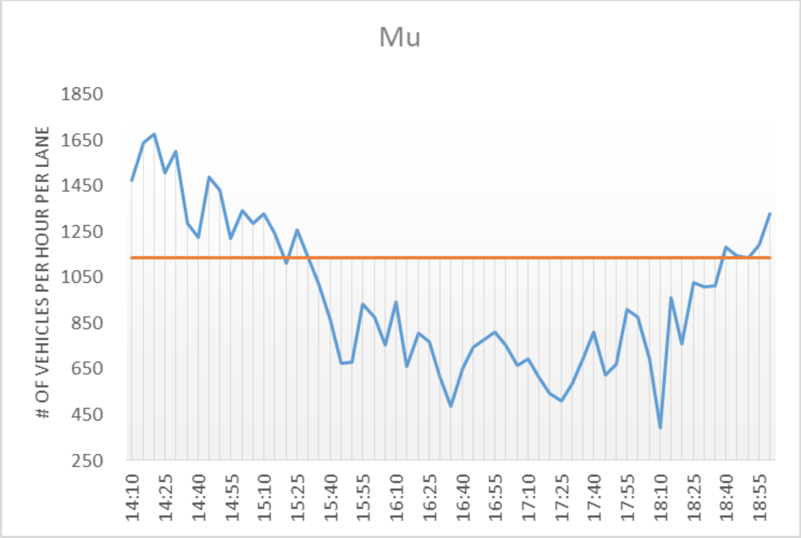
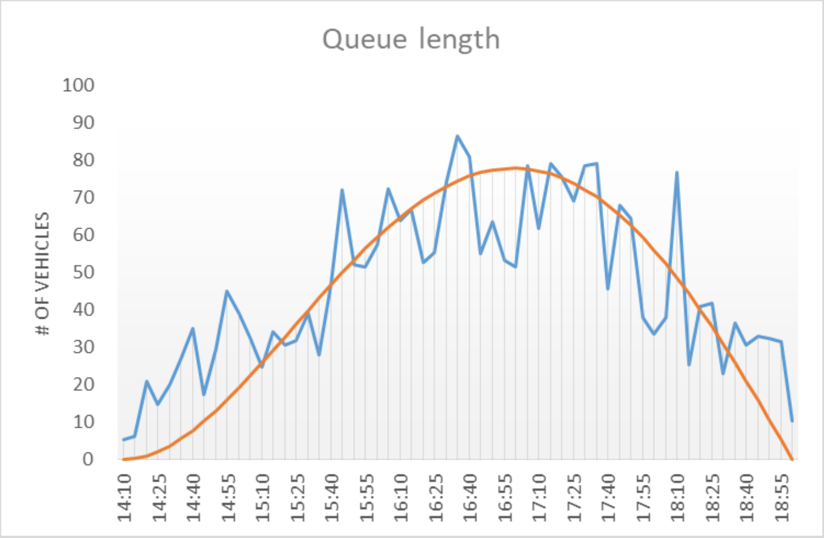
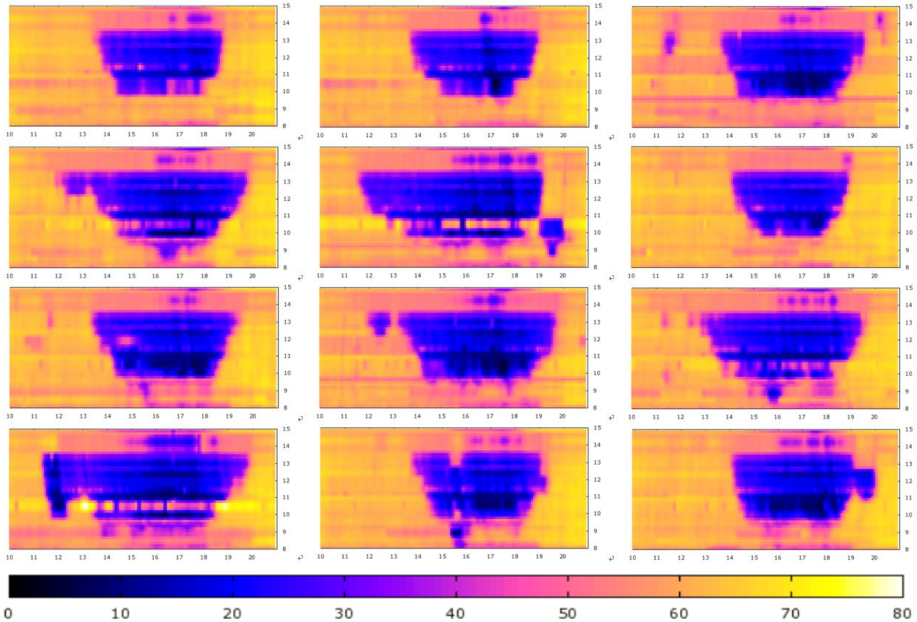
Calibration results: sensor 84





OUTPUT		
mu	1133	veh/hr/ln
gamma	2.919345	veh/hr^4

How to calibrate it with data from multiple days?



Speed evolution process from 10:00 am to 21:00 pm

Day *N*	t_0	t_3	*P*
Day 1	15:00	18:00	3 hour
Day 2	15:25	18:35	3.17 hour
Day 3	14:45	18:10	3.42 hour
Day 4	15:40	18:20	2.67 hour
Day 5	15:30	18:30	3 hour
Day 6	15:10	18:00	2.83 hour
…	…	…	…

Summary: Polynomial inflow rate-based Queueing Model

A family of polynomial-function-based formulations

Arrival rate form	Arrival rate function	Average travel time function
Constant form	$\lambda(t)=\begin{cases}\pi_1>\mu,\ t_0\le t<t_2\\ \pi_2<\mu,\ t_2\le t\le t_3\end{cases}$	$tt=t_f\cdot\left[1+\frac{(\pi_1-\mu)(\mu-\pi_2)}{2\mu(\pi_1-\pi_2)\cdot t_f}\cdot\left(\frac{D}{\mu}\right)\right]$
Linear form	$\lambda(t)=-\kappa(t-t_2)+\mu,\ \kappa>0$	$tt=t_f\cdot\left[1+\frac{\kappa}{12\mu\cdot t_f}\cdot\left(\frac{D}{\mu}\right)^2\right]$
Quadratic form	$\lambda(t)=-\rho(t-t_0)(t-t_2)+\mu,\ \rho>0$	$tt=t_f\cdot\left[1+\frac{\rho}{36\mu\cdot t_f}\cdot\left(\frac{D}{\mu}\right)^3\right]$
Cubic form	$\lambda(t)=\gamma(t-t_0)(t-t_2)(t-\overline{t})+\mu$	$tt=t_f\cdot\left[1+\frac{\gamma\cdot g(m)}{\mu\cdot t_f}\cdot\left(\frac{D}{\mu}\right)^4\right]$

Related to free flow travel time, capacity, demand, shape parameter, (m).

D.1: Motivation for Queue-based Volume-Delay Function

Functional requirements

- Capture queue building-up, propagation, dissipation
  - Key: how to detect queue spills back upstream link(s)
- Represent multiple origin-destination flow
  - Freeway merge and diverge
  - Arterial intersections (signal, stop signs, yield signs, no control)

Evaluation Criteria

- Theoretically rigorous
- Numerically reliable
- Computationally efficient

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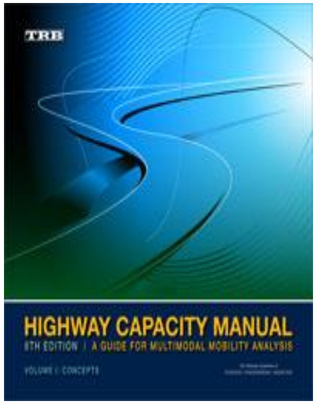
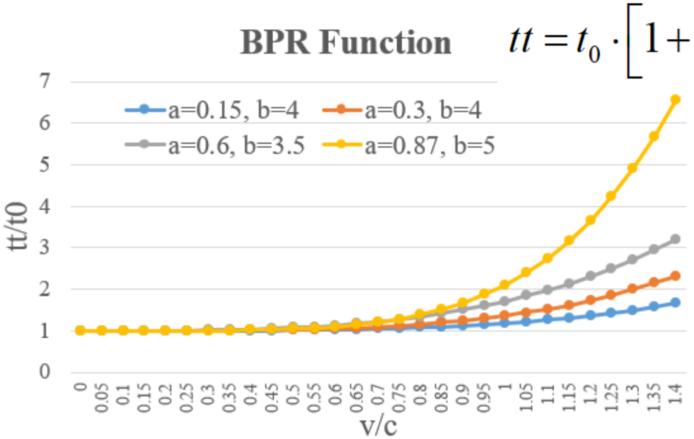
D.2: Volume-Delay Function (VDF)

Typical volume-delay function

Literatures	Mathematical forms	tt/t_0 when $V=C$	tt/t_0 when $V=0$
CATS (1960); Muranyi (1963)	$tt = t_0 \cdot 2^{(V/C)}$	2	1
Smock (1962, 1963)	$tt = t_0 \cdot \exp\left(\frac{V}{C} - 1\right)$	1	0.37
BPR (1964)	$tt = t_0 \cdot \left[1 + 0.15 \cdot \left(\frac{V}{C}\right)^4\right]$	1.15	1
Davidson (1966)[1]	$tt = t_0 \cdot \left(1 + \frac{J_D \cdot V}{C - V}\right), V < C$	$+\infty$	1
Akçelik (1978)[2]	$tt = \begin{cases} t_0 \cdot \left(1 + \frac{J_D \cdot V}{C - V}\right), \text{ if } V \le mC,\ 0 < m < 1 \\ t_m + K_m(V - mC), \text{ if } V > mC,\ 0 < m < 1 \end{cases}$	Related to J_D and m	1
Spiess (1990)	$tt = t_0 \cdot \left[2 - \beta - \alpha\left(1 - \frac{V}{C}\right) + \sqrt{\alpha^2\left(1 - \frac{V}{C}\right)^2 + \beta^2}\right]$, where $\beta = \frac{2\alpha - 1}{2\alpha - 2}, \alpha > 1$	2	1
Tisato (1991)[3]	$tt = \begin{cases} t_0 \cdot \frac{1 - mx}{1 - x}, x \le x_c \\ t_0 \cdot \frac{1 - mx_c}{1 - x_c} + 30T(x - x_c), x > x_c \end{cases}$ where $x = \frac{V}{C}, x_c = 1 - \sqrt{\frac{t_0}{30T}(1 - m)}$	Related to T and m	1
Akçelik (1991)	$tt = t_0 + 0.25T \cdot \left(\frac{V}{C} - 1 + \sqrt{(\frac{V}{C} - 1)^2 + \frac{8J_A V}{TC^2}}\right)$	Related to J_A and T	1

tt: travel time
t_0: free flow travel time
V: traffic volume
C: capacity
J_A, JD, α, β: parameters





$$tt = t_0 \cdot \left[1 + a(v/c)^b\right]$$

$$\log(tt - t_0) = \log t_0 + \log a + b\log(v/c)$$

Background and introduction

BPR volume-delay function

Speed Limit (mph)	Practical Capacity (vehicle per hour)	Model Parameters	
		a	b
0 - 30	0 - 240	0.7312	3.6596
0 - 30	249 - 499	0.6128	3.5038
0 - 30	500 - 749	0.8774	4.4613
0 - 30	750 - 999	0.6846	5.1644
0 - 30	1000+	1.1465	4.4239
31 - 40	250 - 499	0.6190	3.6544
31 - 40	500 - 749	0.6662	4.9432
31 - 40	750 - 999	0.6222	5.1409
31 - 40	1000+	1.0300	5.5226
41 - 50	500 - 749	0.6609	5.0906
41 - 50	750 - 999	0.5423	5.7894
41 - 50	1000+	1.0091	6.5856
50+	500 - 749	0.8776	4.9287
50+	750 - 999	0.7699	5.3443
50+	1000+	1.1491	6.8677

Reference: Mannering et al. (1990)

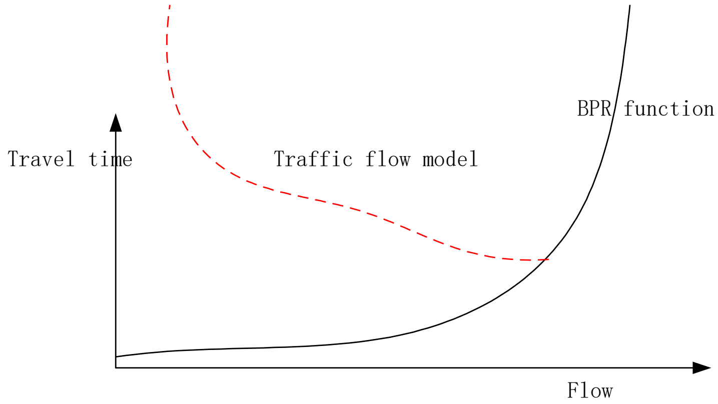
Facility Type	Free-Flow Speed	"a"	"b"
6-Lane Freeway	70 mph	0.88	9.8
	60 mph	0.83	5.5
	50 mph	0.56	3.6
4-Lane Multilane Highway	70 mph	1.00	5.4
	60 mph	0.83	2.7
	50 mph	0.71	2.1

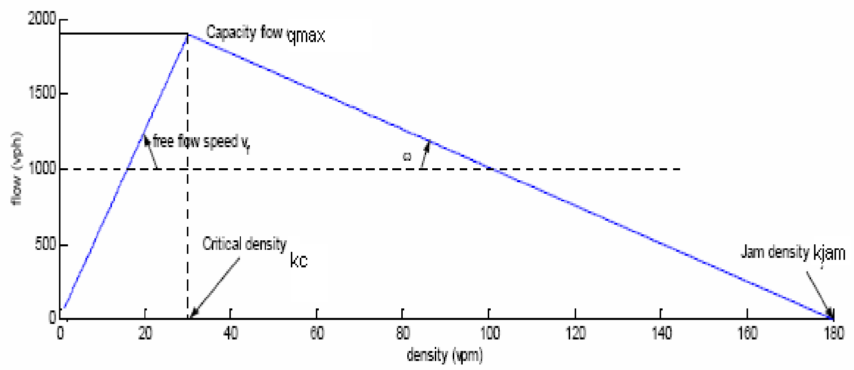
Both for highway and urban road.
Related to speed limit and practical capacity.

D.3: Volume-Delay Function (VDF)

BPR volume-delay function

- **Widely used** in static traffic assignment
- Fail to capture **queue evolution**, building-up, propagation, dissipation
- Fail to represent a **bottleneck** with low flow but high travel time





Recap

Static traffic assignment

- computational efficiency
- easy for implementation
- cannot capture traffic flow dynamics
- cannot describe queue evolution
- cannot be used for oversaturated traffic conditions
- volume over capacity or demand over capacity?
- the used values of alpha and capacity are on the high side

Dynamic traffic assignment

- capture traffic flow dynamics
- describe queue evolution
- point queue or physical queue
- CTM- or LTM-based model
- high input-detail burden
- computational inefficiency

$$t = t_0 \left[1 + 0.15 \cdot \left(\boxed{V/C} \right)^4 \right]$$

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D.4: Discussion in TMIP: STA vs DTA

TMIP FMIP
Better Methods. Better Outcomes.

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HOME FORUM WE

Thu, 03/28/2019 - 4:58pm #6

John Gibb

Norman's article points out the absurdity of volume greater than capacity, but it's a little more tolerable to consider it demand rather than volume per se. Of course, we know that's not what actually flows through or downstream of a bottleneck; the rest of the problems are well known.

Three different impetuses for some form or another of DTA are:

(1) The well-known theoretical problems of static assignment,

(2) To analyze operations and design alternatives not adequately represented by link-level capacities and delay functions,

(3) The limitations of microsimulation without time-dependent traffic-aware path choice.

Planning agencies in mature, built-out areas with operations-oriented project lists rather than freeway plans (e.g. San Francisco) have responded the most to impetus 2 with fairly detailed large-area DTA models. Analysts working with microsimulation as their starting point can say what they will about impetus 3.

Top

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- "… I argue that static assignment should not be used in **freeway capacity planning** studies - either separately or in combination with microsimulation…"
- "… it doesn't work to extract **over-capacity** subarea trip tables and then input them into **capacity-constrained DTA or microsimulation** …"
- "**Is there a non-microsimulation DTA that's better than STA**? (Some DTAs have theoretical problems of their own, e.g. unreasonable FIFO violation.)"
- "Is it good enough to be a **replacement for STA as part of a full-region demand-equilibrium model**?"
- "Since ***all models* are wrong but *some* are useful**, what's *better* or *good enough* depends; more detail is not always better."
- "… but a **high input-detail burden** upon humans under limited budgets and schedules can make such a model less useful and more wrong than a simpler model, particularly for future scenario evaluation…"

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D.5: Discussion in TMIP: STA vs DTA

TMIP FMIP
Better Methods. Better Outcomes.

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Thu, 03/28/2019 - 4:58pm #6

John Gibb

Norman's article points out the absurdity of volume greater than capacity, but it's a little more tolerable to consider it demand rather than volume per se. Of course, we know that's not what actually flows through or downstream of a bottleneck; the rest of the problems are well known.

Impetus 1 does not in itself require microsimulation, nor even HCM-style intersection analysis. Norman's study used DTALite, a kinematic-wave DTA with link capacities. Two separate questions that can follow are:

(1) Is there a non-microsimulation DTA that's better than STA? (Some DTAs have theoretical problems of their own, e.g. unreasonable FIFO violation.)

(2) Is it good enough to be a replacement for STA as part of a full-region demand-equilibrium model?

Since "all models are wrong but some are useful," what's "better" or "good enough" depends; more detail is not always better. A model can be utterly faithful to the effects of every geometric and operational detail scientifically examined, but a high input-detail burden upon humans under limited budgets and schedules can make such a model less useful and more wrong than a simpler model, particularly for future scenario evaluation.

Top

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- Our perspectives:
  - Bottleneck discharge rate
  - Highway capacity
  - Queue evolution: Deterministic fluid approximation vs stochastic m/m/1
  - Queue-oriented travel time performance function

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D.6: well-behaved VDF requirements by Spiess

Consider a link delay function $f(x) = \alpha x^{\beta}$, and revisit the basic well-behaved VDF requirements proposed by **Spiess (1990)** as follows

1. $f(x)$ should be strictly increasing for a feasible range of x. This is the necessary condition for the traffic assignment to converge to a unique solution.
2. $f(0) = 0$ and $f(1) = \text{constant}\ \alpha$. The conditions ensure compatibility with the BPR form.
3. $f'^{(x)} = \alpha\beta x^{\beta-1}$ exists and is strictly increasing. This ensures the convexity of the congestion function, which is important when calculating marginal costs in system optimum assignment.
4. $f'(1) = \alpha\beta$, and the exponent β indicates how sudden the congestion effects change under the oversaturated condition.
5. $f'(x) =< M\beta$, where M is a positive constant. The steepness of the congestion curve is limited so that the derived average delay is reasonable.
6. $f'(0) \geq 0$, which guarantees the uniqueness of the link volumes.
7. The evaluation of $f(x)$ should be computationally efficient.

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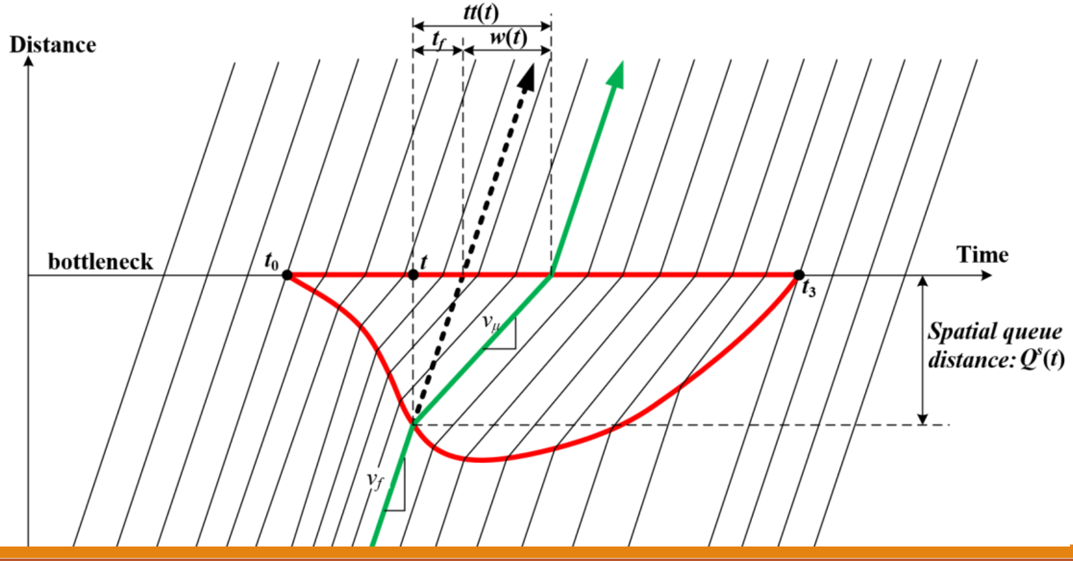
D.7: Requirements for a well-behaved queue-based volume-delay function

Based on our definition of the inflow D/C ratio, we extend the basic requirements proposed by **Spiess (1990)** to develop a well-behaved QVDF. The additional requirements are listed as follows:

1. [**Consistency of congestion demand**] The inflow demand D should be consistent with the congestion duration P and discharge rate μ in the queueing dynamics, that is, $D = P\mu$.
2. [**Consistency of time-averaged delay**] The average speed within the congestion duration should be consistent with the time-averaged delay.
3. [**Consistency between macroscopic parameters and mesoscopic parameters**
4. [**First-In-First-Out**] The time-dependent travel time in the underlying mesoscopic vehicular fluid model should satisfy the FIFO property and capacity constraints.



$$travel\ time\ in\ queue = \frac{Q^s(t)}{v_\mu}$$

$$= t_f + w(t) = \frac{Q^s(t)}{v_f} + w(t)$$

$$w(t) = \frac{Q^v(t)}{\mu} \qquad Q^p(t) = \frac{Q^v(t)}{1 - \frac{v_\mu}{v_f}}$$

D.8: 2 Assumptions for linking D/C to lowest speed

- **Calibration method:** a recent queue-based volume delay function by Zhou et al., (2022)

Basic assumptions

Assumption 1: Link congestion duration and D/C ratio

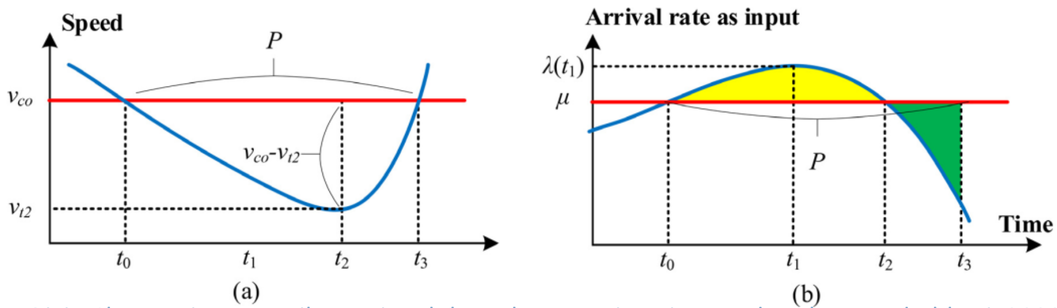
$$P = f_d \cdot \left(\frac{D}{C}\right)^n$$

P: congestion duration
fd: congestion duration constant
D: total inflow demand
C: ultimate capacity
n: oversaturation-to-duration elasticity factor

Assumption 2: Link magnitude of speed reduction and congestion duration

$$MSR = \frac{v_{co} - v_{t_2}}{v_{t_2}} \qquad MSR = f_p \cdot (P)^s$$

v_co: cut-off speed
v_t2: lowest speed in congestion duration
fp: MSR reduction constant
P: congestion duration
s: duration-to-speed reduction elasticity factor



Zhou, Xuesong, Qixiu Cheng, Xin Wu, Peiheng Li, Baloka Belezamo, Jiawei Lu, and Mohammad Abbasi. 2022. "A meso-to-macro cross-resolution performance approach for connecting polynomial arrival queue model to volume-delay function with inflow demand-to-capacity ratio." Multimodal Transportation 1 (2):100017

D.9: Linking time-dependent queue length to time-dependent speed

Avg delay time-dependent delay

Generate time-dependent speed

$$Q(t) = \frac{\gamma}{4}\left(t - t_0\right)^2 \cdot \left(t - t_3\right)^2$$

time-dependent queue

$$w(t) = \frac{\gamma}{4\mu}\left(t - t_0\right)^2 \cdot \left(t - t_3\right)^2$$

time-dependent delay

$$v(t) = \frac{L}{\frac{L}{v_{co}} + w(t)}$$

time-dependent speed

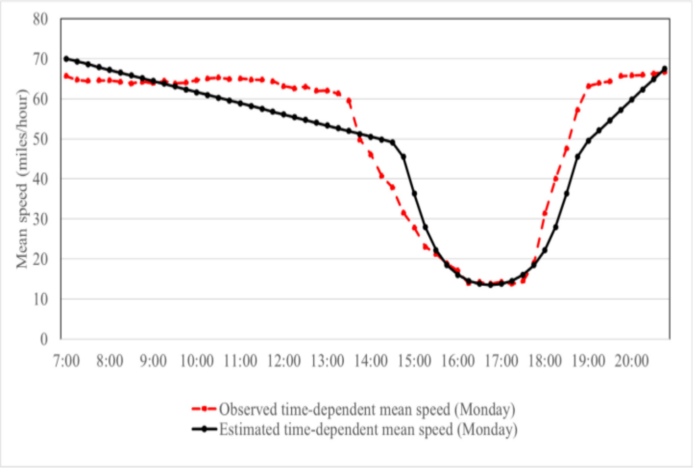


Fig. 14. Observed time-dependent mean speed and estimated speed at detector ID 87 on Monday.

D.10: Linking avg delay to time-dependent speed

Generate average delay

$$\overline{w} = \frac{\gamma}{120\mu} \cdot P^4 = \frac{\gamma}{120\mu} \cdot \left(\frac{D}{\mu}\right)^4.$$

Generate longest delay

$$w_{t_2} = \frac{\gamma}{4\mu} \cdot (t_2 - t_0)^2 \cdot (t_2 - t_3)^2 = \frac{\gamma}{4\mu} \cdot \left(\frac{P}{2}\right)^4 = \frac{\gamma}{64\mu} \cdot P^4.$$

Conversion ratio

$$\theta = \frac{\bar{w}}{w_{t_2}} = \frac{64}{120} = \frac{8}{15}.$$

Generate average speed

$$\bar{v} = \frac{L}{\frac{L}{v_{co}} + \bar{w}} = \frac{L}{\frac{L}{v_{co}} + \theta w_{t_2}} = \frac{L}{\frac{L}{v_{co}} + \theta \cdot \left(\frac{L}{v_{t_2}} - \frac{L}{v_{co}}\right)} =$$

$$= \frac{v_{co}}{1 + \theta\left(\frac{v_{co} - v_{t_2}}{v_{t_2}}\right)} = \frac{v_{co}}{1 + \theta \cdot [f_p \cdot (P)^s]}$$

$$= \frac{v_{co}}{1 + \theta\left[f_p \cdot {f_d}^s \cdot \left(\frac{D}{C}\right)^{n \cdot s}\right]} = \frac{v_{co}}{1 + \alpha\left(\frac{D}{C}\right)^{\beta}}$$

Details: Connecting inflow curvature parameter and magnitude of speed reduction

we create a connection between w_{t_2}(i.e., the longest delay at t_2 compared with v_{co}) and P

$$w_{t_2} = \frac{L}{v_{t_2}} - \frac{L}{v_{co}} = \frac{L}{v_{co}} \cdot \left(\frac{v_{co} - v_{t_2}}{v_{t_2}}\right) = \frac{L}{v_{co}} \cdot MSR = \frac{L}{v_{co}} \cdot f_p \cdot (P)^s$$

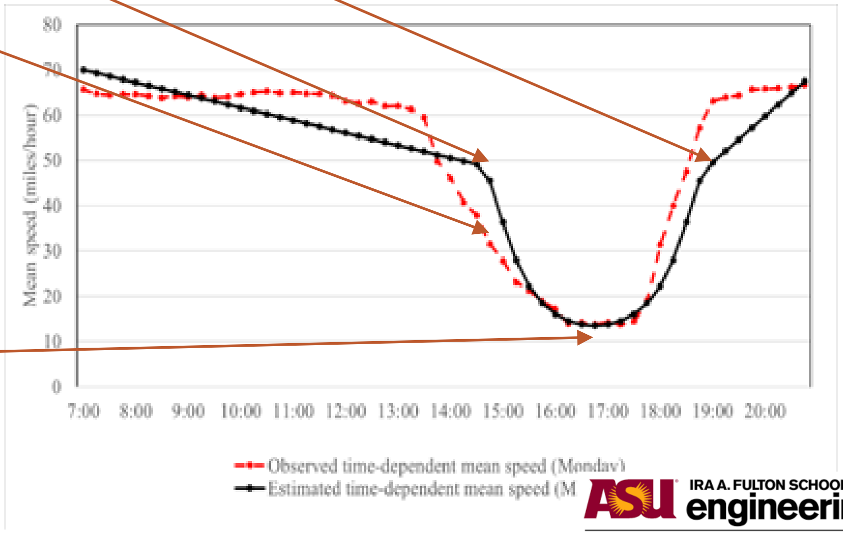
If we use the cubic PAQ model with $m = 1/2$, then we have

$$w(t) = \frac{\gamma}{4\mu} \cdot (t - t_0)^2 \cdot (t - t_3)^2.$$

By assuming $\gamma > 0$ and $m = 1/2$, we have $t_0 = t_2 - P$ and $t_3 = t_2 + P$ according to **Cheng et al. (2022)**. Then the longest time-dependent delay at t_2 becomes available as follows:

$$w_{t_2} = \frac{\gamma}{4\mu} \cdot (t_2 - t_0)^2 \cdot (t_2 - t_3)^2$$

$$= \frac{\gamma}{4\mu} \cdot \left(\frac{P}{2}\right)^4 = \frac{\gamma}{64\mu} \cdot P^4.$$



Details: Time-dependent delay and average speed during congestion duration

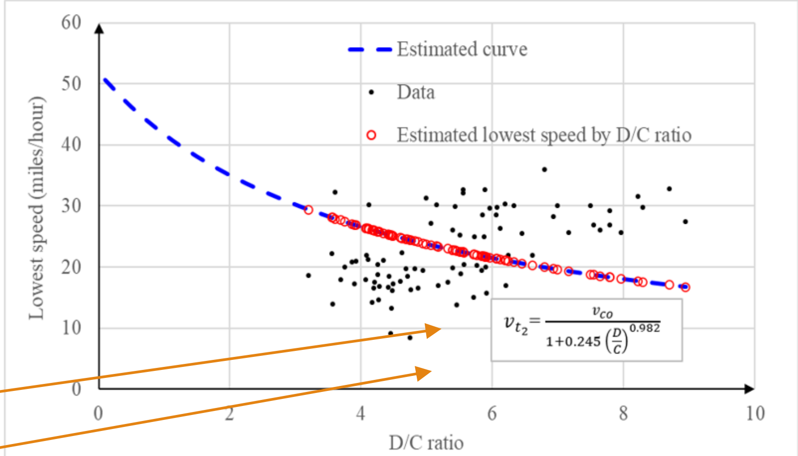
If the cubic model is adopted with $m = 0.5$, we will have the following time-dependent queue and delay.

$$Q(t) = \frac{\gamma}{4}(t - t_0)^2 \cdot (t - t_3)^2$$

$$w(t) = \frac{\gamma}{4\mu}(t - t_0)^2 \cdot (t - t_3)^2$$

Time-dependent speed can be derived as follows:

$$v(t) = \frac{L}{\frac{L}{v_{co}} + w(t)}$$



With the cubic PAQ model and $m = 0.5$, the average delay during a congestion duration can be calculated by the following equation

$$\bar{w} = \frac{\gamma}{120\mu} \cdot P^4 = \frac{\gamma}{120\mu} \cdot \left(\frac{D}{\mu}\right)^4.$$

$$\theta = \frac{\bar{w}}{w_{t_2}} = \frac{64}{120} = \frac{8}{15}.$$

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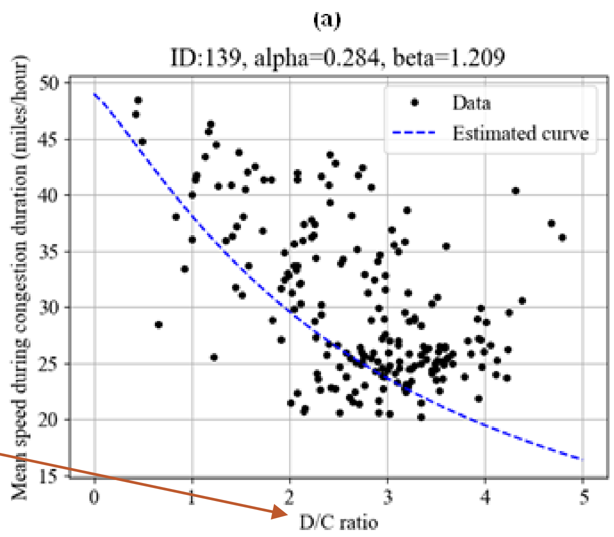
Details: Time-dependent delay and average speed during congestion duration

a BPR-like link performance function

$$\bar{v} = \frac{L}{\frac{L}{v_{co}} + \bar{w}} = \frac{L}{\frac{L}{v_{co}} + \theta w_{t_2}} = \frac{L}{\frac{L}{v_{co}} + \theta \cdot \left(\frac{L}{v_{t_2}} - \frac{L}{v_{co}}\right)} =$$

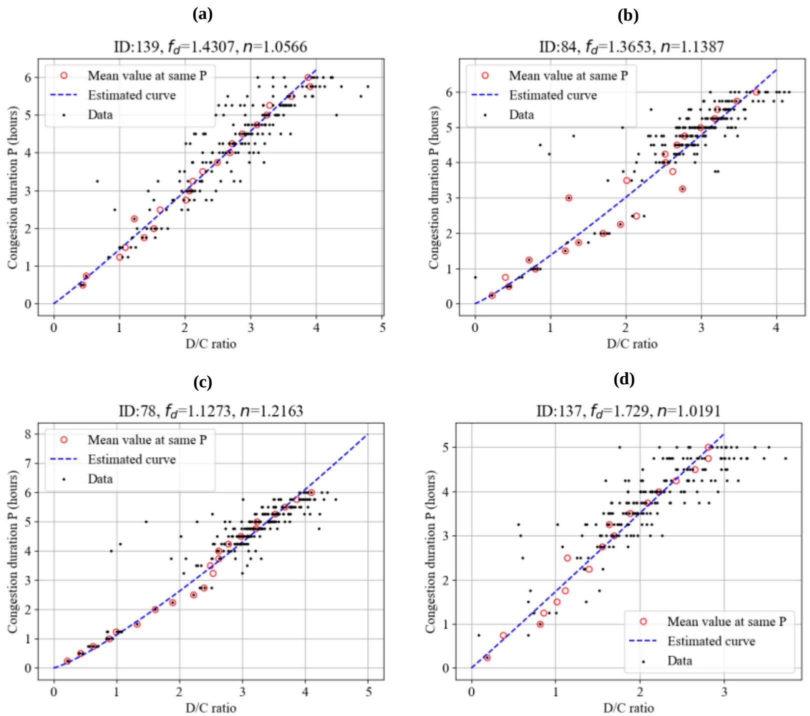
$$= \frac{v_{co}}{1 + \theta\left(\frac{v_{co} - v_{t_2}}{v_{t_2}}\right)} = \frac{v_{co}}{1 + \theta \cdot \left[f_p \cdot (P)^s\right]}$$

$$= \frac{v_{co}}{1 + \theta\left[f_p \cdot {f_d}^s \cdot \left(\frac{D}{C}\right)^{n \cdot s}\right]} = \frac{v_{co}}{1 + \alpha\left(\frac{D}{C}\right)^{\beta}}$$



where $\alpha = \theta f_p {f_d}^s$ and $\beta = ns$. An alternative form can be written as $\bar{w} = \frac{L}{v_{co}} \cdot \alpha \left(\frac{D}{C}\right)^{\beta}$.

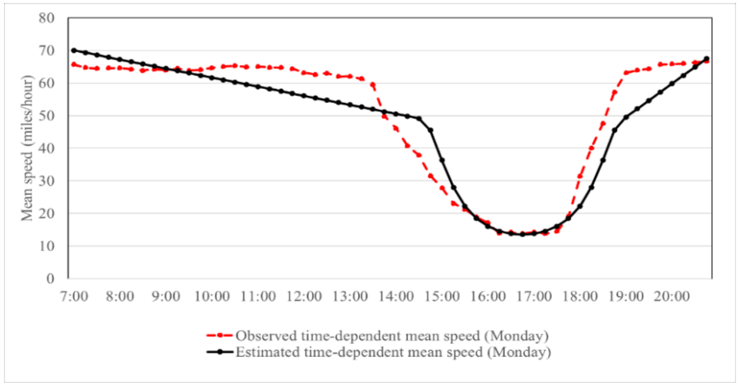
Case Study of Phoenix I-10 Corridor



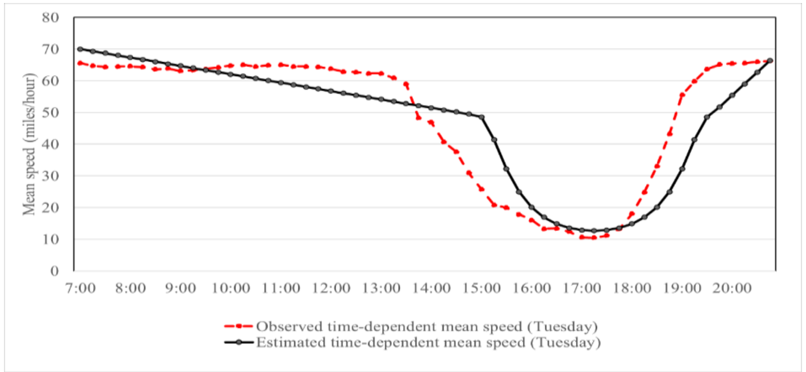
Calibration results of step 1 calibration that links D/C to congestion duration

Detector ID	The first step calibration		The second step calibration,		Parameters for BPR-like average speed function	
	f_d	n	f_p	s	α	β
139	1.43	1.06	0.35	1.14	0.28	1.21
84	1.37	1.14	0.23	1.64	0.21	1.87
78	1.13	1.22	0.11	2.10	0.07	2.55
137	1.73	1.02	0.21	1.71	0.29	1.75

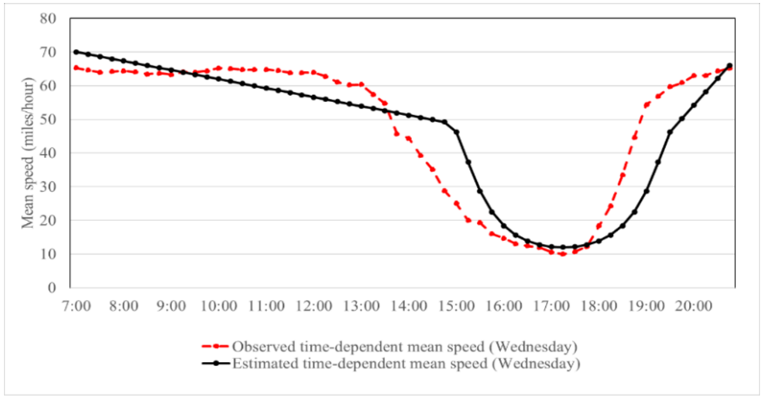
Case Study

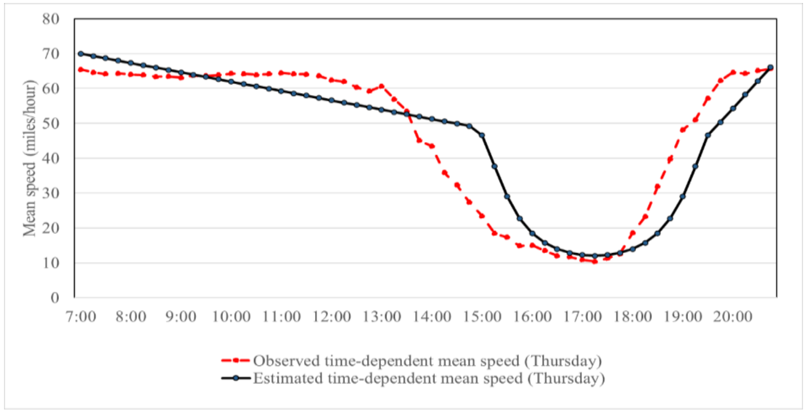


Observed time-dependent mean speed and estimated speed at detector ID 87 on Monday



Observed time-dependent mean speed and estimated speed at detector ID 87 on Tuesday





Observed time-dependent mean speed and estimated speed at detector ID 87 on Wednesday

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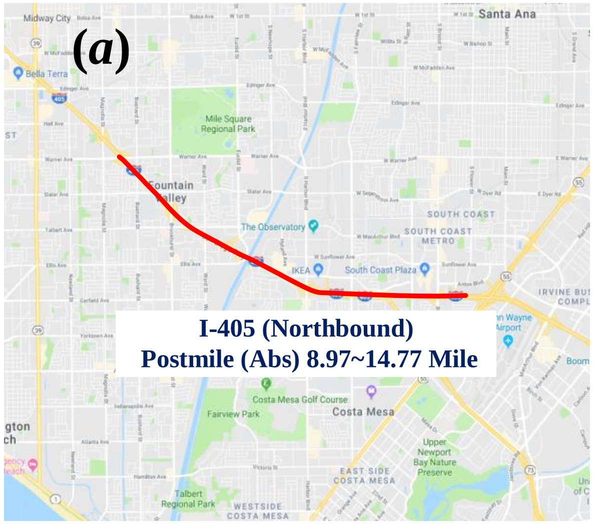
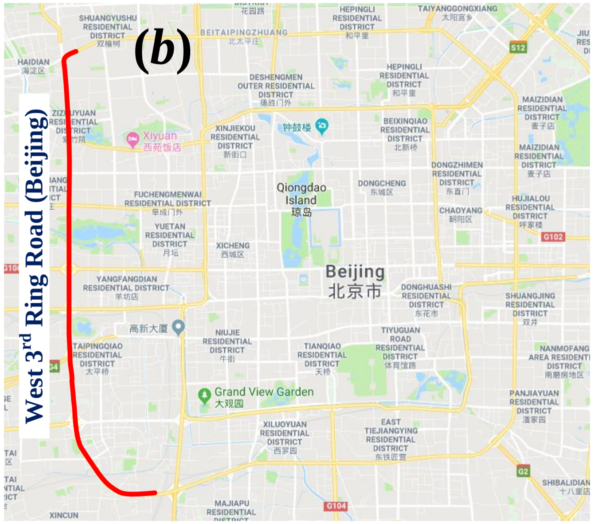
Case Study of 3 Cities



DS1: Los Angeles



DS2: Beijing

DS3: New York

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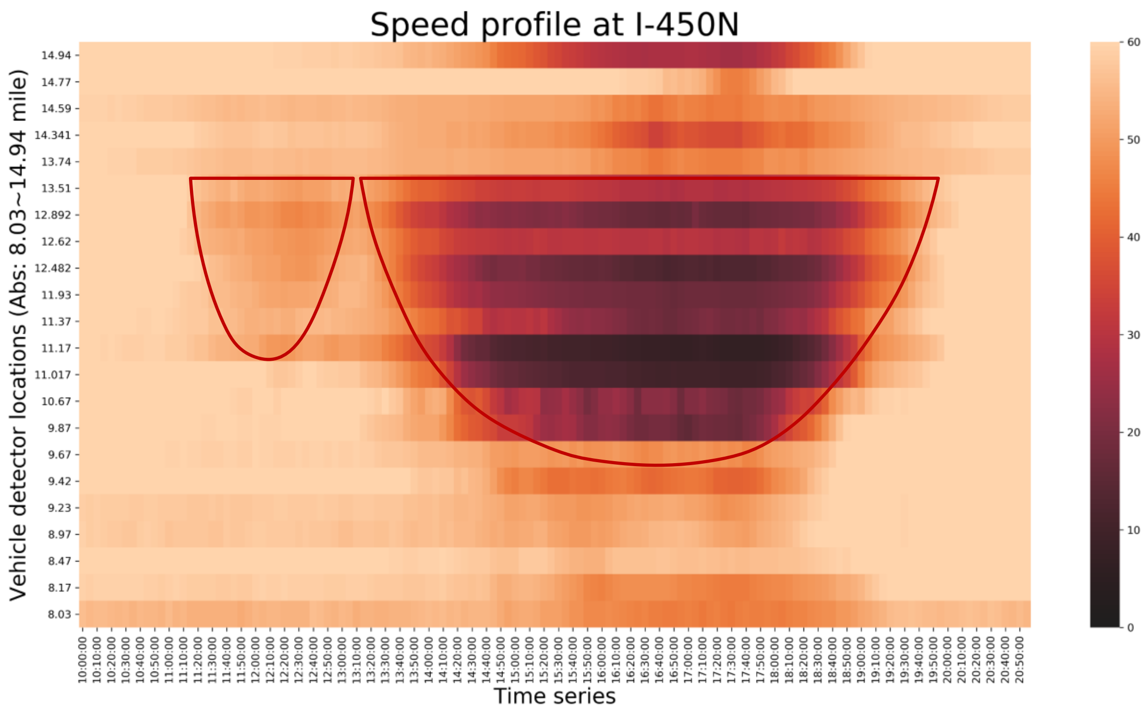
Description of empirical data sets

Data set	Queueing system	Object	Data type and information	Collected time and location
DS1	Traffic system	Vehicle	Freeway detector data with traffic flow, speed, and occupancy, etc.	Collected from the Northbound direction of I-405 freeway between absolute postmile 8.97 to 14.77 mile in Los Angeles on April, 2019, from 11:00 a.m. to 20:00 p.m.
DS2	Traffic system	Vehicle	Remote traffic microwave sensor data with the traffic flow, and probe vehicle data with averaged traffic speed, etc.	Collected from the west-third-ring of Beijing City on June 8, 2018, from 6:00 a.m. to 12:00 a.m.
DS3	Transportation system	Taxi	Taxi trip record data with trip ID, pickup time and location, drop off time and location, etc.	Collected from the Midtown Center of Manhattan to the John F. Kennedy International Airport in New York City on October 2018, provided by the New York City Taxi and Limousine Commission

DS1 Los Angeles

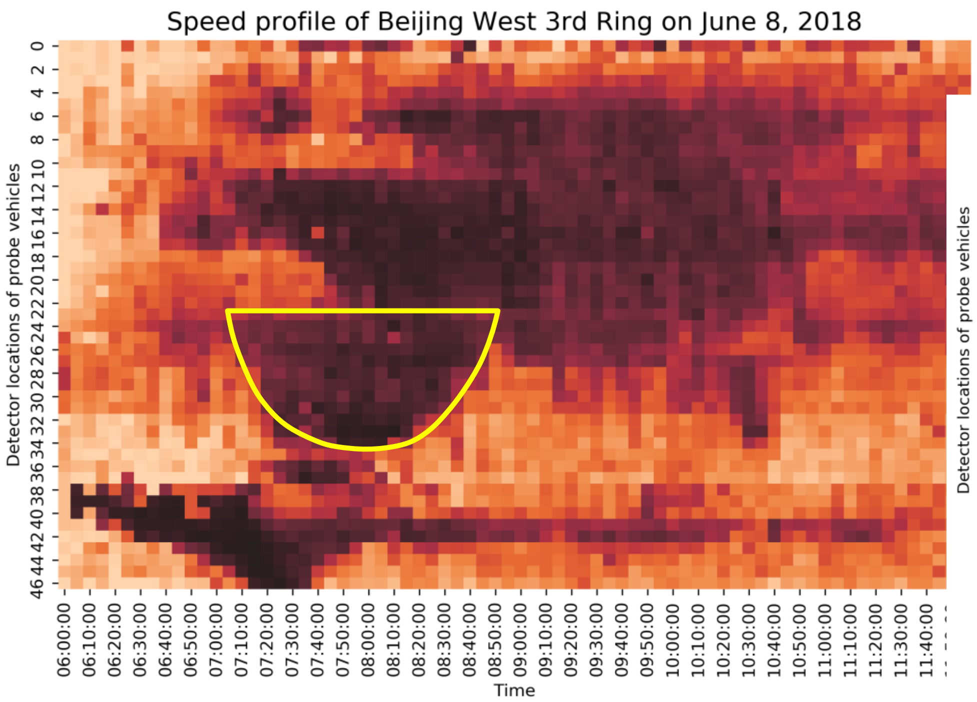
Bottleneck detection with speed contour map



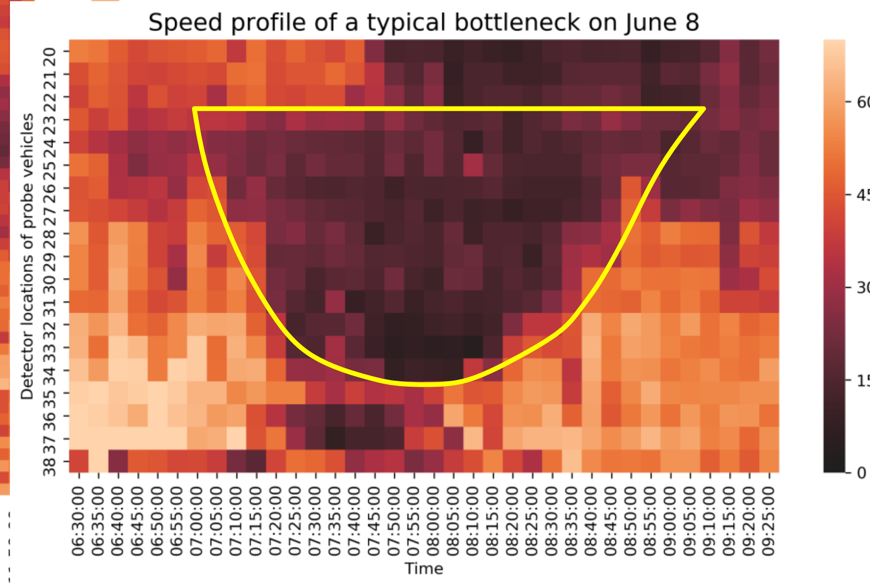
It is clear that the bottleneck is located at Abs=13.51 mile. In this case, we only analyze one single bottleneck with one peak period from t_0 = 13:10 to t_3 = 19:45.

DS2 Beijing

Bottleneck detection with speed contour map

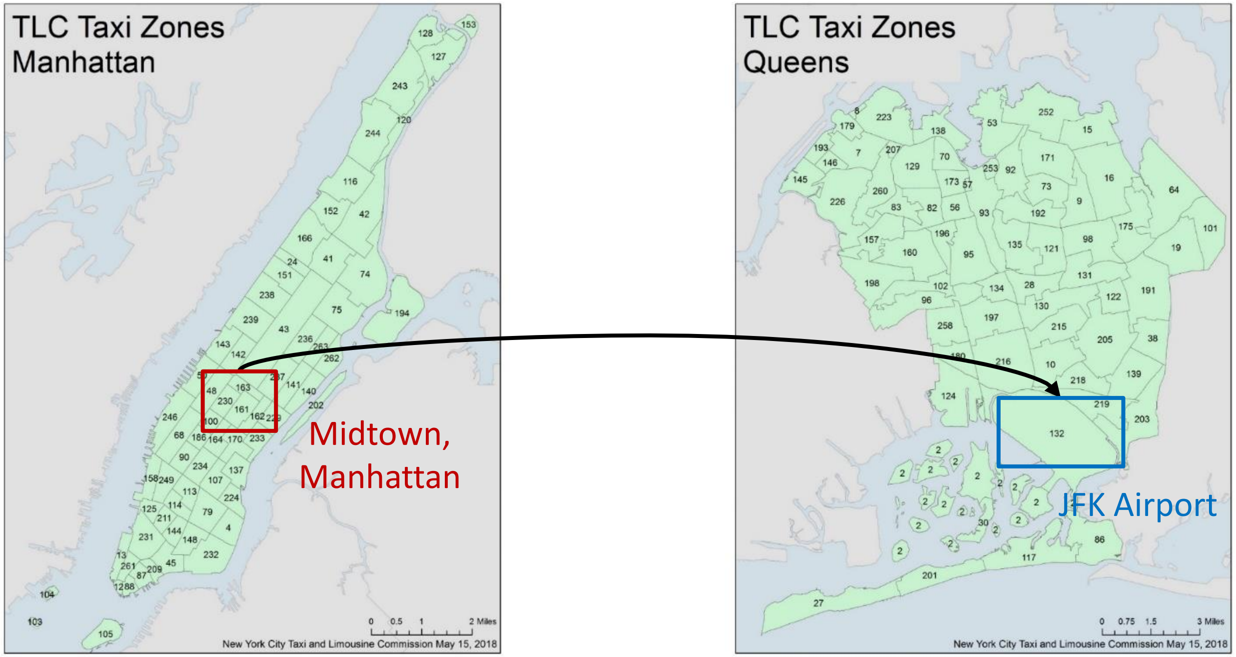


It exists the spatial queue spillback and the temporal queue connection phenomena.



DS3 New York

Bottleneck detection



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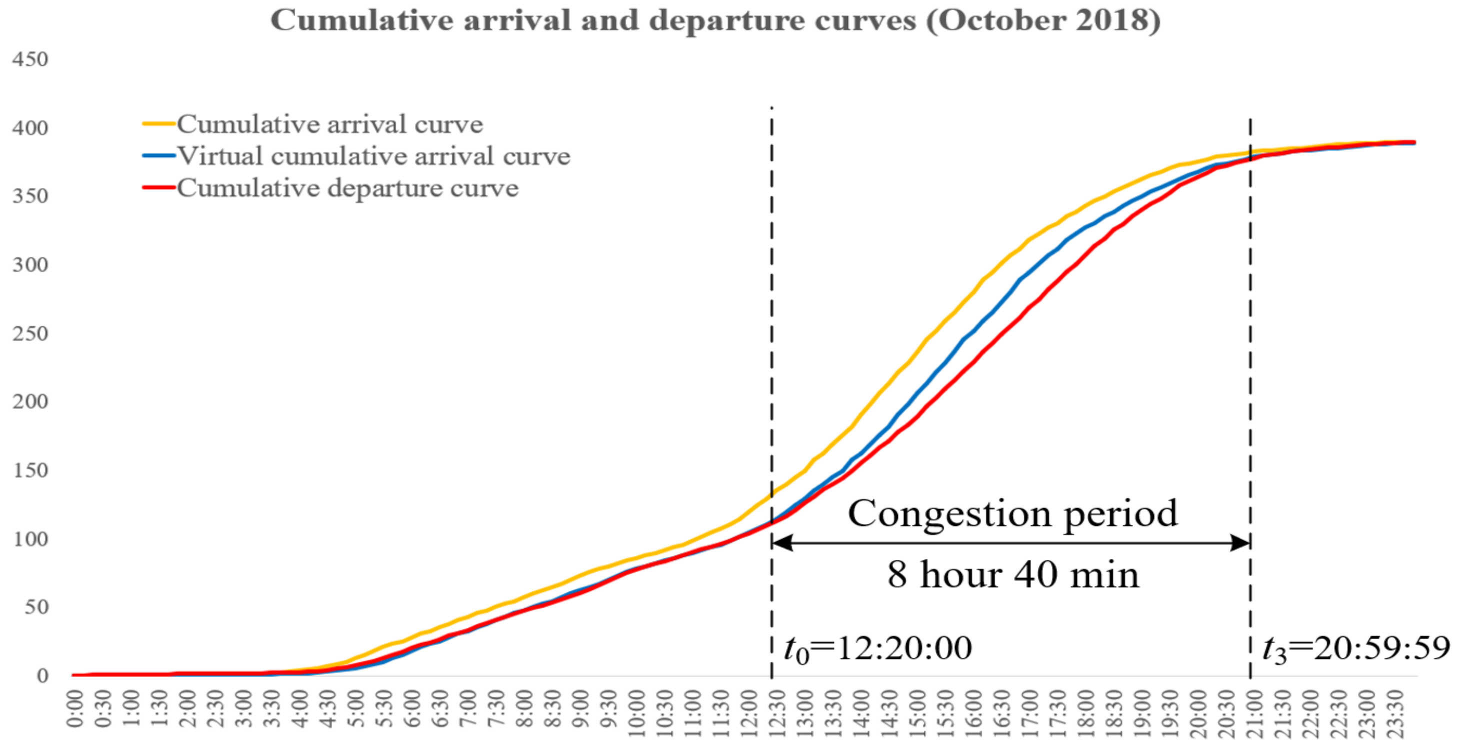
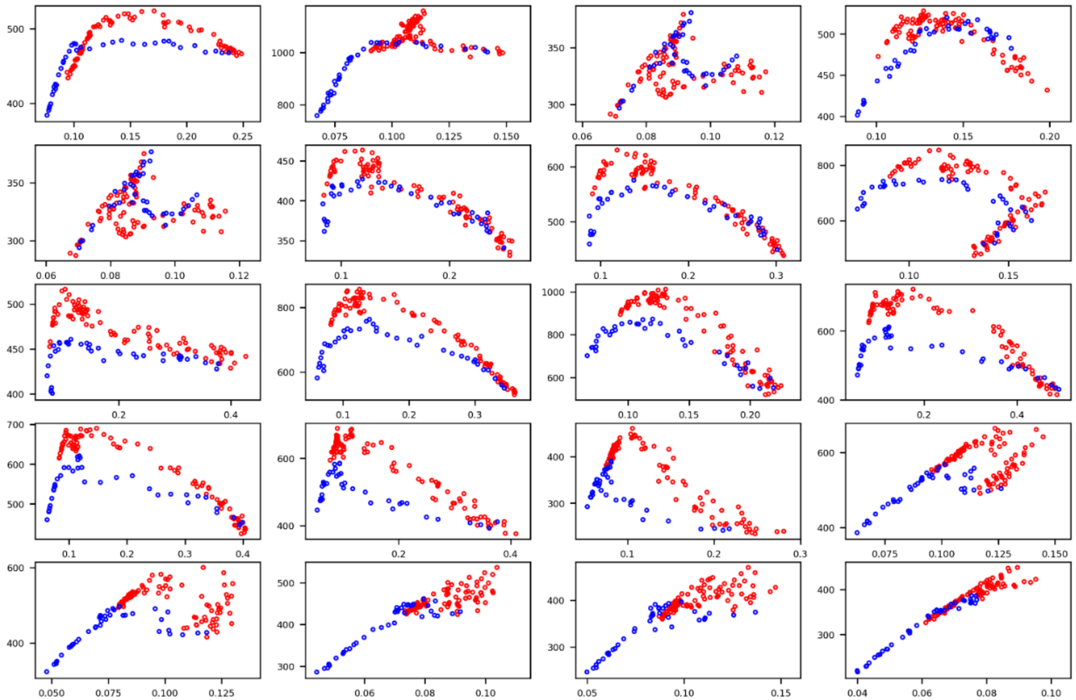
DS3 New York

Cumulative arrival and departure curves



Calibrations: DS1 Los Angeles

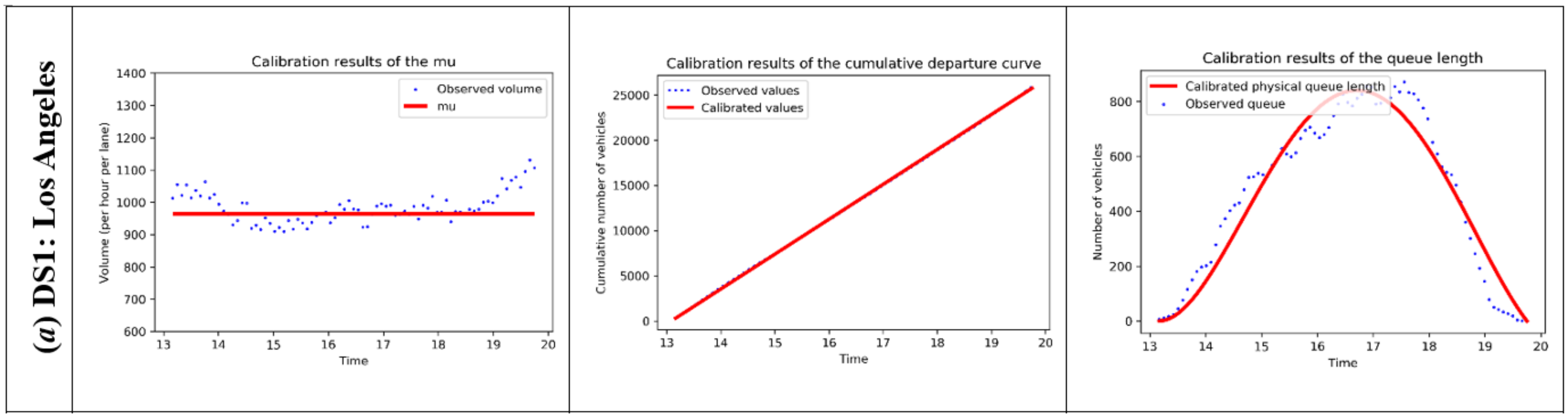
Flow-occupancy plot



The horizontal axis is the **occupancy**, while the vertical axis is the **flow**. The red dots represent the traffic loading process, while the blue dots represent the traffic unloading process. The bottleneck is located on the second row and second column. We can see that the critical occupancy of the queueing system closes to 0.13, which is used to calculated the observed physical queue length for the parameter calibration.

Calibrations: DS1 Los Angeles

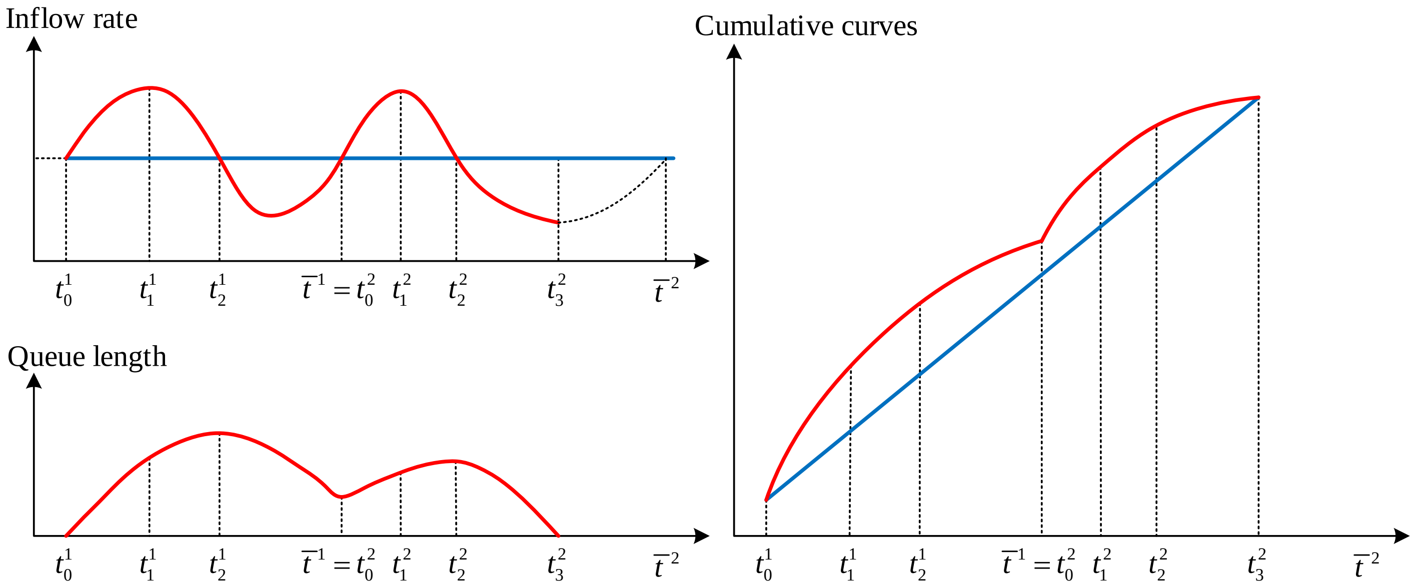
Results



$$\mu_{DS1} = 3860\, veh/hour \quad \text{or} \quad \mu_{DS1} = 965\, veh/hour/lane\,, \quad \gamma_{DS1} = 13 veh/hour^4\,, \quad m_{DS1} = 0.537$$

Calibrations: DS2 Beijing

Illustration of the two peak period model



It can be used to solve the temporal queue connection problem.

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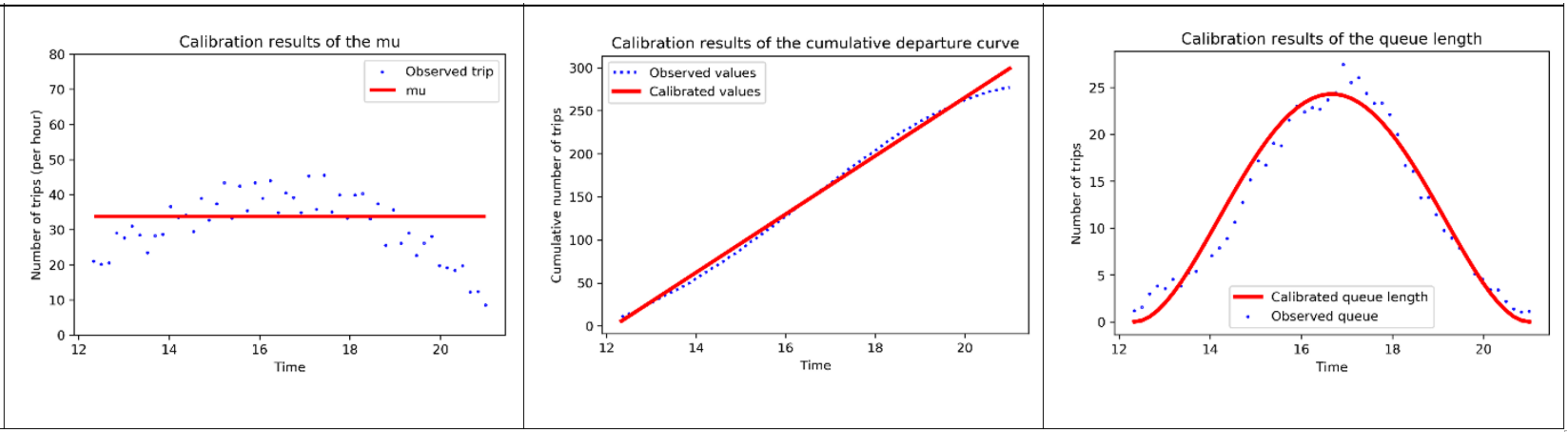
Calibrations: DS3 New York

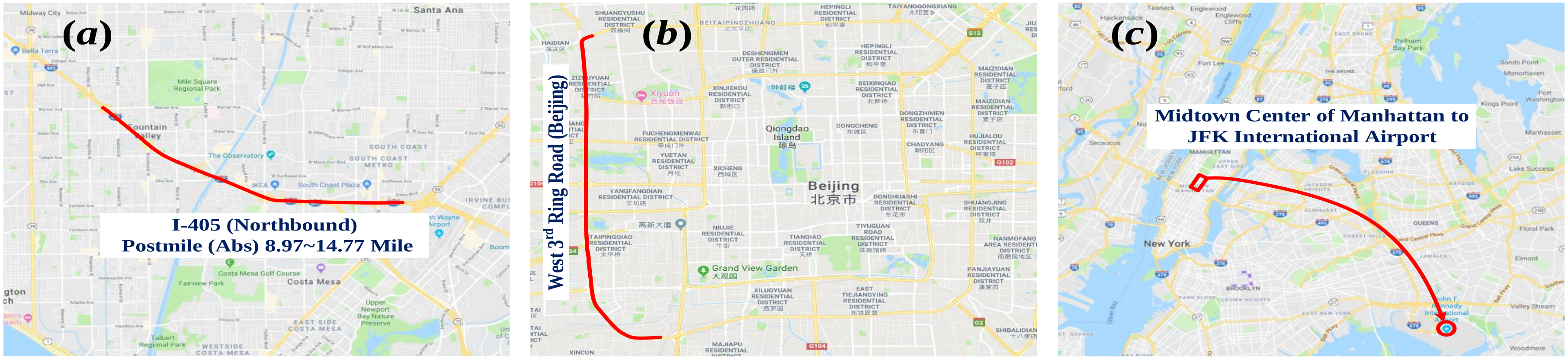
Results

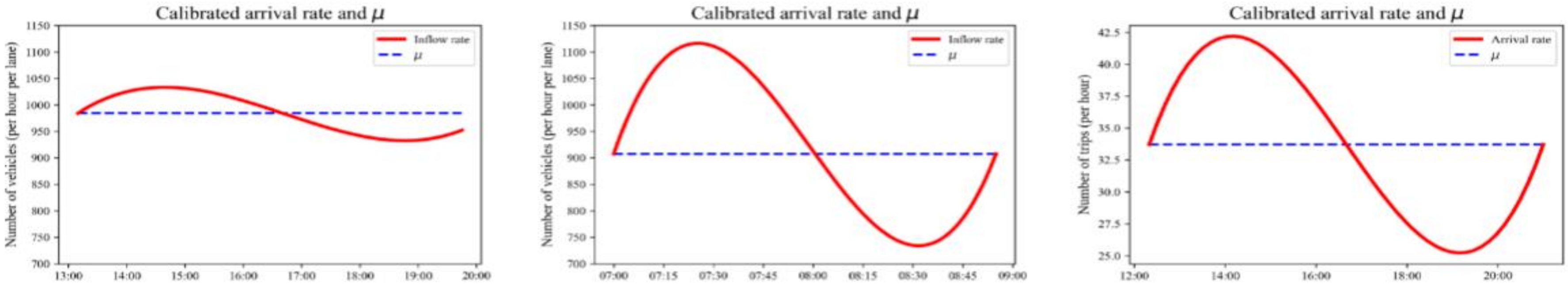
(c) DS3: New York



$$\mu_{DS3} = 34\ trip/hour\ ,\quad \gamma_{DS3} = 0.276\ trip/hour^4\ ,\quad m_{DS3} = 0.500$$

Final comparison across different cities



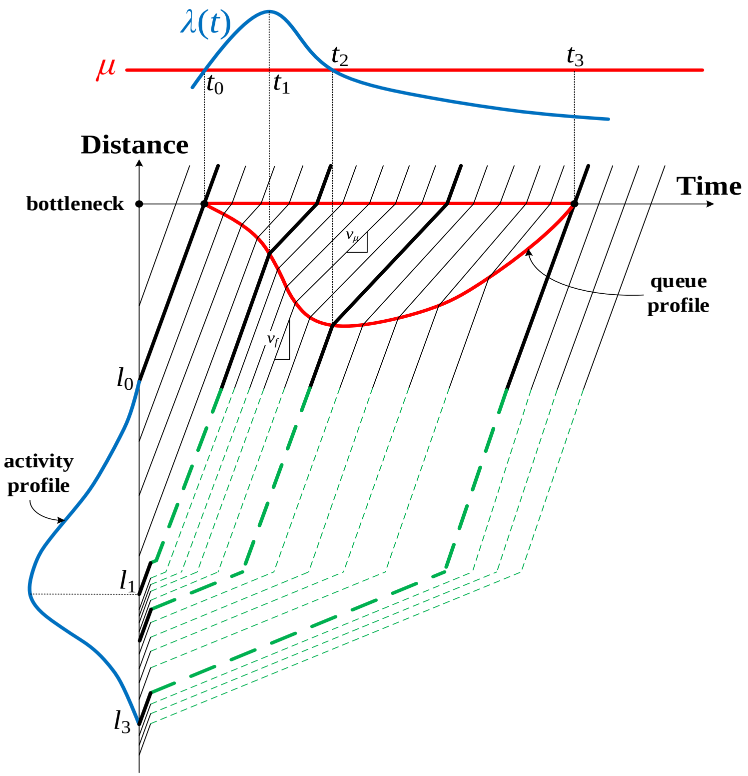


(a) DS1 (b) DS2 (c) DS3

The ratio of λ/μ indicates the variation of the demand over supply.

The results of λ/μ are: $0.937 \le (\lambda/\mu)_{DS1} \le 1.059$, $0.813 \le (\lambda/\mu)_{DS2} \le 1.234$, $0.745 \le (\lambda/\mu)_{DS3} \le 1.255$.

Discussion 1: Activity profile and queue profile



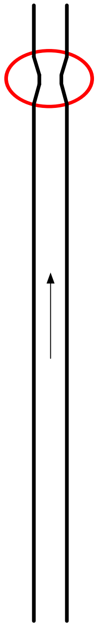
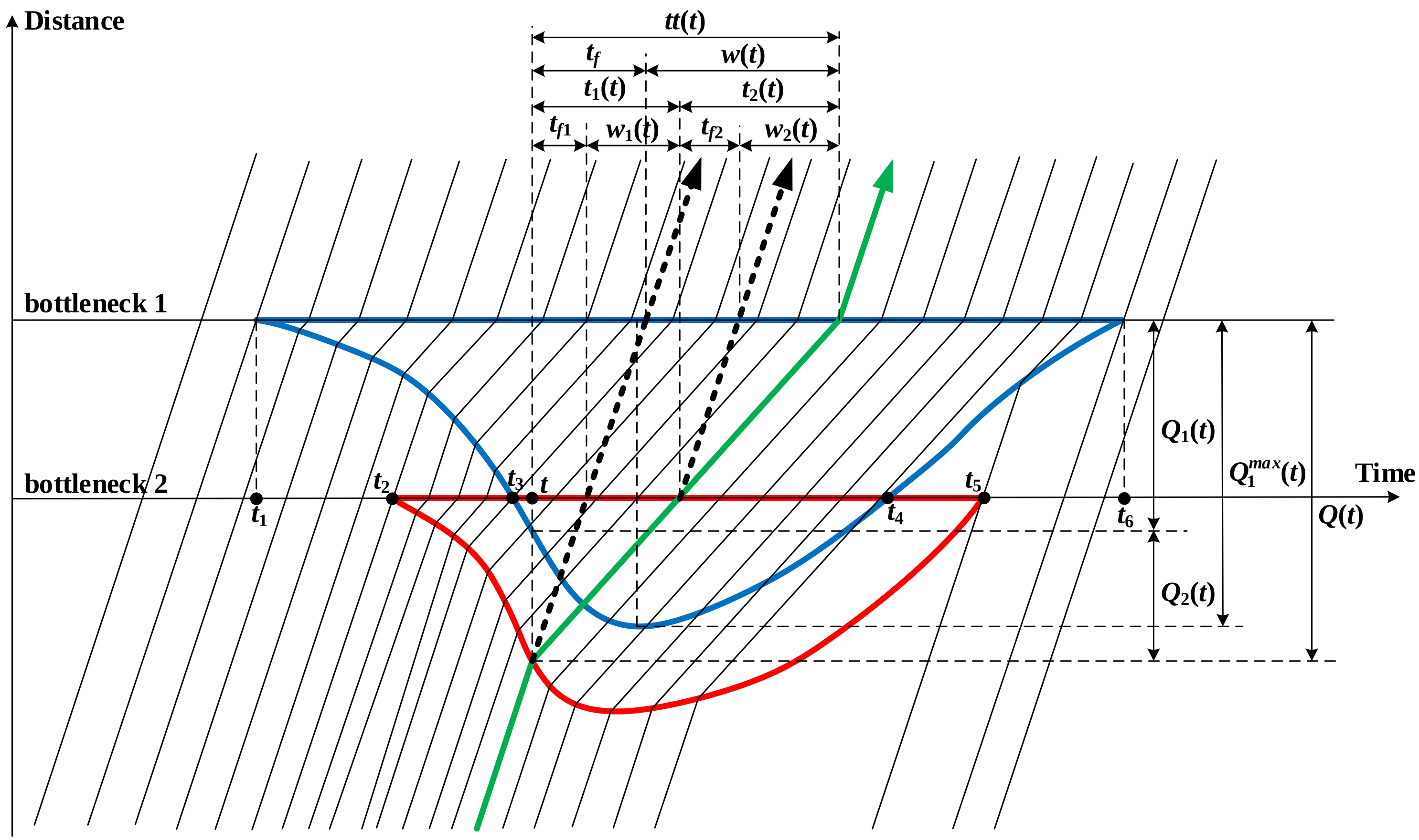


Illustration of the activity profile and queue profile in an oversaturated queueing system. Vehicle trajectories shown with blue colors are illustrated by the broken lines due to space limitation; however, they should be straight lines before they encounter with the back of the queue. It reveals that traffic demand of $\lambda(t)$ and the queue are the consequences of the travel activity upstream the bottleneck.

Discussion 2: Queue spillback



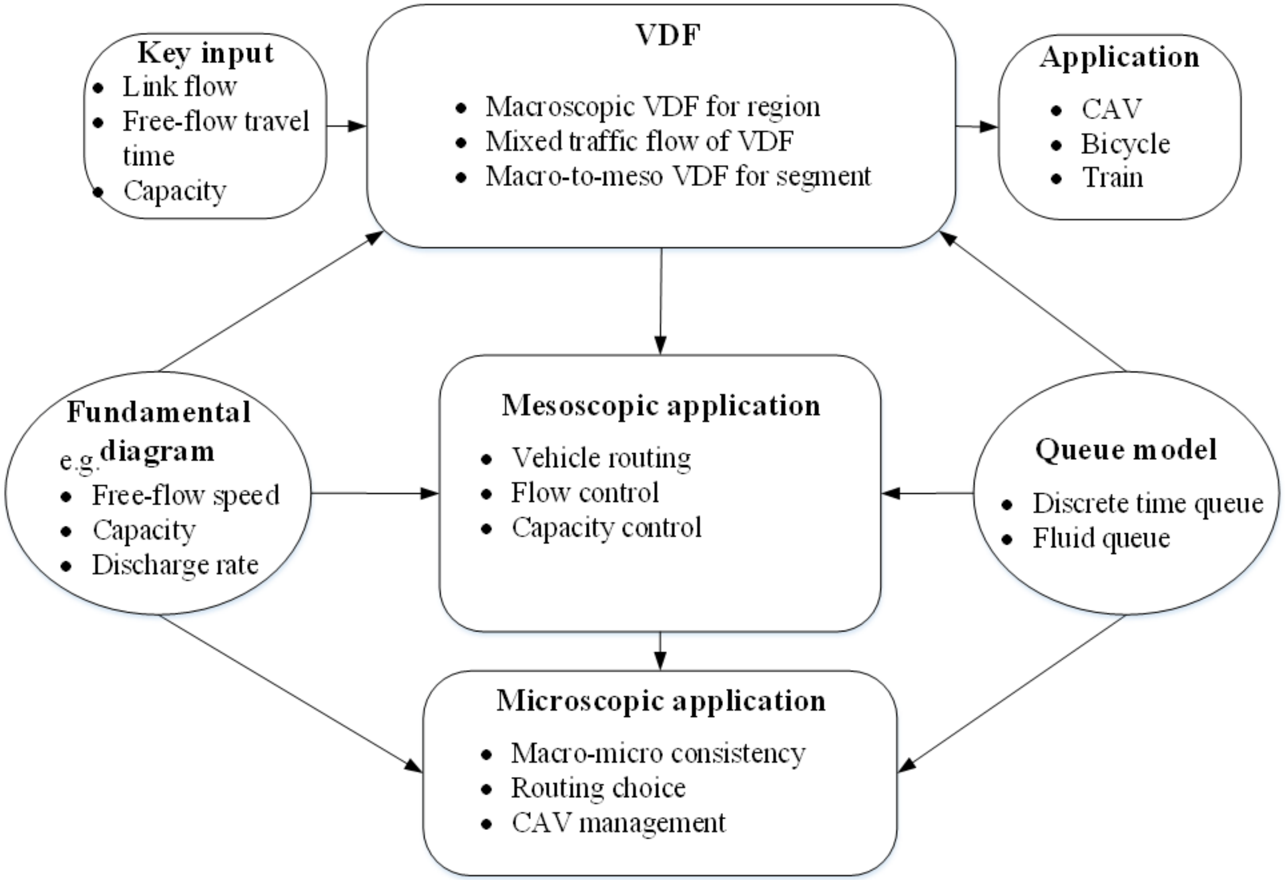
Queue VDF-related modeling for emerging technologies

Stakeholders	Micro	Meso	Macro
Autonomous vehicles (AVs)	• link kinematic wave to capacity • link car following to reaction time • traffic control	• control inflow rate • link capacity to discharge rate • queue evolution	• departure time choice • incoming flow rate shape and pattern
Mobility as a service (MaaS)	• choice pick up service time	• point to point travel time • time-dependent discharge rate	• control inflow rate curves • control departure rates curves
Public transportation and multimodal transit	• departure time choice	• generate time-varying travel time • travel distribution	• trip pattern • rush hour
Energy	• vehicle specific power (VSP)	• time-dependent speed profile	• link average speed from BPR to fluid approximation queue
Emissions and health	• control freeway ramp metering • arterial traffic signal coordination	• dynamic route shifts • traffic dynamics scheduling	• estimating the spatial distribution of travelers and mode shifts • trip patterns

Queue VDF-related modeling for multimodal systems

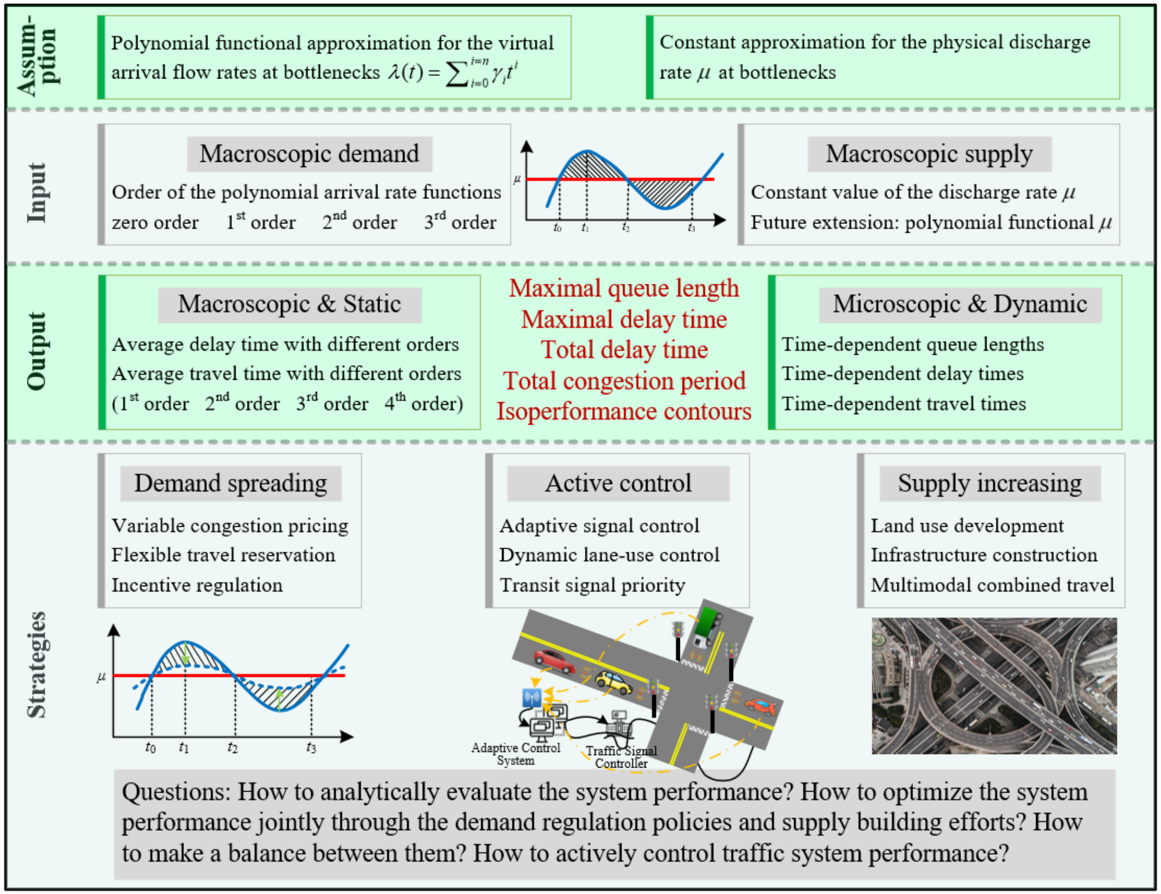
		Underlying Methodology			
Research Problems	Focus	Fundamental diagram	Queueing theory with a stochastic process	Point queues/bottleneck models	Cell transmission model, simplified KW
Multi-modal transportation (rail, air, truck)	Freight flexibility	✓	✓	✓	
	Railway capacity	✓	✓		
Public transportation	Bus accessibility	✓	✓	✓	✓
Bike	Congestion in a single path	✓	✓	✓	
Pedestrians	Bidirectional pedestrian streams	✓	✓		✓
MaaS	Ridesourcing shared transportation	✓	✓		
CAV	Mixed traffic flow	✓	✓		✓

Summary of today' talk



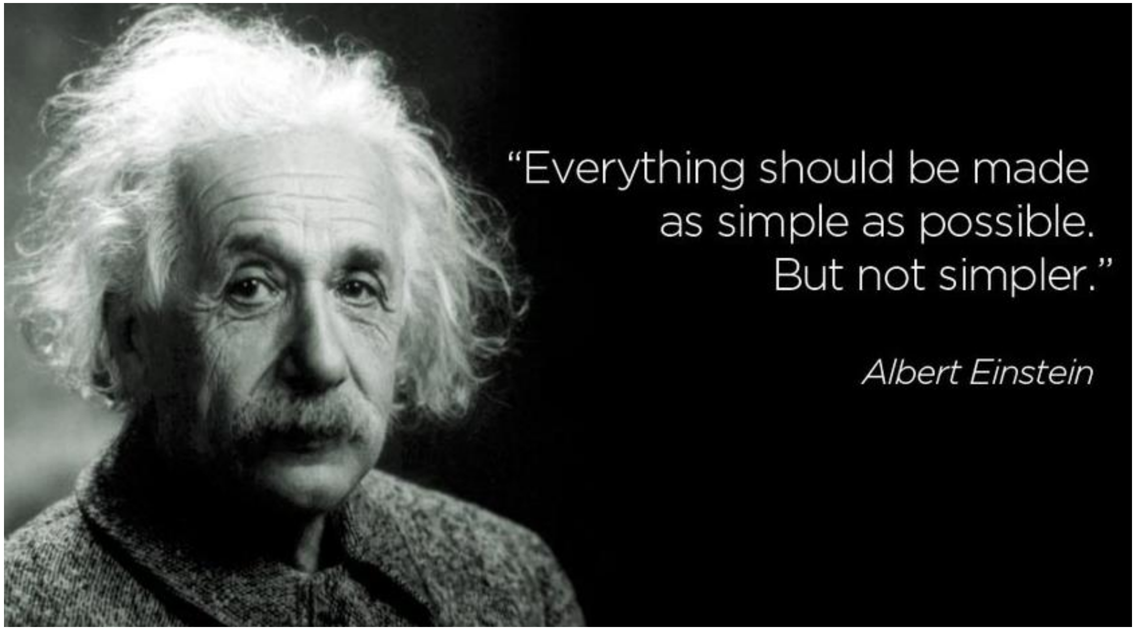
The primary purpose of applying VDF in emerging technology is to equilibrate assigned traffic volumes over the urban network by estimating the level of free-flow or congestion (i.e., delay) condition at the macroscopic, mesoscopic, or microscopic transportation network analysis level. The classification of research problems of VDF in the emerging application is shown in this figure.

Applications of Integrated demand-supply models



Concluding Remarks

- First principle: simple but not simpler;
- Simplify the complexity but still good enough.



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THANK YOU

https://github.com/asu-trans-ai-lab/