Automated Vehicle Modeling Rising Up with Digital Twin: Transforming the interconnection between open data, researchers and city planners

Jiawei (Jay) Lu (jiaweil9@asu.edu)
Xuesong (Simon) Zhou (xzhou74@asu.edu)
School of Sustainable Engineering and the Built Environment
ASU Trans+AI Lab
asu-trans-ai-lab (ASU Trans+AI Lab) (github.com)
Arizona State University

Prepared for 4th International Symposium on Multimodal Transportation (ISMT)

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Evolution of Digital Twins

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

Computer-driven Simulation (1985)

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

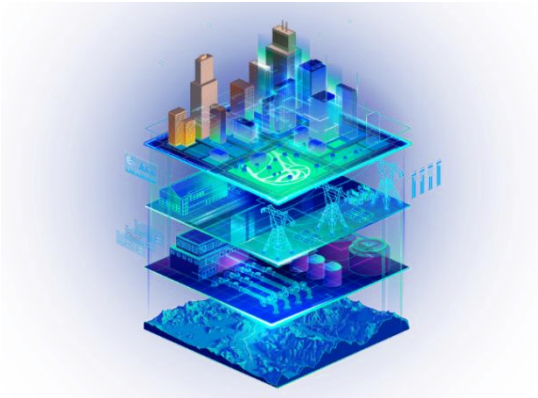
Simulation-driven System Design (2000)

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

Outline

1. Background on Digital Twins

2. Open-specification GMNS Modeling Community

3. Multiresoluion Modeling (MRM) Demonstration (Jay)

4. Analytical Models for Bridging Gaps in MRM

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 OEMS, 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.

Main Research Line

I. Open Data Specification and Open Source Tools

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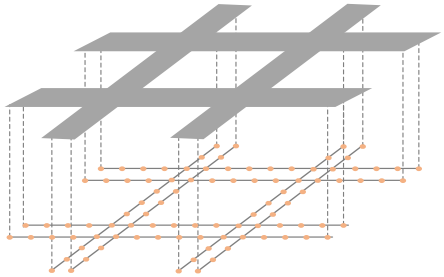
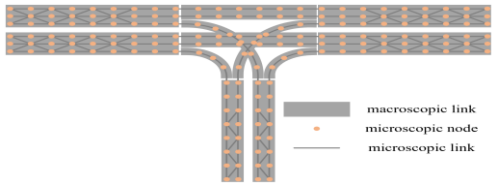
I. Open Data Specification and Open Source Tools

II. High-fidelity integrated CAV Simulation and Optimization

Macroscopic Layer



Microscopic Mesh Layer



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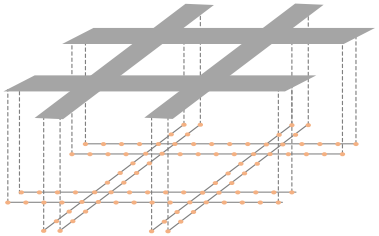
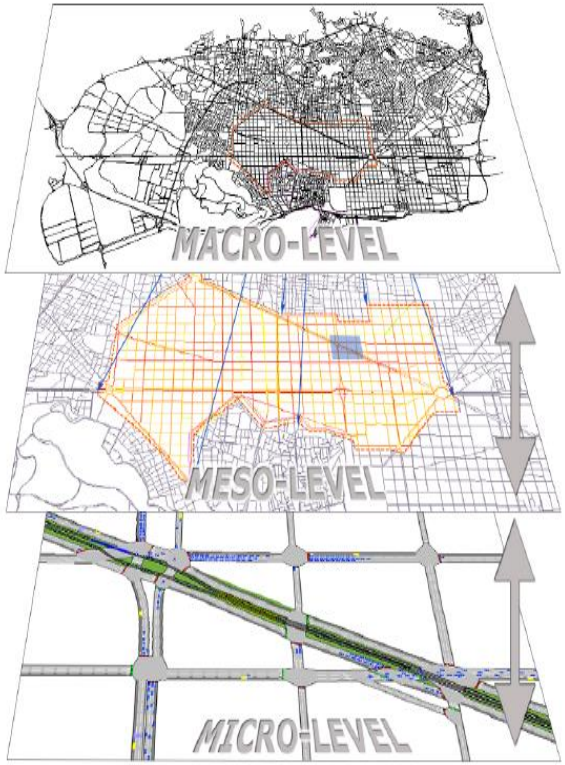


III. Internally consistent multi-resolution model for large scale system

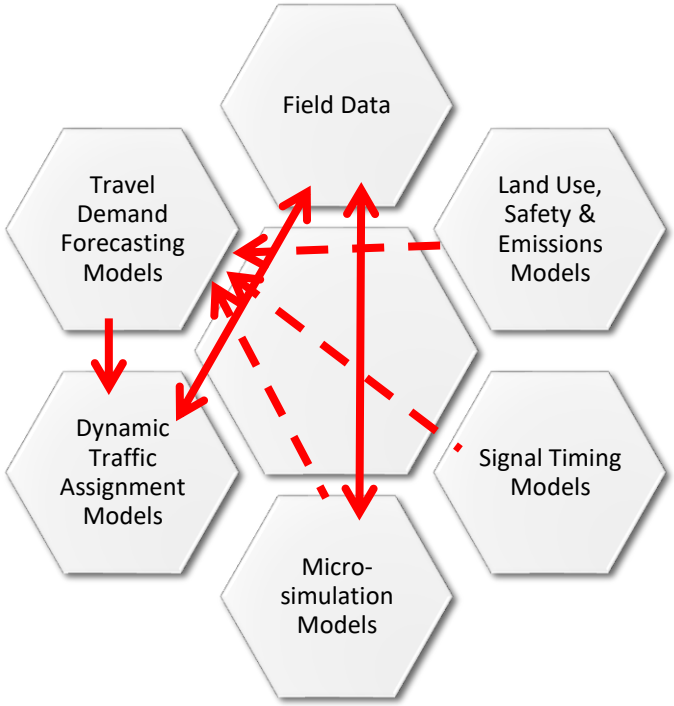


Critical Challenges for SCDT in Transportation Planning

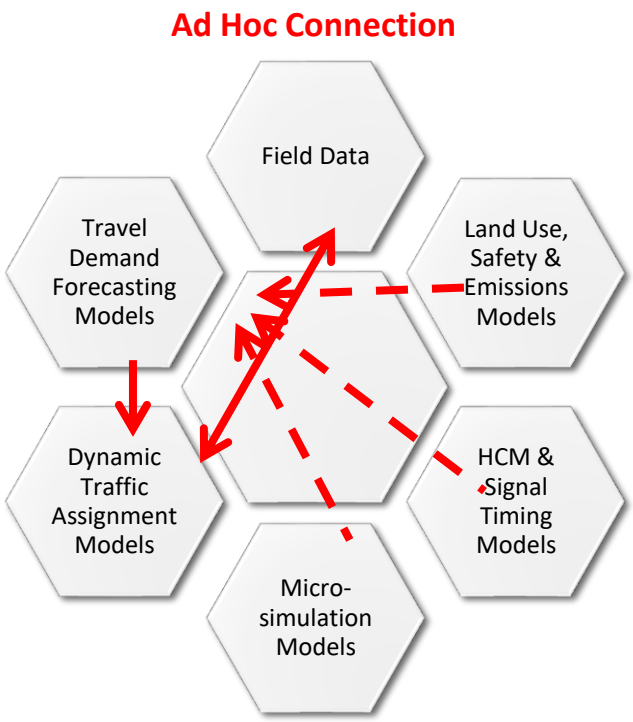
Digital Twin also presents significant challenges that must be addressed before achieving its full potential.

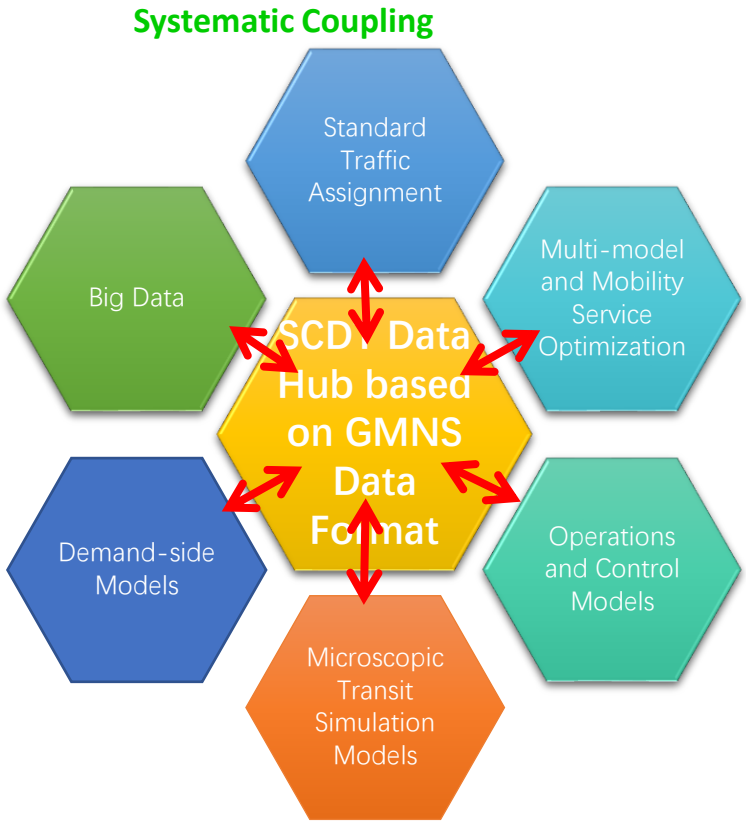
From **data integration** perspectives, there are three critical challenges for SCDT:

1. Digital at scale,
2. Decision intelligence in data-intensive systems,
3. Consistency between objectives, decisions, and execution



Critical Challenges for SCDT





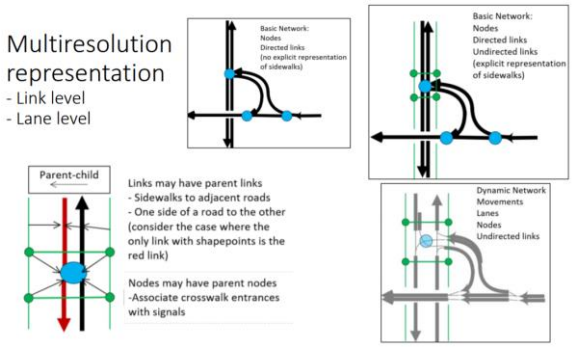
SCDT Data Hub for Transportation Planning Applications

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.

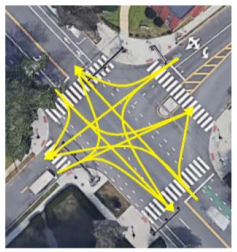
github.com/zephyr-data-specs/GMNS

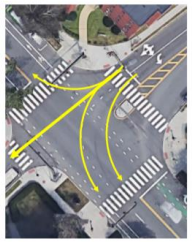


Source: Volpe Center GMNS team
Scott.Smith@dot.gov
Ian.Berg@dot.gov

Movements at an intersection

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





Permitted movements may also be time-of-day specific

Governance

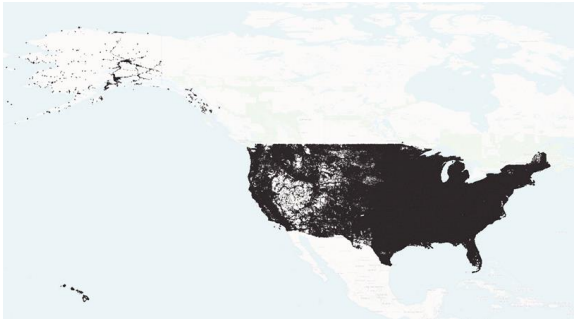
This project is overseen by a board-approved Project Management Group (PMG) as follows:

- 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

(a) 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/

osm2gmns

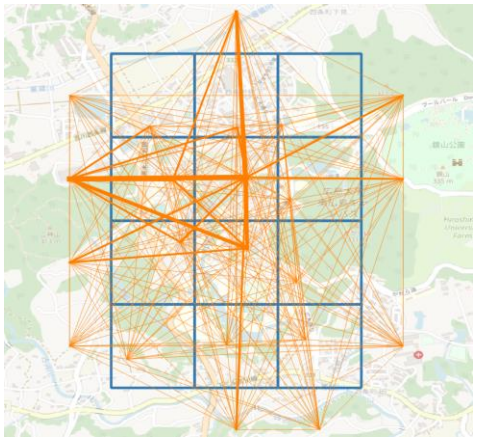
Summary

PyPI link	https://pypi.org/project/osm2gmns
Total downloads	16,445
Total downloads - 30 days	2,788
Total downloads - 7 days	387

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

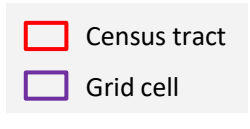
(b) Demand Generation: Grid2Demand

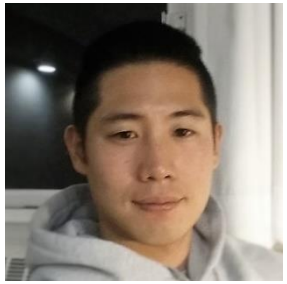
Grid zones can be automatically generated by a given number of grid cells or cell's width and height in meters.



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





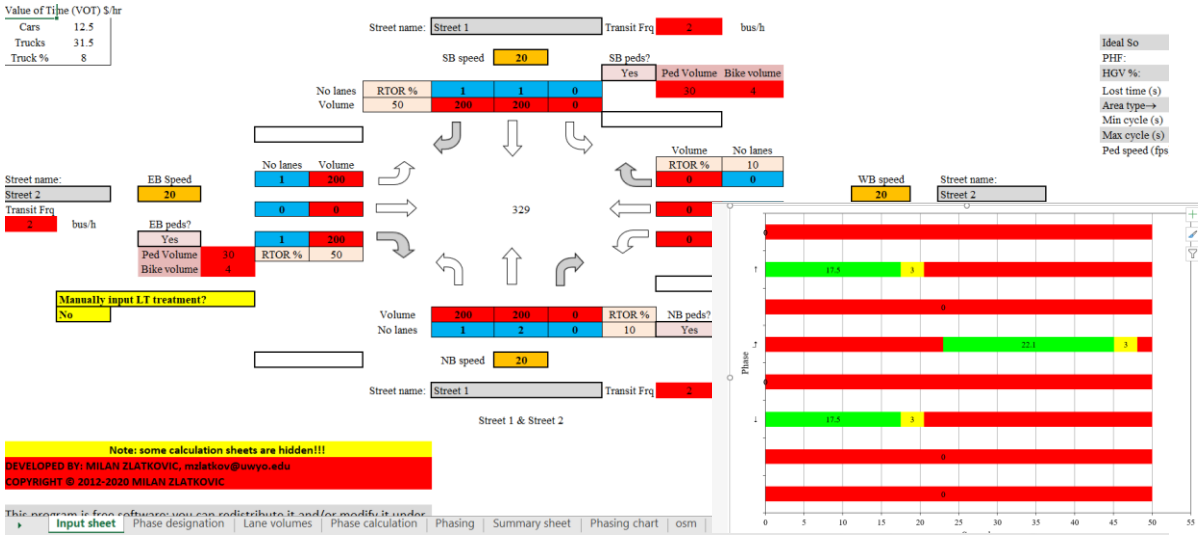
(c) Sigma-X: Excel-based computational engine for signalized intersections Vol2Timing as Python API

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

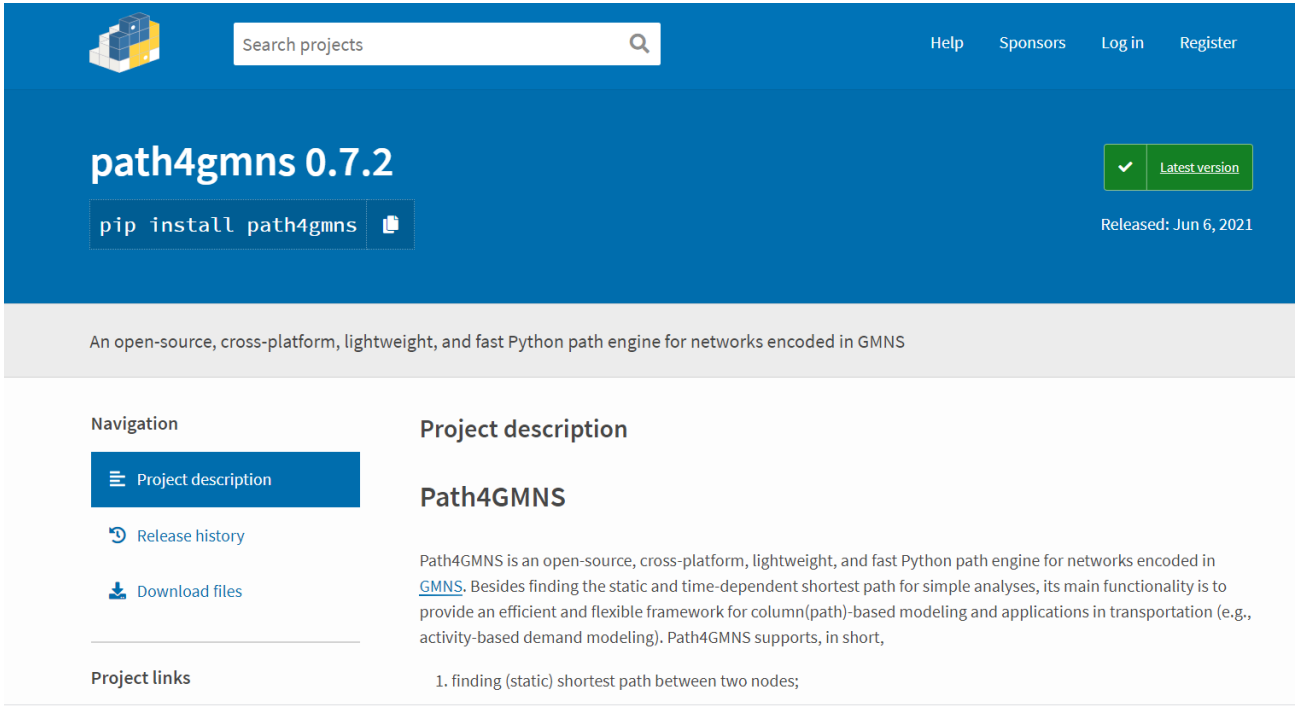
Excel->GMNS, Synchro UTDF -> GMNS

Contributor: Prof. Milan Zlatkovic

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



(d) Path4GMNS



Dr. Peiheng Li

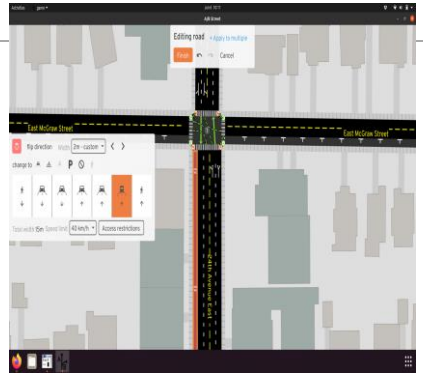
Operations Research Analyst at Norfolk Southern Corporation

ASU Graduate Ph.D. (2017)

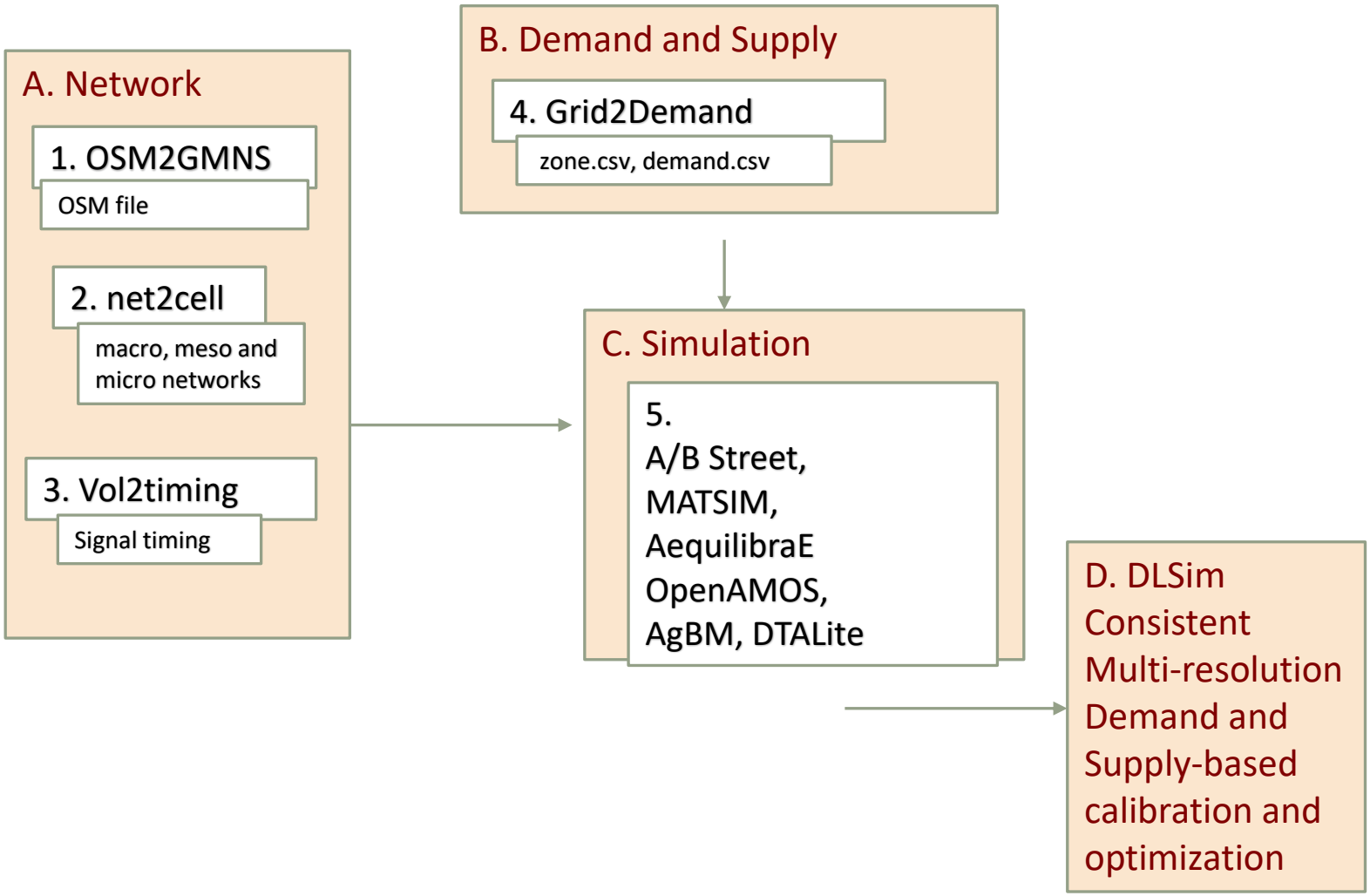
Smart Planning, Digital Twins, & Open Data

DUSTIN CARLINO, MICHAEL KIRK, & YUWEN LI

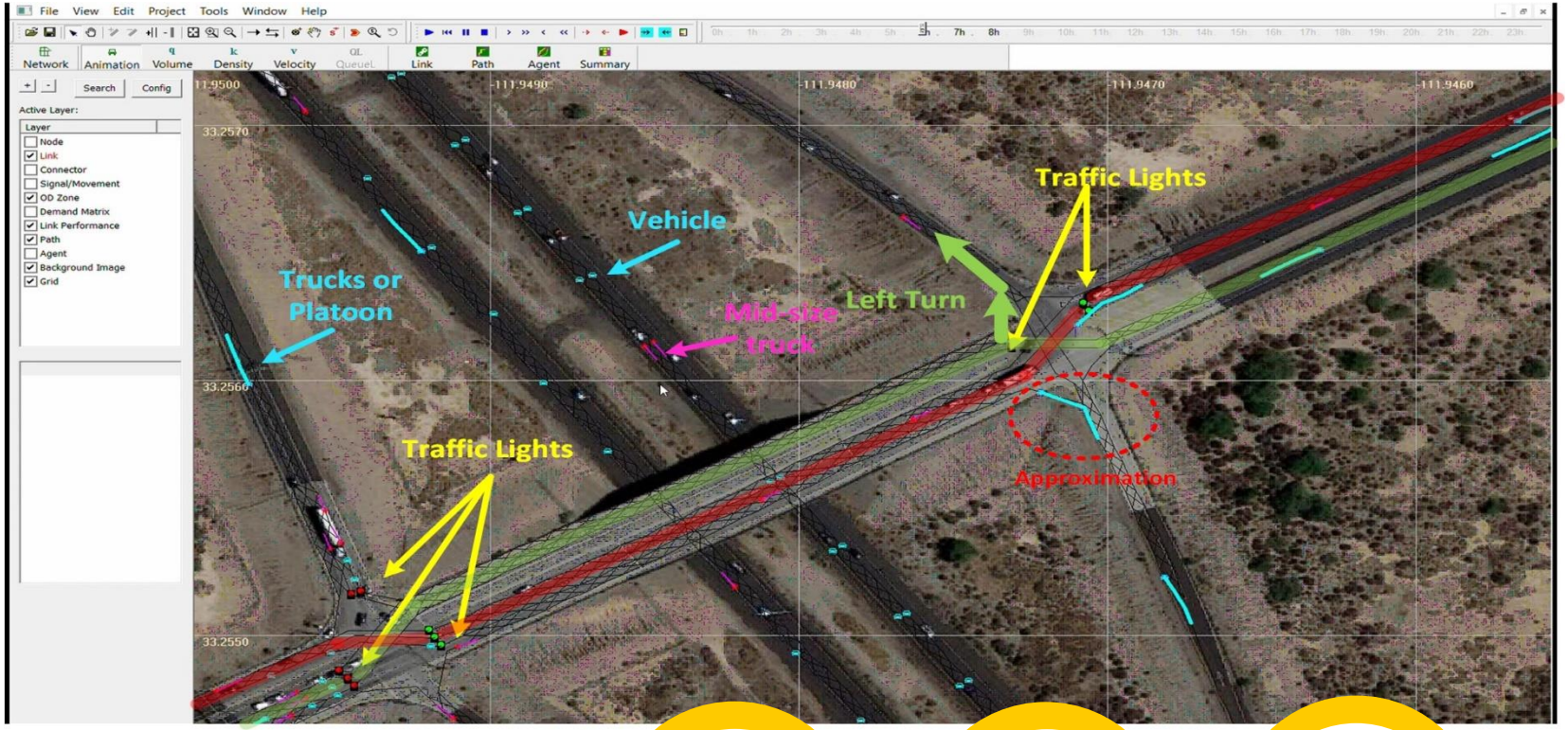
HTTPS://DOCS.GOOGLE.COM/PRESENTATION/D/1TT6OENTUH_Q-WPIC8AUX67HBOCPTJ7YWNKZN-X6NY8W/EDIT?USP=SHARING



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



DLSim: Deep Learning Based Traffic Simulation



Dr. Cafer Avci

Simulation Engine

Jiawei (Jay) Lu

Network Engine

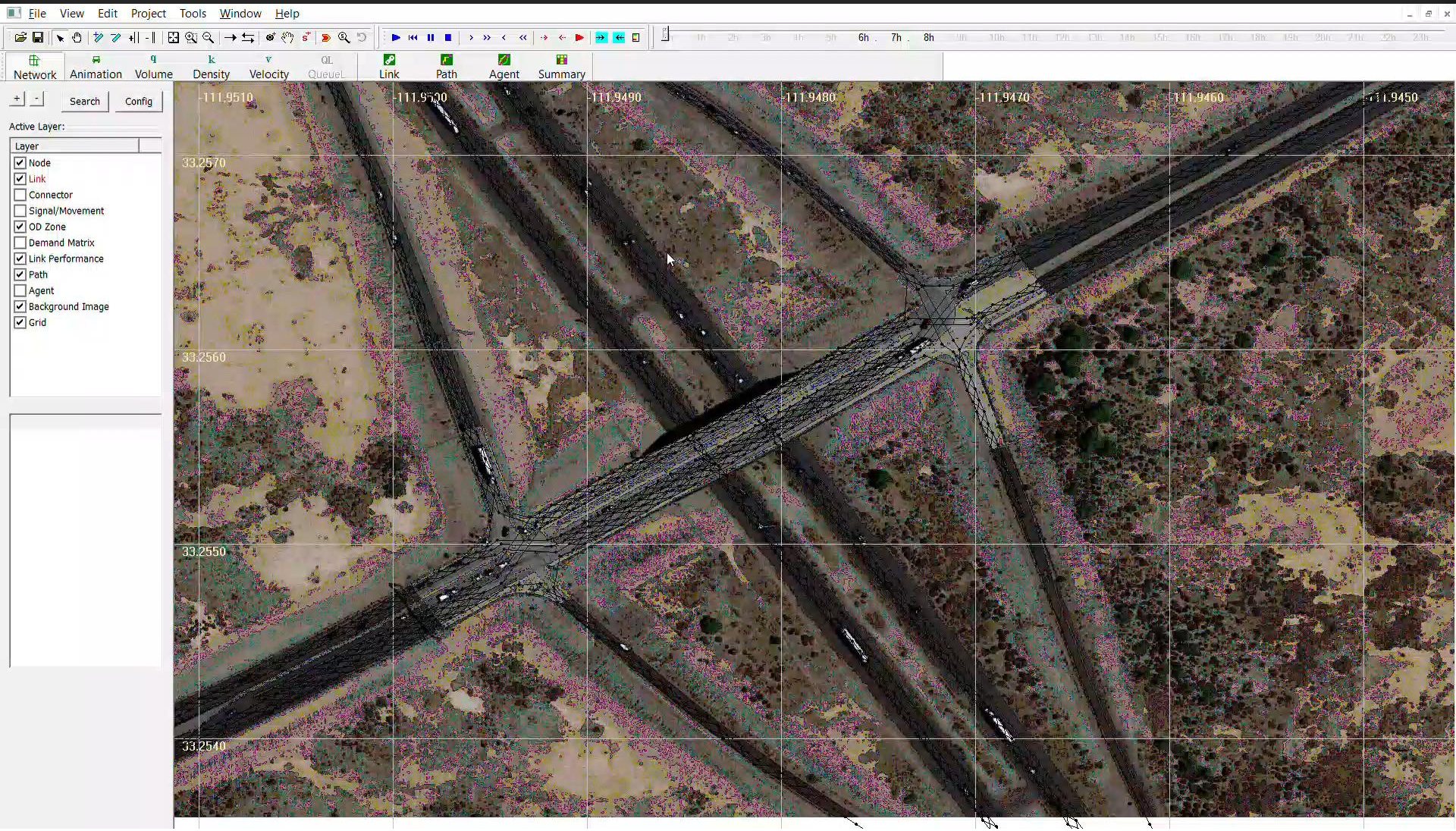
Dr. Peiheng Li

Path Engine

Dr. Xuesong (Simon) Zhou

Architect

DLSIM Sample Simulation of DDI



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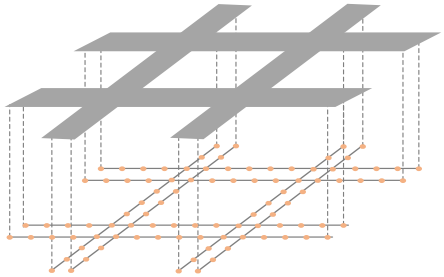
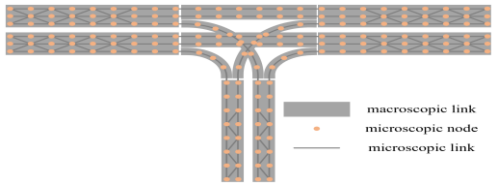
III. Internally consistent multi-resolution model for large scale system

Digital Twins for decision support

Macroscopic Layer



Microscopic Layer



Open-source MRM Tools

Obtain Macroscopic Networks (osm2gmns)

Total downloads: 26k

Build Multi-Resolution Networks (net2cell)

Total downloads: 2.8k

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https://github.com/jiawei92/OSM2GMNS
https://github.com/jiawei92/net2cell

Open-source MRM Tools: osm2gmns

Motivation

As discussed in the article by David Ory[1], a key feature of a travel model is an explicit representation of space.

OpenStreetMap has been a theoretically-appealing option for creating travel model base maps. Practically, however, OpenStreetMap has not been useful for at least the following reasons:

1. it is not routable,
2. the structure of its attributes are not aligned with travel models
3. the attribute data is not sufficiently complete.

The OSMnx package created by Geoff Boeing elegantly solves the first of these problems. OSM2GMNS aims to further address the second challenge using GMNS format.

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[1]https://medium.com/zephyrfoundation/osmnx-software-badge-3e206db65825

Open-source MRM Tools: osm2gmns

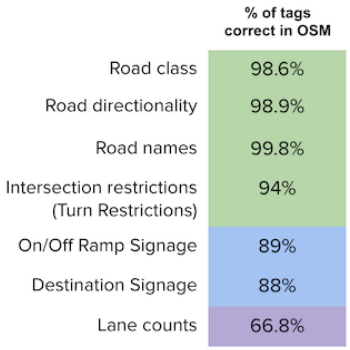
OpenStreetMap (OSM) is a free, open-source, editable map website that can provide free downloads. osm2gmns, as a data conversion tool, can directly convert the OSM map data to node and link network files in GMNS format. Users can convert and model drivable, walkable, railway, or aeroway networks with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

OpenStreet Map Server

Raw Network Data

Standard Network Data GMNS format[1]

Findings: High Map Accuracy across 30 Cities*



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

https://osm2gmns.readthedocs.io/

Open-source MRM Tools: osm2gmns

GMNS format

The General Modeling Network Specification (GMNS) defines a common human and machine readable format for sharing routable road network files. It is designed to be used in multi-modal static and dynamic transportation planning and operations models.

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

Open-source MRM Tools: osm2gmns

Comparison with the existing tools

	QuickOSM	OSMnx	osm2gmns
Routable	No	Yes	Yes
Multimodal network	Yes	Supports road network	Supports road, railway and aeroway networks
Transportation modeling		Network simplification	Network simplification; directed network; intersection consolidation; GMNS standard Point of interest (POI)
Network analysis	No	Yes	No

Open-source MRM Tools: osm2gmns

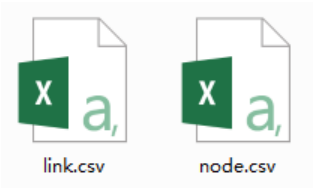
Some examples

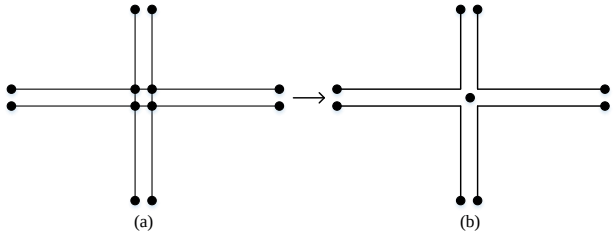
Download OSM data

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

Get a network in GMNS format

```
>>> import osm2gmns as og
>>> net = og.getNetFromOSMFile('asu.osm')
>>> og.outputNetToCSV(net)
```



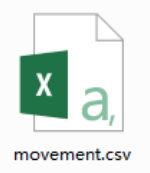


Consolidate Intersections

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

Generate movements at intersections

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



Network Types and POI

```
>>> net = og.getNetFromOSMFile('asu.osm', network_type=('auto','railway','aeroway'))

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

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

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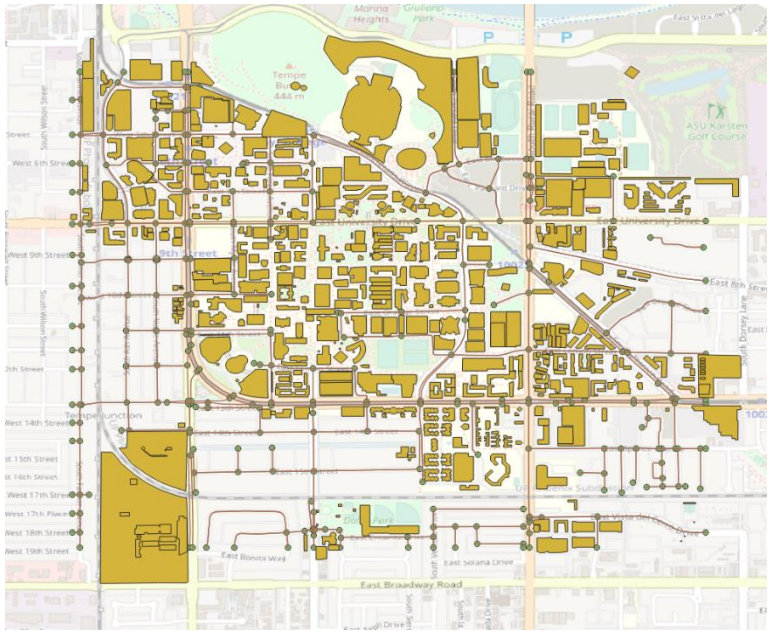
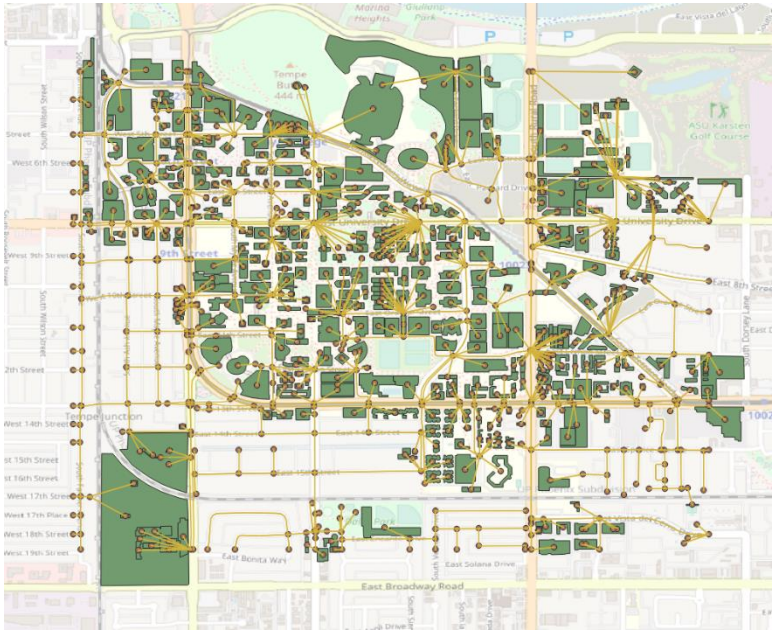
Open-source MRM Tools: osm2gmns

Some examples



Network with POIs



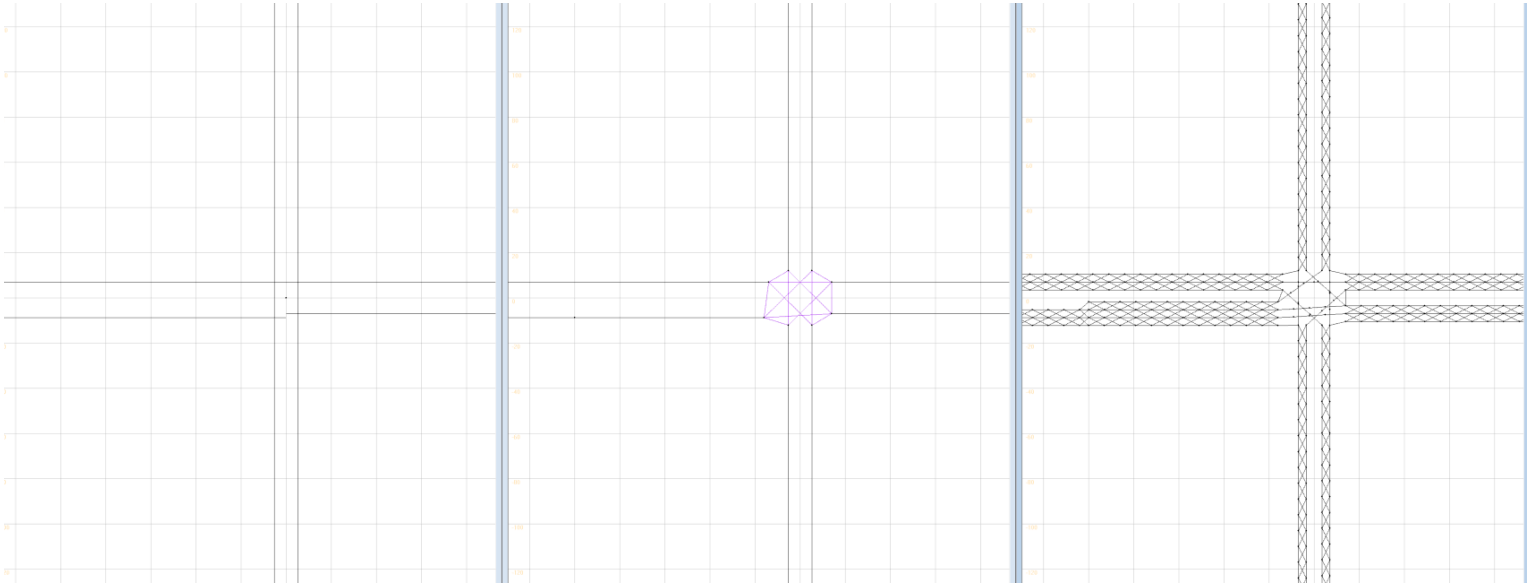
Connect POIs with network

More sample networks

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

Open-source MRM Tools: net2cell

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



Macroscopic Net

net2cell

Mesoscopic Net

net2cell

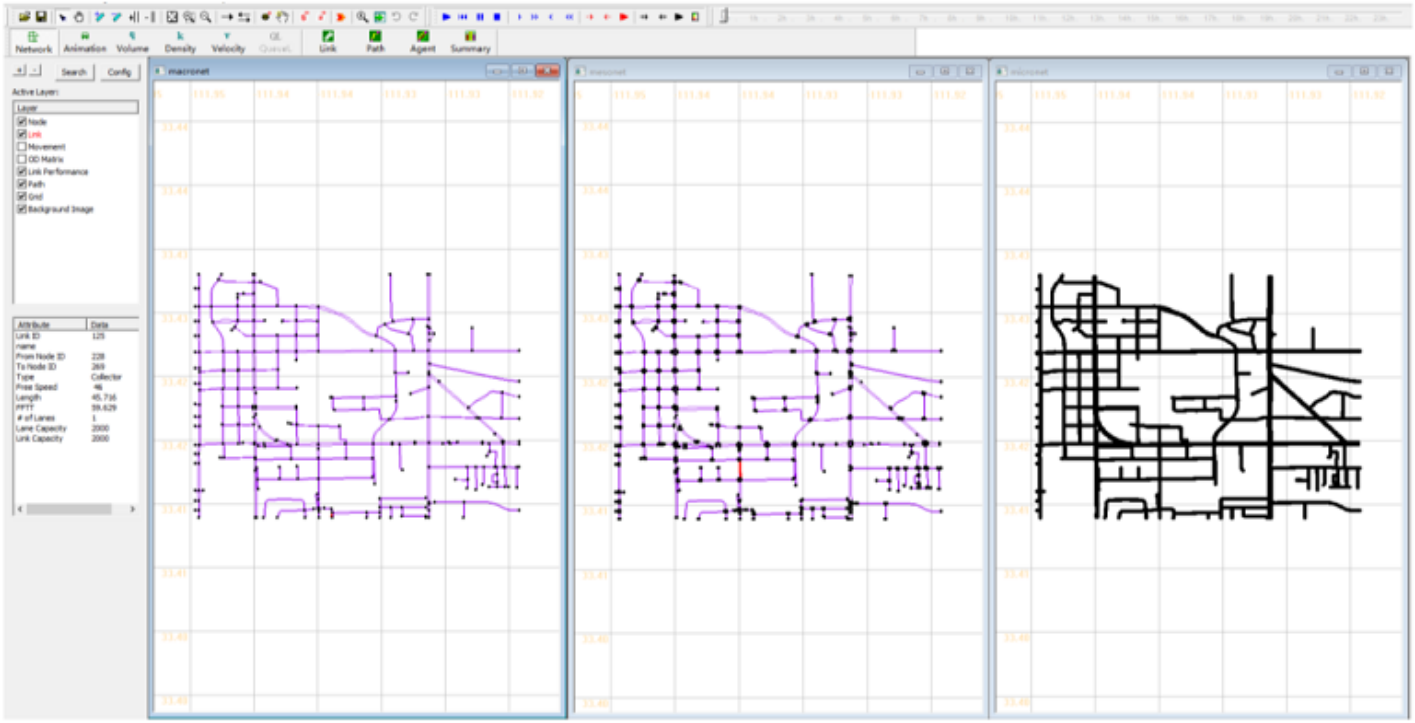
Microscopic Net

Open-source MRM Tools: net2cell

Example

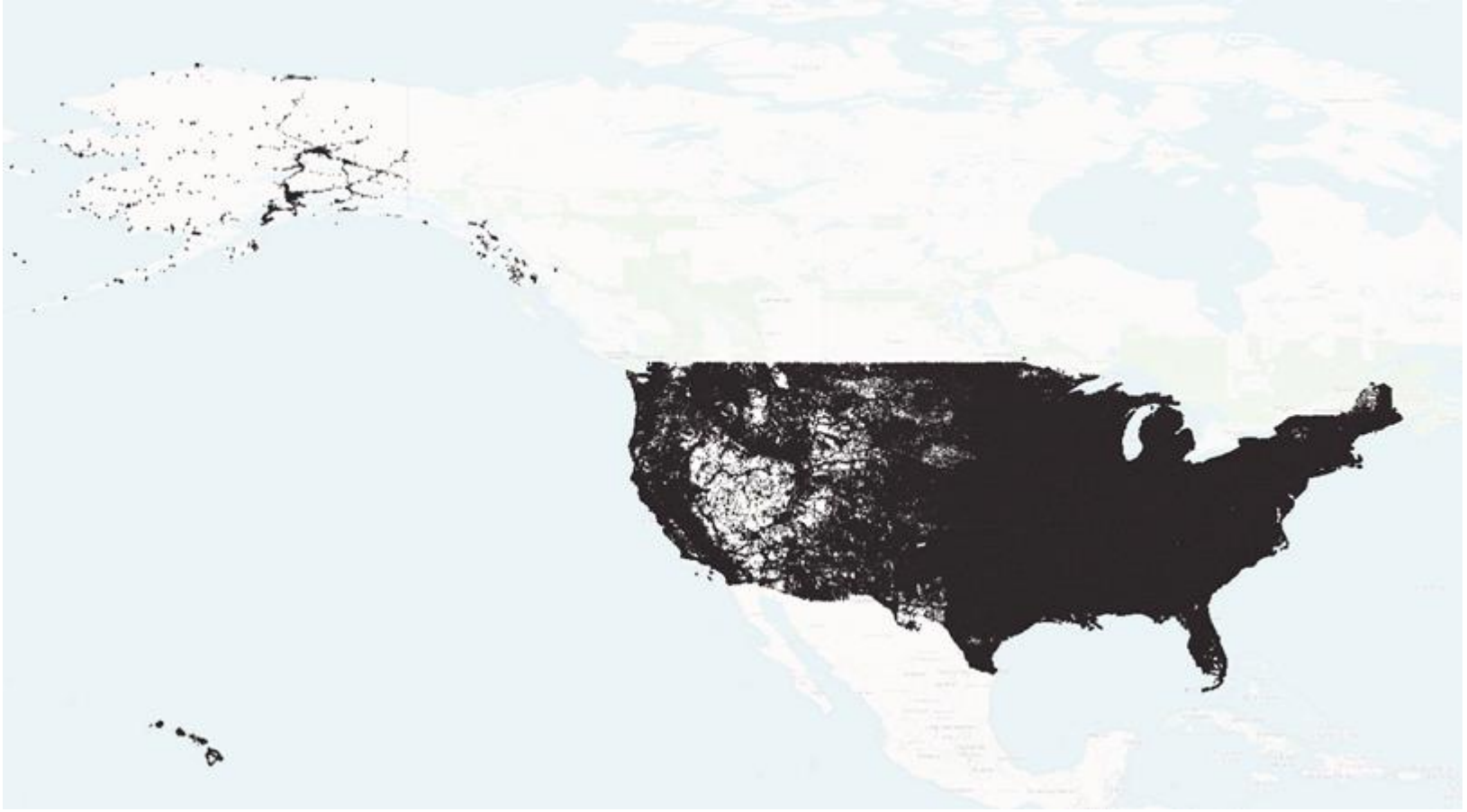
Get multi-resolution networks

```
>>> import net2cell as nc
>>> macro_net = nc.readMacroNet()
>>> nc.generateHybridNets(macro_net)
```



Visualization platform

https://asu-trans-ai-lab.github.io/website_openlayer_4GMNS/



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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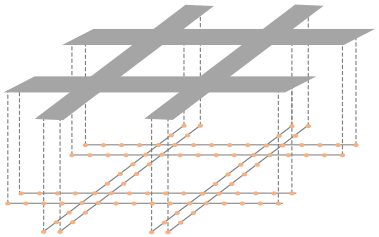
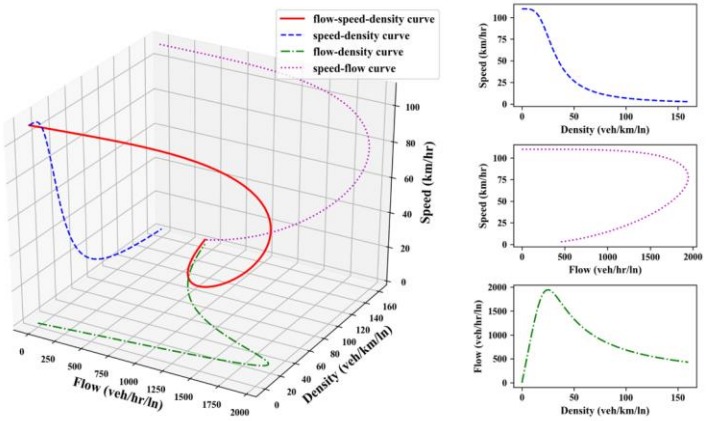
III. Internally consistent multi-resolution model for large scale system

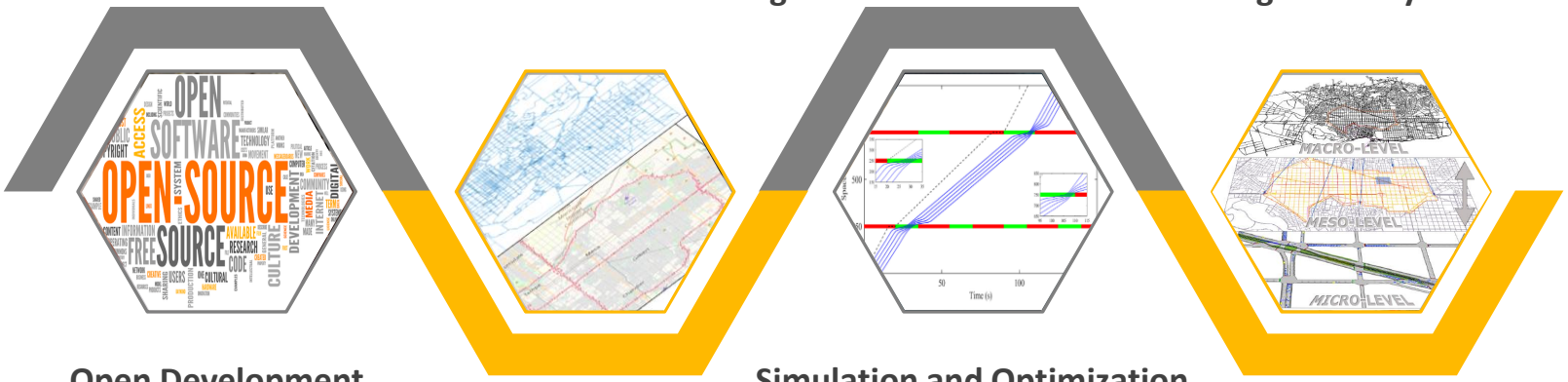
Digital Twins for decision support





In traffic flow theory, **micro** car-following models can be integrated to yield steady-state, average **macro** speed-density relationships.

Long-term Goal 1: Integrate Network, Demand and Supply Elements for SCDT



Macro-Meso-Micro simulation environment

Multi-resolution Modeling

Internally consistent multi-resolution model

Large-scale System

Open Development

Open Data Specification - GMNS
Open-Source Tools

Simulation and Optimization

High-fidelity integrated simulation and optimization

Deep Learning Based Traffic Simulation

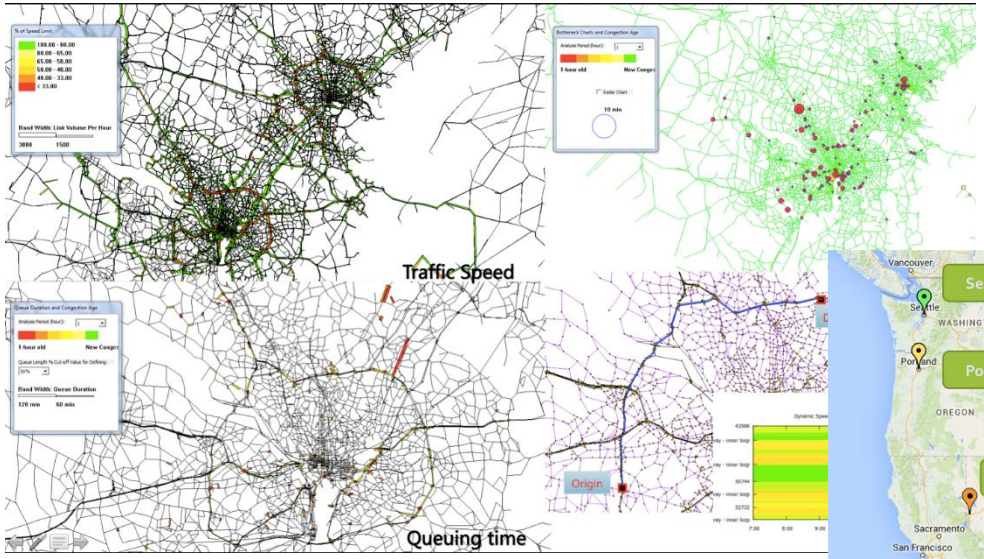
Long-term Goal 2: Decision Support using Digital Twins at Regional Scale

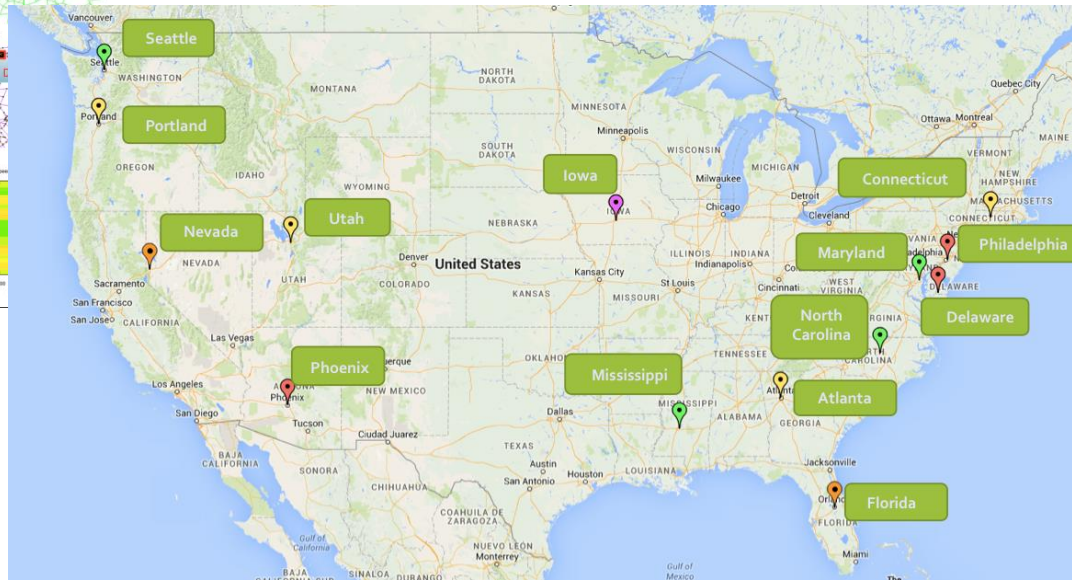
I. Open Data Specification and Open Source Tools

II. High-fidelity integrated CAV Simulation and Optimization

III. Internally consistent multi-resolution model for large scale system

Digital Twins for decision support

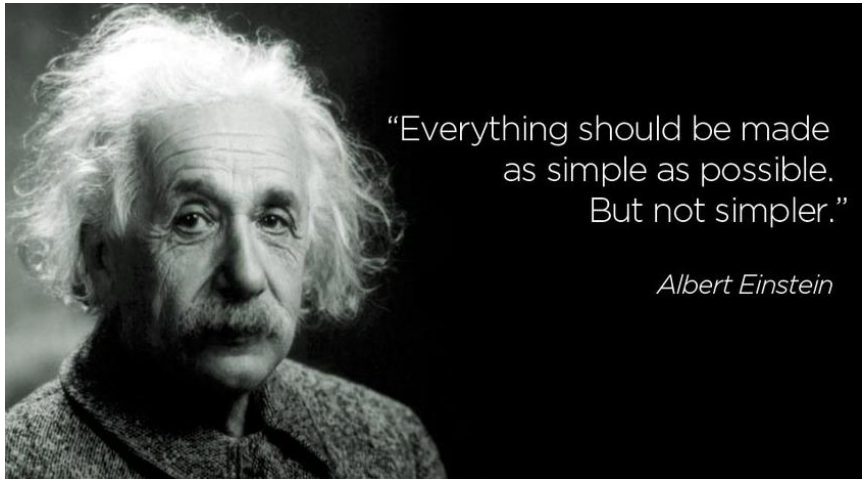




Our Research: DTALite Development and Application (2010- ongoing)

Complexity vs. Simplification

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



Example: Derivation of Consistent Macroscopic and microscopic relationship

Derivation of **consistent relationship** between the **third GM** microscopic **car-following** model and the **Greenberg** macroscopic model:

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha_0}{x_n(t) - x_{n+1}(t)} \left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right]$$

Integrating with respect to t yields

$$\dot{x}_{n+1} = \alpha_0 \left[\ln x_n - x_{n+1}\right] + C_1$$

If μ is substituted for $\dot{x}_{n+1}$ and $1/k$ is substituted for $x_n - x_{n+1}$, then

Greenberg $$\mu = \alpha_0 \ln\left(\frac{1}{k}\right) + C_1$$

Our proposed s-shaped three-parameter (S3) traffic stream model

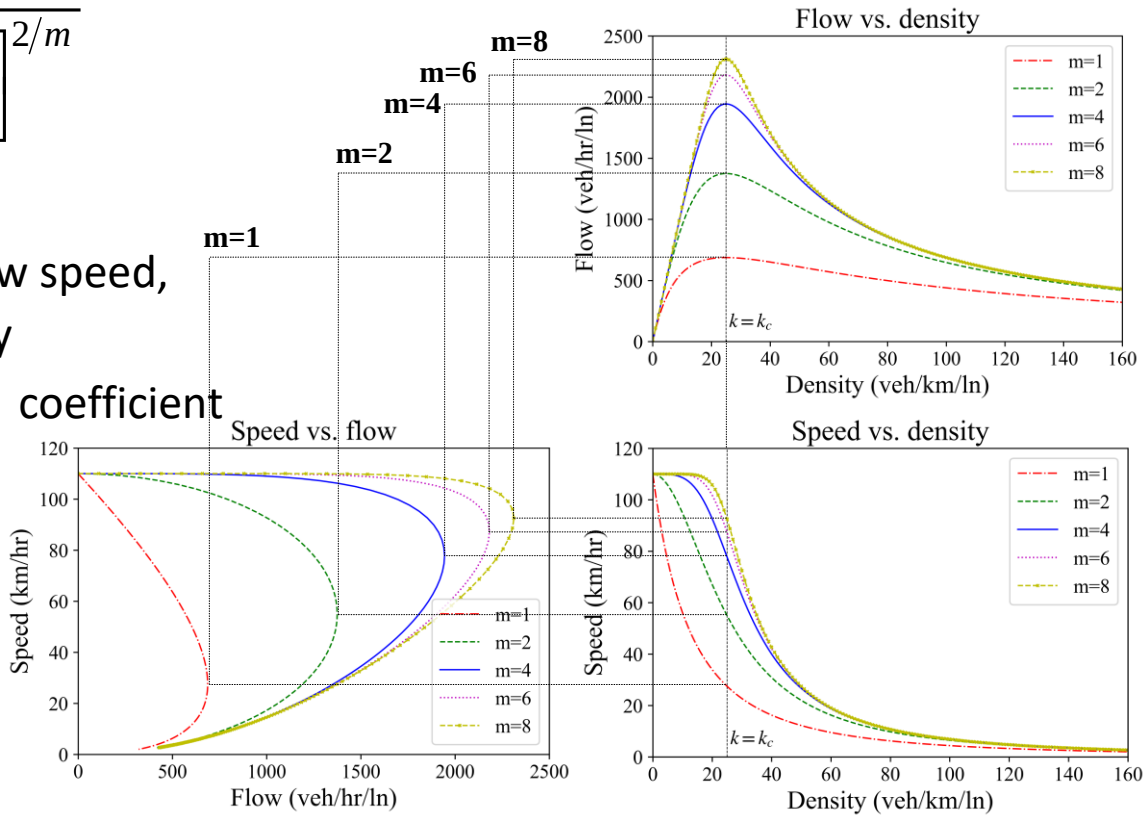
$$v = \frac{v_f}{\left[1+\left(k/k_c\right)^m\right]^{2/m}}$$

where v_f is the free flow speed,

k_c is the critical density

m=maximal flow inertial coefficient

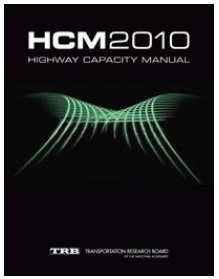
Projections to the 2D planes:



Key Building Block 2: Volume-delay function (VDF)

Typical volume-delay function

- Chicago Area Transportation Study (1963): $t(v) = t_0 \cdot 2^{v/c}$
- Smock (1963): $t(v) = t_0 \cdot e^{(v/c-1)}$
- BPR (1964): $t(v) = t_0 \cdot (1 + 0.15(v/c)^4)$
- Davidson (1966): $t(v) = t_0 \cdot \left(1 + \frac{Jv}{c - v}\right)$
- Spiess (1990): $t = t_0 \cdot \left[2 + \sqrt{\beta^2 \left(1 - \frac{v}{c}\right)^2 + \left(\frac{2\beta - 1}{2\beta - 2}\right)^2} - \beta\left(1 - \frac{v}{c}\right) - \frac{2\beta - 1}{2\beta - 2}\right], \beta > 1$
- Akcelik (1991): $t = t_0 + 0.25t_0 \cdot \left[\left(\frac{v}{c} - 1\right) + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{8J_A \cdot (v/c)}{ct_0}}\right]$



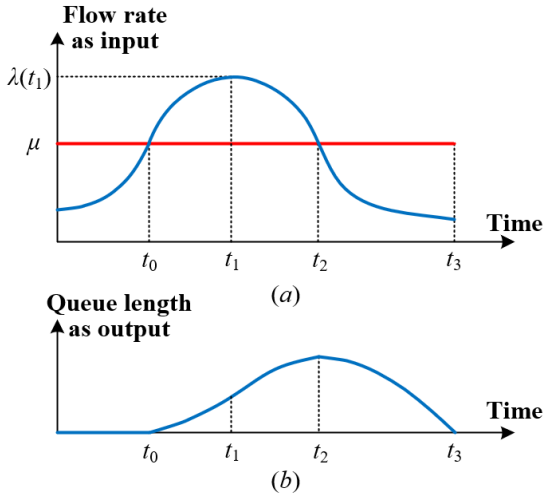
t_0: free flow travel time
v: traffic volume
c: capacity
J, JA, β: parameters

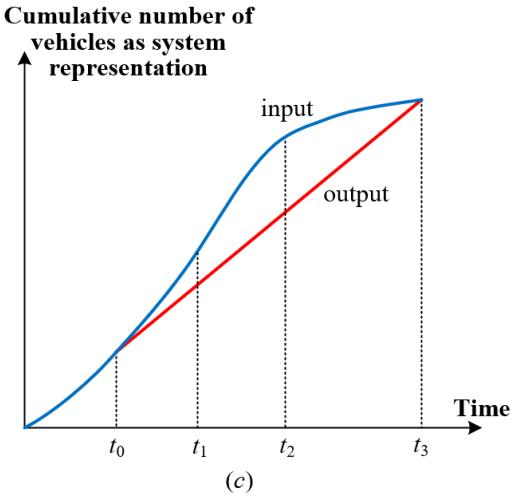
BPR-oriented Queue Approximation and DTA

Newell (1982)

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

$\lambda'(t_1) = 0$, $\lambda''(t_1) = -\rho$



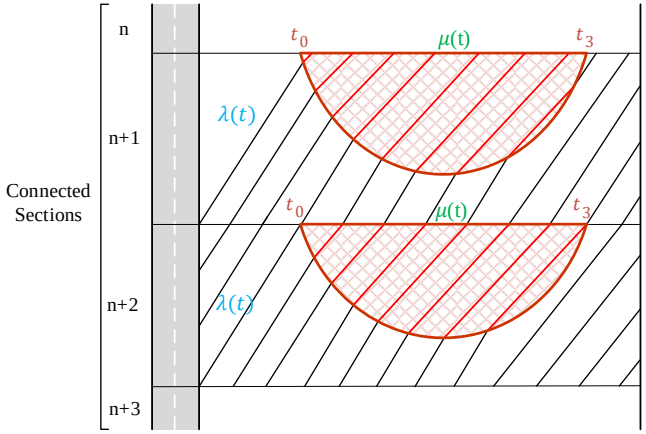


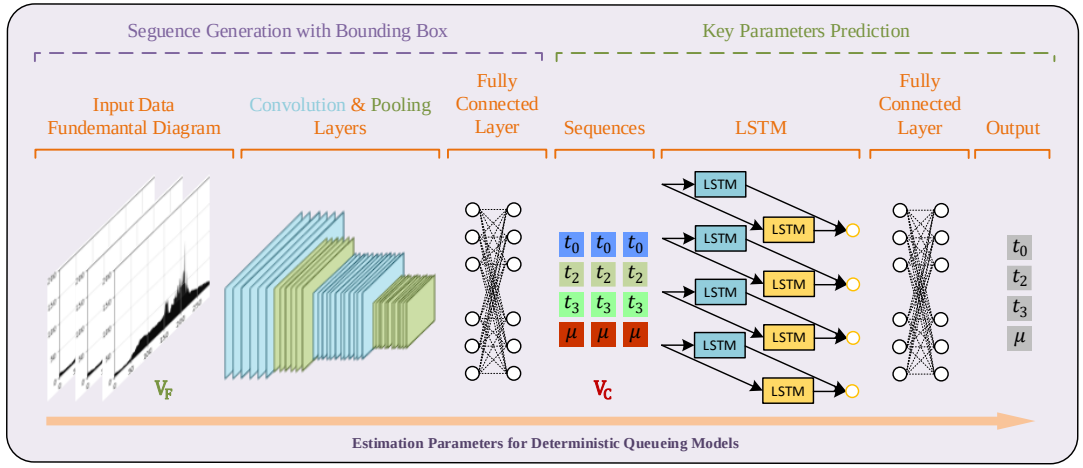
$\lambda(t)$: inflow rate at time t
t_0: start time of congestion period
t_1: time index with maximum inflow rate
t_2: time index with maximum queue length
t_3: end time of congestion period
μ: discharge rate (or capacity)

DLSIM: Fluid Queue based Approximation

Differentiable programming, computational graph

DLSIM uses deterministic queuing models to keep track of traffic entering and leaving each link, and we can make time-dependent estimation by using historical and instantaneous data.





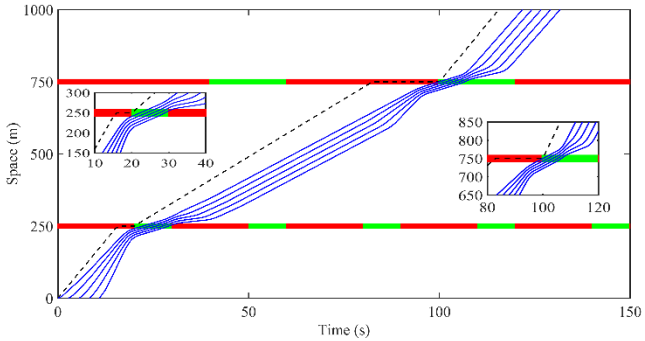
- Bottleneck control area
- $\lambda(t)$ Arrival rate
- $\mu(t)$ Discharge rate
- t_0 First time that the arrival rate exceeds the discharge rate
- t_3 Time that the congestion dissipates

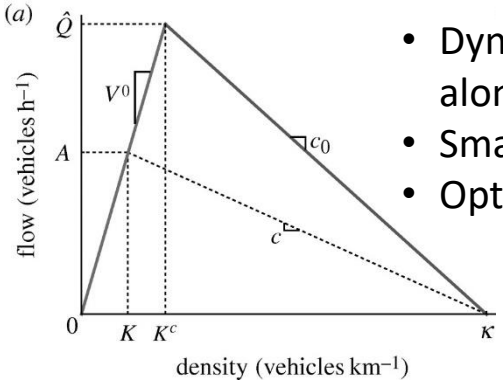
Assuming connected sections including congested areas, we can estimate the perfect departure rate and discharge rate within the determined t_0 and t_3 by using deterministic queuing models

DLSIM: Dynamic Headway Optimization

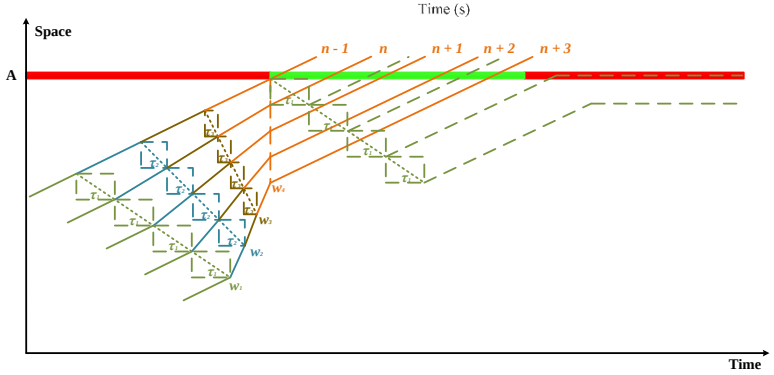
Space time network optimization

- With connectivity and automation features of self-driving cars, how much can road capacity be improved?
- How to optimize multi-vehicle trajectory to improve platoon level or system level traffic operation efficiency?

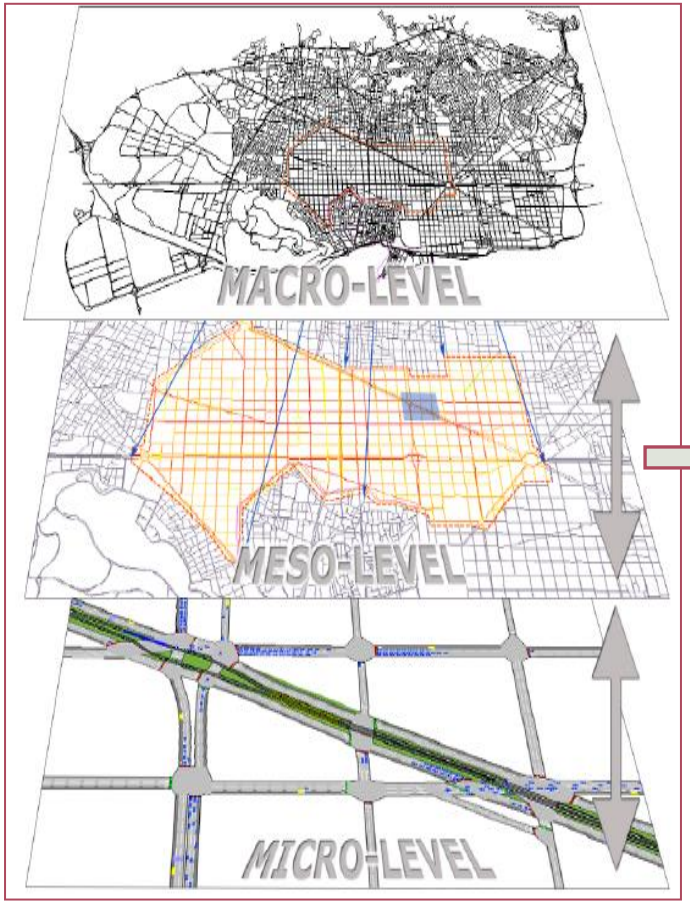


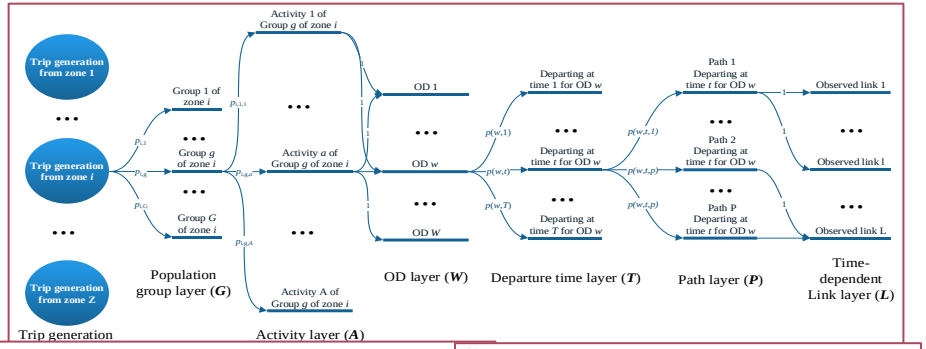


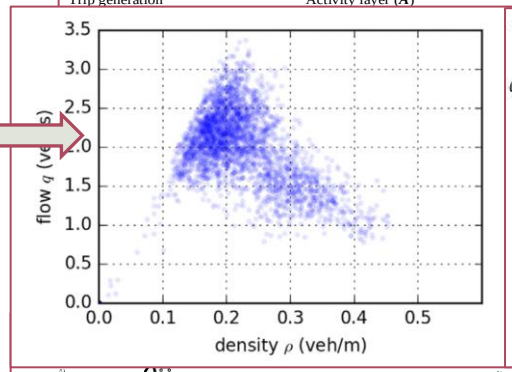
- Dynamic headway optimization along road network
- Smart bottleneck control
- Optimal trajectory

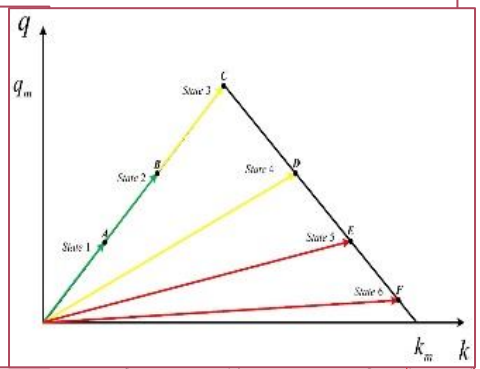


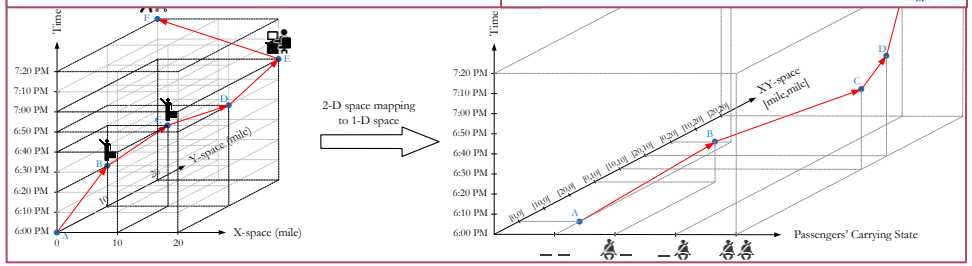
Wei, Y., Avcı, C., Liu, J., Belezamo, B., Aydın, N., Li, P. T., & Zhou, X. (2017).
Dynamic programming-based multi-vehicle longitudinal trajectory optimization with simplified car following models.
Transportation Research Part B: Methodological, 106, 102-129.


MACRO-LEVEL
MESO-LEVEL
MICRO-LEVEL


Trip generation from zone 1
Trip generation from zone i
Trip generation from zone Z
Group 1 of zone i
Group g of zone i
Group G of zone i
Activity 1 of Group g of zone i
Activity a of Group g of zone i
Activity A of Group g of zone i
OD 1
OD w
OD W
Departing at time 1 for OD w
Departing at time t for OD w
Departing at time T for OD w
Path 1 Departing at time t for OD w
Path 2 Departing at time t for OD w
Path P Departing at time t for OD w
Observed link 1
Observed link l
Observed link L
Population group layer (G)
Activity layer (A)
OD layer (W)
Departure time layer (T)
Path layer (P)
Time-dependent Link layer (L)
Trip generation


flow q (veh/s)
density ρ (veh/m)


q
q_m
State 1
State 2
State 3
State 4
State 5
State 6
k_m
k


Time
X-space (mile)
2-D space mapping to 1-D space
XY-space (mile,mile)
Passengers' Carrying State

THANK YOU

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