Prof. S. Travis Waller, PhD, FIEAust

Rapid Traffic Modelling with AI and Big Data Methods: Network Performance and Carbon Sensitivity

Acknowledging the Teams for the Past Open Published Research

2003 - 2011 (Univ. of Texas at Austin)

2011 - 2022 (UNSW, Sydney)

Current research ongoing at TU Dresden, UNSW and the ANU.

So many amazing collaborators to acknowledge:

43 Completed and 9 Current/Finishing PhD Students

100+ Postdocs, Undergrads, MS, Colleagues

More than 40 funding sponsors including

U.S. NSF, ARC, U.S. FHWA, U.S. DOT, TfNSW, Advisian, GoGet Carshare in addition to many other government agencies, software companies, infrastructure firms, advisory firms, banks, insurance companies, startups, etc.

Acknowledging Mobility Thinking Pty Ltd (MOTH)

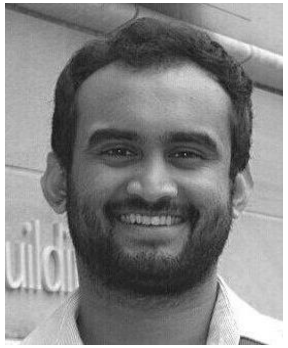
Professor S. Travis Waller
(Managing Director)

Victor Prados-Valerio
(Creative Partner)

Dr. Melissa Duell
(Associate Creative Director)

Dr. David Ashmore
(Creative Partner - MOTH Europe)

Dr. Cecilia da Rocha
(Creative Director)



Dr. Kasun Wijayaratna
(Creative Partner)

Some methods transitioned from university for commercialization

MOTH established in 2018 in Australia

Primary provider for rapid planning services

Our two core pillars of research and development

Emerging **Technologies**

Automation | Connectivity
Applied AI | Infrastructure Digitisation
Blockchain | Digital Twin

Evolving **Social Consciousness**

Result in new ***behaviour***, ***tools*** and ***solutions***

We need **models** and **simulations** that can represent all of these **changes** to inform future planning and management of transport solutions for mobility

Today: Background/State of the Art, Automated Planning and Digitising Social Values (ethical metrics)

Theoretical, but also practical

Thanks to 40+ industry/government sponsors (incl.):

Australia Research Council ($2.3m+) incl.
"Quantifying Ethics-Related Metrics for Transport Networks Systems"
"Understanding Impact of Autonomous Vehicles on Behaviour and Interactions"

U.S. National Science Foundation ($1m+) incl.
Industry-University Cooperative Research Center
"Transportation and Electricity Convergence"

U.S. Federal Highway Administration($1.8m) incl.
"Intersection Control for Autonomous Vehicles Transport for NSW"

Transport for New South Wales ($1.5m) incl.
"A Partnership to Develop and Deploy Novel Integrated Network Techniques to Enhance the NSW Transport System"

Background and Earlier Work

On Faculty at UT-Austin until 2011
- From Assistant Professor to Full Professor

Relocated to UNSW in 2011
- Took up the Evans & Peck Chair of Transport Innovation
- Founding Director of Research Centre for Transport Innovation (rCITI)
- Head of School of Civil and Environmental Engineering
- Deputy-Dean of Faculty of Engineering

Relocated to the Technische Universität Dresden in 2022
- Lighthouse Professor and Chair of Transport Modeling and Simulation
- Simultaneous (part-time) Professorship at the Australian National university

Scientific <u>Representation</u> of Models
Underlying mathematical definitions, often of behavior

Opens up new questions from model explanatory capability

Model and Simulation Computational <u>Performance</u>
Faster, bigger models (across macro/micro/meso)

Opens up new questions from scale

Interdisciplinary <u>Scope</u> of Model
What does the model attempt to explain

Opens up new questions into non-traditional fields

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When I arrived to Sydney in 2011, I provided the first of many talks and collaborations with Evans & Peck/Advisian

My very first talk in 2011, covered the subsequent topics
- Displaying the actual slides used back in 2011

1. Electric Vehicles

Very early research in the area of

Studying the future behavior of travelers with the emerging reality of electric vehicles

Our work began on this topic in 2007

Collaborative with Prof. Mladen Kezunovic (Chair in Electrical Engineering, NAE Member)

The NSF Center continued following my relocation

Additional projects and research contributions made over the subsequent years

Center for Transportation and Electricity Convergence

- Awarded August, 2010
  - UT-Austin lead with Texas A&M
    - Additional universities and agencies/companies planning to join
  - National Science Foundation Industry and University Cooperative Research Center (NSF IUCRC)
  - Renewable up to 15+ years, approx. $7.5M+
- Industry/agency members include:

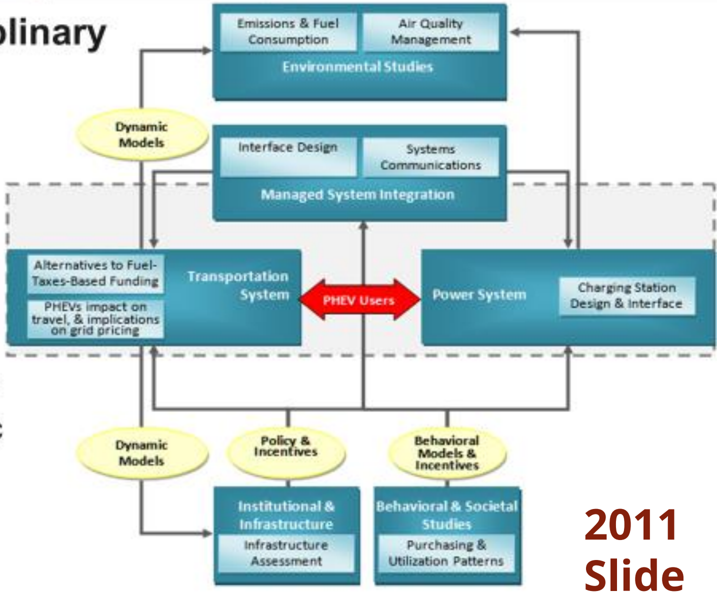
Texas DOT	City of Austin
Innov8 Inc.	NRG Energy
CenterPoint Energy	City of Houston
Texas Transportation Institute	
North Central Texas Council of Governments	

2011 Slide

Research Overview

- **Multi-disciplinary**

Transport
Electrical Engineering
Sustainability
Built environment
Business development
Socio-economic
Policy
Behavioral



2011 Slide

2. Environmental Justice Across Protected Groups

One of the early quantifications of EJ for Transport Network Planning in the literature (2008)

With my former PhD student, Dr. Jen Duthie (now head of Innovation for Cintra)

The primary research paper on the work won the U.S. Transportation Research Board Fred Burggraf Award

TRB is a division of the US National Academy of Science, Engineering and Medicine

While the work was mathematical in nature, it was also highly practical for usage

Environmental Justice, Emissions, Sustainability and Uncertainty

- Quantifiable engineering tools for properly accounting for
  - Environmental justice considerations
  - Optimizing network improvements for emission reduction
  - Sustainable planning accounting for uncertainty
- Sponsors

  North Central Texas Council of Governments (Dallas MPO)

  Southwestern University Transportation Center

  National Science Foundation

  FHWA

2011 Slide

Definitions difficult. One EJ variation is: ***Avoid disproportionality and maintain/improve access for protected groups***

EJ-UE-DNDP

$$\min_{g\in\{0,1\}} Z(v^*(g), g) \quad (1)$$

$$s.t. \sum_{l\in I} g_l = \theta \quad (2)$$

← total # of improvements

$$v^*(g) = \arg\min_{v} \sum_{l\in L} \int_{x=0}^{v_l} t_l(x)dx \quad (3)$$

$$s.t.\ v = Ah \quad (4)$$

$$d = Bh \quad (5)$$

$$v \geq 0 \quad (6)$$

$$t_l(v_l, g_l) = t_l(0)\times\left(1+\alpha\left(\frac{v_l}{u_l+g_l\gamma}\right)^{\beta}\right), \quad \forall l\in I \quad (7)$$

$$t_l(v_l) = t_l(0)\times\left(1+\alpha\left(\frac{v_l}{u_l}\right)^{\beta}\right), \quad \forall l\in L\setminus I \quad (8)$$

$$d = d^{P_1}+d^{P_2}+\ldots+d^{P_K}+d^{UP}$$

$$g_l = \begin{cases} 1 \text{ if } l \text{ is improved} \\ 0 \text{ o.w.} \end{cases}$$

γ = potential capacity increase

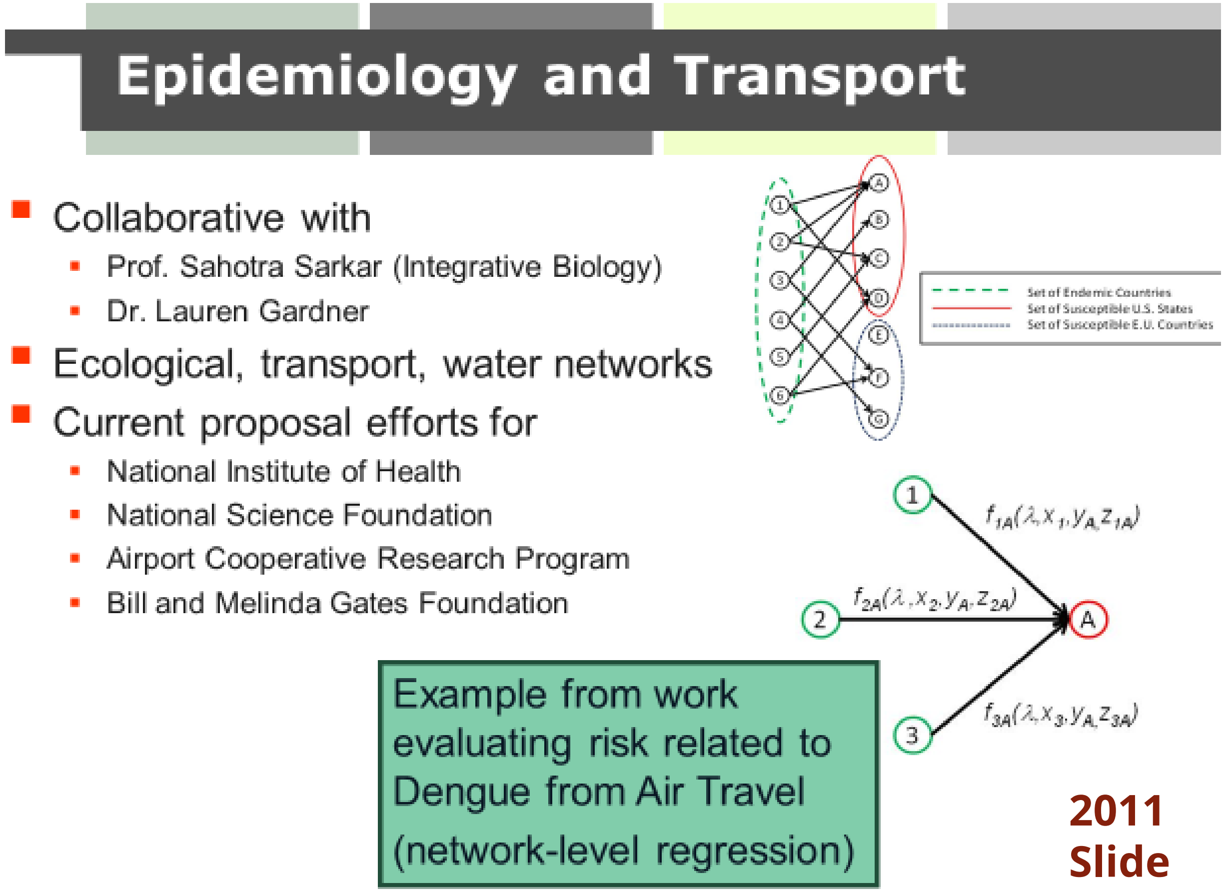
2011 Slide

3. Study of Disease Spreading in Transport Networks

We began studying the spread of disease through transport networks very early (2005 onward)

PhD (2011) thesis topic of Prof. Lauren Gardner (former PhD student at UT Austin and colleague at rCITI, UNSW)

Prof. Gardner would go on to create the well-known COVID19 Dashboard after her relocation to Johns Hopkins University



2011 Slide

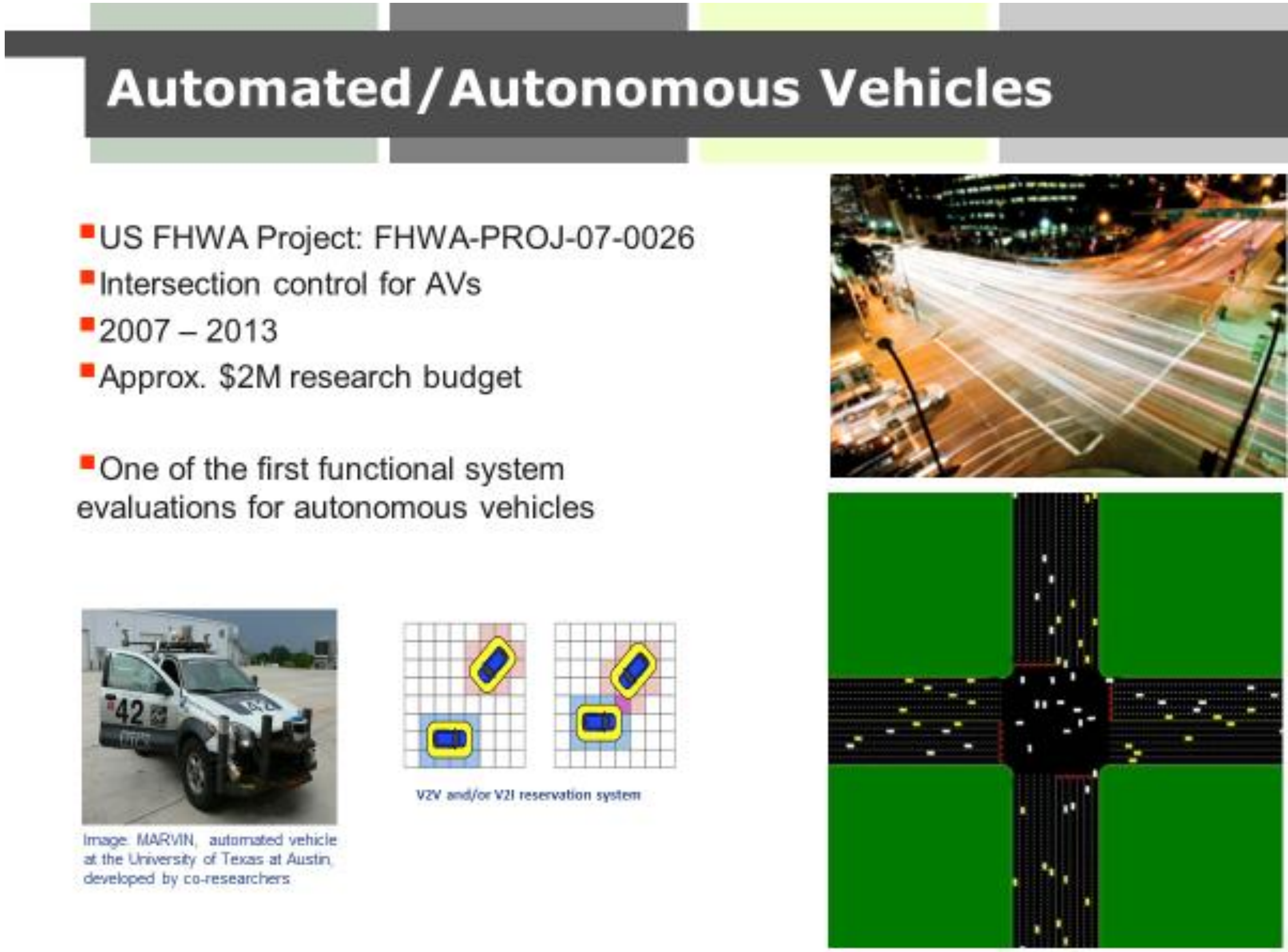
4. Automated/Autonomous Vehicles

Jointly conducted first large (over $1.8m) project globally to study

- How AVs would function in a transport system
- Comparison with traditional traffic management
- Travel behavior changes

This project was collaborative work with Computer Science Professor Peter Stone (beginning in 2006)

- And core work of PhD student Kurt Dresner



2011 Slide

The Present and Future: Evolution and Progress

From these emerging topics (all pre-2010):

1. **Electric Vehicles**
2. **Environmental Justice Including Impact Across Protected Groups**
3. **Pandemics in Transport Networks**
4. **Automated/Autonomous Vehicles**

Also, my own PhD thesis topic(2000) and NSF CAREER Award which led to

1. Adaptive Network **Equilibrium** Under **Information Provision** (due to ***emerging data***)

Now and onward

- **Trying to better understand emerging technology on mobility systematically**
  - In particular, **automating transport planning** (much of my current work)
- **Searching for a unifying framework for "Ethical Metrics" (my current ARC DP)**
  - e.g., road traffic carbon, equity, environmental justice, etc.

The Need for Planning Models

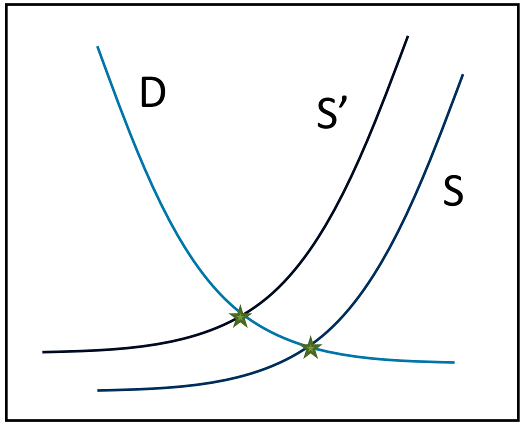
Transportation system behaviour

Responds non-linearly to changes

Is the aggregate response of thousands to millions of individuals making their own self-optimizing decisions

Therefore, it is traditionally represented as an equilibrium system

Models employ market dynamic explanations



As a result

An underlying equilibrium-based mathematical model has traditionally been necessary for transportation planning and business cases

The global universal approach since the 1950s has been the “four step process” for transportation modelling

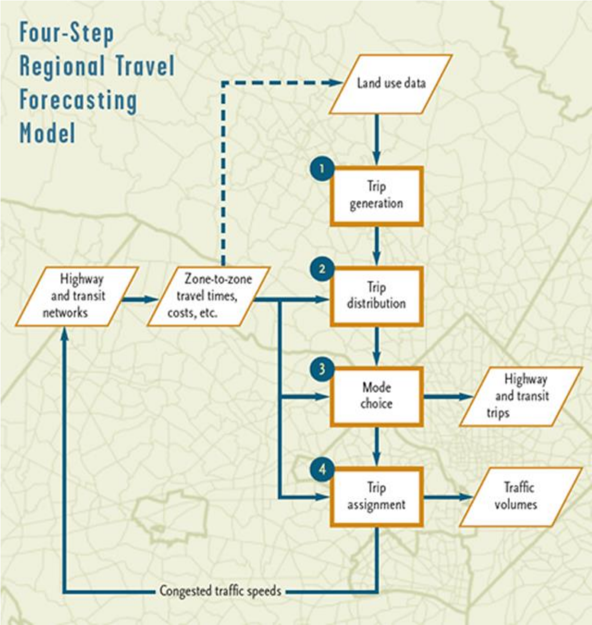
The four-step travel model is a ubiquitous framework for determining transportation forecasts that goes back to the 1950s. It was one of the first travel demand models that sought to link land use and behavior to inform transportation planning. (McNally, 2000)

Traditional Four-step Model for Transportation Planning

The approach is so common, there are Wikipedia pages on each step

- https://en.wikipedia.org/wiki/Trip_generation
- https://en.wikipedia.org/wiki/Trip_distribution
- https://en.wikipedia.org/wiki/Mode_choice (used when multiple modes are in scope)
- https://en.wikipedia.org/wiki/Route_assignment

- **Practically, the process often includes**
  - Initial step: household travel survey
  - Physical network monitoring (roadway counts, etc)
  - Ongoing network coding and information archiving of infrastructure
  - Ongoing model calibration
- **At the final step, traffic assignment, the model estimates or predicts**
  - Traffic metrics (volumes, speeds, travel times)
- **Because of the need for survey and ongoing monitoring**
  - The overall traditional process can consume months or even years



Metropolitan Washington Council of Governments. https://www.mwcog.org/transportation/data-and-tools/modeling/four-step-model/ (Accessed April 2024)

Also, https://www.transitwiki.org/TransitWiki/index.php/Four-step_travel_model (maintained by UCLA and Caltrans)

Key Innovation for the Presented Modelling Methodology

- From pervasive data: we begin at the 4th step with traffic metrics, then use machine learning/AI to estimate the travel demand
- The relevant steps are run in reverse (without the need for surveys or ongoing network monitoring)
- Critical: We maintain the traffic assignment and trip modelling steps
  - A key difference from purely data analytic or statistical approaches which do not utilize the step-models at all!

Traditional "static" Traffic Assignment

For hypothetical planning, we need specialized models to represent traffic routing behaviour.

The network flow must respond to changes in the system and environment

Formulation (Beckman, 1956)

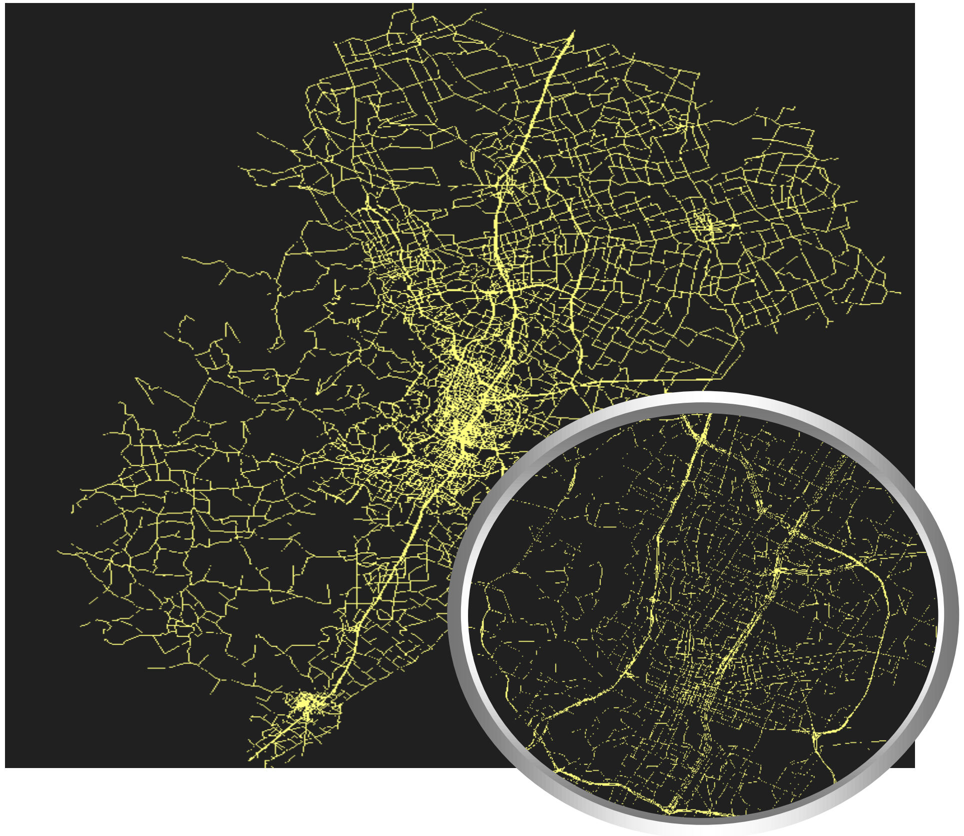
$$\min \sum_a \int_0^{x_a} c_a(\omega)\,d\omega$$

s.t.

$$\sum_k h_k^{rs} = q_{rs} \qquad \forall r, s$$

$$h_k^{rs} \geq 0 \qquad \forall k, r, s$$

$$x_a = \sum_r \sum_s \sum_k h_k^{rs} \delta_{a,k}^{rs} \qquad \forall a$$



Output: Every network link flow
Input: Origin-Destination (OD) trip values
Behaviour: Each traveller is self-optimizing (equivalent to a basic Nash Equilibrium)

This formulation (and the resulting optimisation/SP algorithms & software) are what permit transport planners to analyze large networks

Increasing realities for Network Behaviour

Numerous advances over the past 60+ years

Stochasticity

Dynamics

Multiple classes of travel behaviour

Pricing

Network design

Signal design

Connectivity and Information

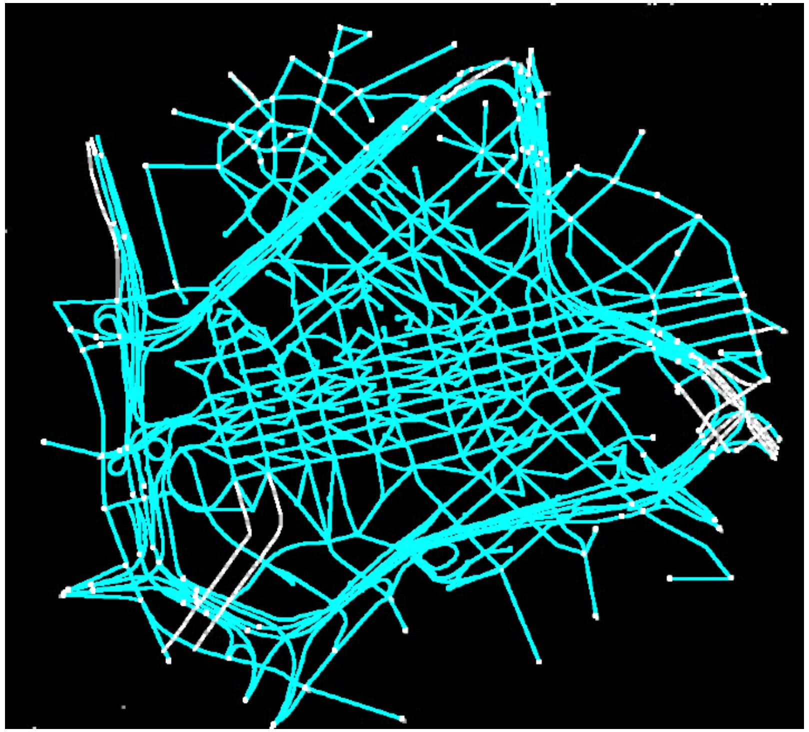
Demand/Supply integration

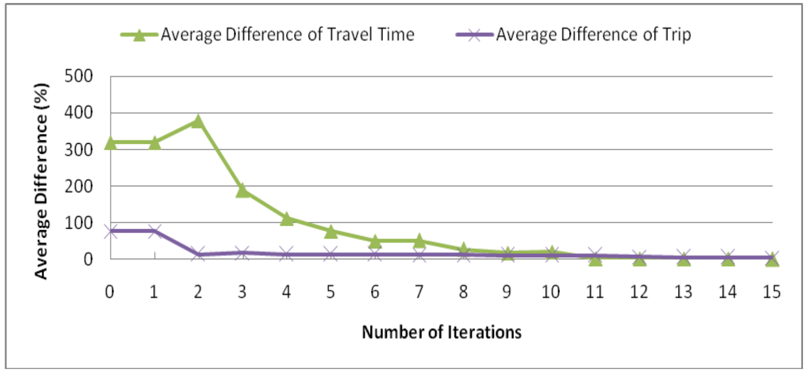
Automated Vehicles

Many others

Concepts of equilibrium remains vital for planning

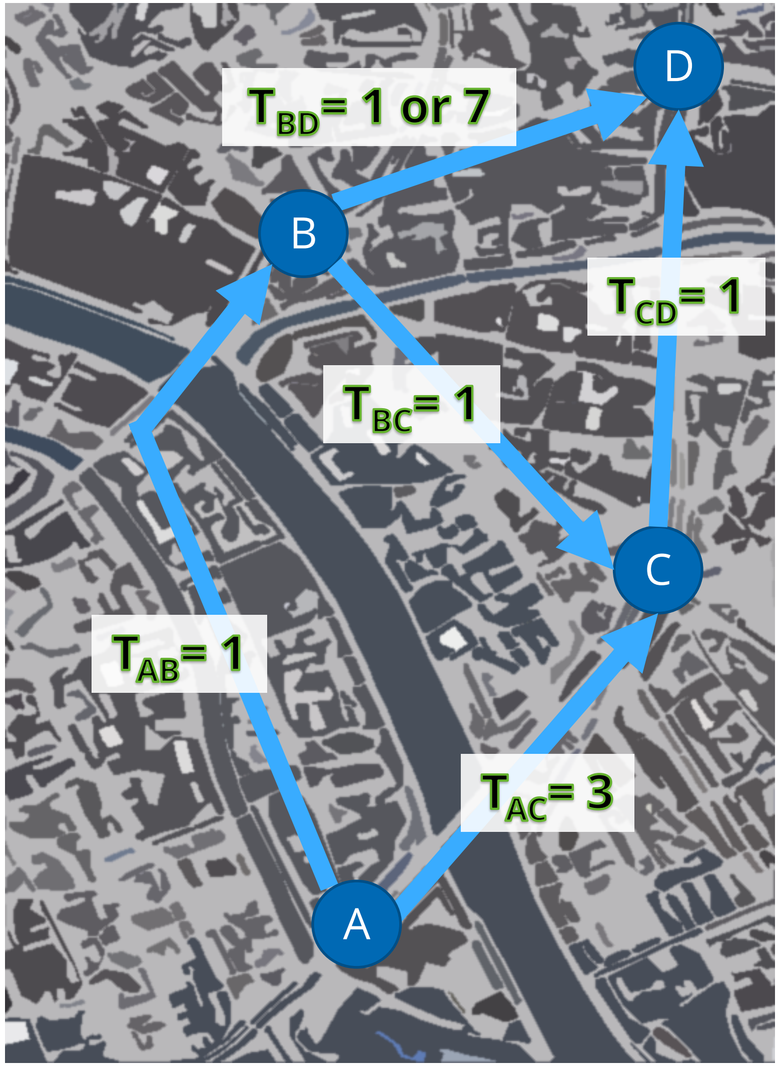
Network Equilibrium often requires advances in graph theory (e.g., shortest path algorithms)





Lin et al. (2007)
Integration of ABM and DTA

Shortest Path with Information
From Waller and Ziliaskoupolos (2002)



- If we have information at point B
- **We now have 5 Hyperpaths**
  - **A – C – D**
  - **A – B/1 – C – D**
  - **A – B/1 – D**
  - **A – B/2 – C – D**
  - **A – B/2 – D**
- **Optimal strategy**
  - A – B/1 –D = 2 (with probability .5)
  - A – B/2 –C –D = 3 (with probability .5)
  - Expected cost = 2(.5) + 3(.5) = **2.5**
- **Information** and **adaptivity** reduced the expected cost
  - from 3 to 2.5

Online Shortest Path Algorithm: 1 of 3
Waller and Ziliaskopoulos (2002)

<u>Step 1.</u>

$E[d|i,s]=0 \quad \forall\ i\in \Gamma^{-1}(d),\ \ s\in S_{i,t}$

$E[n|i,s]= \infty \quad \forall\ n\in N/d, \quad i\in\Gamma^{-1}(n),\ s\in S_{i,n}$

SE:= d

<u>Step 2.</u>

while SE$\neq \emptyset$

Remove an element, n, from the SE

for each $i\in\Gamma^{-1}(n),\ s\in S_{i,n},\ j\in\Gamma(n)$

$$\pi[n\,|\,i,s] = \sum_{k\in S_{n,j}} p_{s,k}^{i,n,j}\,(c_k^{n,j} + E[\,j\,|\,n,k])$$

If $\pi[n|i,s] < E[n|i,s]$, then $E[n|i,s] := \pi\ [n|i,s]$

SE:=SE $\cup\{j\in\Gamma^{-1}(i)\}$

Algorithms are presented for variants of spatial, temporal and combined dependency

Issue

Only works for fixed costs

But, costs are a function (change with flow)

User Equilibrium with Recourse: Model A
Unnikrishnan and Waller (2009)

CONVEX FORMULATION

$$Min\ Z[F(H)] = \sum_{iju} \int_{x=0}^{f_{i-j/u}} p_u . C_{i-j/u}(x) dx$$

Subject to $F = \Delta H \quad t = BH \quad H \geq 0$

EQUILIBRIUM CONDITION

$$H^T [P^T C[\Delta H] - B^T u] = 0$$

$$P^T C[\Delta H] - B^T u \geq 0$$

$$H \geq 0$$

INSIGHTS

- All used hyperpaths will have equal (and minimum) expected cost.
- This implies that those network users who follow a UER solution without options, still receive precisely the same benefit as those users who actually experience the options.

Adaptive Equilibrium

No information: **12 Travellers from A - D**

3 Paths

- Path 1: A – C –D
- Path 2: A – B – D
- Path 3: A – B – C –D

Adaptive Equilibrium

No information: **12 Travellers from A - D**

3 Paths

- Path 1: A – C –D
- Path 2: A – B – D
- Path 3: A – B – C –D

Without information

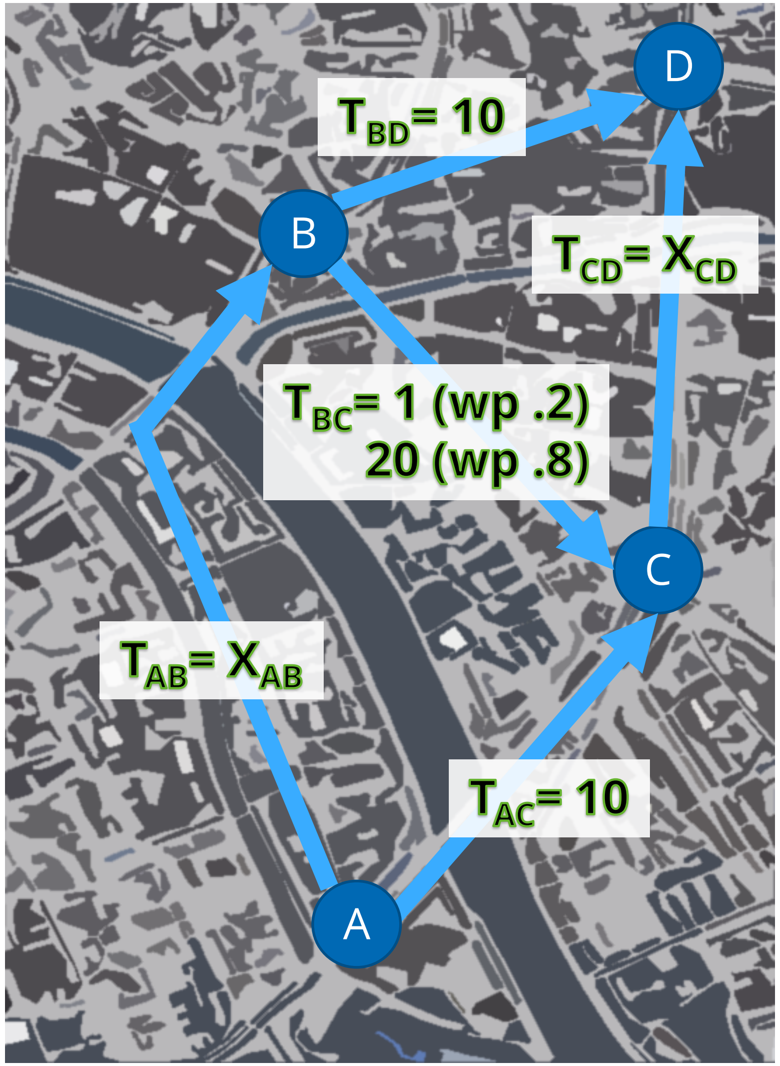
- Take average cost of link B –C
- Expected Cost of T_{BC} = 16.2

Equilibrium solution

- Path 1 Flow = Path 2 Flow
- No one uses link B-C
- Cost = X + 10 = 6 + 10 = 16

Everyone in the system has a cost of 16

Adaptive Equilibrium



With information: **12 Travellers from A - D**

There are 5 Hyperpaths

H1: A-C-D

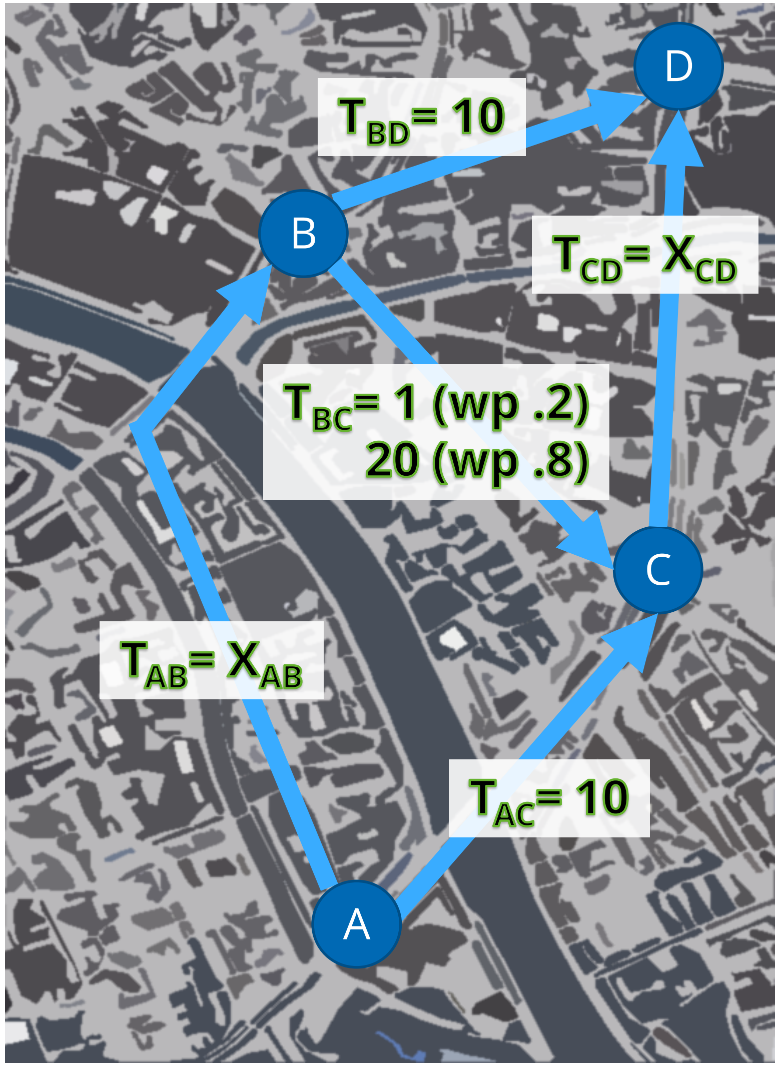
H2: A-B/1-C-D & A-B/2-C-D

H3: A-B/1-C-D & A-B/2-D

H4: A-B/1-D & A-B/2-D

H5: A-B/1-D & A-B/2-C-D

Adaptive Equilibrium



With information: **12 Travellers from A - D**

There are 5 Hyperpaths

H1: A-C-D

H2: A-B/1-C-D & A-B/2-C-D

H3: A-B/1-C-D & A-B/2-D

H4: A-B/1-D & A-B/2-D

H5: A-B/1-D & A-B/2-C-D

Equilibrium solution

HYPERPATH	*FLOW*	*EXP COST*
H1	4	18
H2	0	20.8
H3	0	20.8
H4	3	18
H5	5	18

Everyone in the system has a cost of 18!

Tragedy of the commons again!

Experimental Economics

How do real people play this game?

Examined with polling and incentivized games

Driving lab experiments

Also exploring global pervasive data

Transport Tools

DIXIT, V. V., ORTMANN, A., RUTSTROM, E. & UKKUSURI, S. 2015. Understanding Transportation Systems Through the Lenses of Experimental Economics: A Review. *Available at SSRN*.

Review of Experimental Economics

DIXIT, V. V. & DENANT-BOEMONT, L. 2014. Is equilibrium in transport pure Nash, mixed or Stochastic? Transportation Research Part C: Emerging Technologies, 48, 301-310

Experiment focusing on Transport Equilibrium

RAPOPORT, A., KUGLER, T., DUGAR, S. & GISCHES, E. J. 2009. Choice of routes in congested traffic networks: Experimental tests of the Braess Paradox. Games and Economic Behavior, 65, 538-57

Experiment focusing on Transport Paradoxes

LU, X., GAO, S., BEN-ELIA, E. & POTHERING, R. Information impacts on travelers' route choice behavior in a congested risky network. Transportation Research Board 91st Annual Meeting, 2012

Focus on information, but not equilibrium

Experimental Economic Analysis of Adaptive Equilibrium

K. Wijayaratna, V. Dixit, L. Denant-Boemont, and S.T. Waller

An experimental study of the Online Information Paradox: Does en-route information improve road network performance?

Plos Vol 12 Issue 9, 2017

- 144 participants
- Groups of six players
- 20 iterative periods

Results: Learning to Equilibrate

No information case compared to information case

Individual traffic states shown below

No Information

Mean Individual User Travel Costs: Treatment 1 (No Information)

Period	Session 1		Session 2		Session 3		Session 4		Session 5		Session 6	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
1	17.833	18.333	16.667	16.833	16.333	16.833	17.833	16.833	19.167	17.333	16.667	18.167
2	17.167	17.500	16.667	16.667	18.333	17.167	17.167	18.333	16.667	16.333	17.500	19.167
3	17.333	17.167	17.833	19.167	17.167	16.833	16.667	17.833	16.333	16.833	17.500	17.500
4	18.167	16.667	17.167	17.167	17.833	16.833	16.333	17.167	17.833	17.167	16.667	17.833
5	17.167	17.167	17.167	16.333	17.333	16.833	16.667	17.500	17.333	17.667	16.667	17.333
6	24.667	24.000	20.000	20.000	26.583	26.250	16.333	17.167	16.333	17.833	18.167	17.167
7	17.833	19.167	20.500	20.500	24.000	24.000	17.167	16.833	21.333	21.917	16.833	16.000
8	21.917	22.250	16.833	17.167	24.167	21.917	17.333	16.833	18.250	21.917	17.833	16.667
9	19.833	17.917	21.333	20.000	17.500	16.667	17.167	16.833	16.833	17.500	16.833	16.333
10	18.250	17.917	19.833	21.917	18.917	16.167	16.667	16.333	16.333	17.833	22.250	24.167
11	16.667	16.333	17.667	16.333	16.667	16.833	17.917	19.833	16.667	16.667	16.833	17.167
12	16.667	16.333	17.333	16.333	16.333	16.333	21.917	17.917	16.333	17.333	16.333	17.333
13	17.333	16.333	16.333	16.333	16.833	16.333	16.667	16.833	16.333	16.333	16.000	16.333
14	16.333	16.000	16.667	16.667	16.167	16.333	17.500	16.667	16.667	16.667	16.167	16.167
15	16.333	16.000	16.333	18.333	16.333	16.333	17.667	16.833	16.667	17.333	16.167	17.500
16	16.000	16.167	16.667	16.333	16.333	16.667	29.167	21.917	17.917	19.833	17.917	19.833
17	16.000	16.000	16.333	16.167	16.667	16.667	16.333	16.333	16.167	17.917	17.917	18.250
18	16.000	16.000	16.333	16.333	16.333	16.667	17.917	17.917	16.000	16.333	16.000	16.333
19	16.000	16.167	16.000	16.333	16.667	16.000	16.000	16.000	16.000	16.000	16.000	16.000
20	16.167	16.000	16.000	16.000	16.000	16.667	16.000	16.000	16.000	16.333	16.000	16.000
Group Mean	17.883	17.471	17.483	17.546	18.125	17.717	17.821	17.388	17.068	17.864	17.118	17.583

Standard Deviation of Individual User Travel Costs: Treatment 1 (No Information)

Period	Session 1		Session 2		Session 3		Session 4		Session 5		Session 6	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
1	1.030	0.492	0.778	1.267	0.888	1.267	1.030	1.267	0.718	2.060	1.969	2.725
2	0.835	1.567	0.778	0.778	0.492	0.835	0.835	0.492	1.969	0.888	1.567	2.329
3	2.462	0.835	1.030	0.718	0.835	1.267	0.778	1.030	0.888	1.267	1.567	1.567
4	2.290	1.670	0.835	0.835	1.030	1.267	0.888	0.835	1.030	0.835	0.778	1.030
5	0.835	0.835	0.835	0.888	2.462	1.267	0.778	1.567	2.060	0.492	0.778	2.060
6	8.500	8.863	6.606	6.606	9.258	9.498	0.888	0.835	0.888	1.030	2.725	0.835
7	1.030	2.329	6.544	6.544	8.863	8.863	0.835	1.267	6.344	7.902	1.267	0.000
8	7.902	7.794	1.267	0.835	8.778	7.902	2.060	1.267	4.864	7.902	1.030	0.778
9	6.617	4.776	6.344	6.606	1.567	0.778	0.835	1.267	1.267	1.567	1.267	0.888
10	4.864	4.776	6.617	7.902	4.963	1.030	0.778	0.888	0.888	1.030	7.794	8.778
11	1.670	0.888	0.492	0.888	1.670	1.267	4.776	6.617	0.778	0.778	1.267	0.835
12	1.670	0.888	2.060	0.888	0.888	0.888	7.902	4.776	0.888	2.462	0.888	2.060
13	2.462	0.888	0.888	0.888	1.267	0.888	0.778	1.267	0.888	0.888	0.000	0.888
14	0.888	0.000	1.670	1.670	1.030	0.888	1.567	0.778	0.778	1.670	1.030	1.030
15	0.888	0.000	0.888	3.025	0.888	0.888	0.492	1.267	1.670	2.462	1.030	1.567
16	0.000	1.030	1.670	0.888	0.888	1.670	9.292	7.902	4.776	6.617	4.776	6.617
17	0.000	0.000	0.888	1.030	1.670	0.778	0.888	0.888	1.030	4.776	4.776	4.864
18	0.000	0.000	0.888	0.888	0.888	1.670	4.776	4.776	0.000	0.888	0.000	0.888
19	0.000	1.030	0.000	0.888	1.670	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	1.030	0.000	0.000	0.000	0.000	1.670	0.000	0.000	0.000	0.888	0.000	0.000
Group Standard Deviation	3.807	3.704	3.340	3.594	4.726	4.398	4.237	3.100	2.686	3.594	2.828	3.396

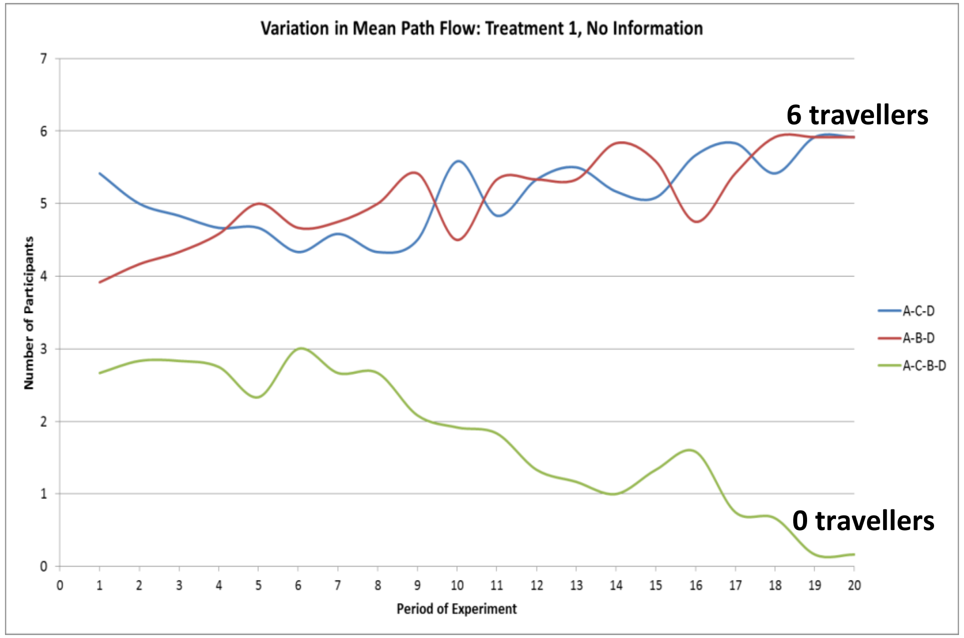
Information

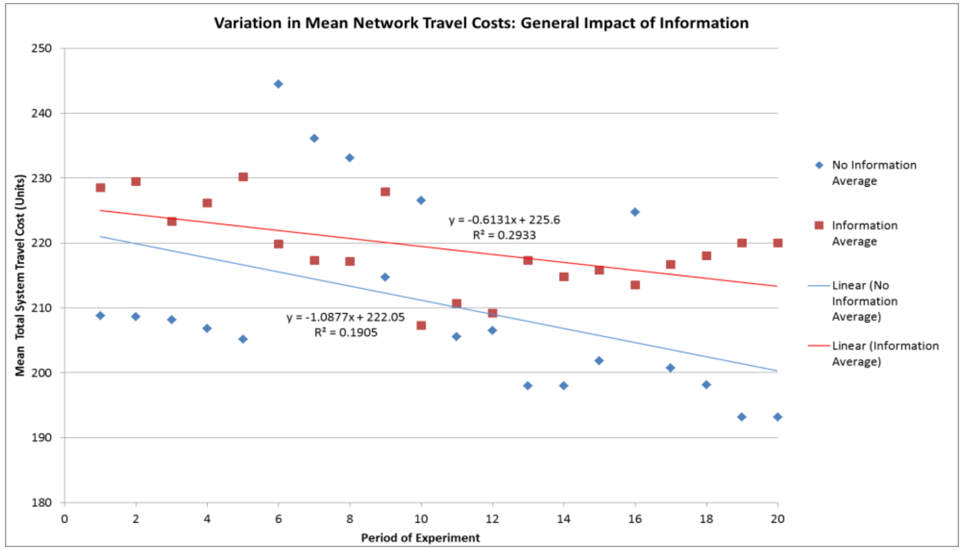
Mean Individual User Travel Costs: Treatment 2 (Information)

Period	Session 1		Session 2		Session 3		Session 4		Session 5		Session 6	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
1	18.333	19.167	19.667	19.000	18.333	20.333	19.333	16.833	17.167	19.667	18.667	22.000
2	19.667	19.667	18.167	19.333	17.833	18.333	18.667	21.667	19.833	17.833	20.167	18.333
3	18.667	17.167	18.333	19.000	18.333	18.667	18.333	19.000	19.667	19.167	18.333	18.667
4	18.667	19.333	18.333	18.333	18.333	18.333	20.167	18.667	20.833	19.000	18.333	17.833
5	18.333	18.667	19.167	19.333	19.167	19.667	17.833	18.333	21.333	19.167	19.333	19.833
6	21.667	18.333	17.500	16.667	19.000	18.333	20.500	17.167	17.333	18.333	17.167	17.833
7	16.667	16.667	17.333	18.333	19.167	19.000	16.667	18.333	19.167	19.000	18.667	18.333
8	18.333	18.667	17.833	18.333	19.167	20.333	17.667	17.667	17.167	18.333	17.500	16.167
9	18.333	18.333	17.833	18.333	17.500	27.250	19.167	19.667	16.167	16.167	20.500	18.667
10	18.333	18.333	16.667	16.667	16.833	18.667	16.167	16.667	18.333	17.833	16.167	16.667
11	18.333	18.333	16.667	16.667	16.667	16.167	16.667	16.167	19.833	18.333	19.667	17.167
12	18.667	16.667	16.167	16.167	17.500	16.667	17.167	18.333	19.333	19.667	16.667	16.167
13	17.667	20.167	19.167	20.833	16.167	20.167	16.167	16.167	16.667	16.667	17.167	20.333
14	16.167	16.167	18.333	20.167	17.167	20.167	16.667	16.667	17.667	19.000	18.333	18.333
15	19.333	18.333	19.333	18.333	17.667	17.833	18.333	18.333	16.667	16.167	17.833	17.667
16	16.667	16.667	17.833	18.333	17.667	17.833	18.333	17.167	18.333	17.167	17.833	19.667
17	18.333	18.667	17.167	19.333	18.333	18.333	17.833	18.333	17.500	16.667	17.833	18.333
18	18.333	18.333	17.500	17.833	18.333	19.167	18.333	17.833	18.333	17.833	18.333	17.833
19	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333
20	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333	18.333
Group Mean	18.368	18.217	17.863	18.383	17.992	18.096	18.083	17.983	18.400	18.133	18.258	18.325

Standard Deviation of Individual User Travel Costs: Treatment 2 (Information)

Period	Session 1		Session 2		Session 3		Session 4		Session 5		Session 6	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
1	1.775	2.758	1.303	0.000	0.492	2.462	1.826	1.267	0.835	1.303	1.231	0.000
2	1.303	1.303	2.725	1.826	1.030	0.492	1.231	0.651	0.389	1.030	0.835	0.492
3	1.231	0.835	0.492	0.000	0.492	1.231	1.775	0.000	1.303	0.718	0.492	1.231
4	1.231	1.826	0.492	0.492	0.492	0.492	0.835	1.231	1.030	0.000	1.775	1.030
5	0.492	1.231	2.329	1.826	0.718	1.303	1.030	0.492	0.492	2.329	1.826	0.389
6	0.651	0.492	2.714	1.969	0.000	1.775	2.714	0.835	2.060	0.492	0.835	1.030
7	1.969	1.969	2.060	0.492	2.758	0.000	0.778	0.492	0.718	0.000	1.231	1.775
8	0.492	1.231	1.030	0.492	0.718	2.060	0.492	0.492	0.835	0.492	2.714	1.030
9	0.492	0.492	1.030	0.492	2.714	8.719	2.758	1.303	1.030	1.030	6.544	3.114
10	0.492	0.492	1.969	1.969	1.267	1.231	1.030	1.969	0.492	1.030	1.030	1.969
11	1.775	1.775	1.969	1.969	1.969	1.030	1.969	1.030	0.389	0.492	1.303	0.835
12	3.114	1.969	1.030	1.030	2.714	1.969	0.835	0.492	1.826	1.303	1.969	1.030
13	0.492	0.835	2.329	0.577	1.030	2.887	1.030	1.030	1.969	1.969	0.835	2.462
14	1.030	1.030	1.775	0.835	0.835	0.835	1.969	1.969	0.492	0.000	0.492	0.492
15	1.826	0.492	1.826	0.492	0.492	1.030	0.492	0.492	1.969	1.030	1.030	0.492
16	1.969	1.969	1.030	0.492	0.492	1.030	1.775	0.835	0.492	0.835	1.030	1.303
17	0.492	1.231	0.835	1.826	0.492	0.492	1.030	0.492	2.714	1.969	1.030	0.492
18	0.492	0.492	1.567	1.030	0.492	0.718	0.492	1.030	0.492	1.030	0.492	1.030
19	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492
20	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492	0.492
Group Standard Deviation	1.686	1.863	1.823	1.604	1.600	3.140	1.820	1.676	1.822	1.600	2.118	1.837





Results: Online Information Paradox

Wijayaratna et al (2017)

Experimental results support the presence of the Online Information Paradox

	Treatment 1: No Information	Treatment 2: Information Provided at Node B	
State	E(S1,S2)	S1	S2
Cost of A-B-D	16.871	14.438	19.115
Cost of A-C-B-D	18.588	32.146	17.828
Cost of A-C-D	16.917	17.708	17.714
Observed TSTC	**210.629**	**219.163**	

Results: Online Information Paradox

Wijayaratna et al (2017)

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Cost of A-C-D	16.917	17.708	17.714
Observed TSTC	**210.629**	**219.163**	

So, what does this all mean?

* Consequence of Unnikrishnan & Waller (2009)

In the absence of deception, inducement or pricing,

the power of **information** is that it makes us more efficient at being **selfish.**

For mobility, this can lead us to the classic "tragedy of the commons" outcome.

* Consequence of Unnikrishnan & Waller (2009)

In the absence of deception, inducement or pricing,

the power of information is that it makes us more efficient at being selfish.

As observed, network re-routing behaviour is critical

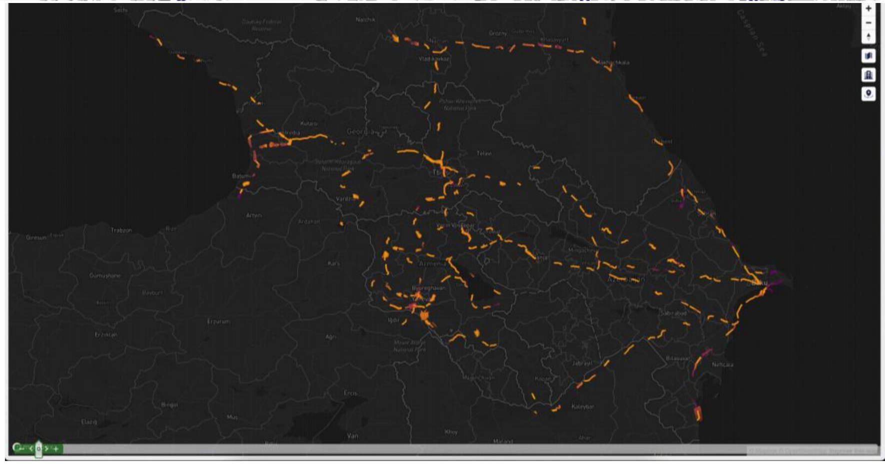
But, how can we build network models much more rapidly so as to be more useful

Automated Modeling for Rapid Planning by Embedding Equilibrium

Given the importance of network planning models

How can we cut the time to deploy such models?

How do we maintain relevance for hypothetical scenarios?



By doing so, we create space to grow their use and usefulness

Standardize across regions

Increase transparency and engagement

Incorporate novel metrics

- Equity
- Sustainability
- Environmental impact/justice
- Resilience

Critical Note:

In doing all of this, we must not lose the capacity to appropriately model “what-if” scenarios.

If we lose this, we lose our purpose in the planning process.

To plan is not simply to analyse. It is not just data analytics.

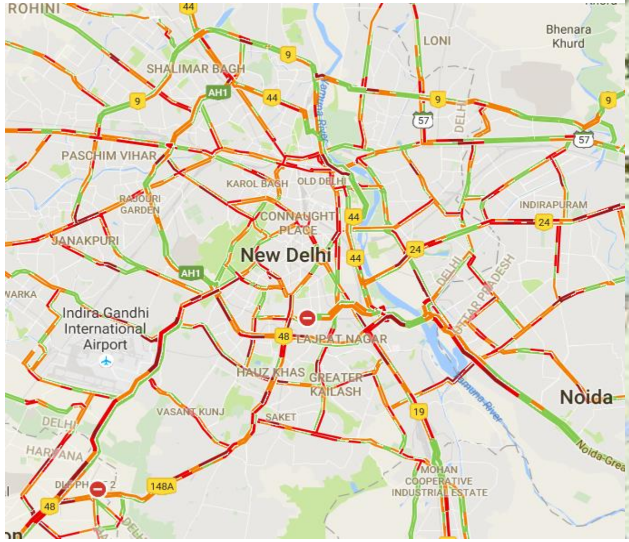
We would like to acknowledge collaboration with NVIDIA.

Big Data: Networked Mobility Information
Google Map Outreach Grant

Nearly a decade ago, while at rCITI@UNSW we were the first non-US group to have the Google Maps Outreach Grant

Numerous previous initiatives

- Introducing and validating new planning methodologies that account for adaptive traveller behaviour
- Explored novel traffic management strategies with TfNSW, RMS, & US FHWA
- Worked in India and elsewhere to leapfrog with digital infrastructure




Big Data: Networked Information

Google/Telecommunications/Apps

- Ubiquitous
- Potentially multi-modal
- Operational/statistical challenges for some applications

Social Media

- Understanding human text

Financial

- Also ubiquitous
- Reveals economic drivers

Destination choice

Socio demographic and economic attributes

Travel attributes: location, time

Travel attributes: location, time duration, purpose, mode of transport.

Information is Bi-directional:
Analytics is half the problem/opportunity. Information also transfers out, changing **behaviour**.

TH Rashidi;A Abbasi;M Maghrebi;S Hasan;ST Waller (2017) '**Exploring the capacity of social media data for modelling travel behaviour: Opportunities and challenges**', Transportation Research Part C: Emerging Technologies, vol. 75, pp. 197 - 211.

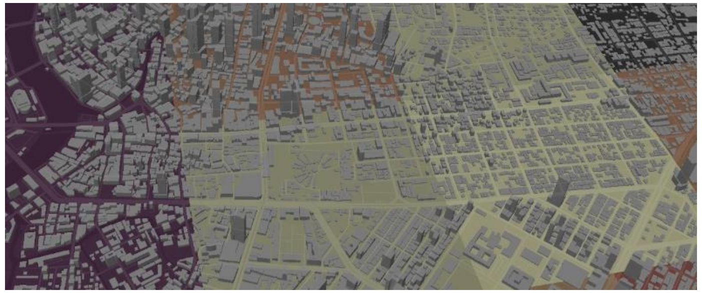
Rapid Planning Methodology

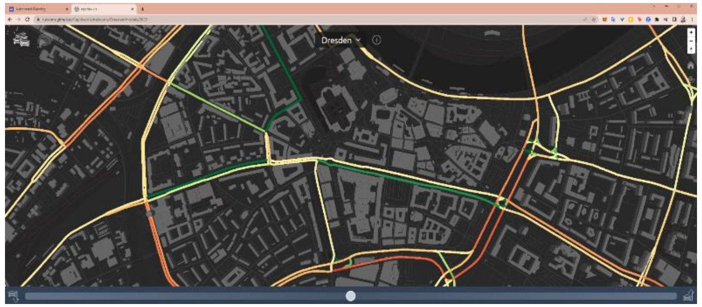
A network supply model is automatically built from OSM

The trip estimation combines evolutionary algorithms with embedded network User Equilibrium (UE)

Each fitness function evaluation requires UE to be solved

Google POI and other demographic data (e.g., WorldPop) help to devise initial solutions





*ST Waller, S Chand, A Zlojutro, D Nair, C Niu, J Wang, X Zhang, and VV Dixit **(2021) "Rapidex: A novel tool to estimate origin–destination trips using pervasive traffic data"** Sustainability (Switzerland), vol. 13, pp. 11171 – 11171. https://doi.org/10.3390/su132011171

D Ashmore, ST Waller, K Wijayaratna, and A Tessler **(2022) "Automated Planning For The Strategic Management of Transport Systems In Developing Countries"** Australasian Transport Research Forum Proceedings 28-30 September, Adelaide, Australia. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4191661

S Chand, ST Waller, and D Ashmore **(2022) "Building and Benchmarking Equitable Infrastructure Systems in the Wake of Rapid Urbanisation"** Policy Brief for Task Force 8: Inclusive, Resilient, and Greener Infrastructure Investment and Financing, T20 Summit, Indonesia. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4203715

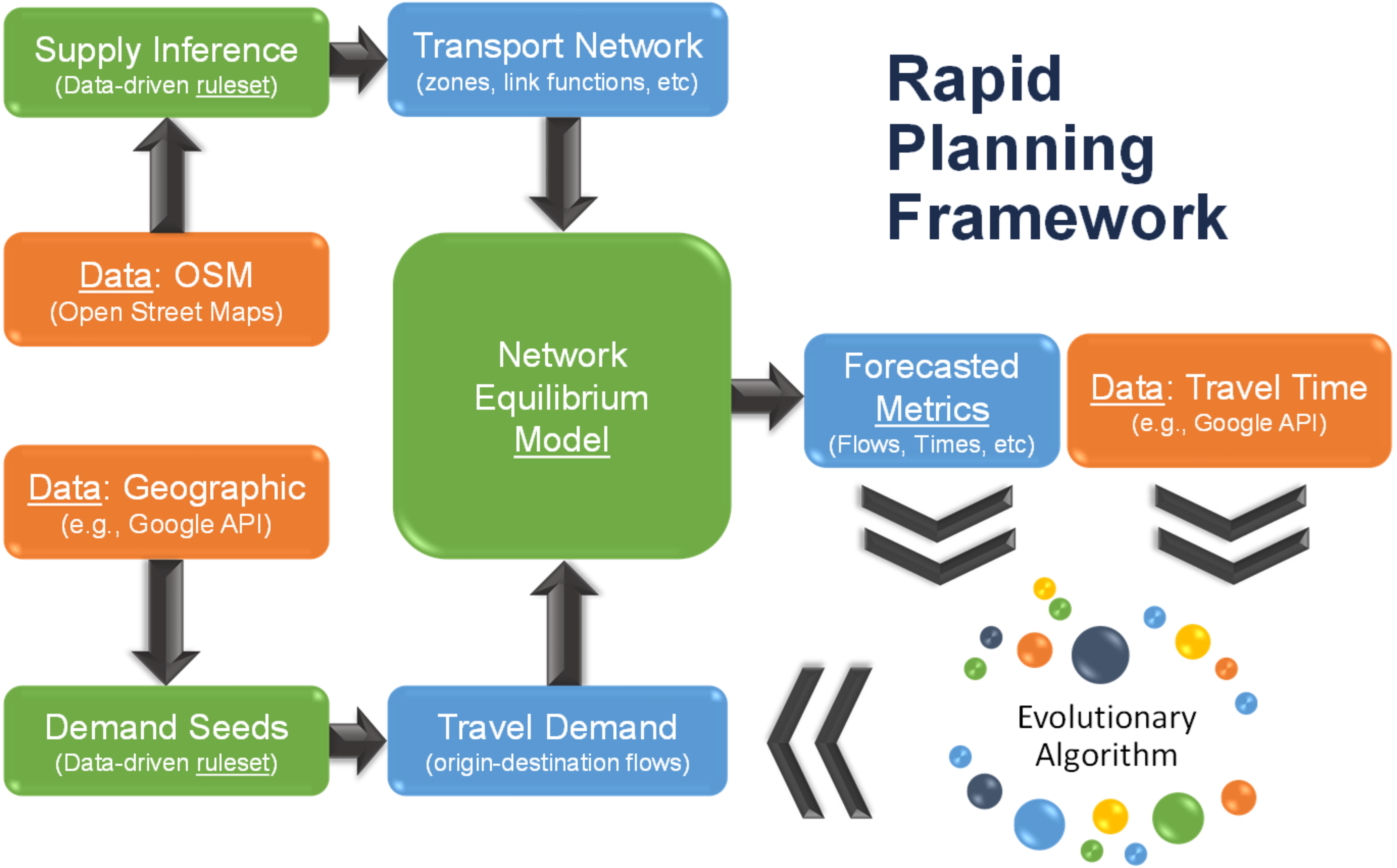
*ST Waller, M Qurashi, A Sotnikova, L Karva, S Chand **(2023) "Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data"** Transportation Research Record, Volume 2677, Issue 10, https://doi.org/10.1177/03611981231161622

R Amrutsamanvar, S Chand, M Qurashi, and ST Waller **(2023) "Rapid Planning: Opportunities with Pervasive Data for Sustainable Mobility"** IEEE Smart Cities Symposium, Prague.

Rapid Transport Planning: Methodological Framework

Waller et al. (2021)

- Use crowd sourced and pervasive big data.
- Network inference tools to automatically develop planning network from OSM and historic data on transport capacities.
- An AI/Machine Learning (Evolutionary Algorithm) implementation to infer aggregate origin-destination travel demand forecast from observed data.



Sample of Our Past & Ongoing AI/Evolutionary Algorithm Applications in Mobility

Traffic Signal Optimization

Sun D; Benekohal RF; Waller ST (2003) **'Multi-objective traffic signal timing optimization using non-dominated sorting genetic algorithm II'**, Lecture Notes in Computer Science, vol. 2724, pp. 2420 - 2421, http://dx.doi.org/10.1007/3-540-45110-2_143

Sun D; Benekohal RF; Waller ST, 2006, **'Bi-level programming formulation and heuristic solution approach for dynamic traffic signal optimization'**, Computer-Aided Civil and Infrastructure Engineering, vol. 21, pp. 321 - 333, http://dx.doi.org/10.1111/j.1467-8667.2006.00439.x

Vending Machine Allocation

Grzybowska H; Kerferd B; Gretton C; Travis Waller S (2020) **'A simulation-optimisation genetic algorithm approach to product allocation in vending machine systems'**, Expert Systems with Applications, vol. 145, http://dx.doi.org/10.1016/j.eswa.2019.113110

Transport Network Design

Jeon, K., J.S. Lee, S. Ukkusuri, and S.T. Waller (2009) ‘**New approach for relaxing computational complexity of discrete network design problem using selectorecombinative genetic algorithm**’ Journal of the Transportation Research Board, Vol 1964, Issue 1, pp. 91-103, 2006. https://doi.org/10.1177/0361198106196400111

Lin DY; Unnikrishnan A; Waller ST (2009) **'A genetic algorithm for bi-level linear programming dynamic network design problem'**, Transportation Letters, vol. 1, pp. 281 - 294, http://dx.doi.org/10.3328/TL.2009.01.04.281-294

Lin DY; Waller ST (2009) **'A quantum-inspired genetic algorithm for dynamic continuous network design problem'**, Tr. Letters, v. 1, pp. 81 - 93, http://dx.doi.org/10.3328/TL.2009.01.01.81-93

Ready-Mixed Concrete Delivery

Maghrebi, M., Periaraj, V., Waller, S. T., & Sammut, C. (2014) “**Solving Ready-Mixed Concrete Delivery Problems: Evolutionary Comparison between Column Generation and Robust Genetic Algorithm**.” In R. Issa (Ed.), ASCE - Computing in Civil and Building Engineering. Orlando, USA, 23-25 Jun 2014. https://doi.org/10.1061/9780784413616.176

Maghrebi M; Waller ST; Sammut C (2014) **'Sequential Meta-Heuristic Approach for Solving Large-Scale Ready-Mixed Concrete–Dispatching Problems'**, Journal of Computing in Civil Engineering, vol. 30, pp. 04014117 - 04014117, http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000453

Rapid Transport Modelling (including network and trip estimation)

Waller ST; Chand S; Zlojutro A; Nair D; Niu C; Wang J; Zhang X; Dixit VV, 2021, **'Rapidex: A novel tool to estimate origin–destination trips using pervasive traffic data'**, Sustainability (Switzerland), vol. 13, pp. 11171 - 11171, http://dx.doi.org/10.3390/su132011171

Waller, Travis and Qurashi, Moeid and Sotnikova, Anna and Karva, Lavina and Chand, Sai, ‘**Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data**’ Transportation Research Record: Journal of the Transportation Research Board, Vol 2677, Issue 10, pp. 491-507, 2023. https://doi.org/10.1177/03611981231161622

Travel Origin-Destination Demand Estimation

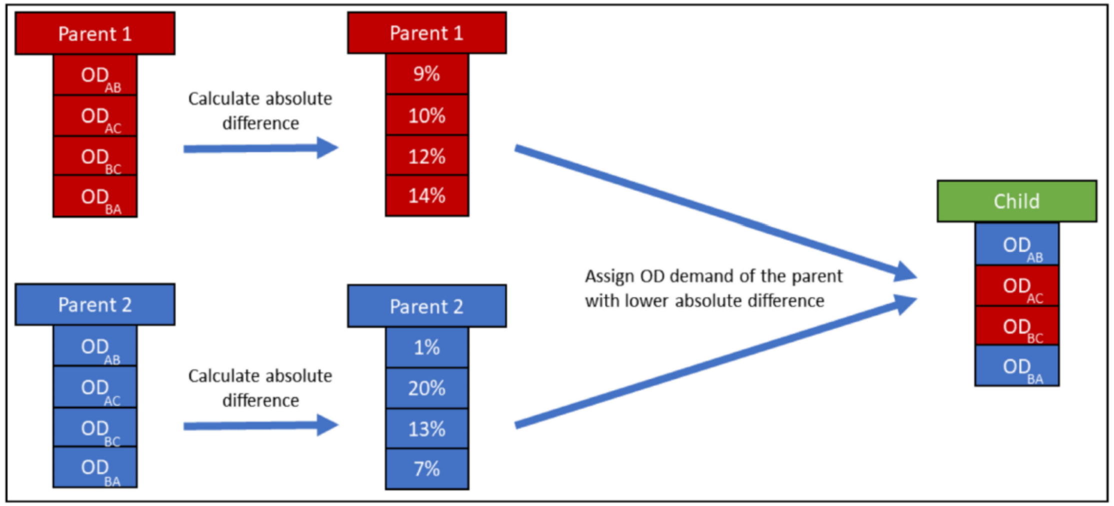
Waller et al. (2021)

Fitness Functions

Acronym	Method Name	Governing Equation	Notation
MAPE-ODTT	Mean absolute percentage error of OD travel times.	$E = \sum_{rs} d_{rs} \cdot \frac{\left\lvert TT_{rs}^{est} - TT_{rs}^{obs} \right\rvert}{TT_{rs}^{obs}}$	• E—Error value. • TT_{rs}^{est}—Estimated (from a solution) travel time between OD pair r and s. • TT_{rs}^{obs}—Observed (from any pervasive platform) travel time between OD pair r and s. • N_{OD}— Number of OD pairs. • f_{ij}^{est}—Estimated (from a solution) flow between link i and j. • f_{ij}^{obs}—Observed (from loop detector or other sources) flow between link i and j. • N_f—Number of links in the network where flow values are known. • t_{ij}^{est}—Estimated (from a solution) travel time between link i and j. • t_{ij}^{obs}—Observed (from any pervasive traffic platform) travel time between link i and j. • N_t—Number of links in the network where travel time values are known. • R_i^{est}—Estimated (from a solution) travel time along a user defined route/corridor i. • R_i^{obs}—Observed (from any pervasive platform) travel time along a user defined corridor i. • N_R—Number of user-defined corridors.
RMSE-ODTT	Root mean square error of OD travel times.	$E = \sqrt{\frac{\sum_{rs} \left(TT_{rs}^{est} - TT_{rs}^{obs} \right)^2}{N_{OD}}}$	
MAPE-LF	Mean absolute percentage error of link flows.	$E = \sum_{ij} \frac{\left\lvert f_{ij}^{est} - f_{ij}^{obs} \right\rvert}{f_{ij}^{obs}}$	
RMSE-LF	Root mean square error of link flows.	$E = \sqrt{\frac{\sum_{ij} \left(f_{ij}^{est} - f_{ij}^{obs} \right)^2}{N_f}}$	
RMSE-LTT	Root mean square error of link travel times.	$E = \sqrt{\frac{\sum_{ij} \left(t_{ij}^{est} - t_{ij}^{obs} \right)^2}{N_t}}$	
MAPE-LTT	Mean absolute percentage error of link travel time.	$E = \sum_{ij} \frac{\left\lvert t_{ij}^{est} - t_{ij}^{obs} \right\rvert}{t_{ij}^{obs}}$	
MAPE-C	Mean absolute percentage error of corridor travel times.	$E = \sum_{i} \frac{\frac{\left\lvert R_i^{est} - R_i^{obs} \right\rvert}{R_i^{obs}}}{N_R}$	

Initial Solutions

Acronym	Method Name	Governing Equation	Notation
TFM	Travel time—free flow travel time model.	$d_{rs} = \frac{\frac{TT_{rs}^{obs}}{TT_{rs}^{f}}}{\sum_{rs} \frac{TT_{rs}^{obs}}{TT_{rs}^{f}}} \cdot D$	TT_{rs}^{obs}—Observed (from any pervasive platform) travel time between OD pair r and s. $TT^f{}_{rs}$—Observed free-flow travel time between OD pair r and s. k_{rs}—Average shortest distance between the OD pair r and s when the network is empty. G_r—user-defined proportion value of zone r, where $\sum G_r = 1$. A_s—user-defined proportion value of zone s, *where* $\sum A_s = 1$.
FDM	Free flow travel time—distance model.	$d_{rs} = \frac{\frac{TT_{rs}^{f}}{k_{rs}^2}}{\sum_{rs} \frac{TT_{rs}^{f}}{k_{rs}^2}} \cdot D$	
TDM	Travel time distance model.	$d_{rs} = \frac{\frac{TT_{rs}^{obs}}{k_{rs}^2}}{\sum_{rs} \frac{TT_{rs}^{obs}}{k_{rs}^2}} \cdot D$	
CGM	Custom gravity model.	$d_{rs} = \frac{\frac{G_r A_s}{k_{rs}^2}}{\sum_{rs} \frac{G_r A_s}{k_{rs}^2}} \cdot D$	



Travel Origin-Destination Demand Estimation

Waller et al. (2021)

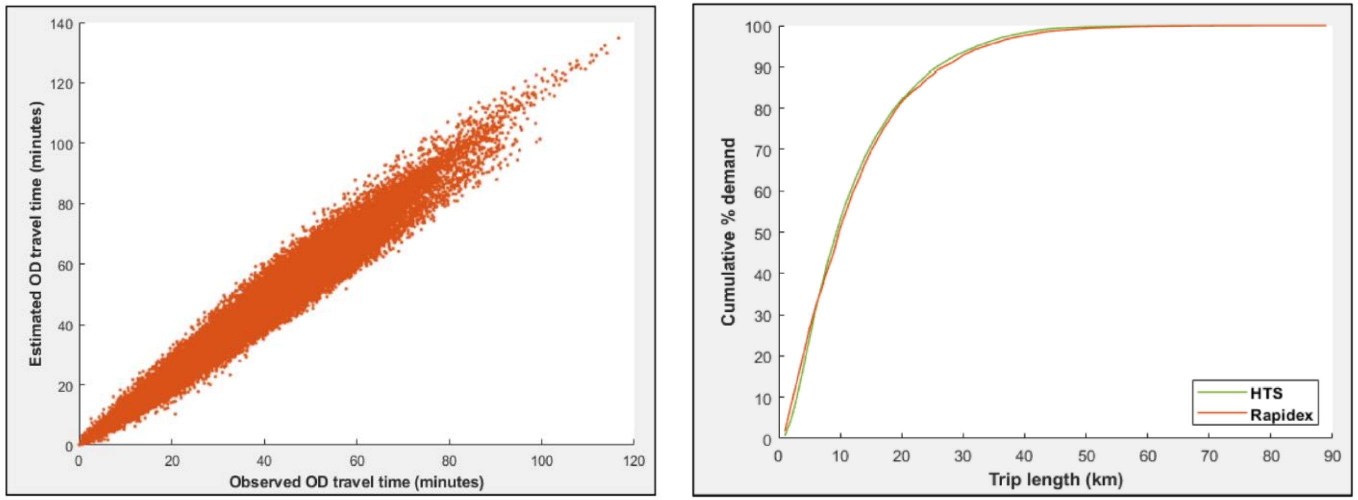


Figure 4. Observed vs. estimated OD travel times.

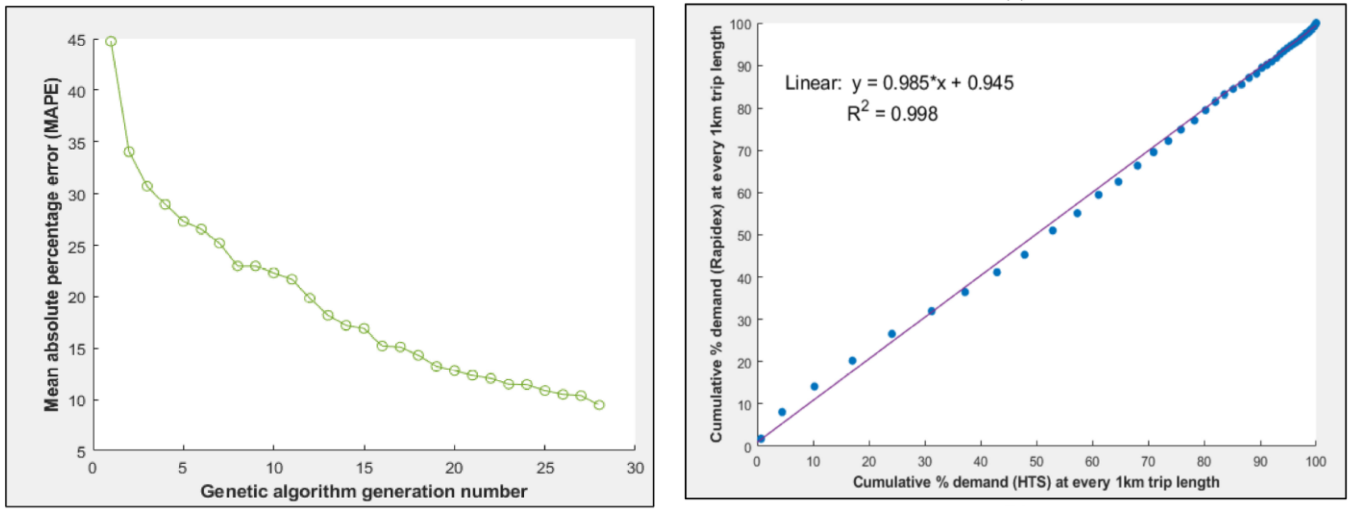
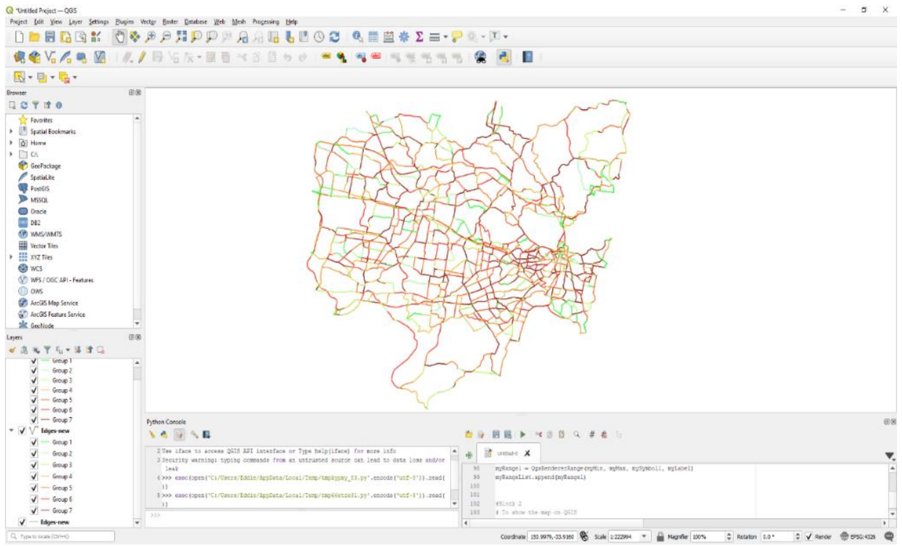


Figure 5. Convergence of the genetic algorithm solution.

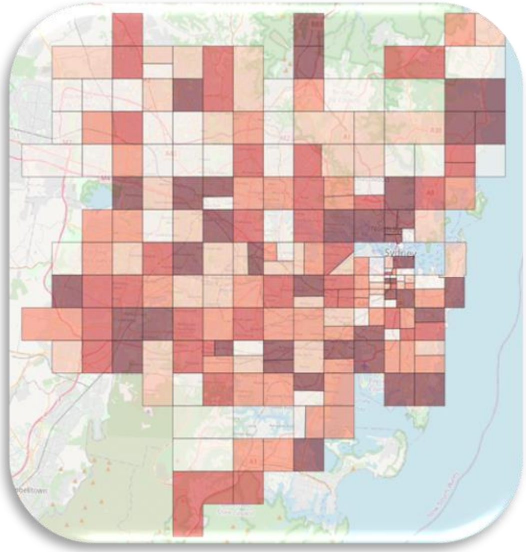
Comparison with

- Observed Data
- Household Travel Survey
- More refined (time-intensive) strategic planning model

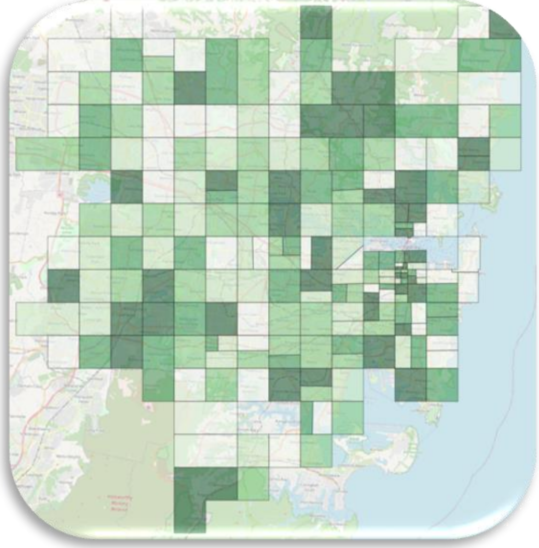
Case Study 1: Sydney Region



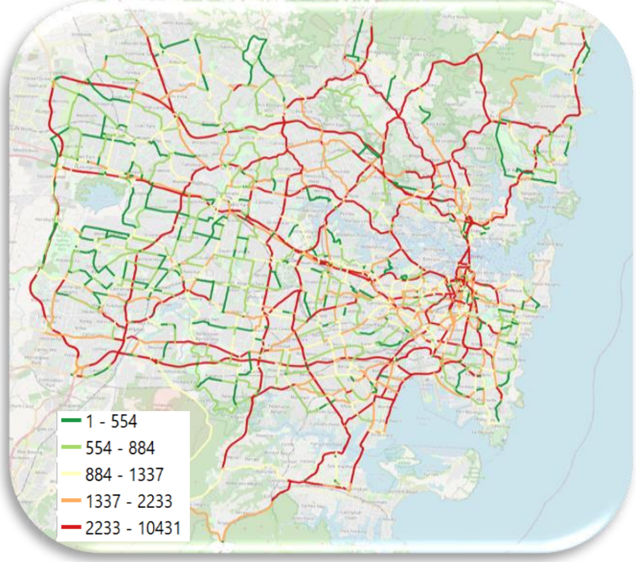
Generations



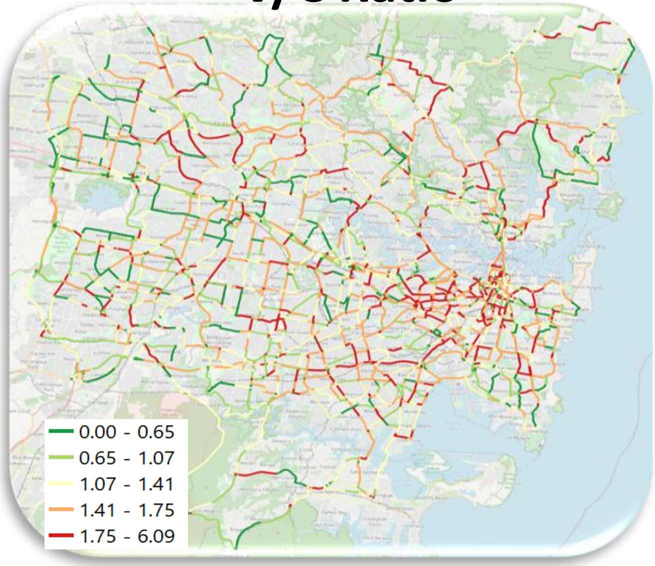
Attractions



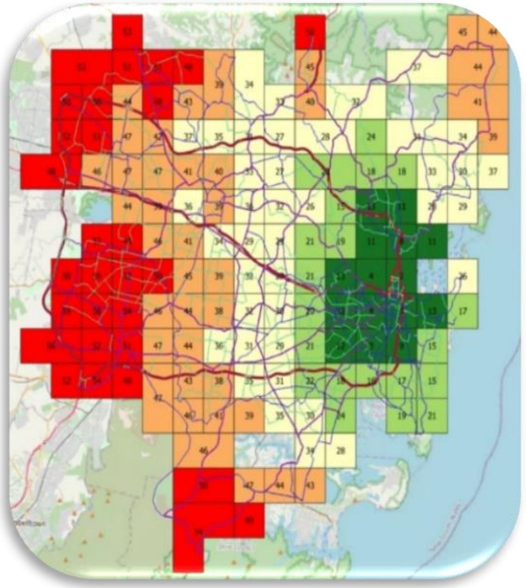
Volume



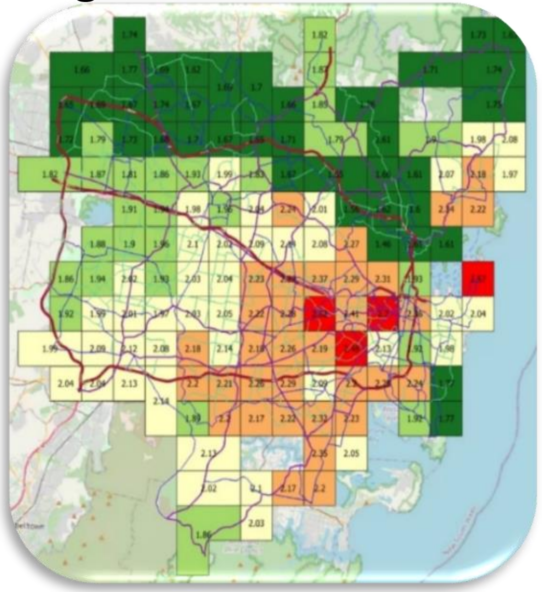
V/C Ratio



Travel time to CBD



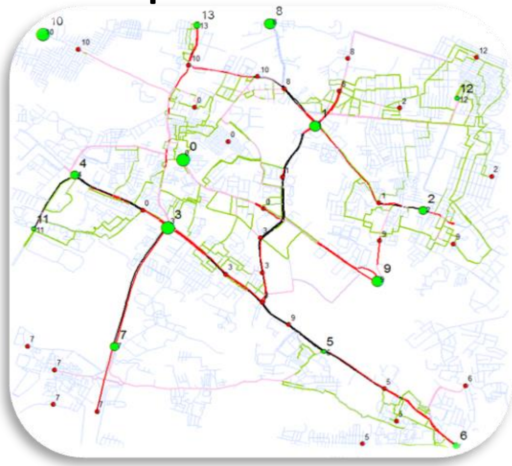
Congestion Index to CBD



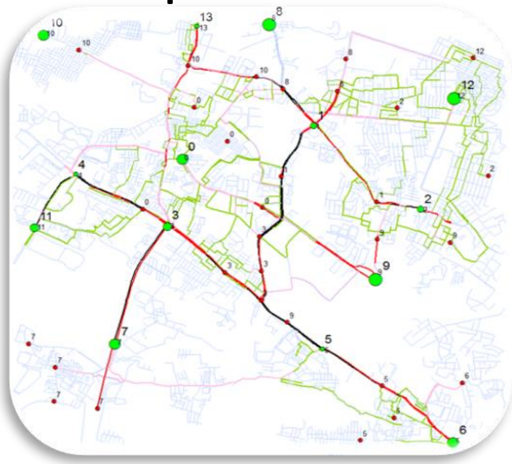
Case Study 2: HiTech City, Hyderabad (India)

Project: needed to establish a model, with no data from agency, to evaluate traffic operational changes related to construction of new metro

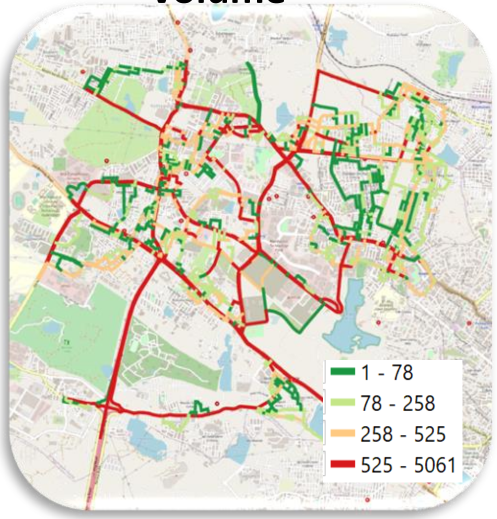
Trip Generations



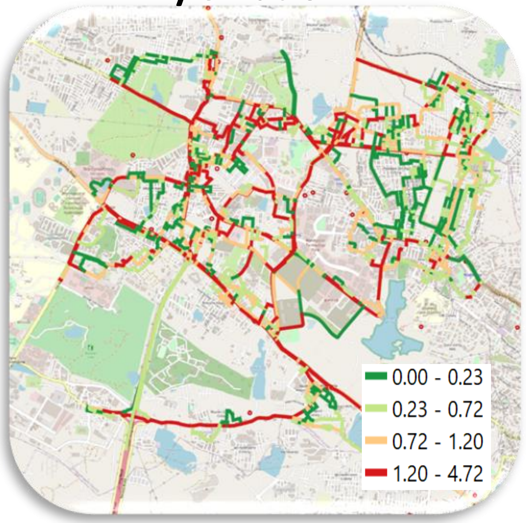
Trip Attractions



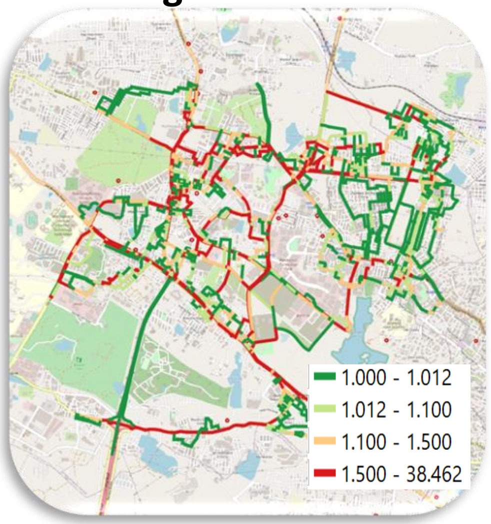
Volume



V/C Ratio



Congestion Index



Models in Ukraine

Waller et al. (2023)

Analysis for 26 February 2022 to 12 April 2022

Focusing on Coefficient of Variance (Std/Mean)

First known paper on travel behavior during human conflict.

Focuses on those who remain in place rather than evacuation/refugee movements.

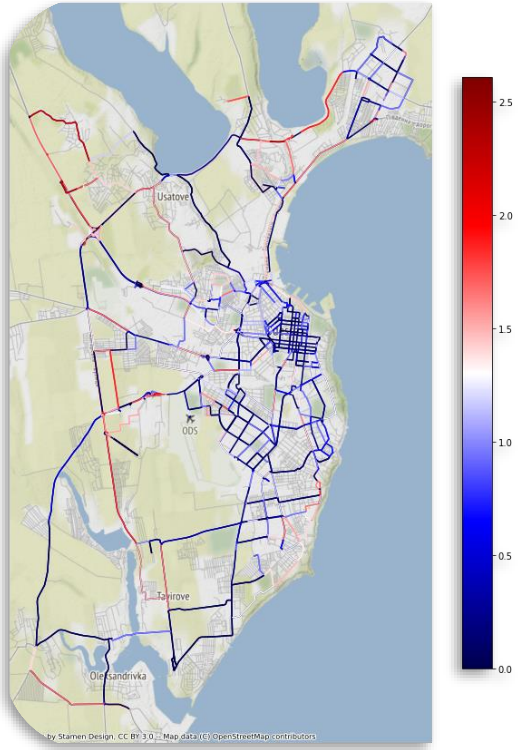
Applications being explored include:

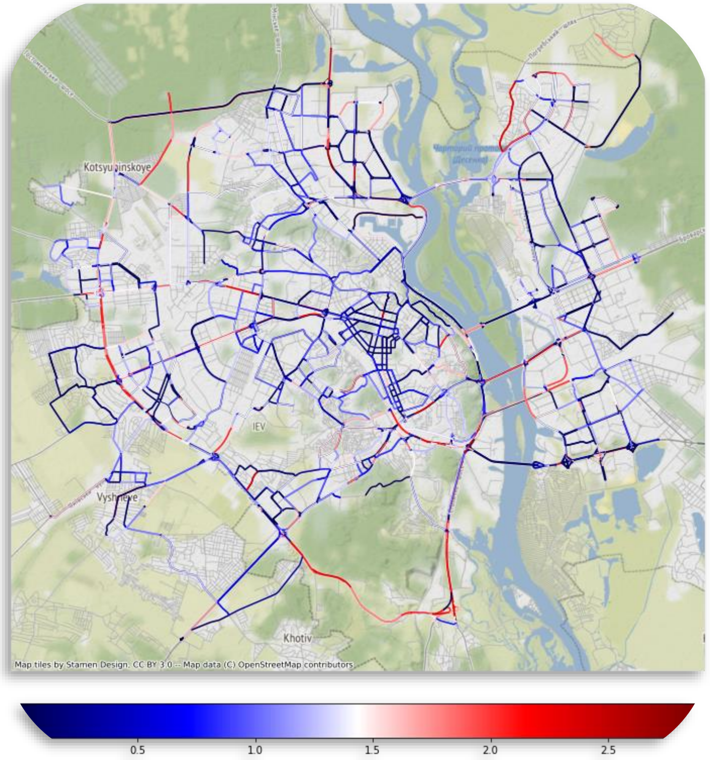
- **Rapid estimation of reconstruction needs**
- **Designing cities that are more resilient to human-conflict**

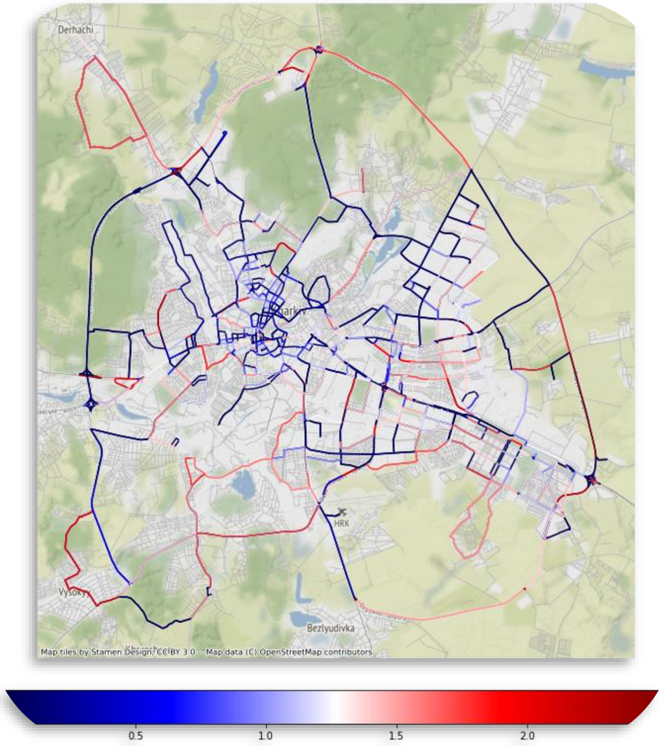
Kyiv
— Links: 4069
— Nodes: 2224

Kharkiv
— Links: 2453
— Nodes: 1017

Odesa
— Links: 1765
— Nodes: 800







Waller, Travis and Qurashi, Moeid and Sotnikova, Anna and Karva, Lavina and Chand, Sai, "**Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data**" *Transportation Research Record: Journal of the Transportation Research Board*, Vol 2677, Issue 10, pp. 491-507, 2023.

Synthesized Timeline (Feb 24, 2022 to April 18, 2022)

(Preprint) Waller, Travis and Qurashi, Moeid and Sotnikova, Anna and Karva, Lavina and Chand, Sai, '**Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data**' (Accepted for Presentation, TRB 2023, In Review Publication)
SSRN: https://ssrn.com/abstract=4185753

Table 1 Ukraine war timeline over the study period

Kyiv		
Ref.	**Event**	**Date(s)**
1	A series of powerful airstrikes on various objects in Kyiv	24.2.2022
2	Battles on Peremogy Avenue and Degtyarivska Street (west part of the city)	25-26.2.2022
3	Rocket attack on a residential building; Kyiv metro goes into shelter mode; passenger transportation is not carried out	26.2.2022
3	Curfew	26-28.2.2022
4	Hit on radioactive waste disposal site of the Kyiv branch of "Radon Association".	28.2.2022
5	Hit in the direction of the TV tower	1.3.2022
6	A Russian projectile hit the Lavina Mall shopping center	14.3.2022
7	Curfew	15-17.3.2022
8	Russian missile partially destroyed Retroville shopping center	20.3.2022
9	Deoccupation of the whole Kyiv region	2.4.2022
Kharkiv		
Ref.	**Event**	**Date(s)**
1	Russian troops began shelling Kharkiv	24.2.2022
2	Massive shelling of residential areas (thirteen times). Several Russian tanks entered Kharkiv	26.2.2022
3	Rocket attack on Freedom Square; regional state administration building partially destroyed; bombs, rockets and shells hit residential buildings and civilian objects. (Casualties: 23)	1.3.2022
4	Mass attack on residential areas in which "Northern Saltivka" micro-district was most affected (40 apartment buildings destroyed, Casualties: 34)	3.3.2022
5	Missile strikes on the Regional State Administration building, Assumption Cathedral, and Karazin University. Shelling of sleeping areas	4.3.2022
6	Russian troops tried to storm Kharkiv. Artillery shelling continued.	15.3.2022
7	The market "Barabashovo" and the town of Merefa were shelled, destroying a school and a cultural center (Casualties: 28)	17.3.2022
8	At least 50 shellings during the day. The Russian military blew up one of the gates of the Oskil reservoir dam (Casualties: 11)	3.4.2022
9	During the night, time-delayed landmines were scattered remotely using artillery in various districts (Casualties: 7)	11.4.2022
Mariupol		
Ref.	**Event**	**Date(s)**
-	Shelling of the city	24.2.2022 (until now)
1	Tanks moved from Donetsk towards Mariupol but were destroyed by the Ukrainian army	27.2.2022
2	In the evening, electricity, gas, and the Internet were cut off in most areas of the city.	28.2.2022
3	Encirclement and blockade of the city by Russia	1.3.2022 (until now)
3	Strikes in all areas of the city, including critical and communal infrastructure objects. Another attempt to break through the defense of Mariupol	1.3.2022
4	Russian troops shelled the Epicenter shopping center, the 22nd and 17th neighborhoods and a blood transfusion station	3.3.2022
5	The capture of Mangush and exit to the sea	8.3.2022
6	An airstrike destroyed a maternity hospital and a hospital in the city center	9.3.2022
7	The capture of Naydenivka, Lyapin, Vynogradar, Sartana	10.3.2022
8	The capture of Volnovakha and the eastern suburbs of Mariupol	12.3.2022
9	"Green corridor" for evacuation	15-18.3.2022
10	Airstrike on the Mariupol Theater (bomb shelter). Russian army broke through the eastern part of the city.	16.3.2022
11	Ukrainian military controls only half of the city, while the occupiers control 17-23 micro districts, the Left Bank, and other parts of Mariupol	17.3.2022
12	Battles for individual buildings and whole blocks	23.3.2022 (until 28.03.2022
Dnipro		
Ref.	**Event**	**Date(s)**
1	Three airstrikes at a kindergarten, an apartment building and a shoe factory	11.3.2022
2	Missile attack on the Dnipro International Airport	15.3.2022

Full time-line at: https://tu-dresden.de/bu/verkehr/ivs/tms/forschung/research-works/travel-behaviour-analysis-of-ukraine-invasion

With indication of severity and event remarks

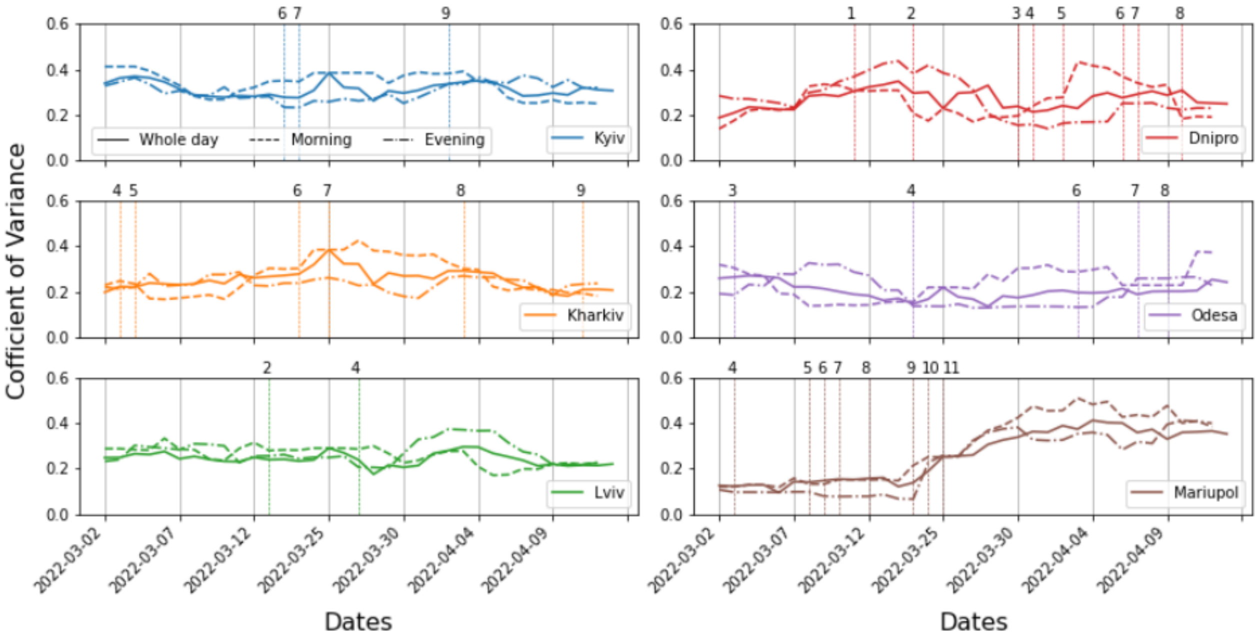
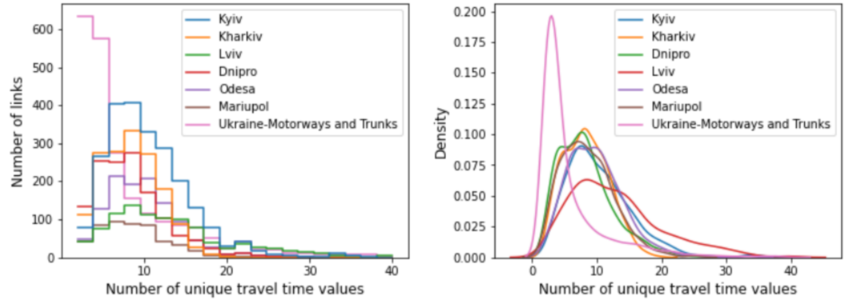


Figure **3** *Network averaged link coefficient of variance for travel times (7-day moving)*

Table 2 Key Statistics from the OD Estimation Analysis

City	*Date*	*% change in average trip length compared to the base case*	*% change in average travel time compared to the base case*	*% change in total demand compared to the base case*
Kyiv	February 28 2022	-	-	-
	March 16 2022	-5.52	-0.28	+3.90
	April 12 2022	+2.74	+1.92	+0.11
Kharkiv	February 28 2022	-	-	-
	March 31 2022	-3.14	+1.55	+6.05
	April 12 2022	+3.40	+11.79	+2.63
Mariupol	February 28 2022	-	-	-
	March 16 2022	+13.11	+28.44	-2.50
	April 12 2022	-6.76	-11.66	+0.58



(a) Histograms of unique link travel times

(b) Probability density functions for unique link travel times

Figure 1 TomTom data reliability plots

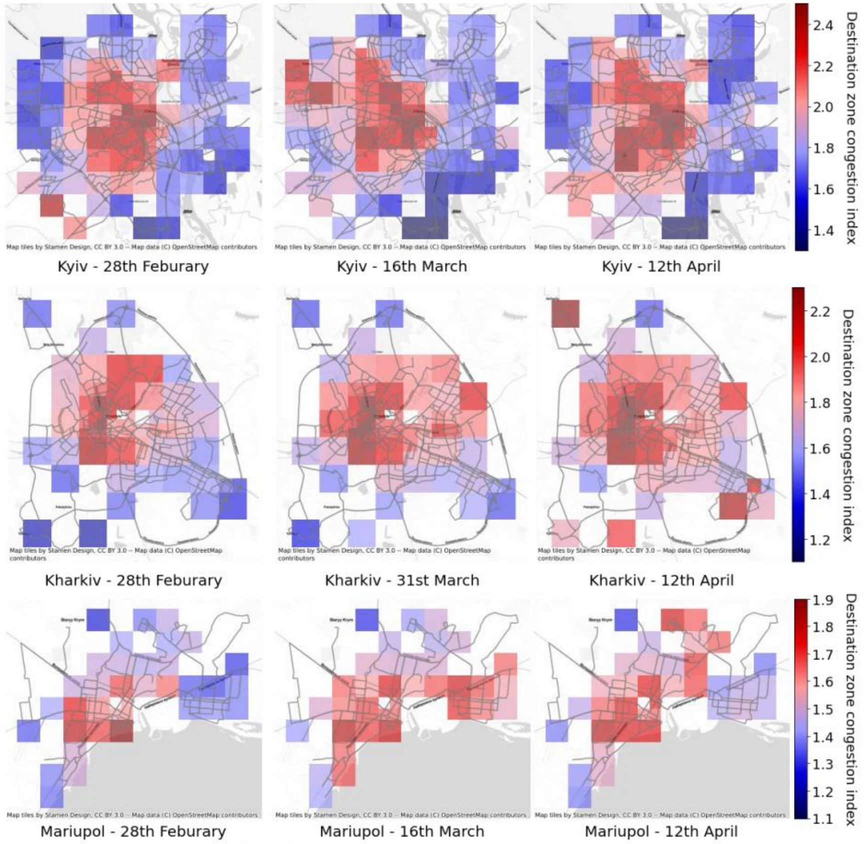


Figure 5 Hue maps of average congestion index for zones as the destination

Rapid Planning Model: Armenia

Links: 3,677

Nodes: 1,962

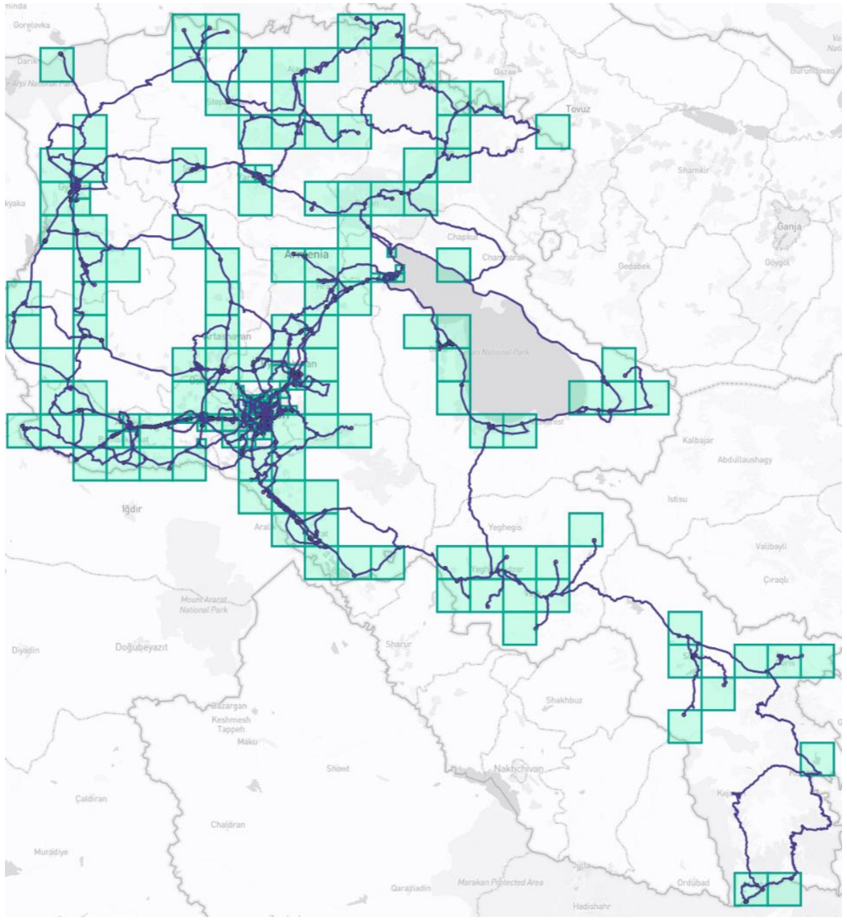
Zones: 175

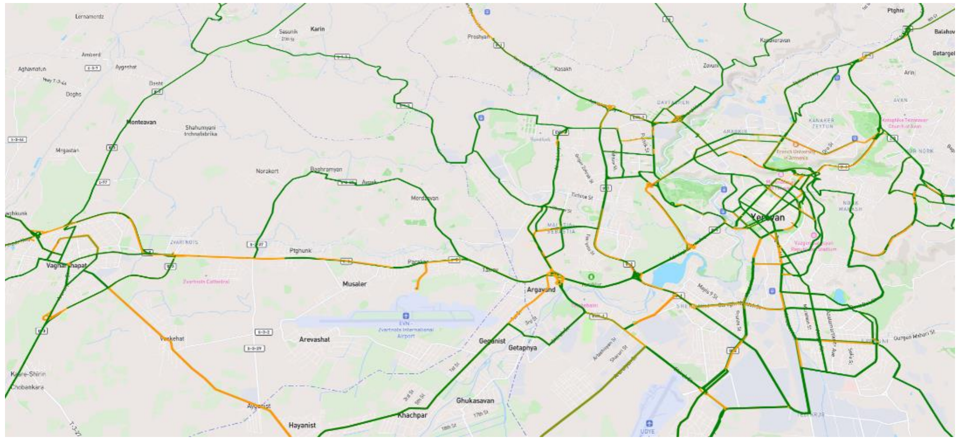
Avg Travel Time: 37 min

Avg Distance: 30.57 km

Modelled:

- **Traffic route assignment**
- **Volume/Capacity**
- **Travel Time**
- **Speed**
- **Congestion**



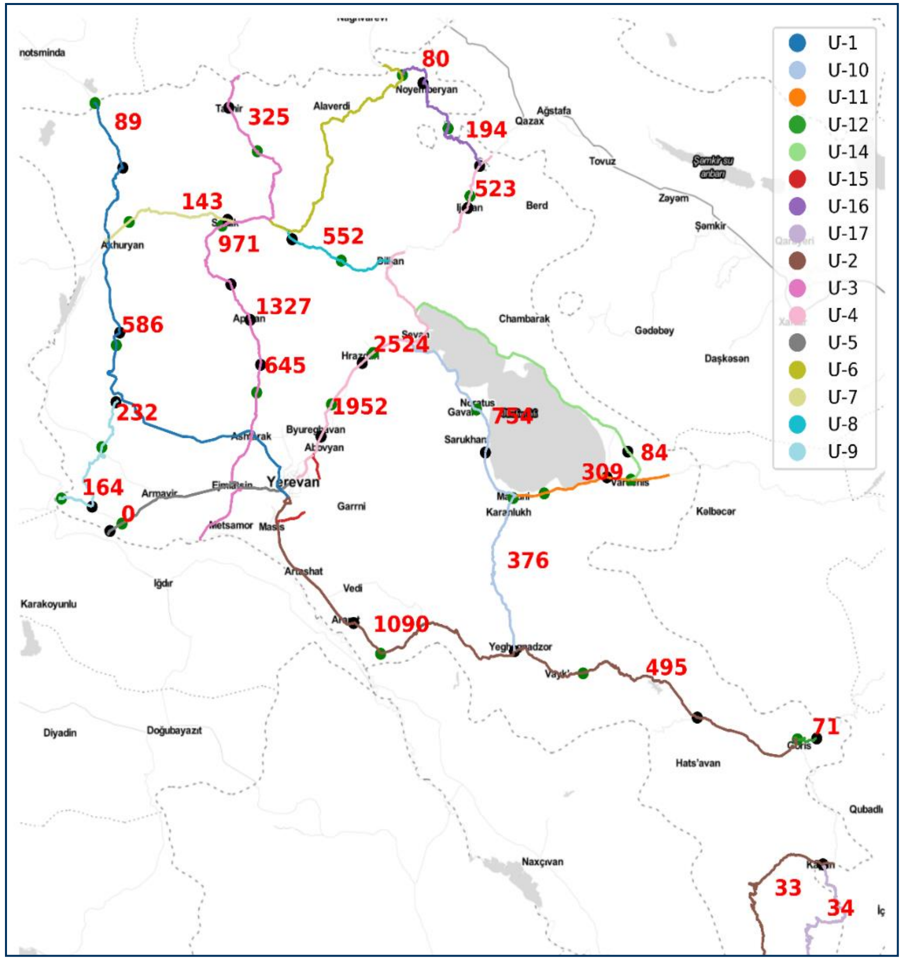


Rapid Planning Model Comparison with Reported Daily Flows

*Reported data is from 2019 unless noted otherwise due to report data omission

Road type	RPModel Estimated AADT	Reported AADT	RPModel Lengths	Reported Lengths
Interstates	3,612 vpd	3,600 vpd	1,798 km	1,724 km
Republican	1,107 vpd	1,078 vpd	1,452 km	1,968 km

Road No.	Name	Reported AADT 2019 Average (vpd)	Rapid Planning Modelled AADTs Monday (12-12-2022 Snapshot in 9-10am) **Throughput** flow along roadway (AADT vpd)
M-1	Yerevan-Gyumri- Georgia border	24,551	23,484
M-3:	Margara-Vanadzor-Tashir-Georgian border:	6,294	8,226
M-4:	Yerevan-San-Ijan-Adr:	19,512	25,932
M-5:	Yerevan-Armavir-Turkey border:	20,390	22,292
M-8:	Vanadzor-Dilijan	1,415 (2018)	3,423
M-10:	Saint-Martuni-Getap	5,117	5,756



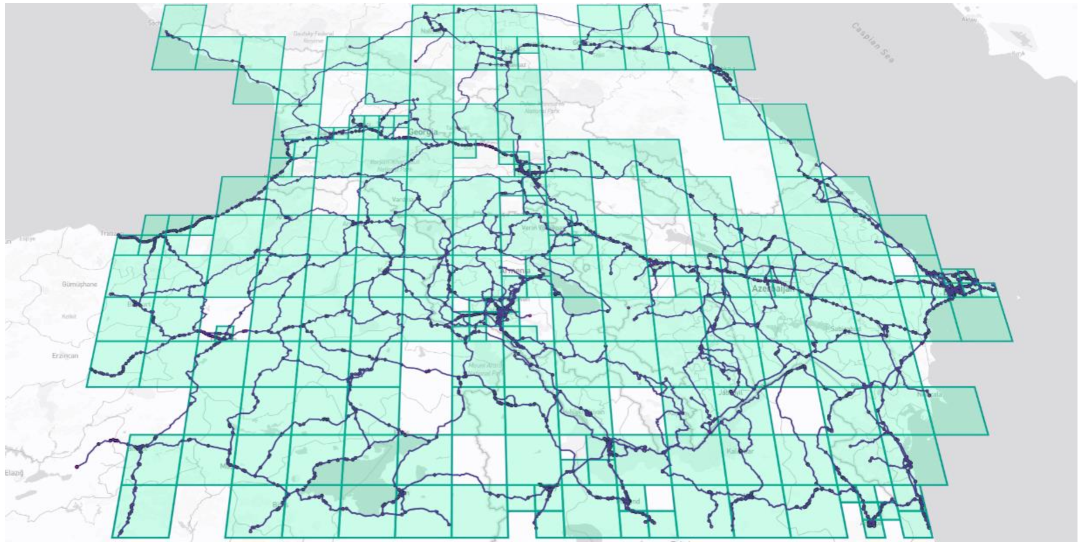
South Caucasus Model

Coverage including
Armenia, Azerbaijan and Georgia
with parts of Iran, Turkey, and Russia.

Two network versions were modelled

<u>First network</u>
20,274 links
Total length of 39,392 km
221 traffic analysis zones

<u>Second streamlined network</u>
6,839 links
Total length of 12,542 km
119 traffic analysis zones



We would like to acknowledge collaboration with NVIDIA

South Caucasus Model

Base Case

63,357,589 total Vehicle Kilometers Traveled (VKT)

Comparison

Travel times collected on ***all*** links

— RMSE 16.19 seconds

76 specific link counts were also provided to support direct comparison by the broader team

Under all borders fully operational "What if" scenario

62,621,005 VKT

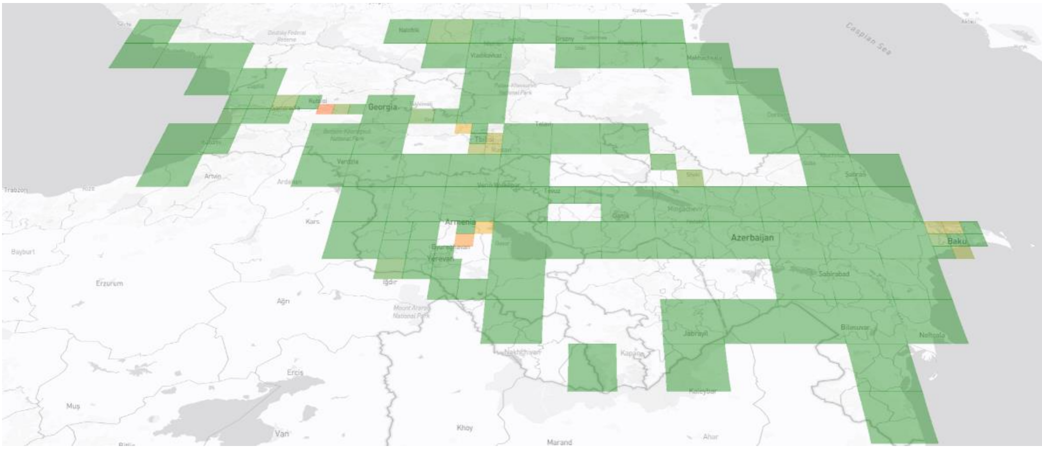
736,586 (1.16%) reduction

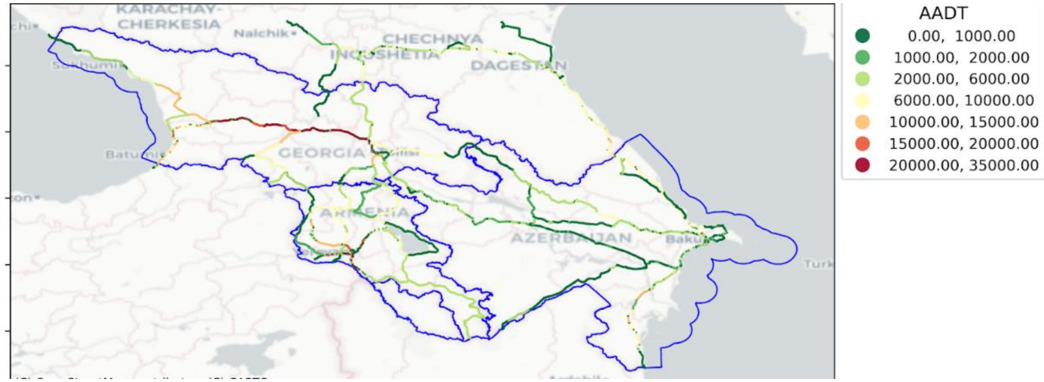
— Note, based on scope of work did not include induced future demand

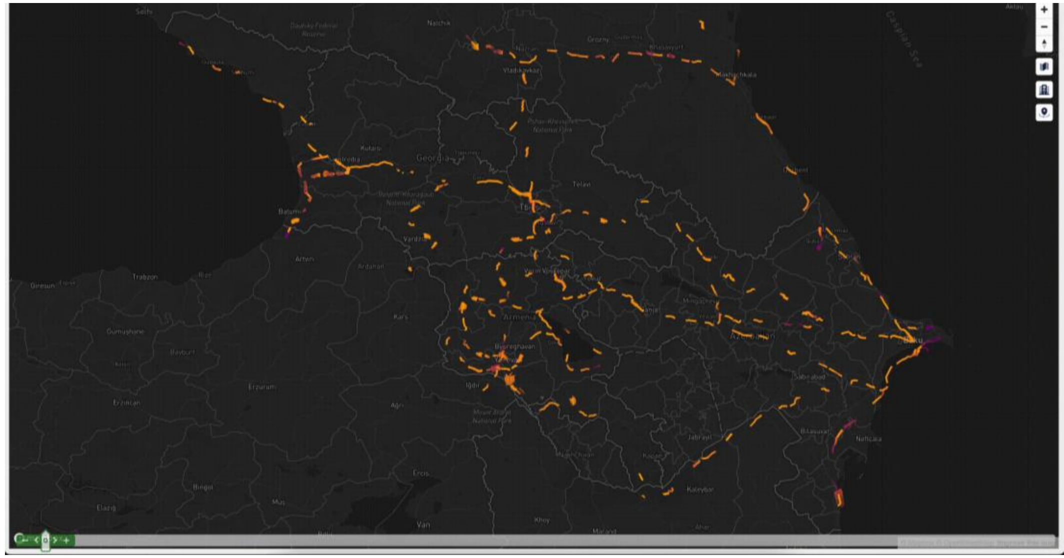
Post-Disaster Needs Assessment (PDNA)

The Armenian and SCR Models are also being used to provide input for a PDNA

- Major flooding in Armenia in May, 2024
- Significant network rerouting observed due to temporary closure of M6





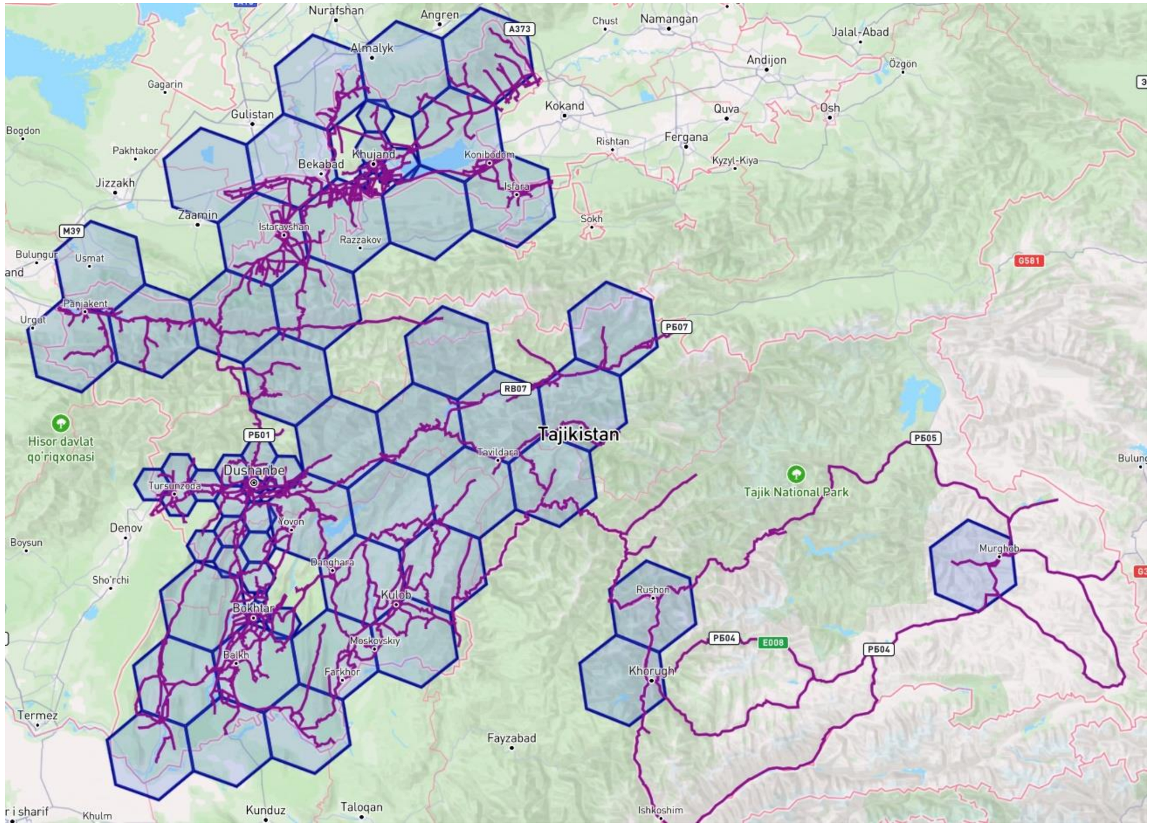


Current Work (in draft) - Tajikistan National Road Network Model

National coverage spanning:

Primary,
Secondary and
Trunk roadways

Total links: 4170



Traffic counts available on 109 links
Travel times collected from Google (midweek, morning)

Network-wide statistics comparing link counts and travel times

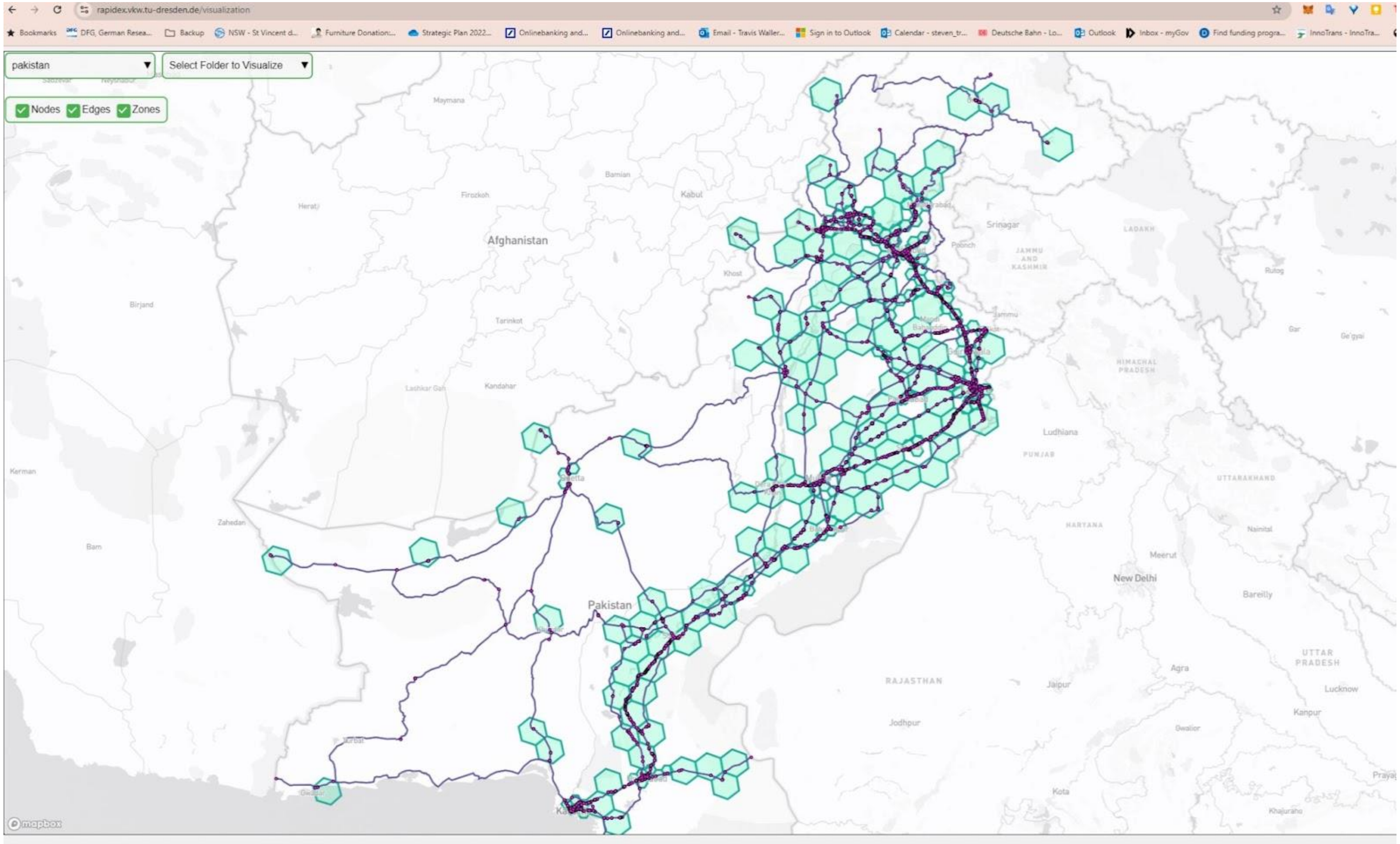
VKT_Estimated (for observed links)	4,499,025 km
VKT_Observed (for observed links)	4,489,053 km
Percentage .Diff	0.22 %
Percentage .Diff for Total Travel Time	6.65 %
Percentage .Diff for Total (Travel Time * distance)	0.32 %

AADT match by classification

Classification	Estimated_AADT	Observed_AADT	AADT_Percent_diff
trunk	8478	7894	7.4%
primary	4526	4591	-1.42 %
secondary	2759	3181	-13.27%

Objective: The model feeds into multi-hazard risk analysis considering environmental disruptions

Initiating Work - Pakistan



Model Scope: With Automation, We Need Better Methods for Quantifying and Embedding Ethics

Some of our Relevant Papers (Examples)

J Duthie, K Cervenka, ST Waller (2007) “**Environmental justice analysis: challenges for metropolitan transportation planning**” Journal of the Transportation Research Board, Vol 2013, pp. 8-12, (Fred Burggraf Paper Award)

T Zhang, C Niu, D Nair, V Dixit, ST Waller (2023) “Equity analysis and improvement in transportation resilience optimisation at the pre-event stage” Transportation research part D: Transport and Environment, Vol. 122.

D Rey, DJ Nair, K Almi'ani, ST Waller (2018) “**A tree-based heuristic for equitable food relief operations”** In Transportation Research Board 97th Annual Meeting. Washington DC.

EM Ferguson, J Duthie, A Unnikrishnan, ST Waller (2012) "**Incorporating equity into the transit frequency-setting problem**", Transportation Research Part A - Policy and Practice, vol. 46, pp. 190 - 199

Grants (Examples)

Australia Research Council Discovery Grant “**Quantifying Ethics-related Metrics for Transport Network Systems**” ST Waller, TH Rashidi, D Rey, D Nuir and S Jian.

Australia Research Council Linkage Grant “**Planning and operational models for food rescue and delivery to the poor**” V Dixit, TH Rashidi and ST Waller

U.S. Southwestern University Transportation Research Center “**Incorporating Environmental Justice Measures into Equilibrium-Based Transportation Network Design Models**” ST Waller

Will briefly discuss the first of these, Environmental Justice

Duthie and Waller (2009) on Metrics for Environmental Justice

Mandate: Respond to U.S. Presidential Order to use Environmental Justice in infrastructure planning

Agency needed a quantified method of incorporating novel concept for them

An early example of digitizing our emerging values into the formalized planning process

The paper won the TRB Fred Burggraf Award

$$\min_{g \in \{0,1\}} Z\left(v^*(g), g\right) \tag{1}$$

subject to

$$\sum_{l \in L \setminus I} g_l = \theta \tag{2}$$

$$v^*(g) = \arg\min_{v} \sum_{l \in L} \int_{x=0}^{v_l} t_l(x)\,dx \tag{3}$$

subject to

$$v = Ah \tag{4}$$

$$d = Bh \tag{5}$$

$$v \geq 0 \tag{6}$$

$$t_l(v_l, g_l) = t_l(0) \times \left(1 + \alpha\left(\frac{v_l}{u_l + g_l \gamma}\right)^{\beta}\right) \quad \forall l \in I \tag{7}$$

$$t_l(v_l) = t_l(0) \times \left(1 + \alpha\left(\frac{v_l}{u_l}\right)^{\beta}\right) \quad \forall l \in L \setminus I \tag{8}$$

$$Z_1 = \frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij} / e_{ij}^f}{\sum_{ij} d_{ij} p_{ij}}; \qquad Z_2 = \frac{\sum_{ij} s_{ij}^f d_{ij} / e_{ij}^f}{\sum_{ij} d_{ij}};$$

$$Z_3 = \left(\frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij} / e_{ij}^f}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} s_{ij}^f d_{ij} (1 - p_{ij}) / e_{ij}^f}{\sum_{ij} d_{ij} (1 - p_{ij})}\right)^2;$$

$$Z_4 = \left(\frac{\sum_{ij} \left(s_{ij}^f d_{ij} p_{ij} / e_{ij}^f - s_{ij}^0 d_{ij} p_{ij} / e_{ij}^0\right)^2}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} \left(s_{ij}^f d_{ij} (1 - p_{ij}) / e_{ij}^f - s_{ij}^0 d_{ij} (1 - p_{ij}) / e_{ij}^0\right)^2}{\sum_{ij} d_{ij} (1 - p_{ij})}\right)^2;$$

$$Z_5 = \frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij}}{\sum_{ij} d_{ij} p_{ij}}; \qquad Z_6 = \frac{\sum_{ij} s_{ij}^f d_{ij}}{\sum_{ij} d_{ij}};$$

$$Z_7 = \left(\frac{\sum_{ij} s_{ij}^f d_{ij} p_{ij}}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} s_{ij}^f d_{ij} (1 - p_{ij})}{\sum_{ij} d_{ij} (1 - p_{ij})}\right)^2;$$

$$Z_8 = \left(\frac{\sum_{ij} \left(s_{ij}^f d_{ij} p_{ij} - s_{ij}^0 d_{ij} p_{ij}\right)^2}{\sum_{ij} d_{ij} p_{ij}} - \frac{\sum_{ij} \left(s_{ij}^f d_{ij} (1 - p_{ij}) - s_{ij}^0 d_{ij} (1 - p_{ij})\right)^2}{\sum_{ij} d_{ij} (1 - p_{ij})}\right)^2$$

TABLE 2 Range of Fitness and Number of Generations to Convergence

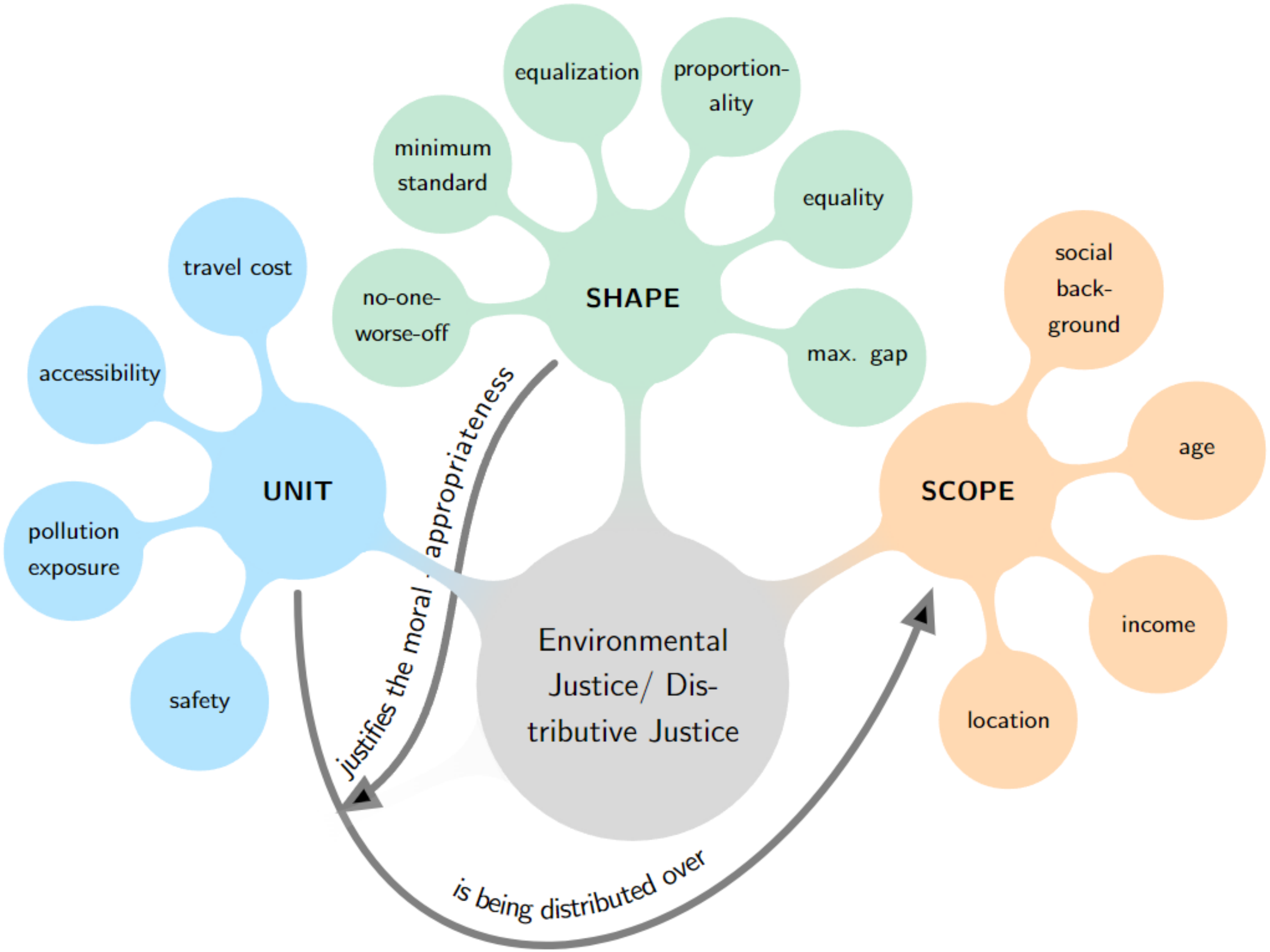
Objective Function	Z^{min}	Z^{max}	$n_{converge}$
Z_1	1.98	2.31	7
Z_2	1.99	2.23	6
Z_3	4.00×10^{-5}	8.52×10^{-4}	17
Z_4	0.44	206.08	29
Z_5	3.91	4.45	5
Z_6	3.98	4.51	5
Z_7	5.27×10^{-3}	8.90×10^{-3}	16
Z_8	8.06	2,480.51	12

Ethics Metrics – Current Ongoing Work (Current ARC Discovery Grant)

Similarly quantify more fundamentally across mobility considering broader ethical foundations (an example set)

Metric	Ethical theory	Type	Target impact
Utilitarian	Consequentialism/ Distributive justice	Equity	Maximizes the welfare of all user groups
Rawl's Egalitarian	Deontological/ Distributive justice	Equity	Maximizes the welfare of the least advantaged user group
CBA with distributive weights	Consequentialism/ Distributive justice	Evaluation measure	Maximizes the welfare by fair distribution of benefits and costs over user groups
CBA with equity weights	Consequentialism/ Distributive justice	Evaluation Measure	Maximizes the welfare by equitable distribution of benefits and costs
Variance	Distributive injustice	Statistical	Minimizes dispersion over user groups
Gini	Distributive injustice	Inequality	Minimizes the deviation of welfare distribution with the (equal) uniform distribution
Theil's Entropy	Distributive injustice	Inequality	Minimizes redundancy, lack of diversity, isolation
Atkinson	Distributive injustice	Inequality	Minimizes the deviation of welfare distribution, given a particular degree of inequality aversion
Social gradient	NA	Enviro. Justice	Quantifies the correlation between welfare/goods and social status

Our Current Work in Germany, Australia and Hong Kong

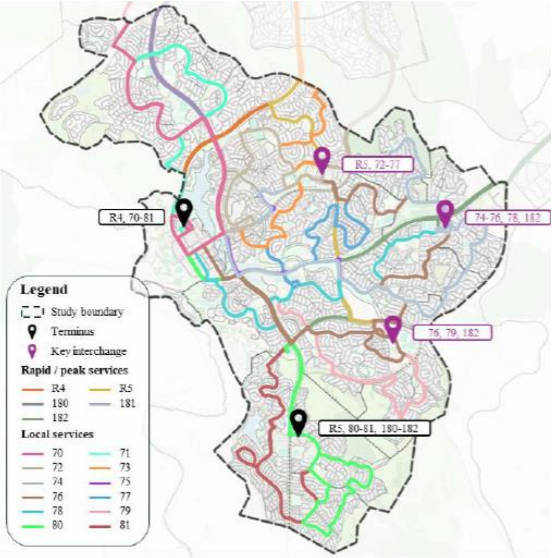


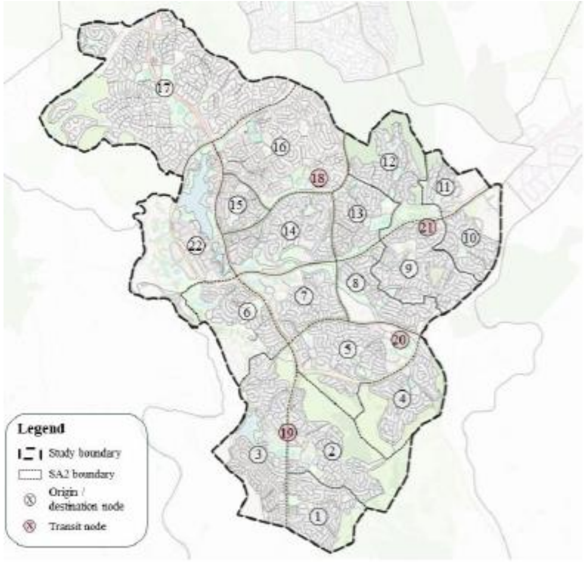
Adapted Jafino (2021) Framework for Model Quantification

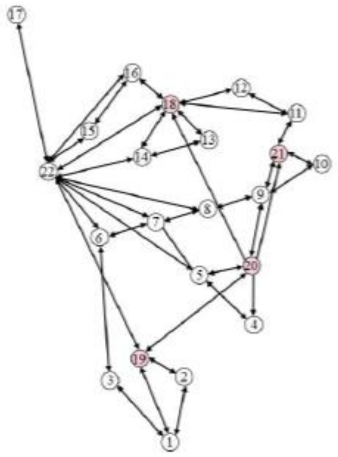
Developing methods to incorporate varying measures for equity and justice into automated transport modeling tools

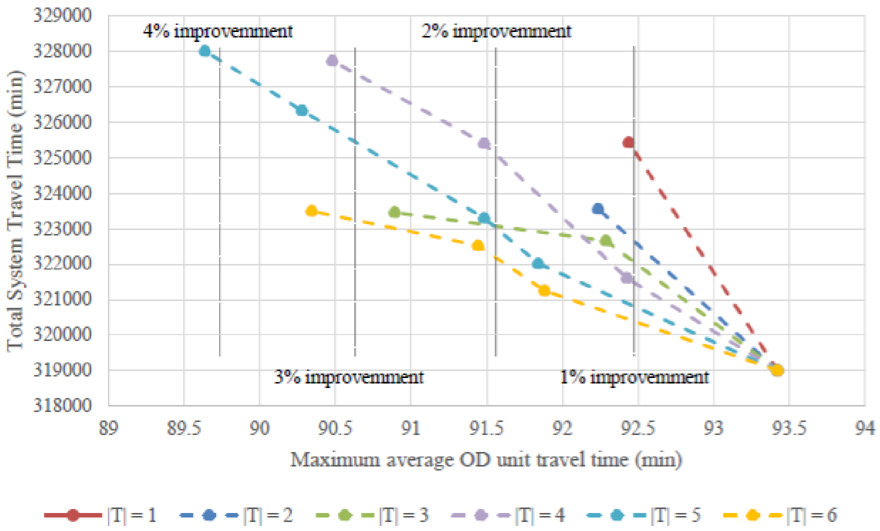
Equity Measurement	Formulation
Rawl's Egalitarian (RE)	$RE = \max \sum_{i=1}^{k} Y_i$
Utilitarianism (U)	$U = \max \sum_{i=1}^{n} Y_i$
Gini index (GINI)	$GINI = \frac{1}{2n^2 \bar{Y}} \sum_{i=1}^{n} \sum_{j=1}^{n} \lvert Y_i - Y_j \rvert$
Theil index (THEIL)	$THEIL = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{Y_i}{\bar{Y}} \log \log \frac{Y_i}{\bar{Y}} \right)$
Atkinson index (ATK)	$ATK = \begin{cases} 1 - \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{Y_i}{\bar{Y}} \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}, \epsilon \neq 1 \\ 1 - \frac{1}{\bar{Y}} \left(\prod_{i=1}^{n} Y_i \right)^{\frac{1}{n}}, \epsilon = 1 \end{cases}$
Sadr's theory of Justice (SADR)	$SADR = \begin{cases} \max \sum_{i=1}^{n} Y_i; \\ s.t\ Y_i > m1 \times Y_j, \forall i,j \\ \sum_{i,j} \frac{Y_i - Y_j}{2n^2 \bar{Y}} < m2 \end{cases}$
Relative mean deviation (RMED)	$RMED = \frac{1}{n} \sum_{i=1}^{n} \lvert \frac{Y_i}{\bar{Y}} - 1 \rvert$
Mean log deviation (LDEV)	$LDEV = \frac{1}{n} \sum_{i=1}^{n} \lvert \log \log Y_i - \log \log \bar{Y} \rvert$

Ongoing Work: Access, Inequality and "Equity over Time" (EoT)









- Canberra, Australia Case Study for bus frequency with **Equity over Time** (EoT):
  E. Qiu, D. Rey, and S.T. Waller "Multi-period bus frequency optimization and fleet rebalancing based on equity over time" (under review), 2024.
- Used "Capability Approach" to Equity
- Quantified trade-offs between equity and efficiency along with novel computational methods for solving the difficult optimization problem

Other Related Works:

J. Rottemberg, M. Ghasri, H. Grzybowska, A. Dockery, S.T. Waller "Inequality and access to services for remote populations: An Australian case study" Journal of Transport Geography, Vol. 105, 2022.

E.M. Ferguson, J. Duthie, A. Unnikrishnan, S.T. Waller "Incorporating equity into the transit frequency-setting problem" Transportation Research Part A: Policy and Practice, Vol. 45, 2012.

Equity in Transportation and Environmental Justice

Understanding Fairness in Transportation

Fairness in transportation ensures that everyone, regardless of background, has access to resources, opportunities, and decision-making.

- **Non-Discrimination**
- **Equal Access**
- **Rights Protection**

Why does it matter in Transportation?

Benefits & burdens should be fairly shared among groups. Addressing disparities ensures that disadvantaged communities aren't unfairly burdened.

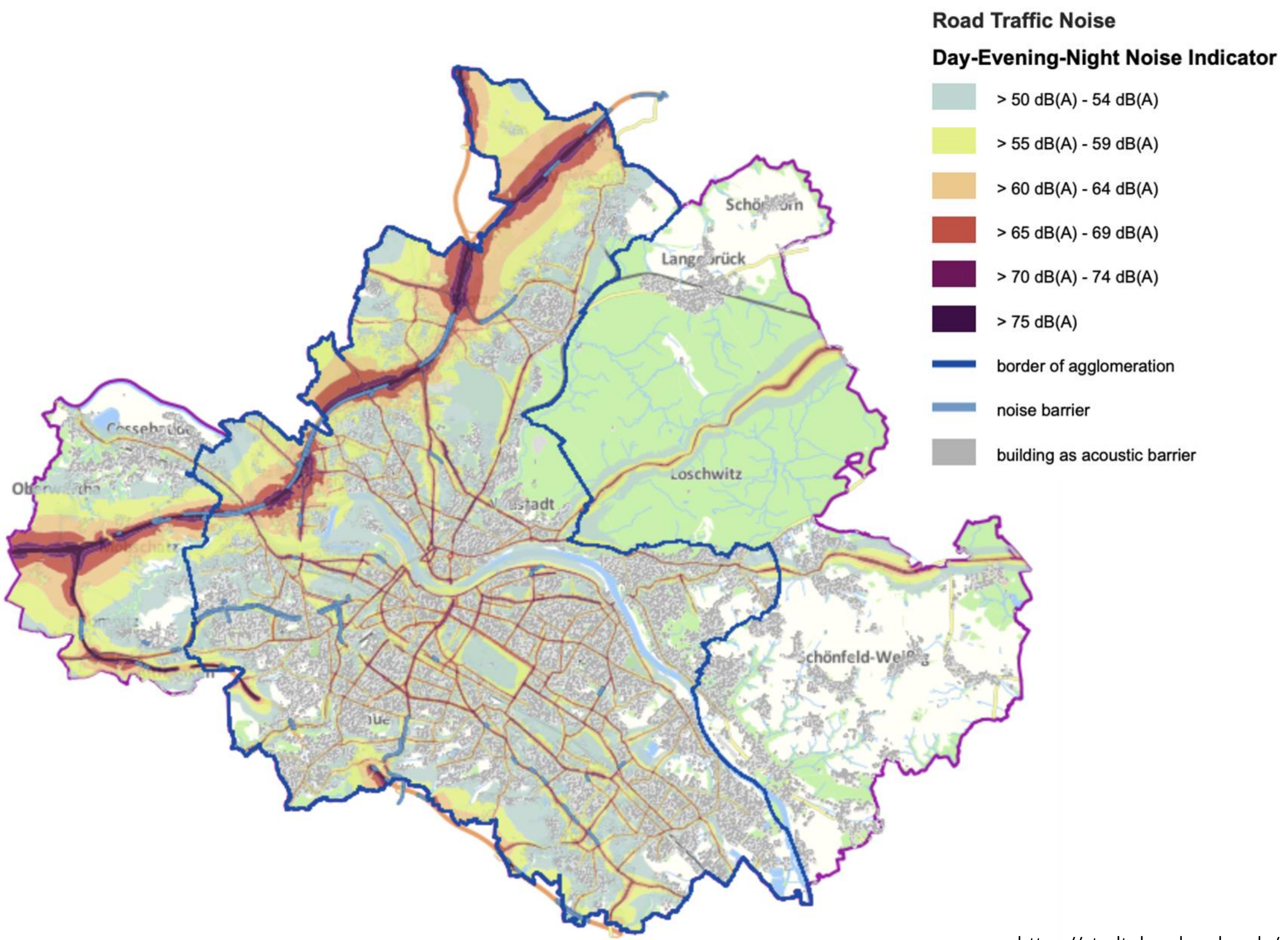
- **Equitable Distribution**
- **Social Equity**

Environmental Justice and Its Impact

Low-income and other disadvantaged communities often face higher levels of traffic-related pollution and noise which leads to sleep disorders, mental health issues, and cardiovascular disease.

- **Pollution Exposure**
- **Health Impacts**

Ongoing Work: Dresden Case-study (Noise map)



https://stadtplan.dresden.de/

Assessing Road Traffic Noise Emissions Across Protected Groups

- **Average Noise of Protected Districts:**

$$\text{Average Noise (Protected)} = \frac{1}{n_{\text{protected}}} \sum_{i=1}^{n_{\text{protected}}} x_i$$

- **Average Noise of Unprotected Districts:**

$$\text{Average Noise (Unprotected)} = \frac{1}{n_{\text{unprotected}}} \sum_{i=1}^{n_{\text{unprotected}}} x_i$$

- **Overall Average Noise Level:**

$$\text{Overall Average Noise} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

- **Absolute Difference in Noise Levels:**

$$\text{Absolute Difference} = |\text{Average Noise (Protected)} - \text{Average Noise (Unprotected}$$

- **Disparity Index Formula:**

$$\text{Disparity Index} = \frac{\text{Absolute Difference}}{\text{Overall Average Noise}}$$

- $n_{\text{protected}}$ and $n_{\text{unprotected}}$: Number of data points in the protected and unprotected districts, respectively.
- x_i: Average noise emission levels in dB(A) for link i.
- n: Total number of data points across all districts.

The research is focused on assessing road traffic noise emissions in Dresden to determine if protected groups are disproportionately impacted by noise pollution.

- **Protected Groups**: Regions with high percentages of foreign populations and low-income levels were identified and considered as protected groups for the purpose of this analysis.
- **RLS-19 Standard**: To calculate average noise emissions across various road links throughout the city of Dresden, specifically focusing on comparing noise levels between protected and unprotected districts.
- **Rapidex Tool**: To gather precise traffic volume and maximum speed data for each link, which were essential for accurate noise modeling and assessing the impact on the identified protected groups.

Key Outputs

- **Disparity Index:** The Disparity Index, calculated as 3.01, highlights the differences in noise exposure between protected and unprotected populations. This metric ***quantifies the extent to which vulnerable groups can be disproportionately affected*** by higher noise levels.

Ongoing Work: Road Vehicle Carbon and Emission Modelling

With the new data and methods, metrics can be more readily calculated

Example: Road vehicle carbon

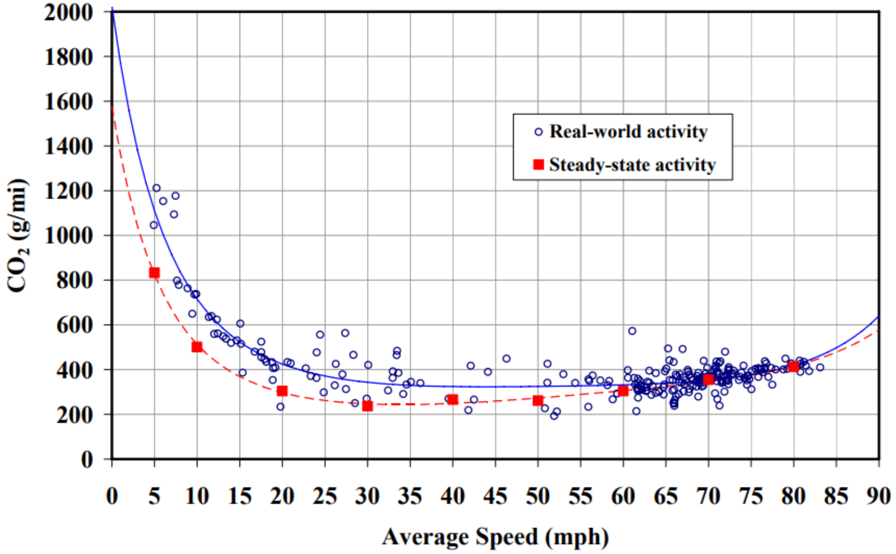
3 Methods examined including:

Method #1:

Utilizing the fitted fourth-order polynomial equation (Barth equation).

Where y is CO2 emissions in g/mi, and x is the average trip speed in mph.

— Barth, M., & Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. Transportation research record, 2058(1), 163-171.



$$\ln(y) = b_0 + b_1 \cdot x + b_2 \cdot x^2 + b_3 \cdot x^3 + b_4 \cdot x^4$$

Table 1. Derived line-fit parameters for Eqn. (1).

	Real-World
N	241
R^2	0.668
b_0	7.613534994965560
b_1	- 0.138565467462594
b_2	0.003915102063854
b_3	- 0.000049451361017
b_4	0.000000238630156

Comparison to the International Energy Agency (IEA) Report for CO_2 emissions

London:

- IEA: UK road transport emissions are 114 million tonnes per year
  - 312k tonnes per day, nationally
- Using a common peak-hour factor of 10 (i.e., two 3-hour peak periods, 4 off-peak)
  - **31k** tonnes per peak hour, nationally
- The Automated London *city model* reports **2.9k** tonnes for a specific 8-9am case
  - Approximately 9.3% of UK road carbon per peak hour

Auckland:

- IEA: New Zealand road transport emissions are 14.3 million tonnes per year
  - **3.9k** tonnes per peak hour
- The automated Auckland city model reports **778** tonnes for a specific 8-9 am case
  - Approximately 19.85% of New Zealand's road carbon per peak hour

Methods 2 and 3 for road carbon estimation

Method 2: Similar to Barth approach though volume-capacity ratios referenced.

Tsanakas, N., Ekström, J., & Olstam, J. (2017). Reduction of errors when estimating emissions based on static traffic model outputs. Transportation research procedia, 22, 440-449.

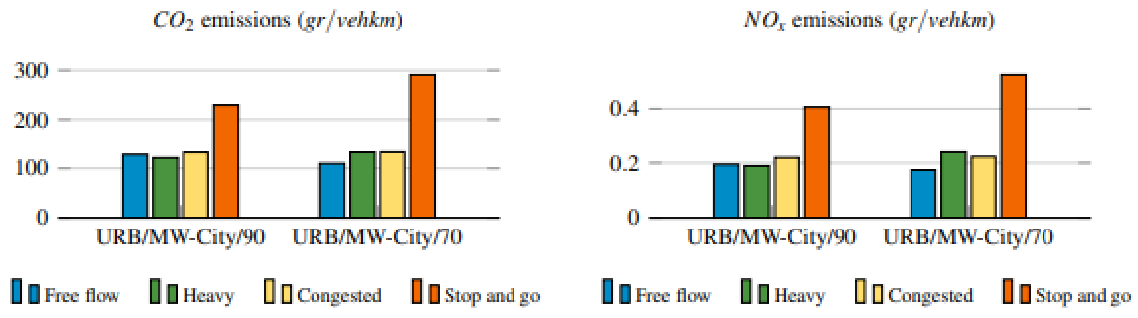


Figure 1. HBEFA emission factors; (a) CO_2 (b) NO_x.

Table 1. Volume/Capacity ratio thresholds.

Speed limit (km/h)	Free flow	Heavy	Congested	Stop and go
90	V/C <0.65	0.65≤ V/C <0.85	0.85≤ V/C <1.35	V/C ≥1.35
70	V/C <0.39	0.39≤ V/C <0.84	0.84≤ V/C <1.35	V/C ≥1.35
<50	V/C <0.52	0.65≤ V/C <0.78	0.65≤ V/C <1.22	V/C ≥1.22

Method 3: uses a MOVES function (U.S. Environmental Protection Agency 2014) to model energy consumption alongside BPR to model link performance function:

BPR function:

$$t_{ij} = t_{ij}^0 \cdot \left(1 + \alpha\left(\frac{x_{ij}}{c_{ij}}\right)^\beta\right) \quad \forall (i,j) \in A \qquad (1)$$

MOVES function:

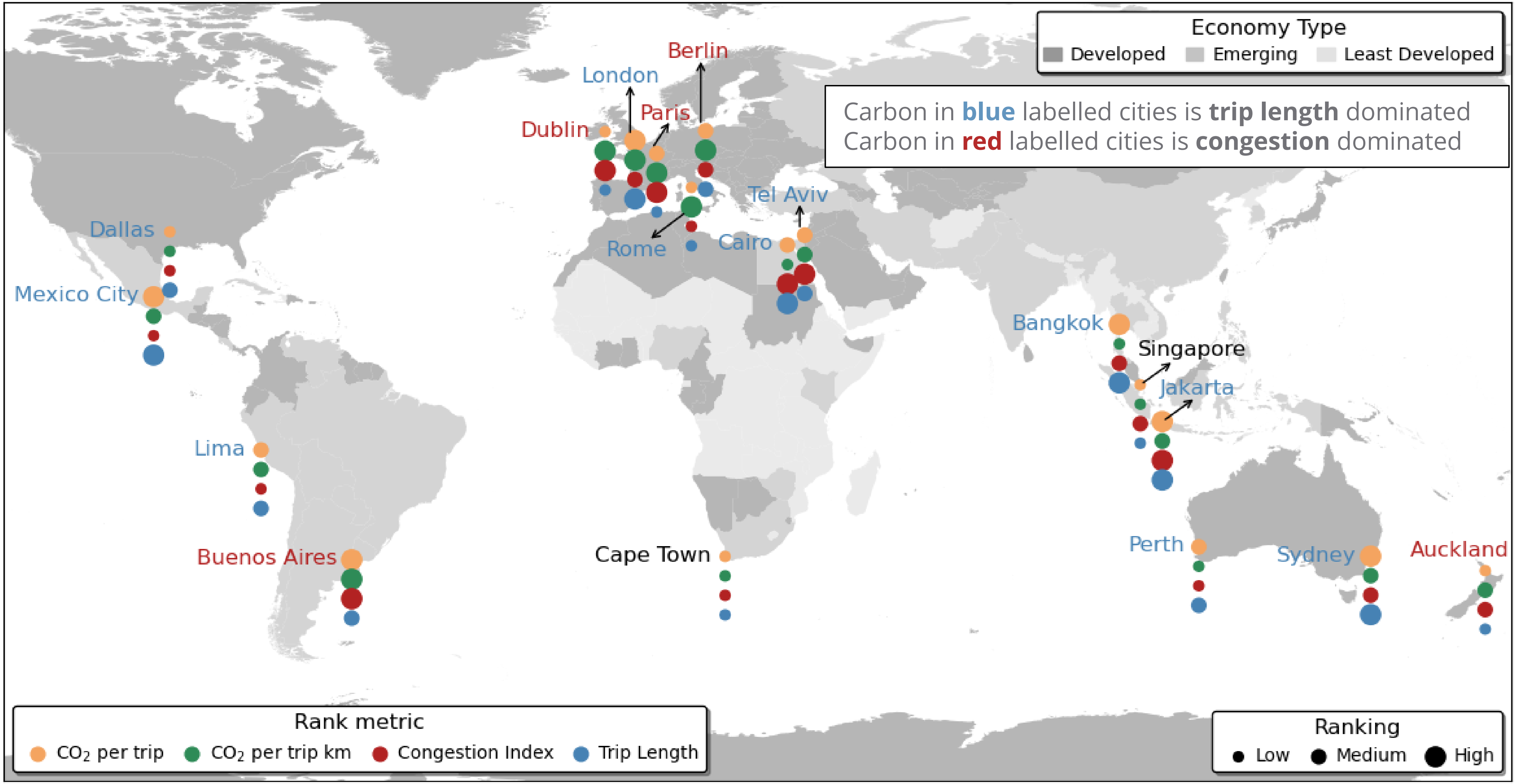
$$\begin{cases} LTEC_{ij} = TEC_{ij} \cdot L_{ij} \\ TEC_{ij} = 9.9 \cdot S_{ij}^{-0.56} \end{cases} \quad \forall (i,j) \in A \qquad (2)$$

where TEC_{ij} is the transport energy consumption rate per vehicle kilometre travelled on link (i,j), which is measured in kWh/km if the dimension of speed S_{ij} is km/h. By substituting the BPR function into Formula (2), the TEC_{ij} function becomes:

We employed this approach in this study:

Zhang, X., & Waller, S. T. (2019). Implications of link-based equity objectives on transportation network design problem. Transportation, 46(5), 1559-158

Comparative analysis of world cities



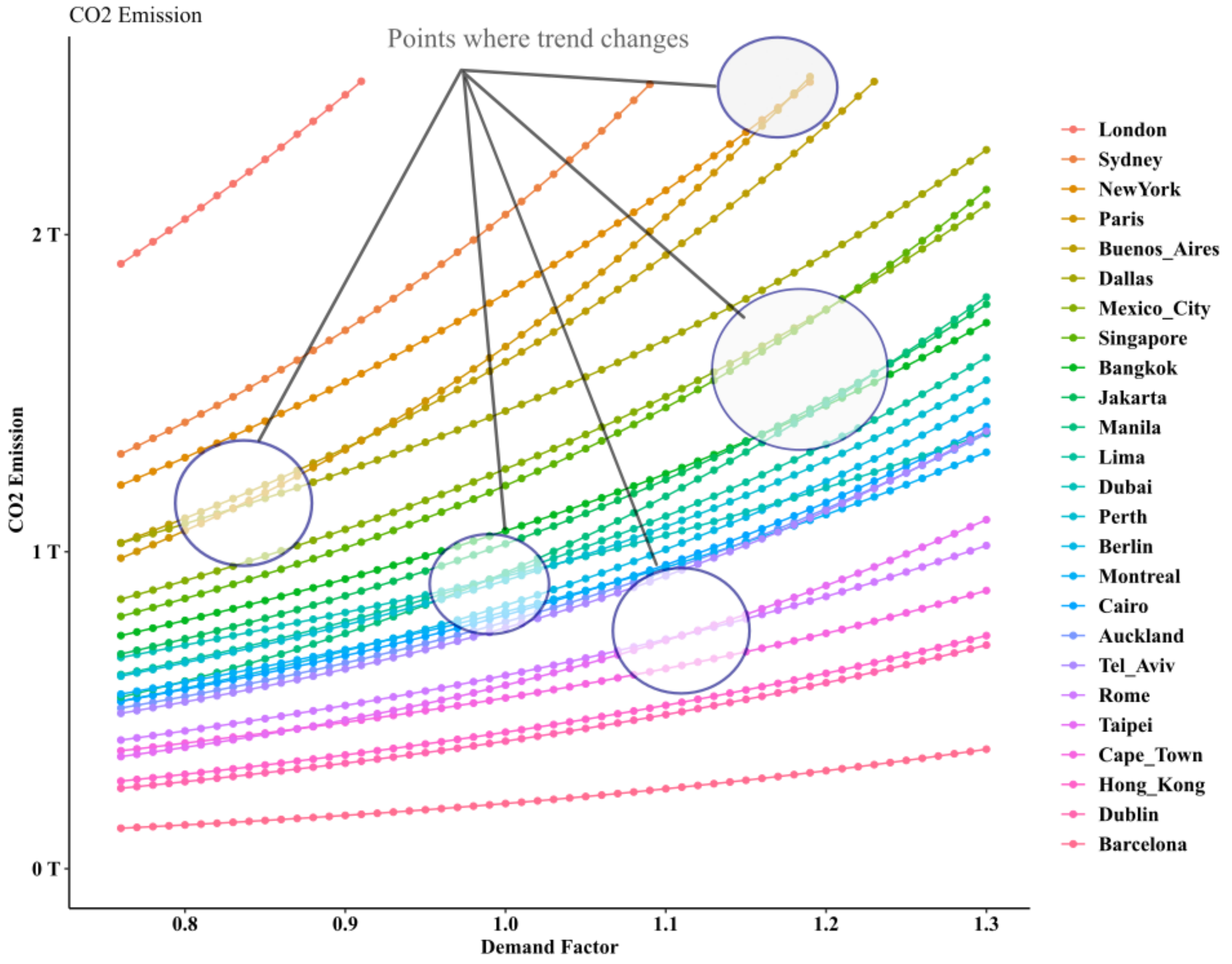
Quantification of the Gradient of Road Traffic Carbon (Carbon Sensitivity)

Current work - in draft

- **The approach embeds a (travel demand)-(network supply) equilibrium**

- **This facilitates examination across numerous demand scenarios**

- **As a result, the gradient of road traffic carbon can be quantified**
  - This allows for a different lens on city to city comparison



Demand sensitivity of carbon emitting intensity

Current work – in draft

Changing demand levels of the network that directly affects congestion to measure the sensitivity of the carbon emitting intensity. Demand sensitivity helps to better filter cities carbon patterns

Demand sensitivity rank

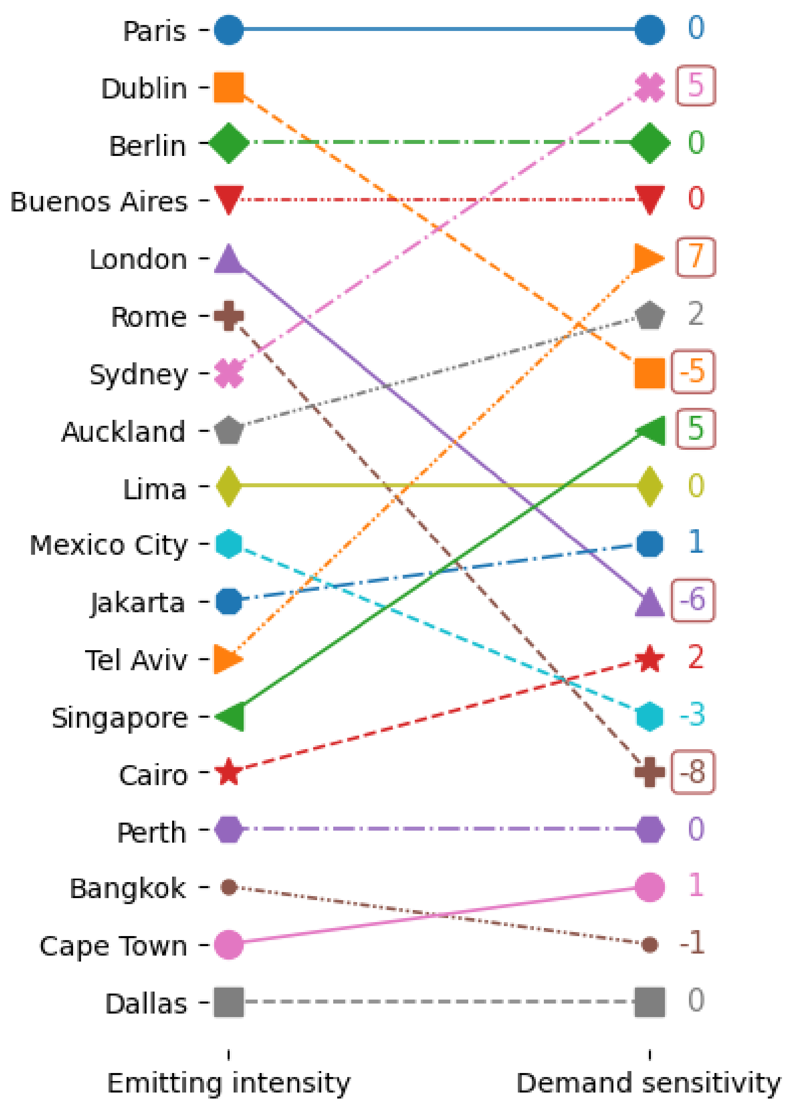
↑ High demand sensitivity refer to more congested cities with higher network traffic saturation

↓ Low demand sensitivity refer to lower congested cities with lower traffic network saturation

Rank change from emitting intensity

↑ Positive to no rank shift refer to cities homogenous in network traffic patterns (well defined case for single target policy)

↓ Negative rank shifts refer to heterogeneity in network traffic patterns (not well defined boundaries may requiring different policies in different areas)



Do network parameters have any influence on gradient of emissions?

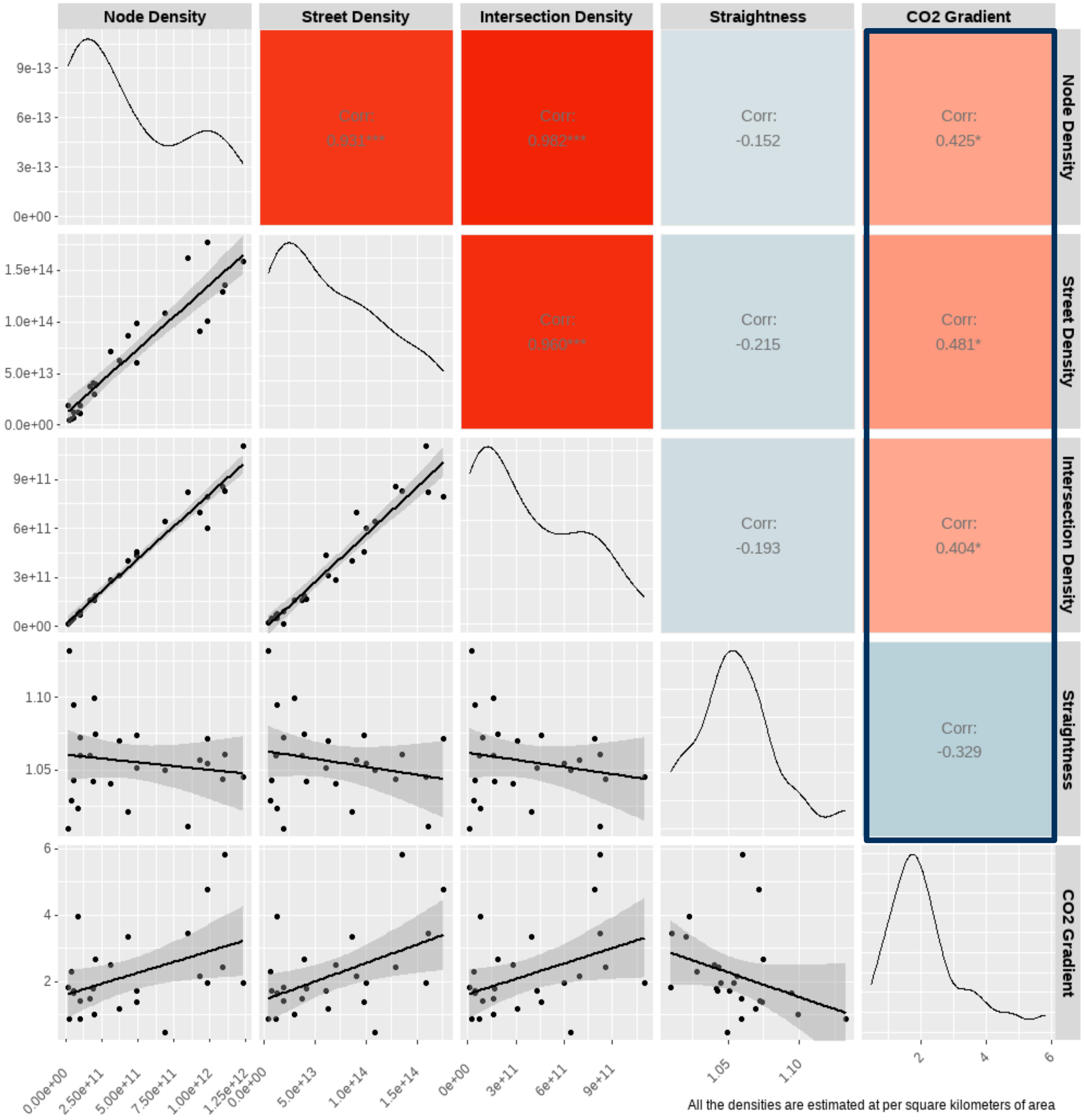
Current work – in draft

More than 25 different network parameters investigated so far

Defining size, shape, capacity, and orientation of road networks in world cities

Parameter examples

(i) Street Density (per km)
(ii) Node Density (per km)
(iii) Intersection Density (per km)
(iv) Straightness / Circuity



All the densities are estimated at per square kilometers of area

Summary

- **Based on previous fundamental research, new methods for the rapid modelling and planning of traffic networks have been deployed**

- **Significant efficiencies have been observed**
  - This frees up time and resources to develop broader metrics and applications
    - Equity, environmental justice, carbon, carbon sensitivity, noise
    - The goal is to automate what can be automated, freeing up resources for emerging problems

- **New observations become possible with this scale of modelling**
  - Including differing "Carbon Sensitivity" to demand changes

- **Most critically: while taking advantage of the advances in AI/Big Data we cannot lose the fundamental ability to plan through hypothetical scenarios**
  - We need planning models, not just analytics

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Thank you!

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