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Australian
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concept

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Australian National University (ANU)

How We Move into the Future: Automated Transport Planning that Leverages Pervasive Data and Evolutionary Algorithms for Humancentric Mobility

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.

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 Professorship at the Australian National university

Scientific Representation of Models

Underlying mathematical definitions, often of behavior

Opens up new questions from model explanatory capability

Model and Simulation Computational Performance

Faster, bigger models (across macro/micro/meso)

Opens up new questions from scale

Interdisciplinary Scope of Model

What does the model attempt to explain

Opens up new questions into non-traditional fields

D I S R U P T I O N

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

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1. Electric Vehicles

Very early research in the area of

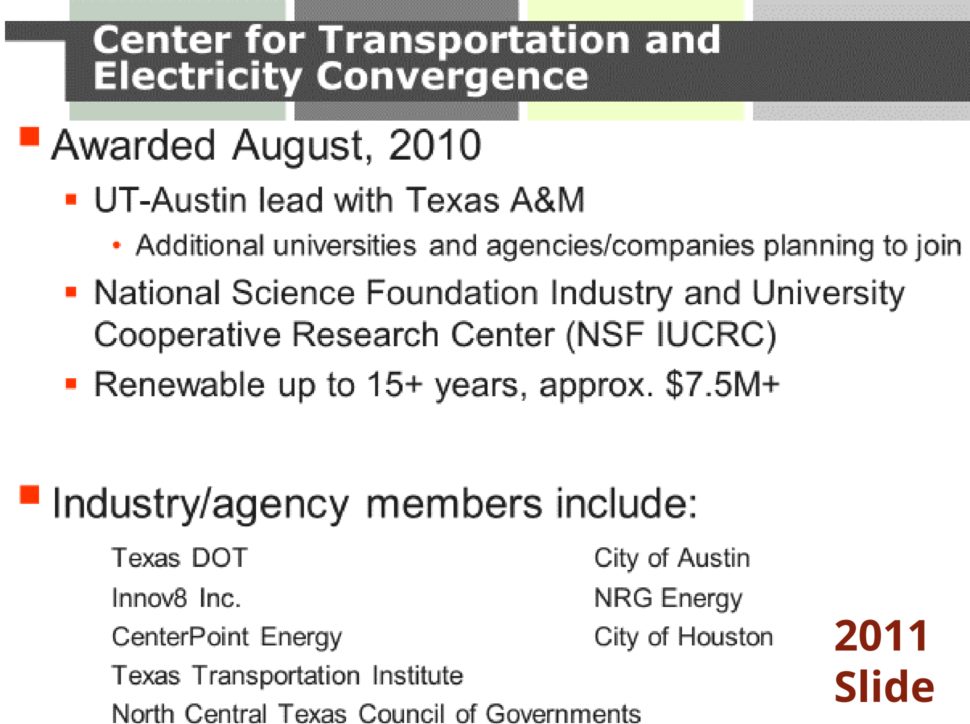
Studying the future behavior of travelers with the emerging reality of electric vehicles

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

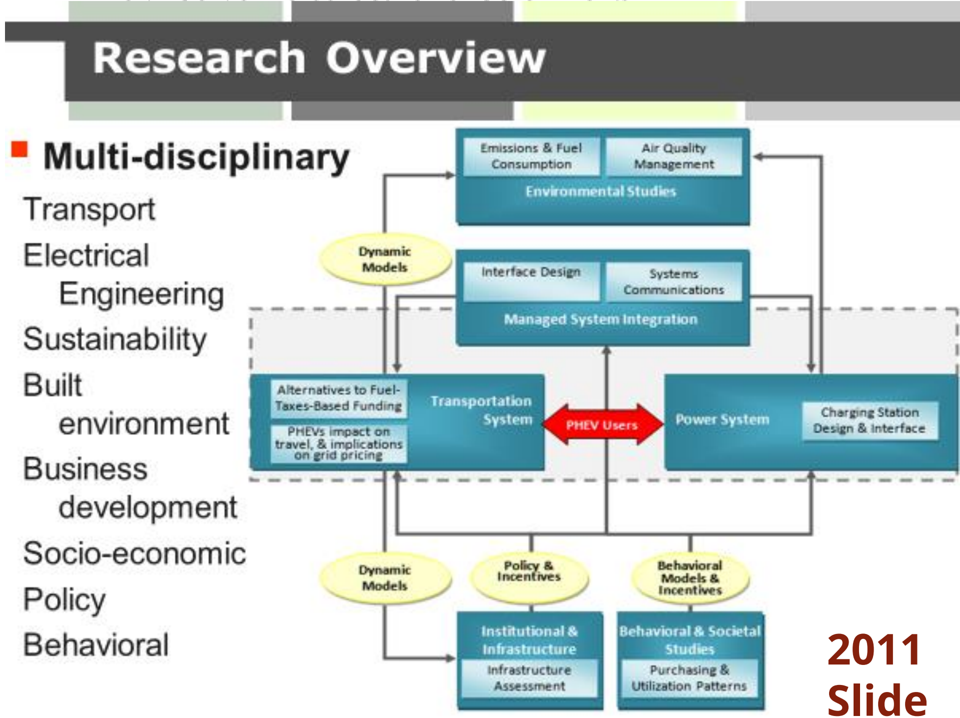


Center for Transportation and Electricity Convergence

- 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

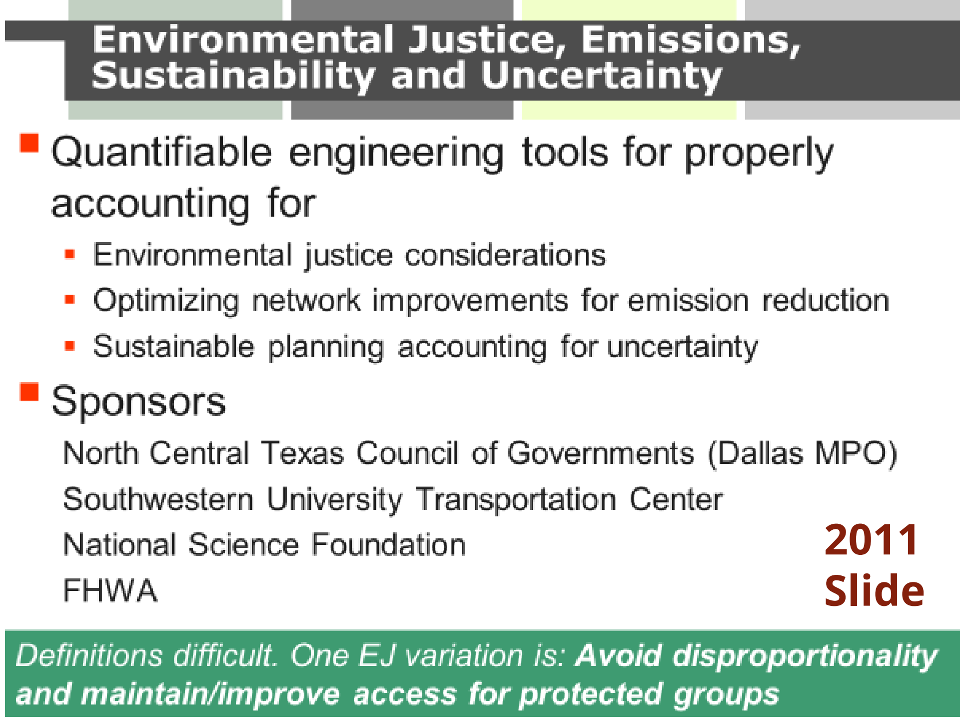
One of the early quantifications of EJ for Transport Network Planning in the literature (2008)

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



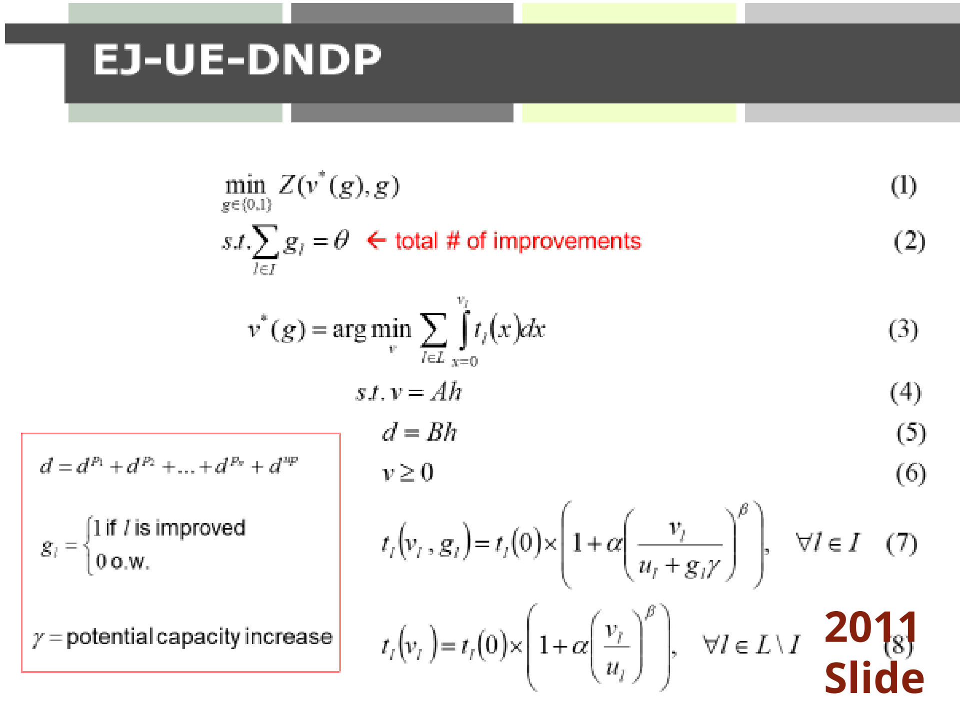
Environmental Justice, Emissions, Sustainability and Uncertainty

- 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

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

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

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

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

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

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

$$d = d^{P_1} + d^{P_2} + \ldots + d^{P_n} + d^{np}$$

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

γ = potential capacity increase

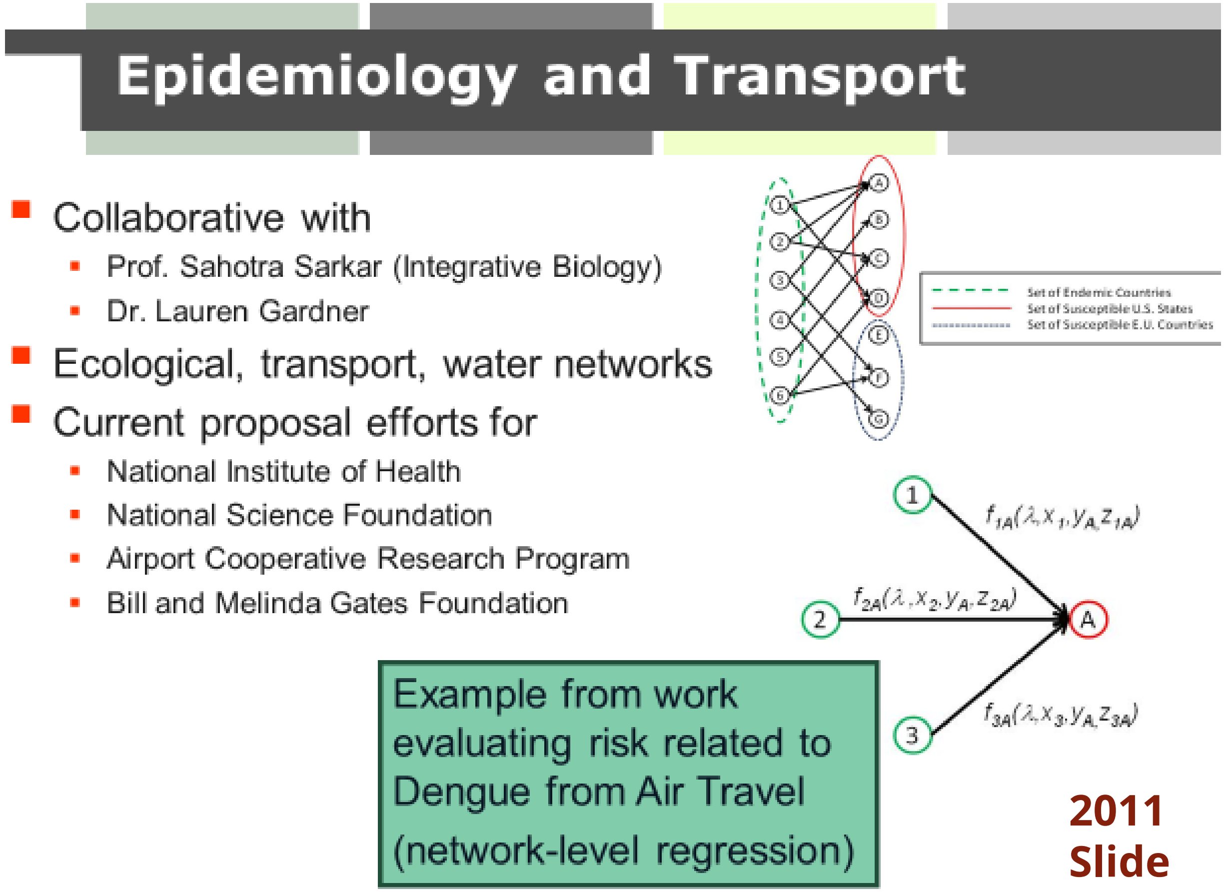
2011 Slide

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



Epidemiology and Transport

- Collaborative with
  - Prof. Sahotra Sarkar (Integrative Biology)
  - Dr. Lauren Gardner
- Ecological, transport, water networks
- Current proposal efforts for
  - National Institute of Health
  - National Science Foundation
  - Airport Cooperative Research Program
  - Bill and Melinda Gates Foundation

Example from work evaluating risk related to Dengue from Air Travel (network-level regression)

2011 Slide

4. Automated/Autonomous Vehicles

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

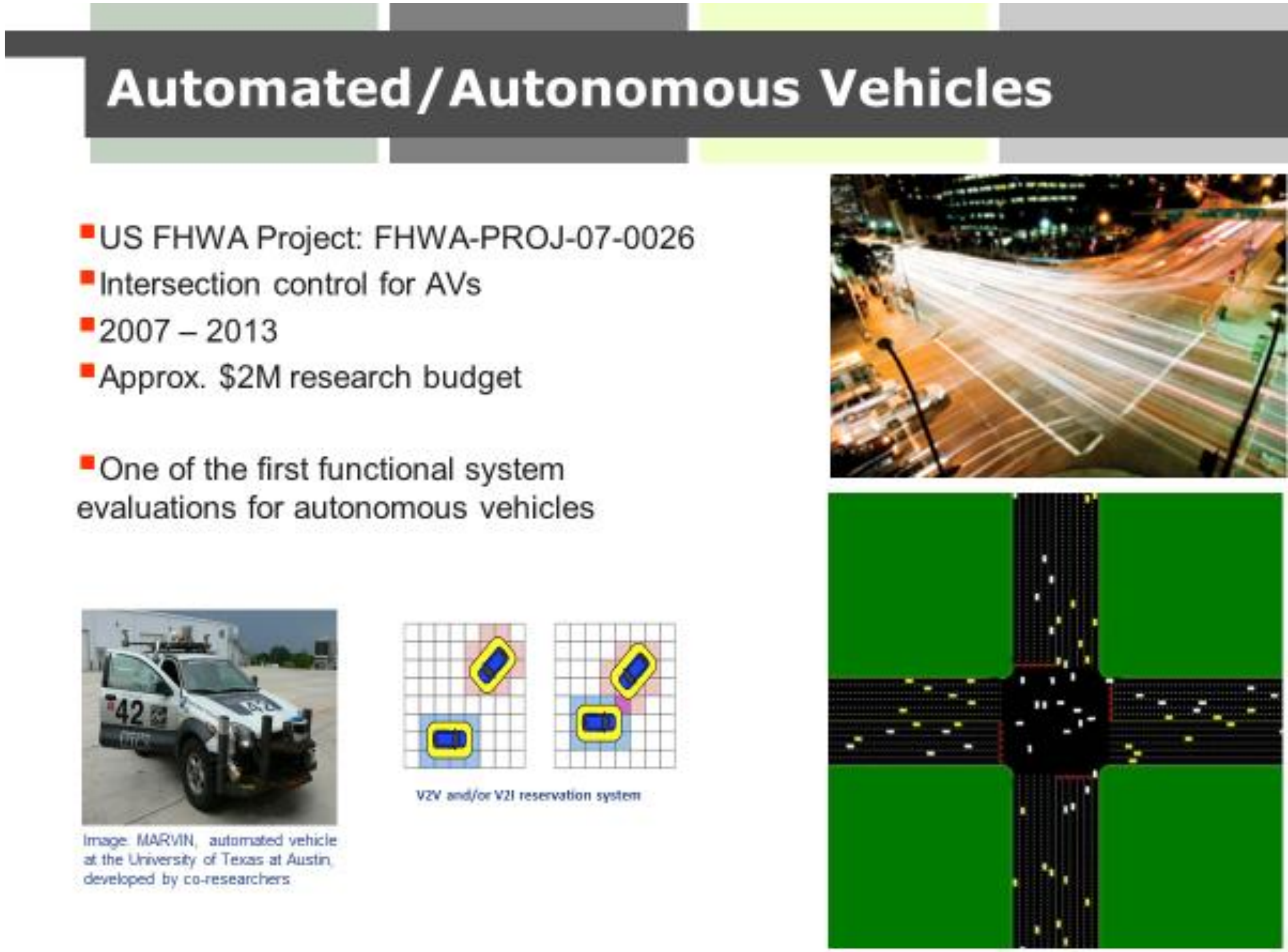
How AVs would function in a transport system

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



Automated/Autonomous Vehicles

- US FHWA Project: FHWA-PROJ-07-0026
- Intersection control for AVs
- 2007 – 2013
- Approx. $2M research budget

- One of the first functional system evaluations for autonomous vehicles

Image: MARVIN, automated vehicle at the University of Texas at Austin, developed by co-researchers

V2V and/or V2I reservation system

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.
- **Understanding "Mobility as a Resource"**

Modelling Transport Network Behaviour to Inform Strategic Decisions

City Layouts II by Luis Dilger licensed and modified under CC BY-NC 4.0

We need approaches that work up to scales **at least** this large or even much larger (multi-national)

We must capture network re-routing behavior

Traditional “static” Traffic Assignment

Formulation (Beckman, 1956)

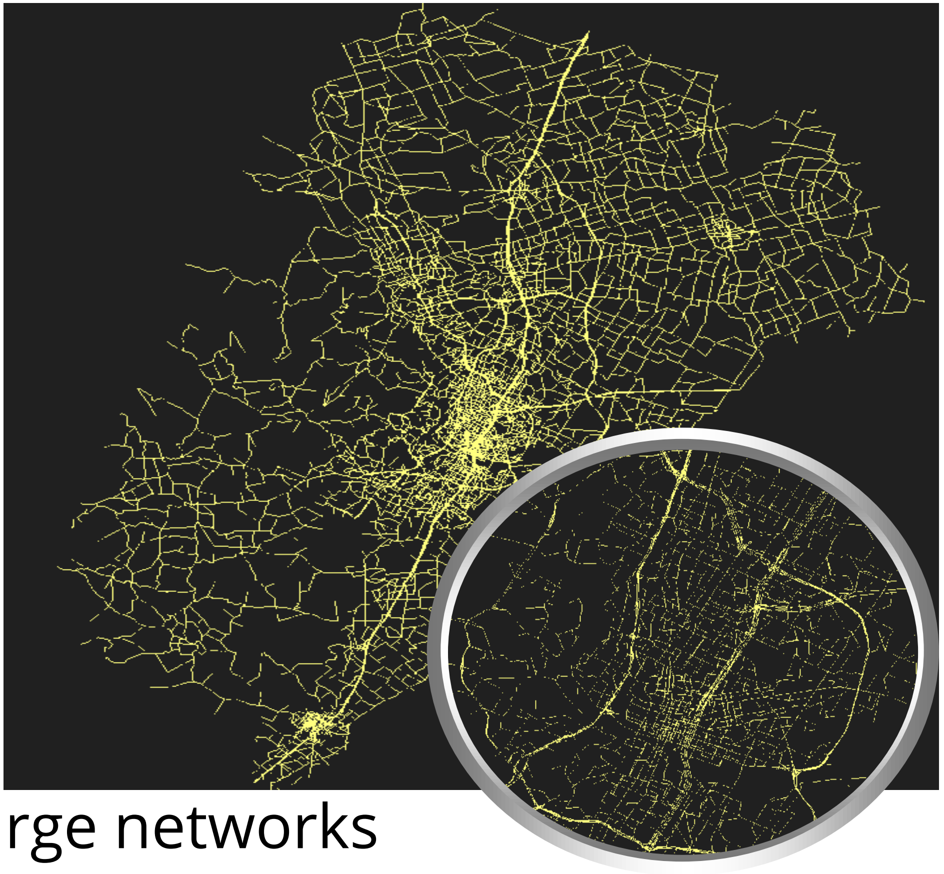
$$\min \sum_{a} \int_{0}^{x_a} c_a(\omega)\,d\omega$$

s.t.

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

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

$$x_a = \sum_{r}\sum_{s}\sum_{k} h_k^{rs}\,\delta_{a,k}^{rs} \qquad \forall a$$



This formulation (and the resulting 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

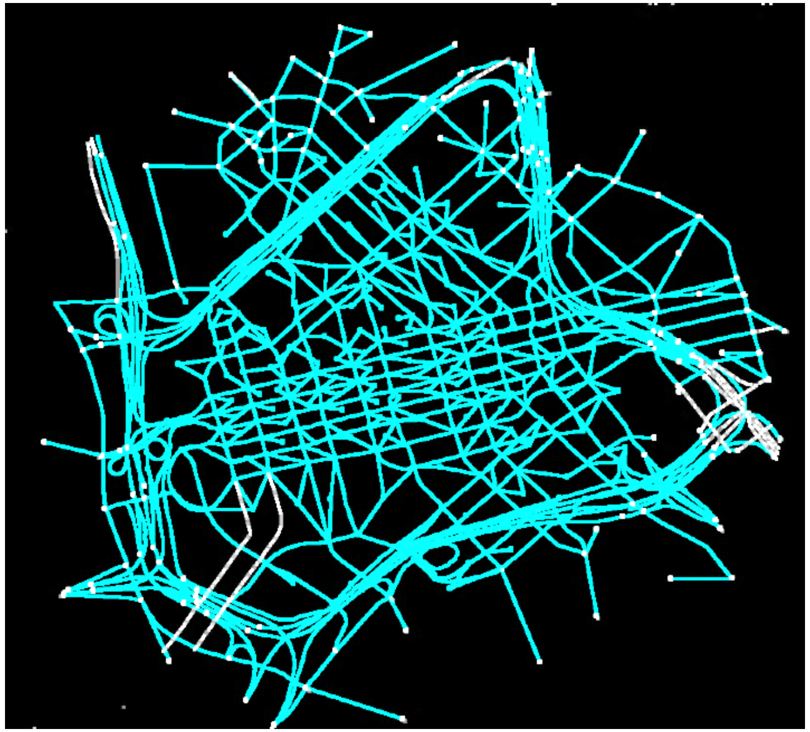
Connectivity and Information

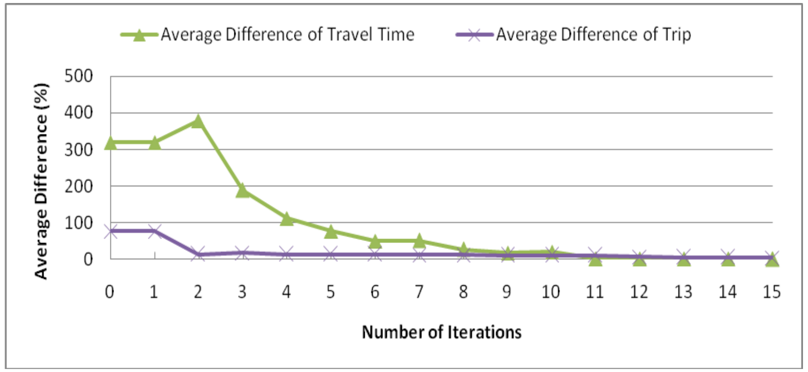
Demand/Supply integration

Automated Vehicles

Many others

Regardless, some concept of equilibrium remains vital





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

Model Representation - Disruptions

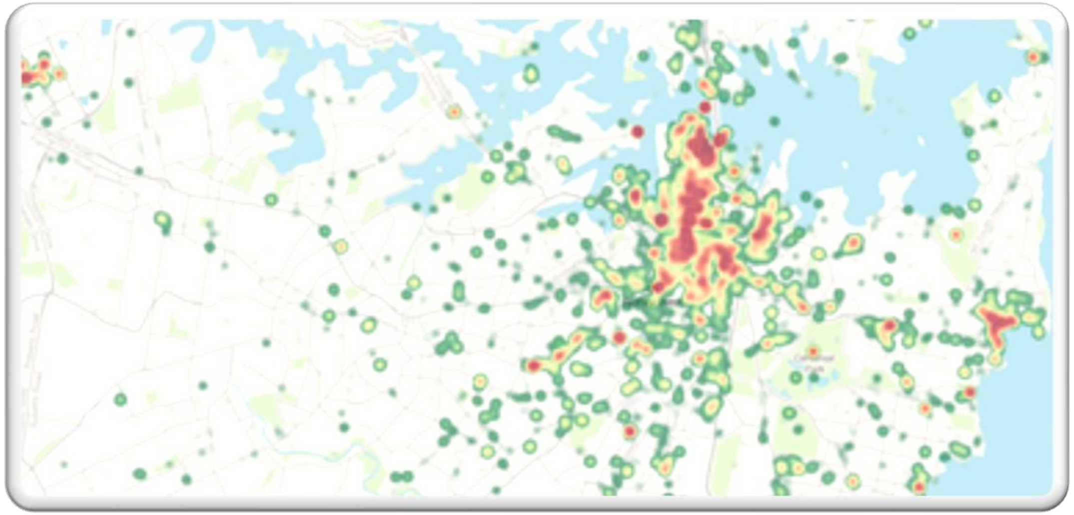
Electric Vehicles: Traveller Behavior
and Infrastructure Funding

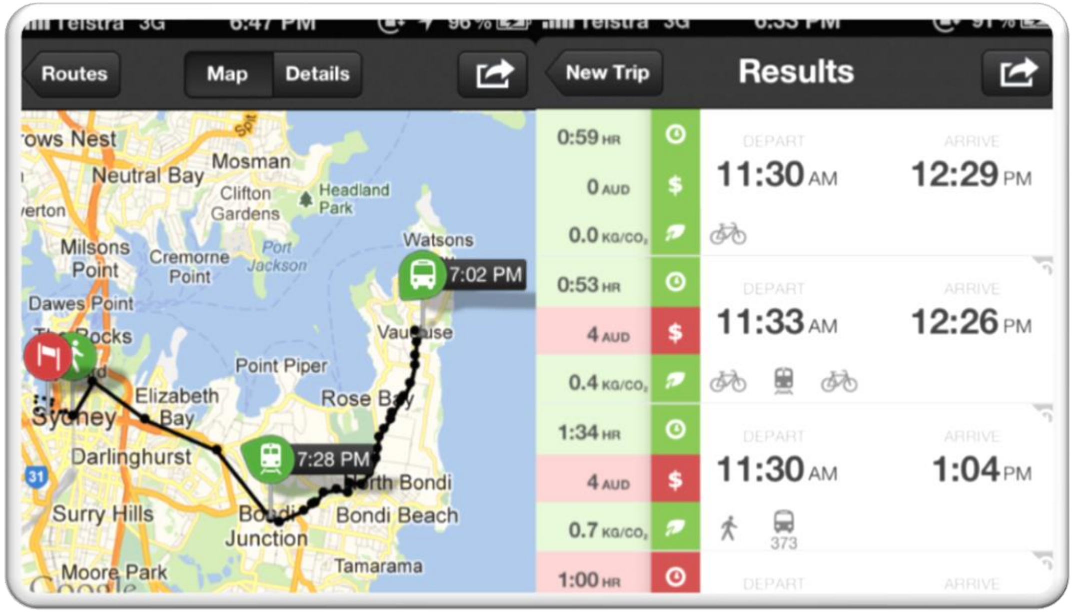
Automated Vehicles

Mobility as a Service

Congestion management

All impact
- Behavior
- How mobility is priced





Congestion pricing is an old problem

Example: A.C. Pigou (1920)

“… a rightly chosen measure of differential taxation against road B would

create an ‘artificial’ situation superior to the ‘natural’ one.

But the measure of differentiation must be rightly chosen.“

Disruption: 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

yelp	Destination choice
in	Socio demographic and economic attributes
flickr	Travel attributes: location, time
Instagram FOURSQUARE	Travel attributes: location, time duration, purpose, mode of transport.

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.

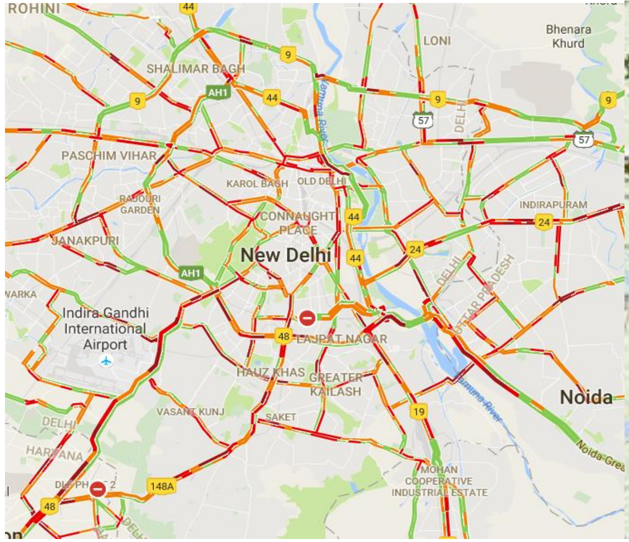
Networked Mobility Information

Google Map Outreach Grant

While at rCITI@UNSW we were the first non-US group to have the Google Maps Outreach Grant

Multiple recent and ongoing 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



Disruption: 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

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

yelp: Destination choice

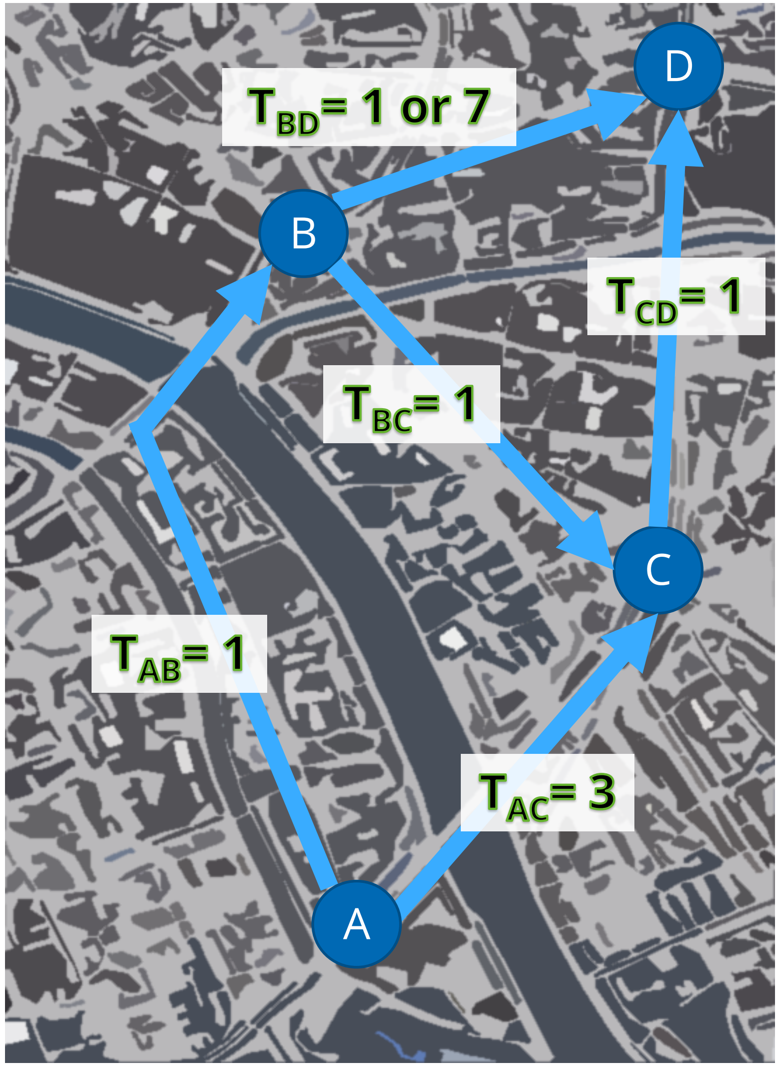
in: Socio demographic and economic attributes

flickr: Travel attributes: location, time

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

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.

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

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

```
Step 1.
$E[d|i,s]=0 \quad \forall\, i\in \Gamma^{-1}(d),\; s\in S_{i,t}$
$E[n|i,s]= \infty \quad \forall\, n\in N/d, \quad i\in\Gamma^{-1}(n),\; s\in S_{i,n}$
$SE:= d$

Step 2.
while $SE\neq \varnothing$
    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)

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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

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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

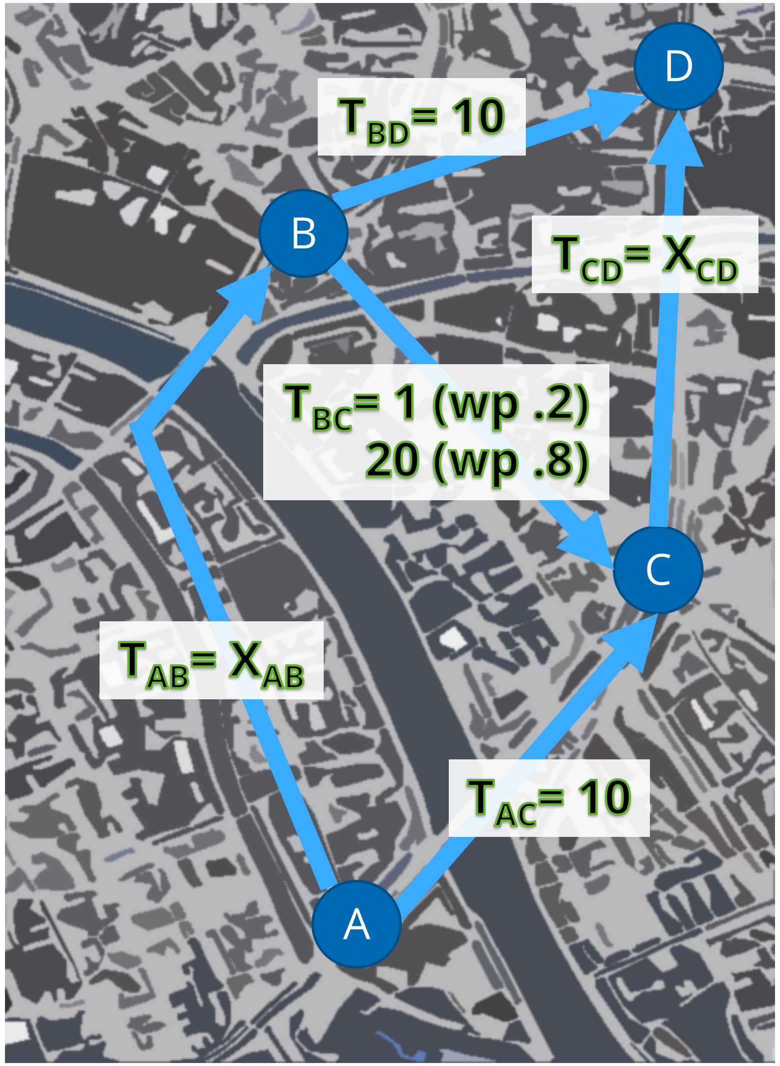
- Take average cost of link B –C
- Expected Cost of T_{BC} = 16.2

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

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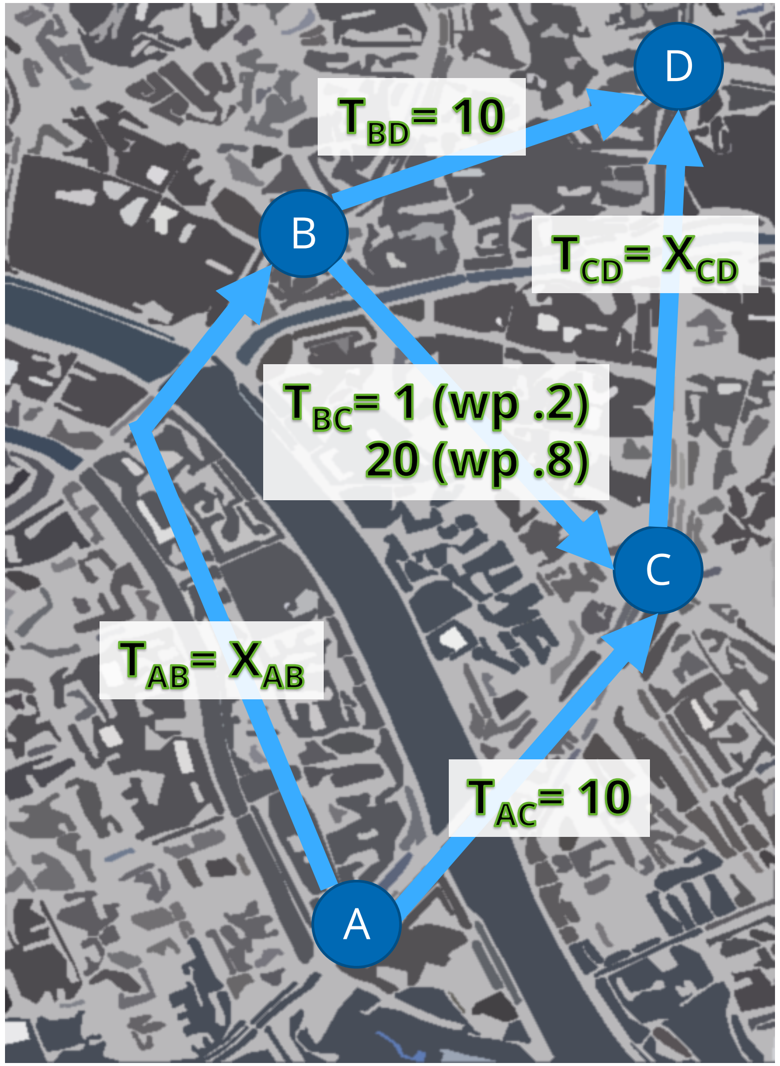
Adaptive Equilibrium



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

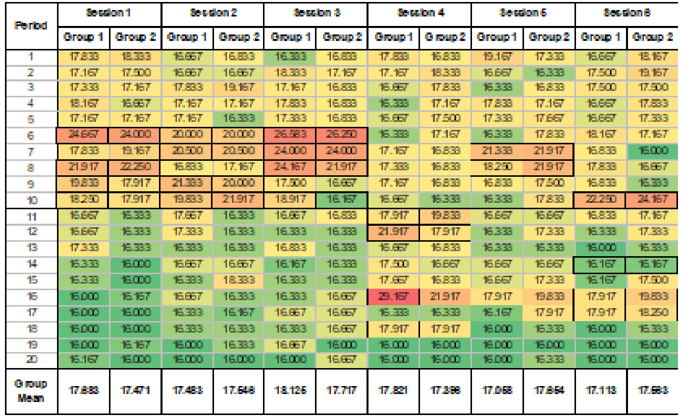
Results: Learning to Equilibrate

No information case compared to information case

Individual traffic states shown below

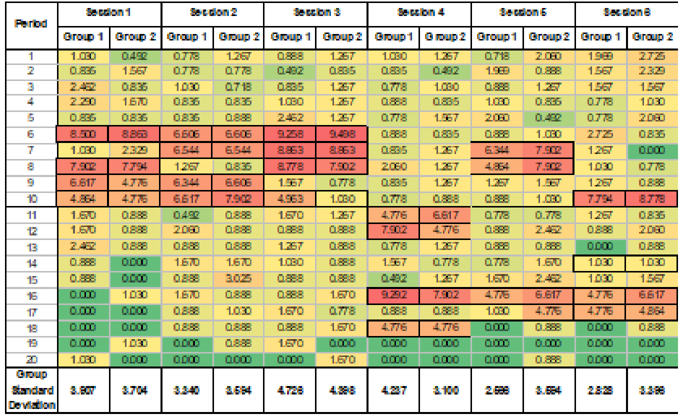
No Information

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

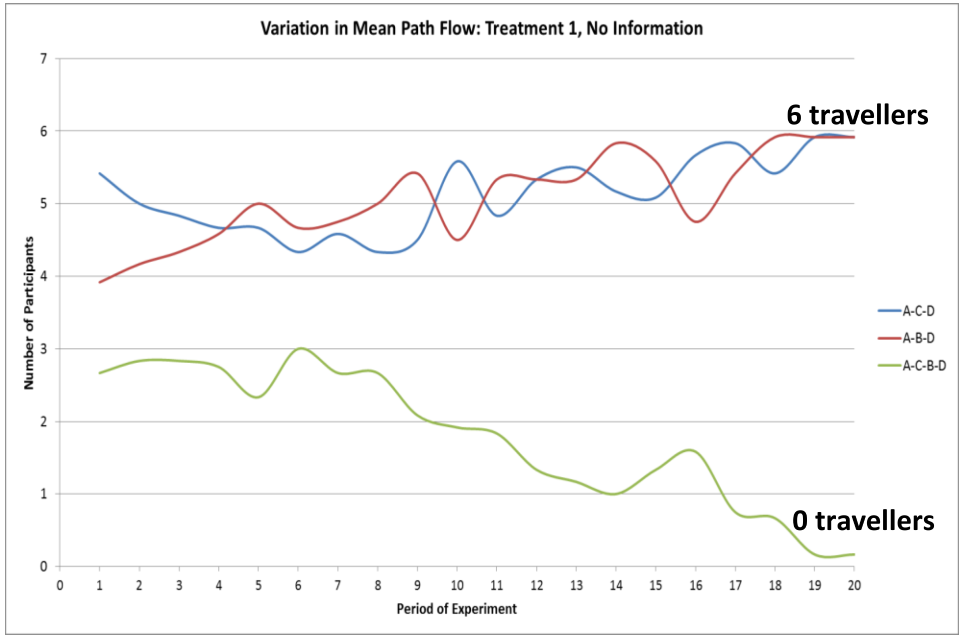


Period	Session 1		Session 2		Session 3		Session 4		Session 5		Session 6	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
1	17.833	18.333	16.667	16.833	16.333	16.833	17.833	16.833	19.167	17.333	16.667	18.167
2	17.167	17.500	16.667	16.667	18.333	17.167	17.167	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	17.548	18.126	17.717	17.821	17.398	17.068	17.864	17.113	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	3.907	3.704	3.240	3.594	4.728	4.398	4.237	3.100	2.698	3.594	2.828	3.398

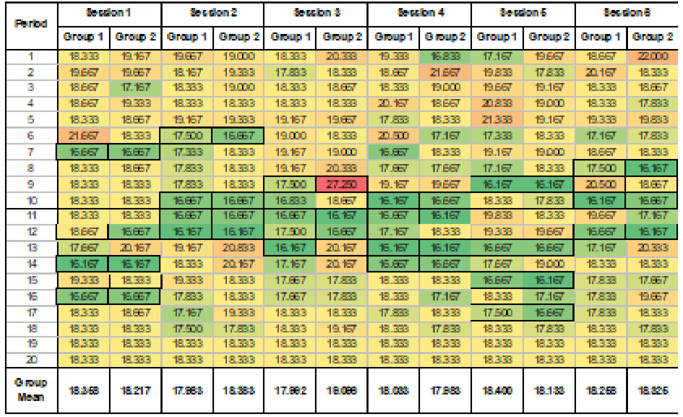


6 travellers

0 travellers

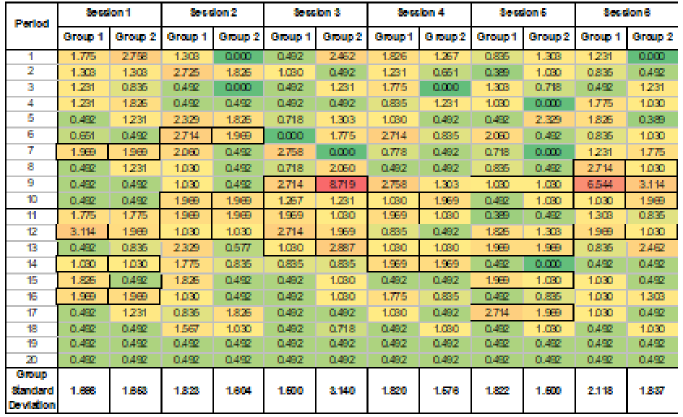
Information

Mean Individual User Travel Costs: Treatment 2 (Information)

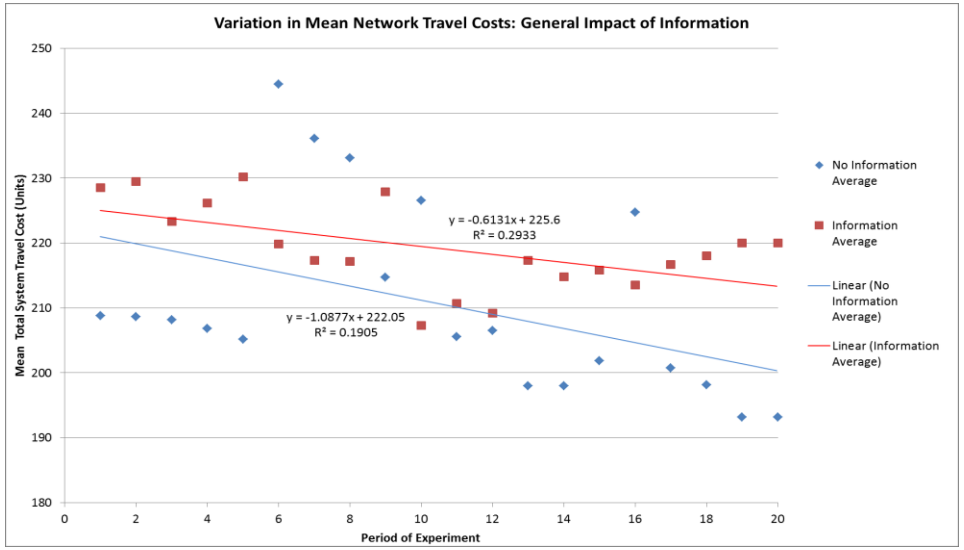


Period	Session 1		Session 2		Session 3		Session 4		Session 5		Session 6	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
1	18.333	19.167	19.667	19.000	18.333	20.333	19.333	16.833	17.167	19.667	18.667	22.000
2	19.667	19.667	18.167	19.333	17.833	18.333	18.667	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	17.983	18.383	17.992	18.098	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	1.888	1.863	1.823	1.604	1.600	3.140	1.820	1.578	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

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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.

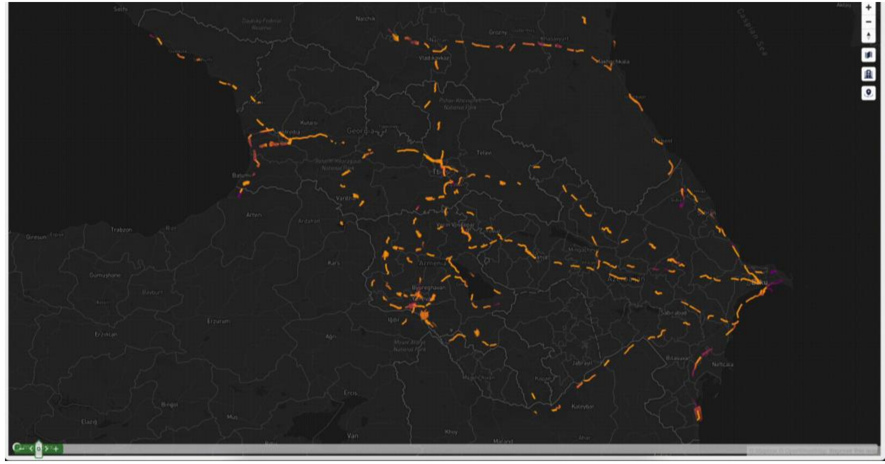
Automated Modeling for Rapid Planning

Given the importance of network equilibrium

How can we cut the time to deploy such models?

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:

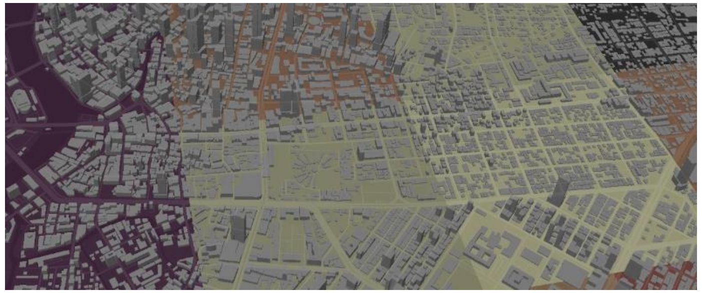
In doing all of this, we must not lose the capacity to appropriately model “what-if” scenarios.

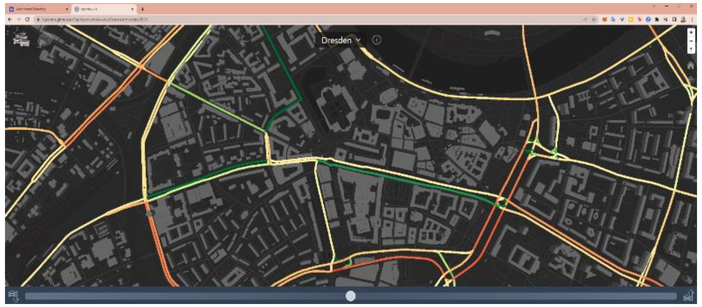
If we lose this, we lose our purpose in the planning process.

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

We would like to
acknowledge
collaboration with NVIDIA.

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

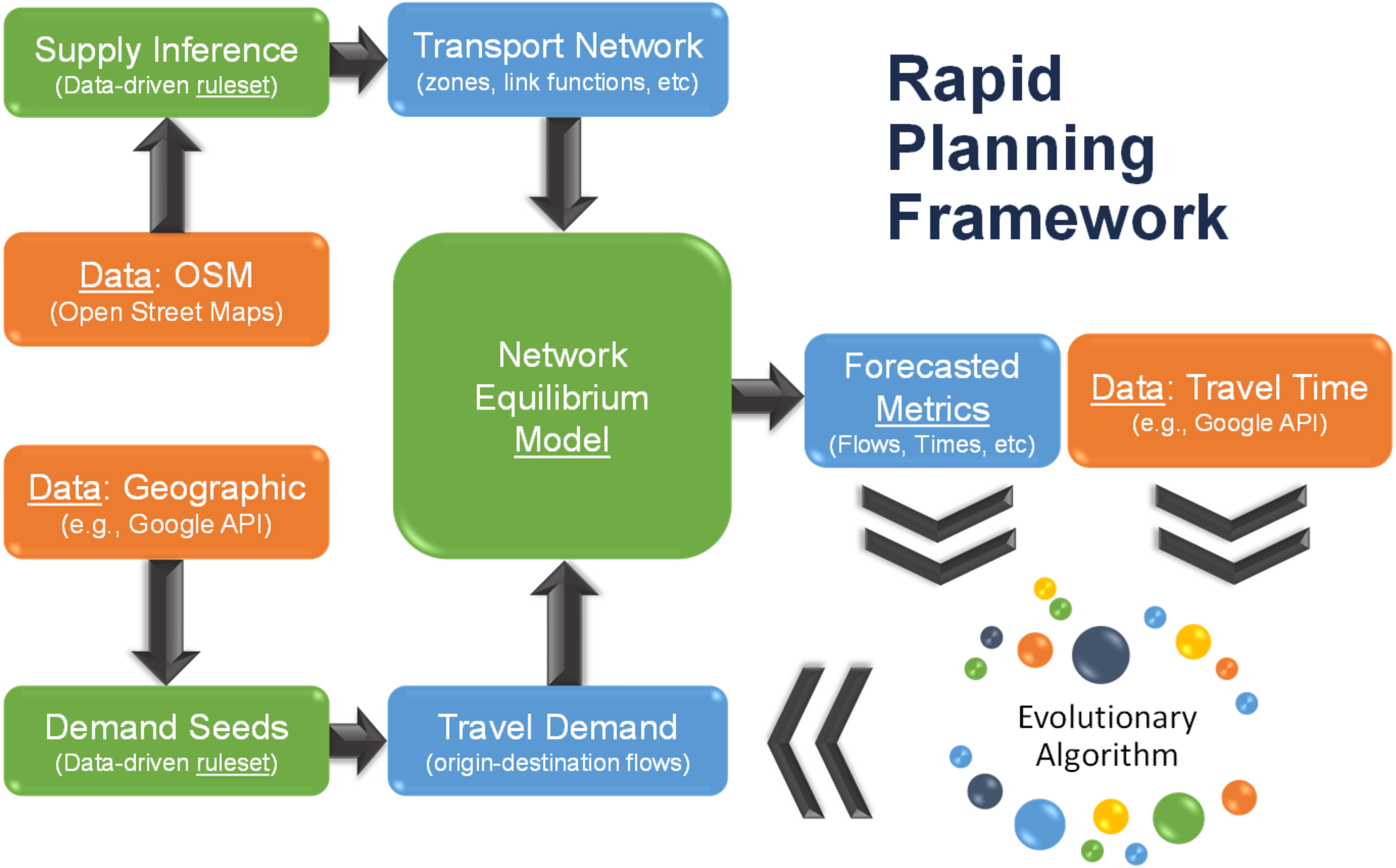
*ST Waller, M Qurashi, A Sotnikova, L Karva, S Chand **(2023) “Analyzing and modeling network travel patterns during the Ukraine invasion using crowd-sourced pervasive traffic data”** Transportation Research Record, Volume 2677, Issue 10, https://doi.org/10.1177/03611981231161622

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 data
- Network inference tools to automatically develop planning network from OSM and historic data on transport capacities.
- A Machine Learning, Evolutionary Algorithm, implemented to infer aggregate origin-destination travel demand forecast from observed data.



Supply Inference
(Data-driven ruleset)

Transport Network
(zones, link functions, etc)

Rapid Planning Framework

Data: OSM
(Open Street Maps)

Network Equilibrium Model

Forecasted Metrics
(Flows, Times, etc)

Data: Travel Time
(e.g., Google API)

Data: Geographic
(e.g., Google API)

Evolutionary Algorithm

Demand Seeds
(Data-driven ruleset)

Travel Demand
(origin-destination flows)

TECHNISCHE UNIVERSITÄT DRESDEN

Sample of Our Past & Ongoing 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)

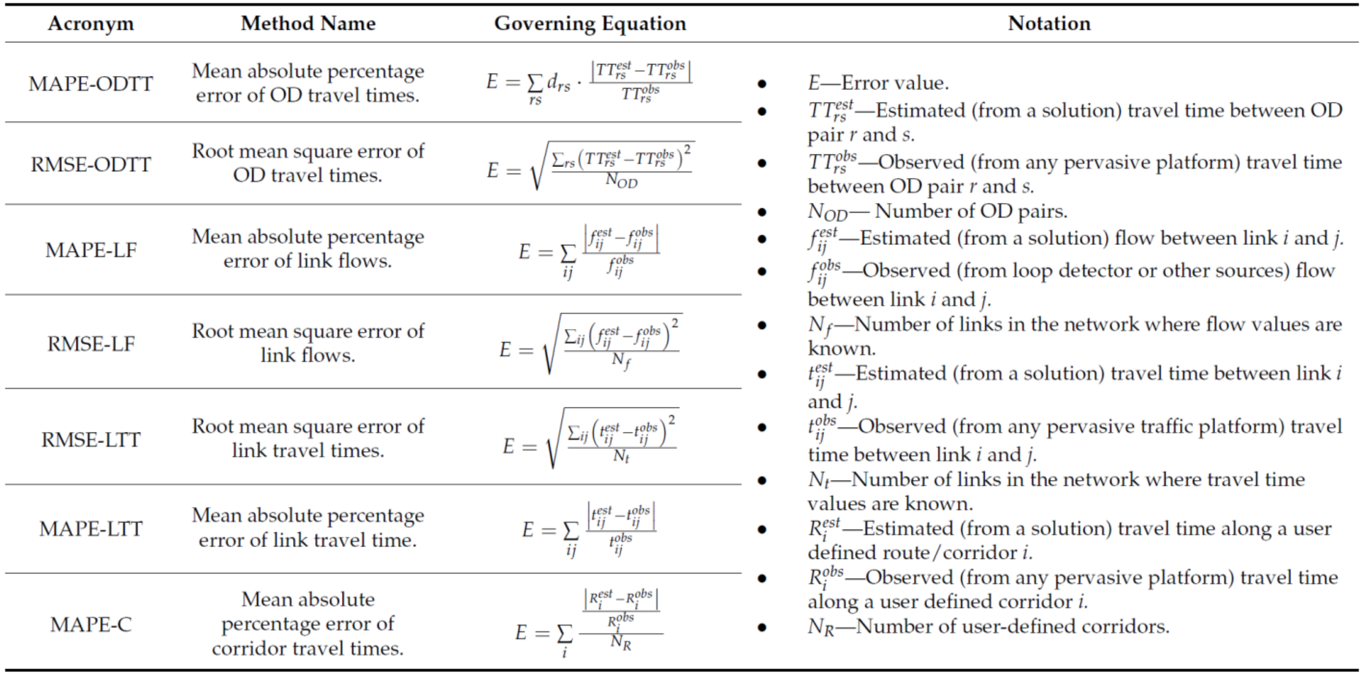
Waller ST; Chand S; Zlojutro A; Nair D; Niu C; Wang J; Zhang X; Dixit VV, 2021, **'Rapidex: A novel tool to estimate origin–destination trips using pervasive traffic data'**, Sustainability (Switzerland), vol. 13, pp. 11171 - 11171, http://dx.doi.org/10.3390/su132011171

(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**' (August, 2022). SSRN: https://ssrn.com/abstract=4185753

Travel Origin-Destination Demand Estimation

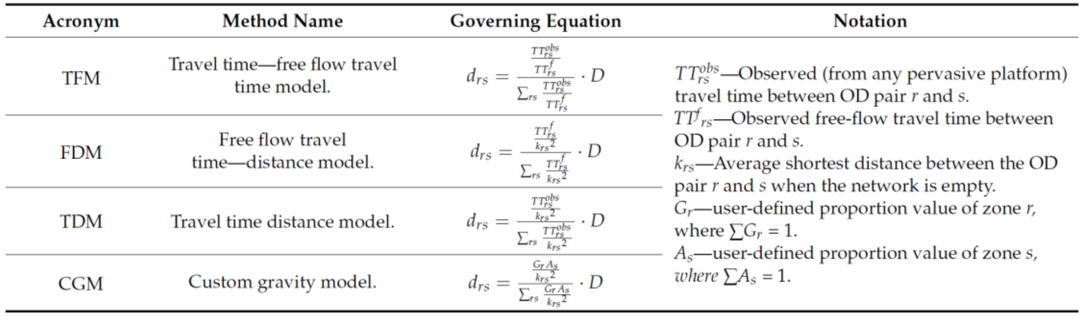
Waller et al. (2021)

Fitness Functions

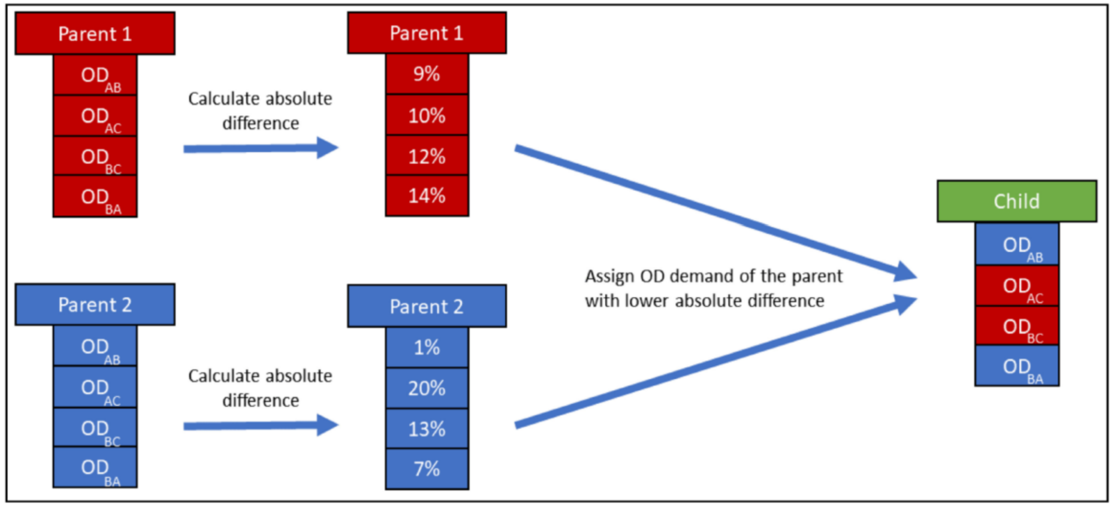


Acronym	Method Name	Governing Equation	Notation
MAPE-ODTT	Mean absolute percentage error of OD travel times.	$E=\sum_{rs} d_{rs}\cdot\frac{\left\|TT_{rs}^{est}-TT_{rs}^{obs}\right\|}{TT_{rs}^{obs}}$	• E—Error value. • TT_{rs}^{est}—Estimated (from a solution) travel time between OD pair r and s. • TT_{rs}^{obs}—Observed (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.	$E=\sum_{ij}\frac{\left\|f_{ij}^{est}-f_{ij}^{obs}\right\|}{f_{ij}^{obs}}$	
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.	$E=\sum_{ij}\frac{\left\|t_{ij}^{est}-t_{ij}^{obs}\right\|}{t_{ij}^{obs}}$	
MAPE-C	Mean absolute percentage error of corridor travel times.	$E=\sum_{i}\frac{\frac{\left\|R_i^{est}-R_i^{obs}\right\|}{R_i^{obs}}}{N_R}$	

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)

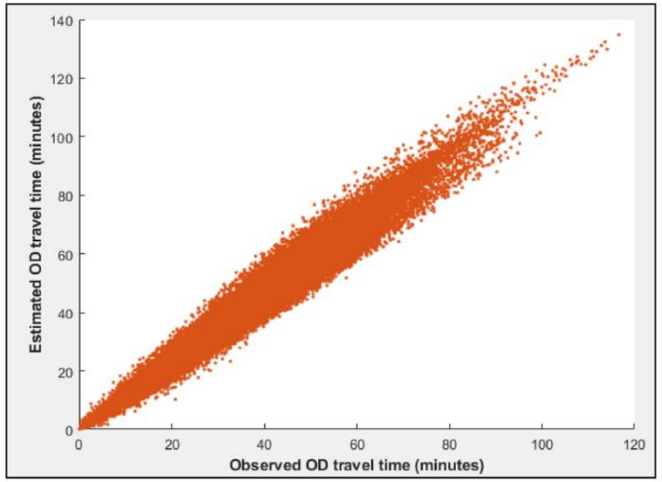
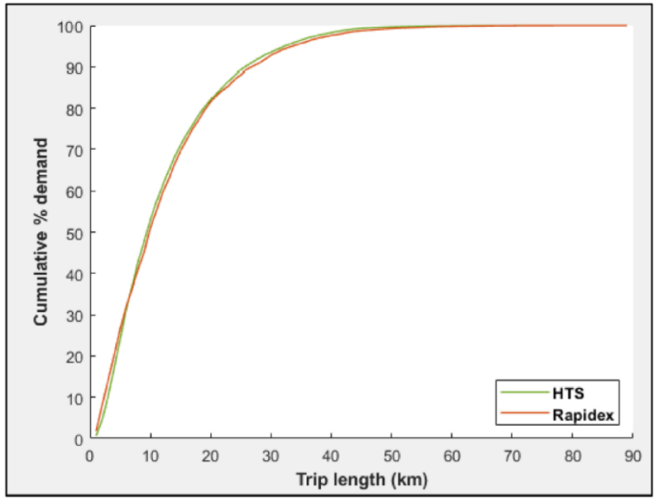


Figure 4. Observed vs. estimated OD travel times.



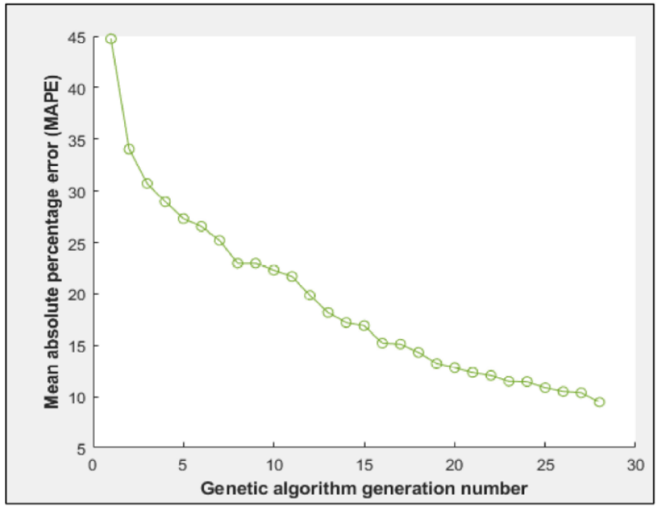
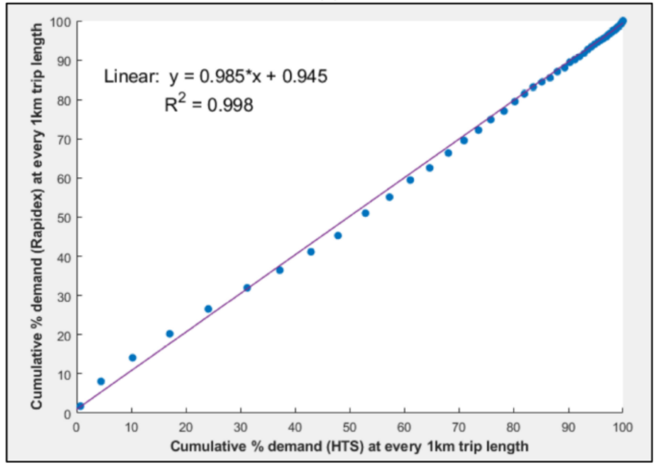


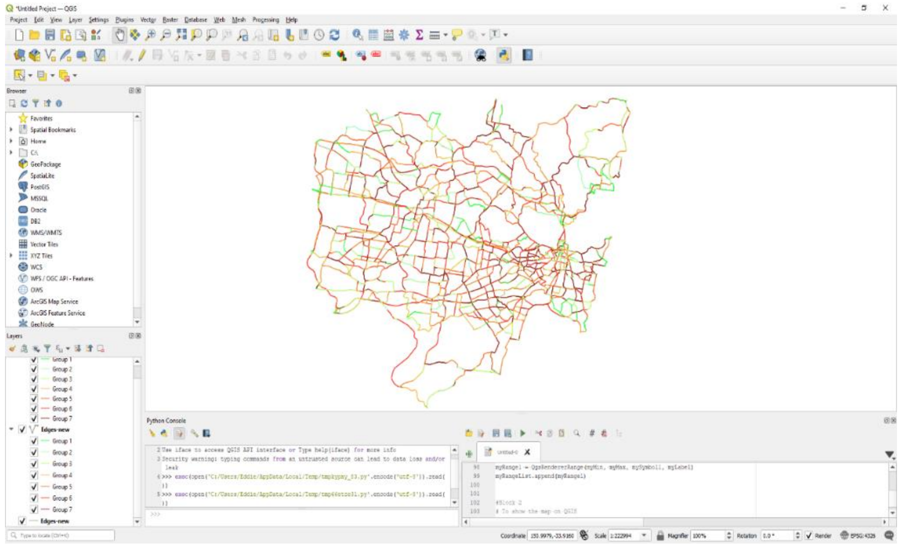
Figure 5. Convergence of the genetic algorithm solution.



Comparison with

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

Case Study 1: Sydney Region



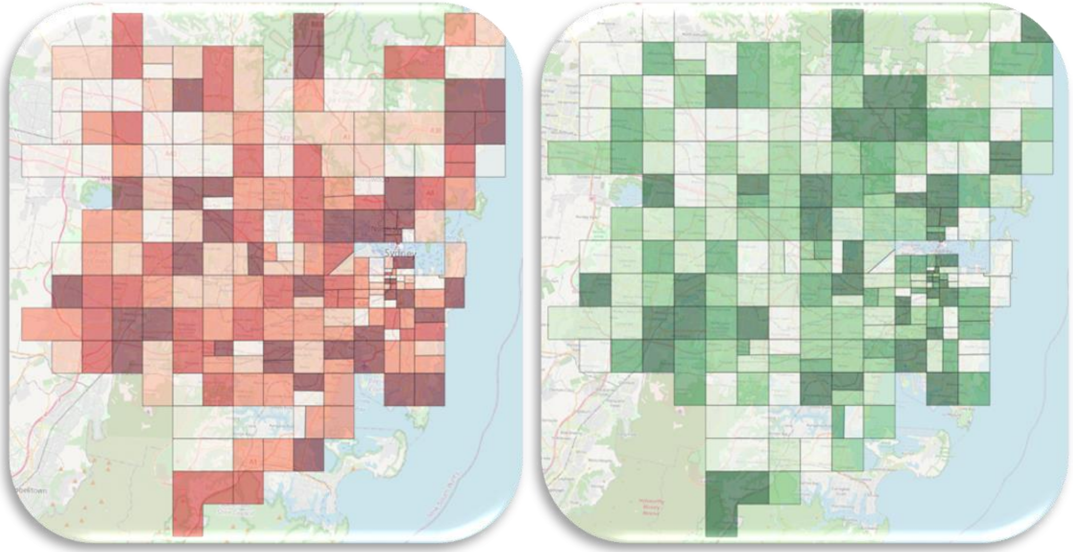
```
2 Use iface to access QGIS API interface or Type help(iface) for more info
3 Security warning: typing commands from an untrusted source can lead to data loss and/or
  leak
4 >>> exec(open('C:/Users/Eddie/AppData/Local/Temp/tmpkypmy_03.py'.encode('utf-8')).read(
  ))
5 >>> exec(open('C:/Users/Eddie/AppData/Local/Temp/tmp66otze31.py'.encode('utf-8')).read(
  ))
```

```
    myRange1 = QgsRendererRange(myMin, myMax, mySymbol1, myLabel1)
    myRangeList.append(myRange1)


#Block 2
# To show the map on QGIS
```

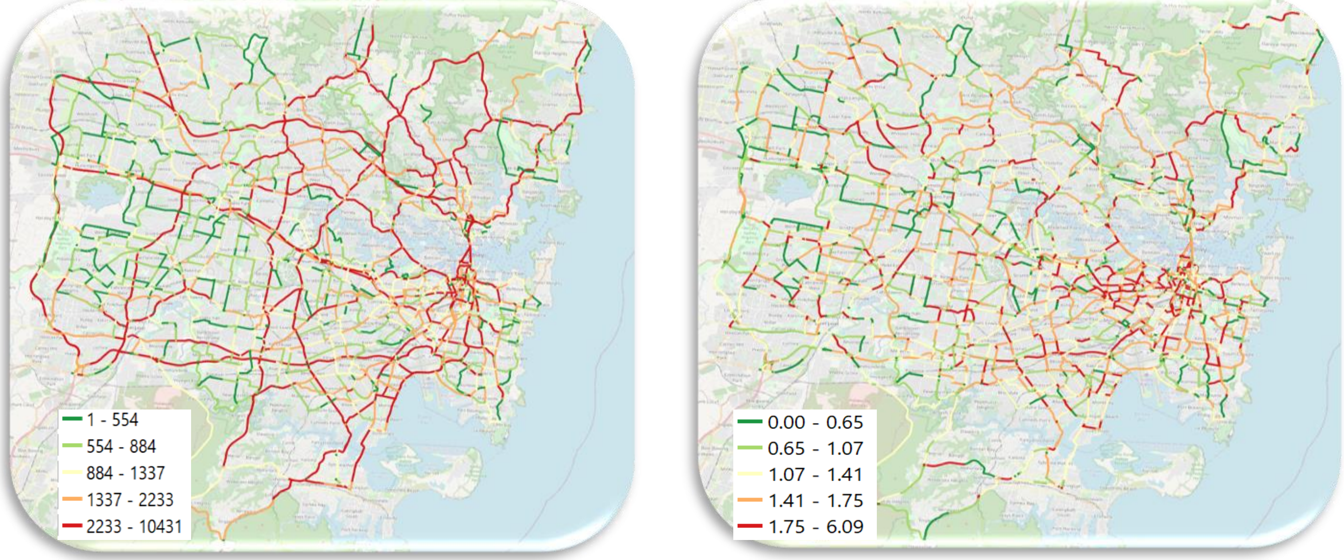
Generations

Attractions



Volume

V/C Ratio



Travel time to CBD

Congestion Index to CBD

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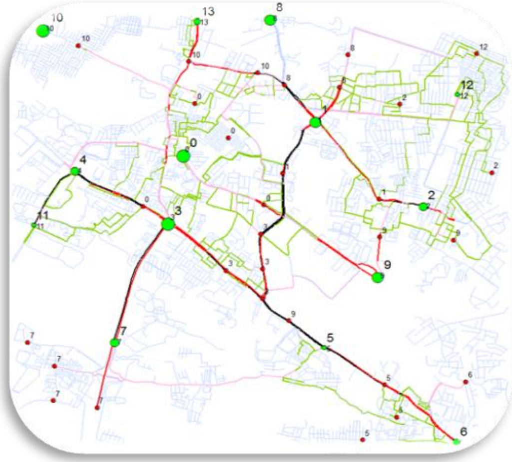
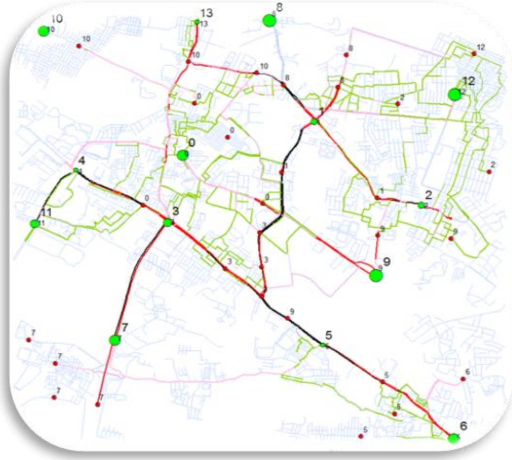
Case Study 2: HiTech City, Hyderabad (India)

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

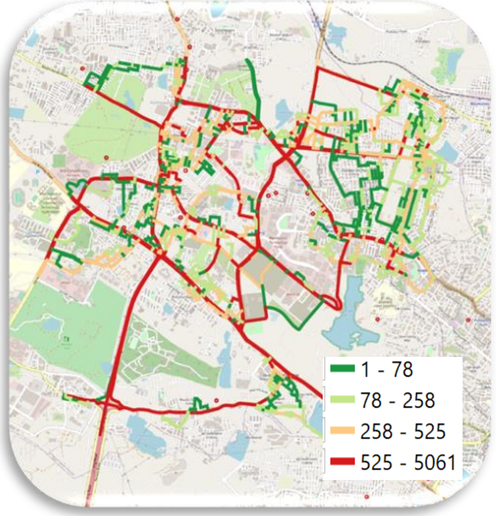
Trip Generations



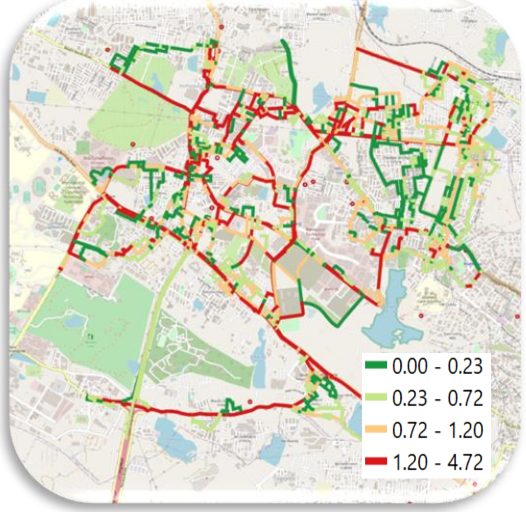
Trip Attractions



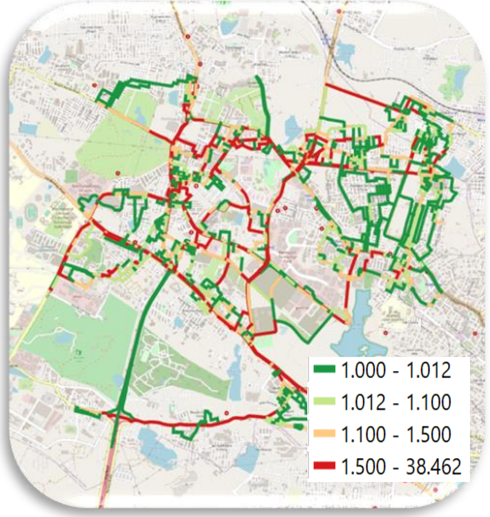
Volume



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.

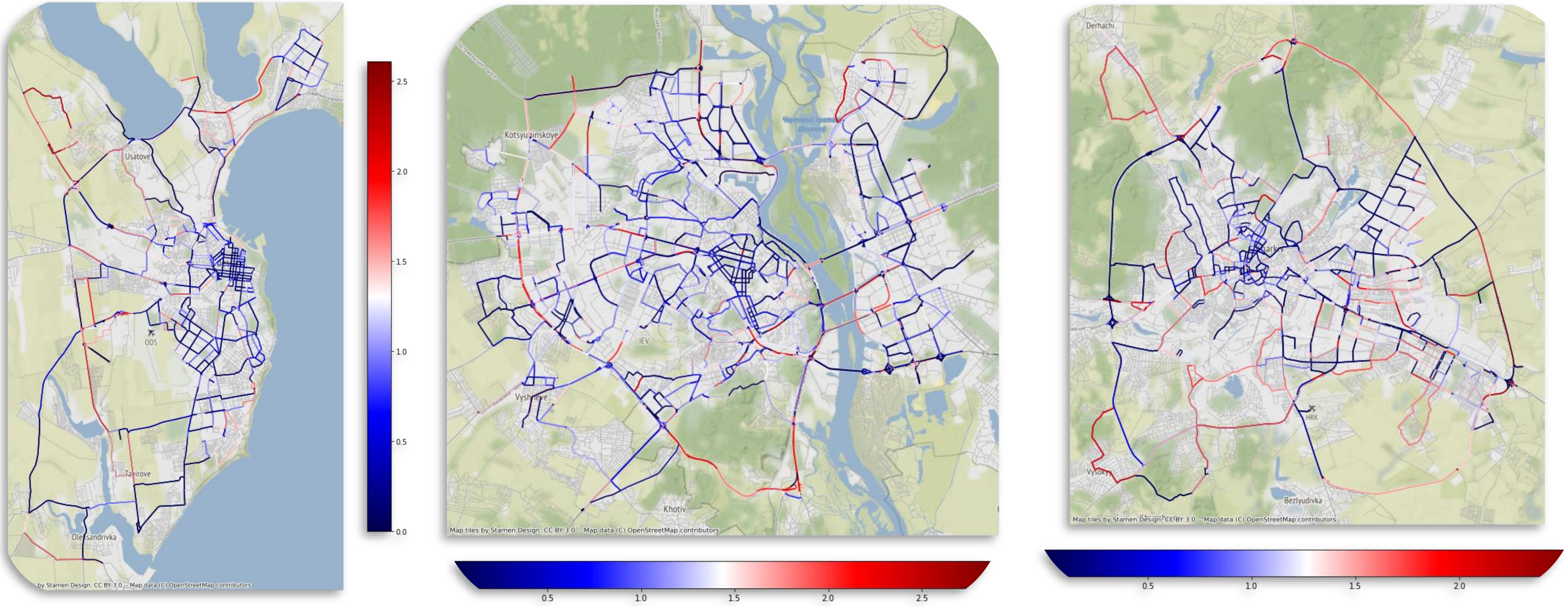
Focuses on those who remain in place rather than evacuation/refugee movements.

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

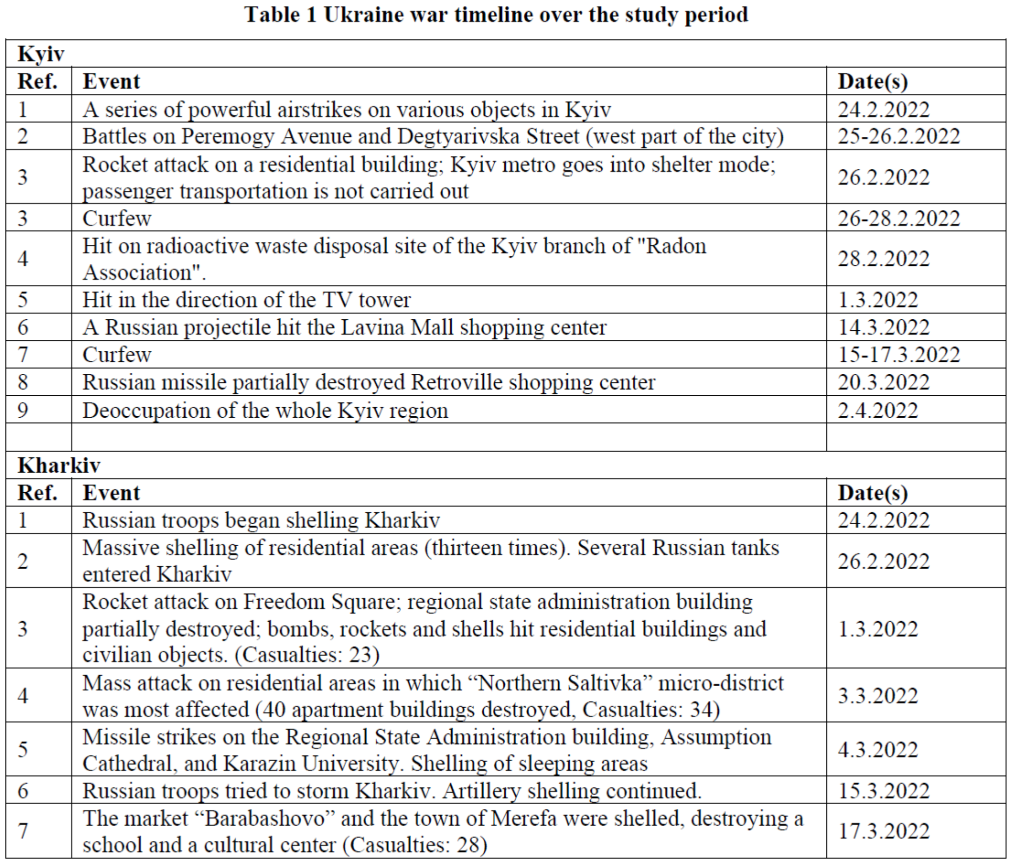
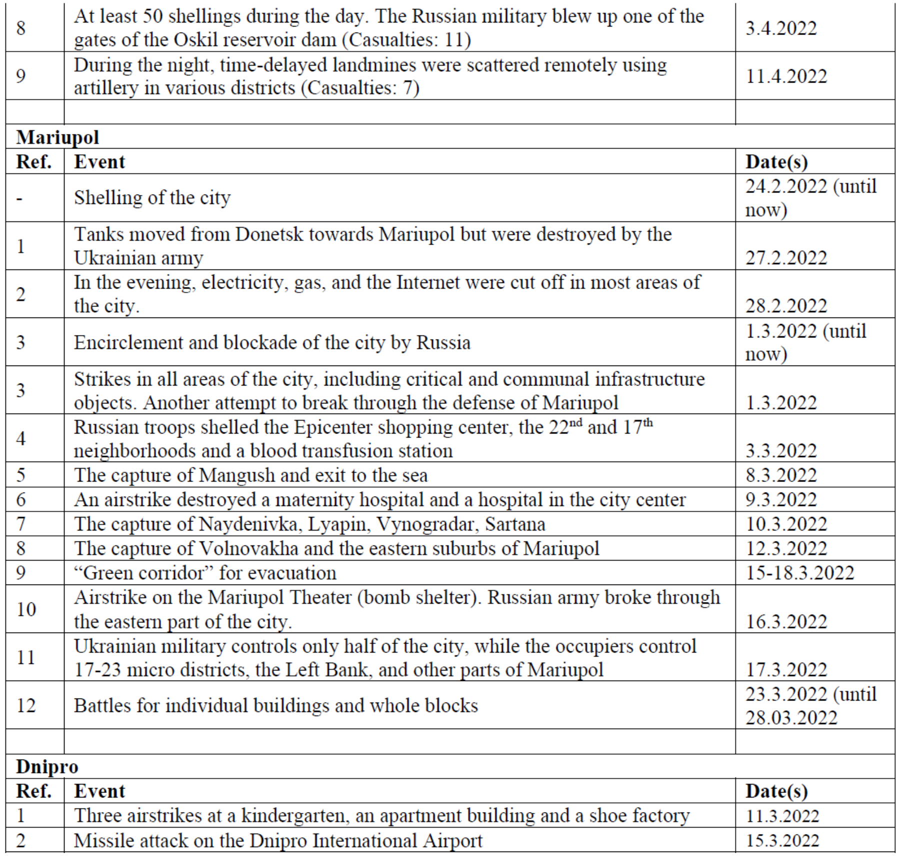


Table 1 Ukraine war timeline over the study period

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

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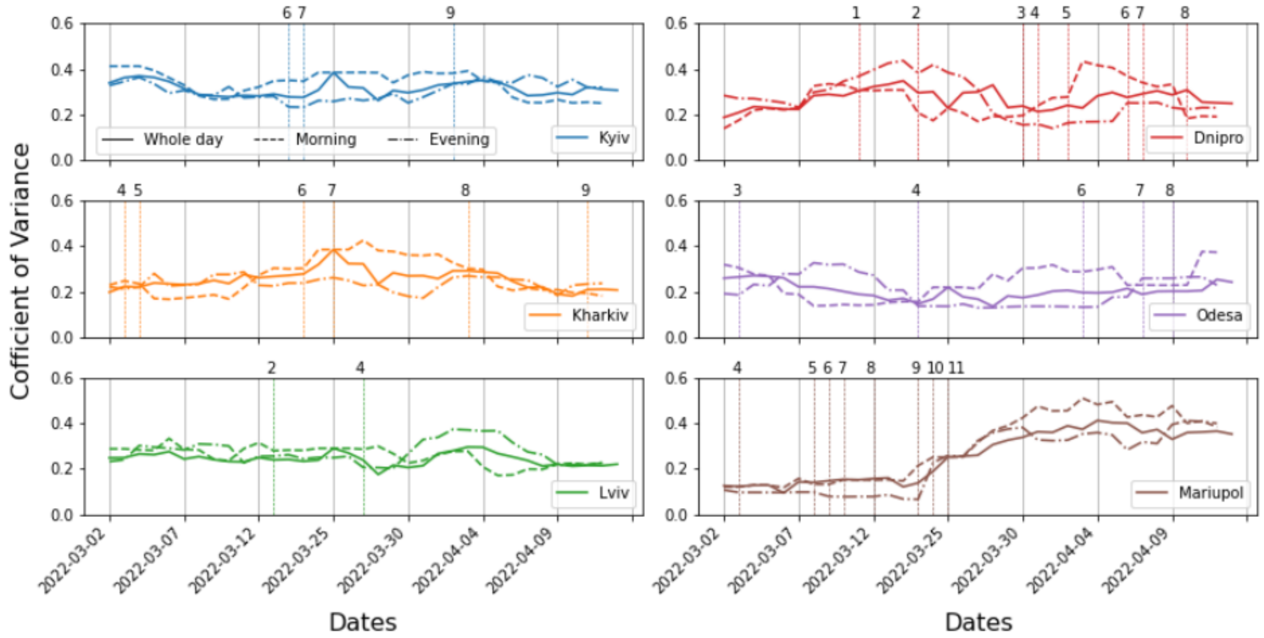
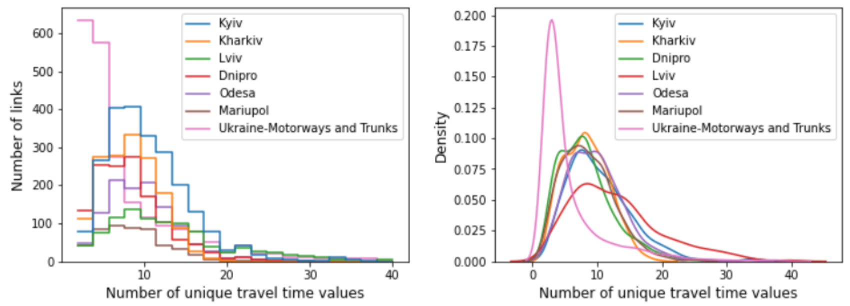


*Figure **3** Network averaged link coefficient of variance for travel times (7-day moving)*

Table 2 Key Statistics from the OD Estimation Analysis

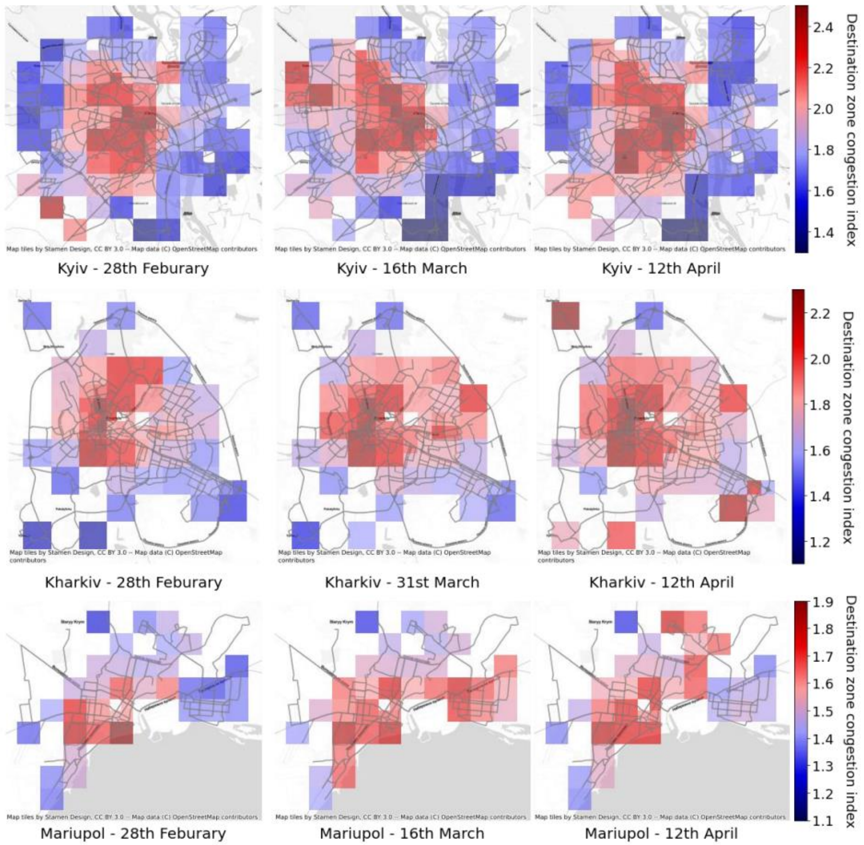
City	***Date***	***% change in average trip length compared to the base case***	***% change in average travel time compared to the base case***	***% change in total demand compared to the base case***
Kyiv	February 28 2022	-	-	-
	March 16 2022	-5.52	-0.28	+3.90
	April 12 2022	+2.74	+1.92	+0.11
Kharkiv	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



Kyiv - 28th Feburary

Kyiv - 16th March

Kyiv - 12th April

Kharkiv - 28th Feburary

Kharkiv - 31st March

Kharkiv - 12th April

Mariupol - 28th Feburary

Mariupol - 16th March

Mariupol - 12th April

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

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Rapid Planning Model: Armenia

Links: 3,677

Nodes: 1,962

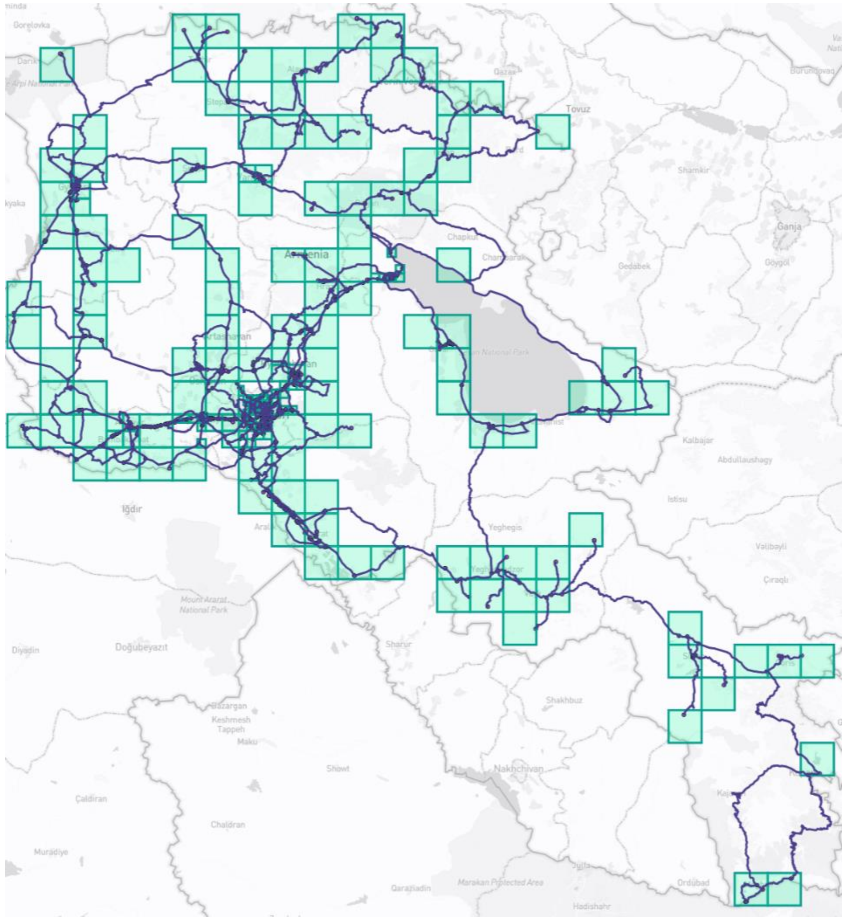
Zones: 175

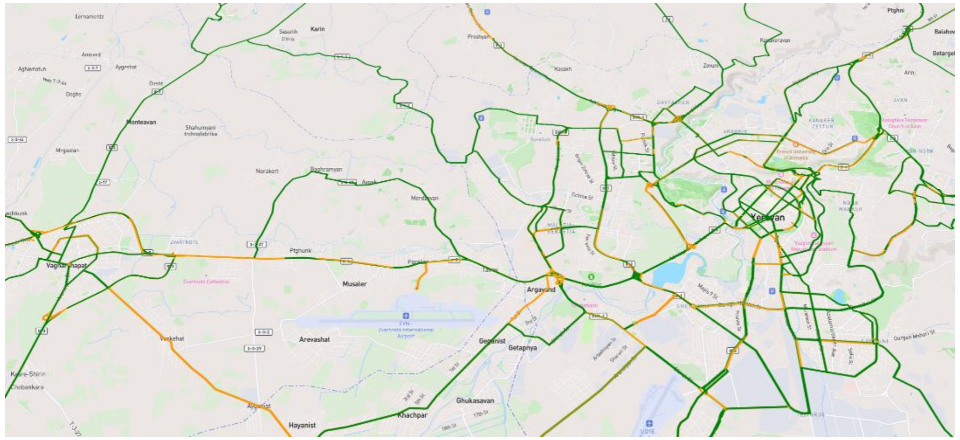
Avg Travel Time: 37 min

Avg Distance: 30.57 km

Modelled:

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



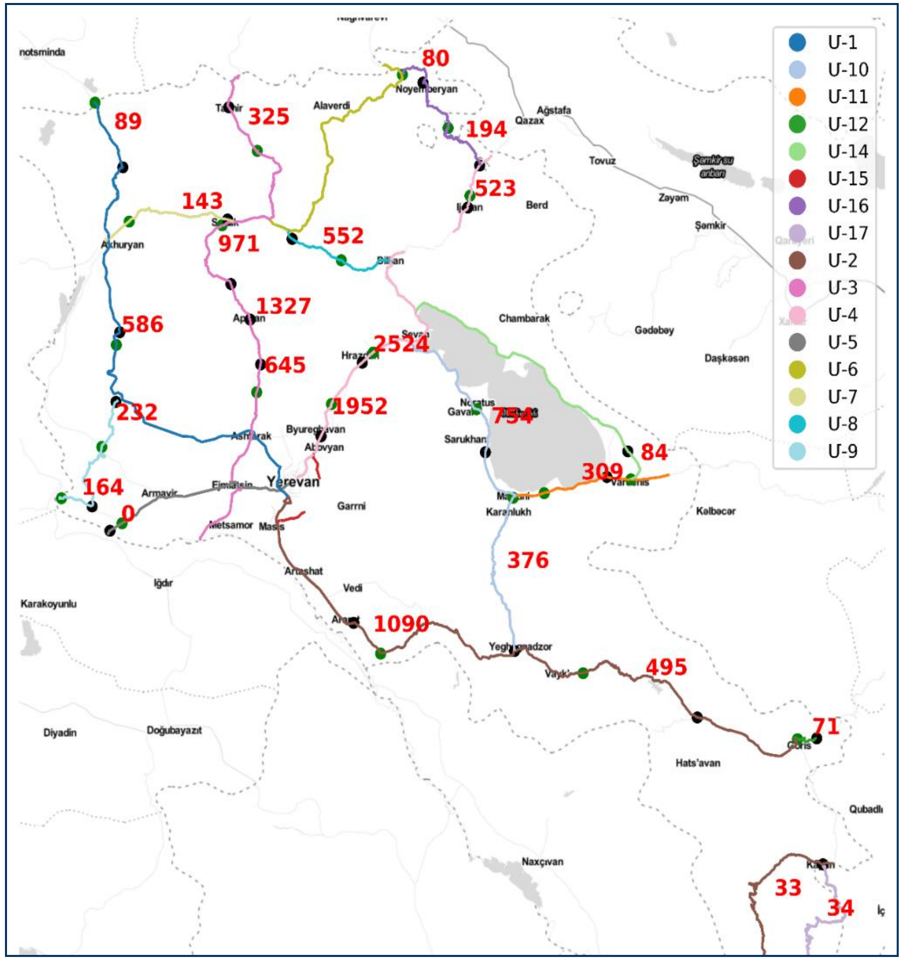


Rapid Planning Model Comparison with Reported Daily Flows

*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

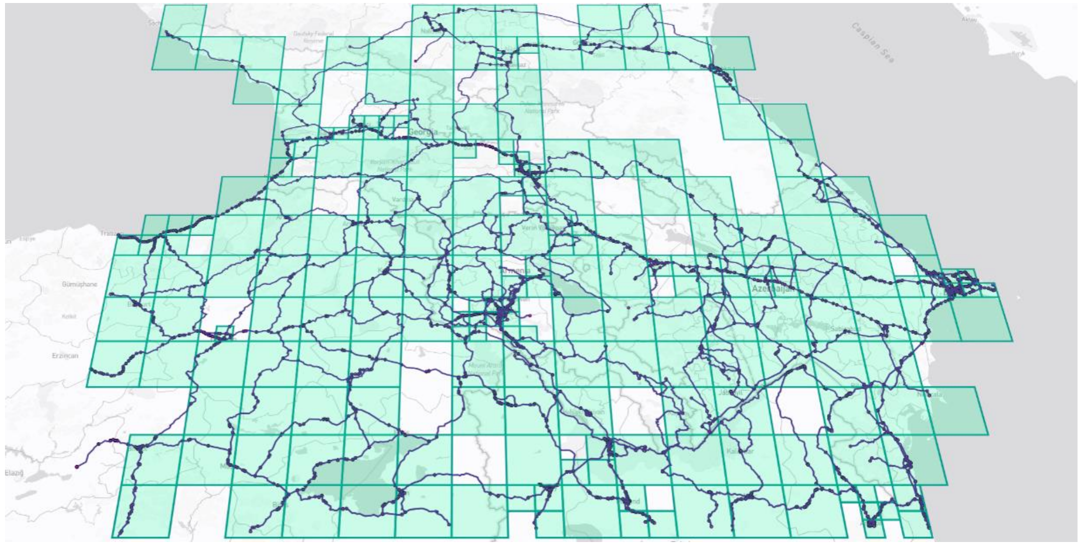
Armenia, Azerbaijan and Georgia

with parts of Iran, Turkey, and Russia.

Two network versions were modelled

First network
— 20,274 links
— Total length of 39,392 km
— 221 traffic analysis zones

Second streamlined network
— 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

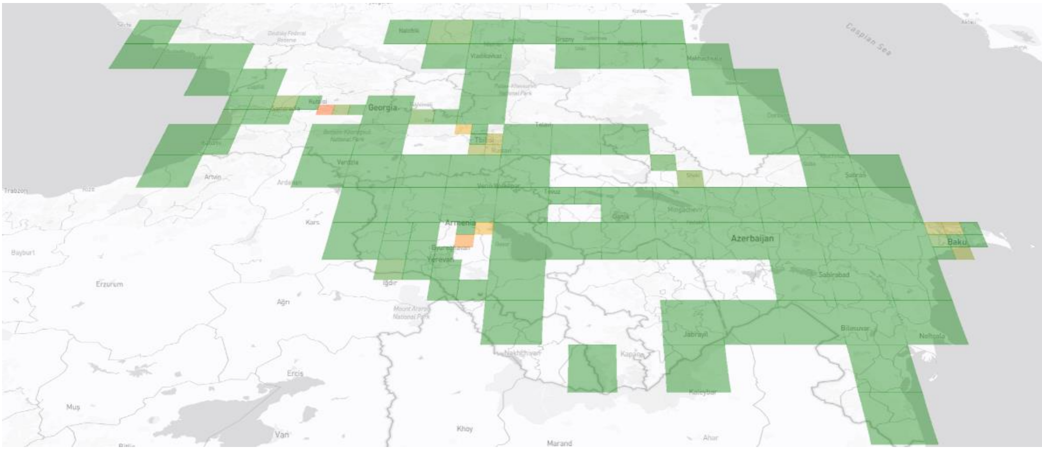
Travel times collected on ***all*** links
— RMSE 16.19 seconds

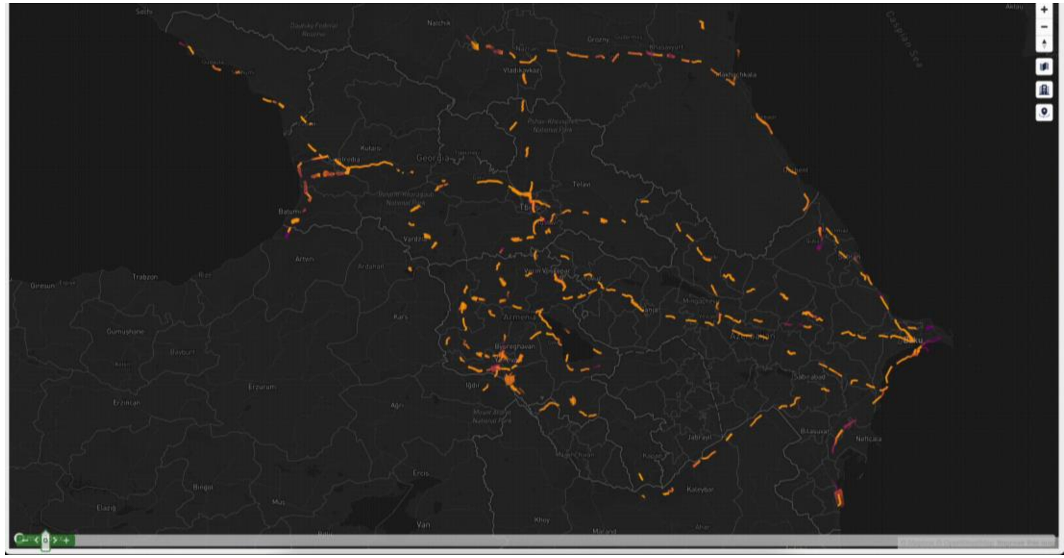
76 specific link counts were also provided to support direct comparison by the broader team

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





Network Design
(Next Steps for Rapid Planning)

Optimization and Meta-Herustics

Automatically Optimize Transport Networks

Macro and Mesoscopic Models

Some of our NDP Papers

Waller, S.T. and Ziliaskopoulos, A.K, “**Stochastic Dynamic Network Design Model**” *Journal of the Transportation Research Board*, pp. 106-113, 2001.

Ukkusuri SV; Mathew TV; Waller ST, 2007, '**Robust Transportation Network Design Under Demand Uncertainty**', *Computer-Aided Civil and Infra. Engineering*, vol. 22, pp. 6 – 18.

Duthie J; Waller ST, 2008, '**Incorporating Environmental Justice Measures into Equilibrium-Based Network Design**', *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2089, pp. 58 – 65

Lin DY; Waller ST, 2009, '**A quantum-inspired genetic algorithm for dynamic continuous network design problem**', *Transportation Letters*, vol. 1, pp. 81 – 93

Unnikrishnan A; Valsaraj V; Damnjanovic I; Waller ST, 2009, '**Design and management strategies for mixed public private transportation networks: A meta-heuristic approach**', *Computer-Aided Civil and Infrastructure Engineering*, vol. 24, pp. 266 – 279

Duell M; Gardner LM; Waller ST, 2018, '**Policy implications of incorporating distance constrained electric vehicles into the traffic network design problem**', *Transp. Letters*, vol. 10, pp. 144 - 158,

Zhang X; Waller ST, 2018, '**Mixed-Vehicular Aggregated Transportation Network Design Considering En-route Recharge Service Provision for Electric Vehicles**', *Journal of Systems Science and Complexity*, vol. 31, pp. 1329 – 1349

Zhang X; Waller ST, 2019, '**Implications of link-based equity objectives on transportation network design problem**', *Transportation*, vol. 46, pp. 1559 – 1589.

Zhang X; Waller ST; Rey D; Duell M, 2019, '**Integrating uncertainty considerations into multi-objective transportation network design projects accounting for environment disruption**', *Transportation Letters*, vol. 11, pp. 351 - 361,

Model Scope - Mobility as a Resource

How to model mobility transitioning from

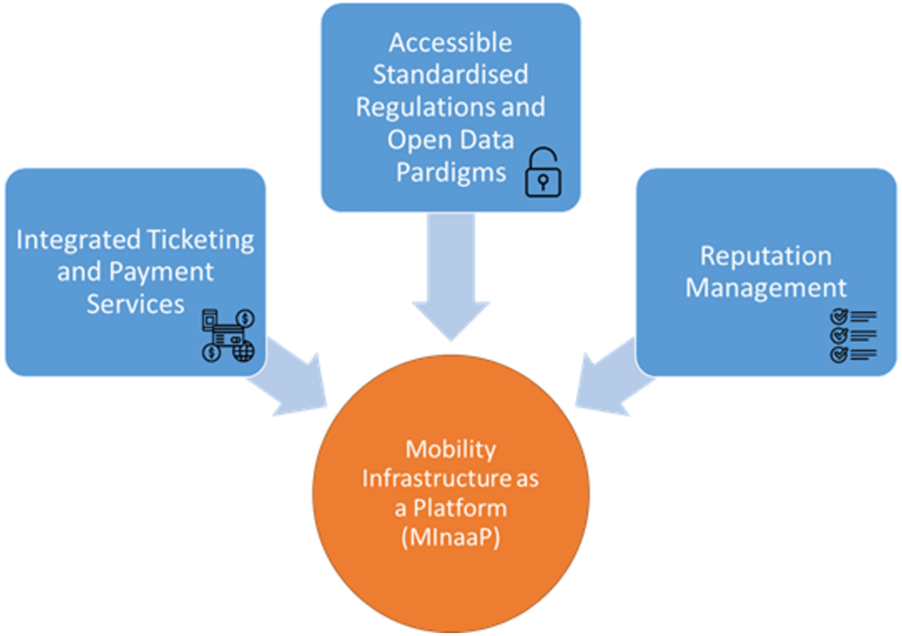
<u>Product</u> to <u>Service</u> to <u>Resource</u>

As well as the underlying platform

Mobility Infrastructure as a Platform

Key technology

Blockchain for decentralized mobility market transacttions



ST Waller, K Wijayaratna, and V Prados-Valerio (2021), "**All your transport options in one place: why mobility as a service needs a proper platform**" The Conversation. Available at: https://theconversation.com/all-your-transport-options-in-one-place-why-mobility-as-a-service-needs-a-proper-platform-157243.

Mohammad Chinaei, T.H. Rashidi, and S.T. Waller (2022) "**Digitally Transferable Ownership of Mobility-as-a-Service Systems Using Blockchain and Smart Contracts**“ Transportation Letters, pp. 1-8.

Mohammad Chinaei, T.H. Rashidi, and S.T. Waller (2021, In Review) "**DeMaaS: Towards A Decentralised and Automated Mobility-as-a-Service based on Tokenised Economy**" (In Review).

Towards Decentralisation

Unlocking mobility as a resource via markets

Mobility resources can be packaged and traded

Smart contracts provide the trusted means

When requiring human interaction, reputation needs systemised

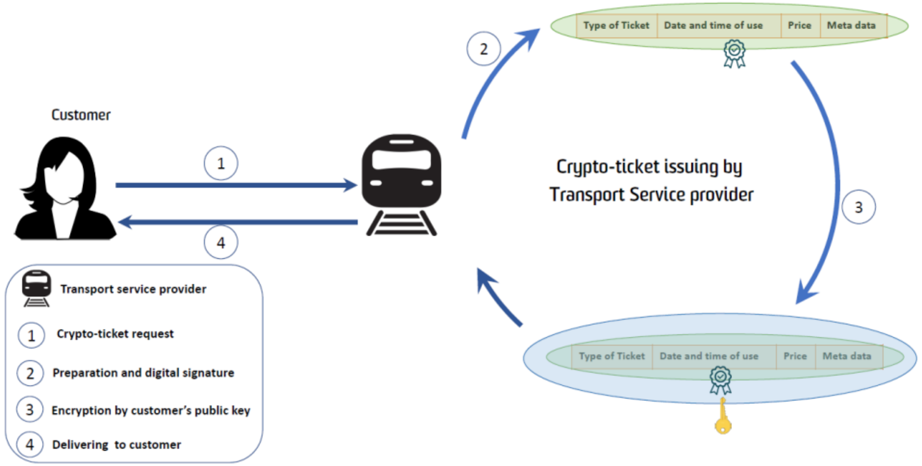


Fig. 1. Issuing a crypto-ticket off the blockchain by TSP

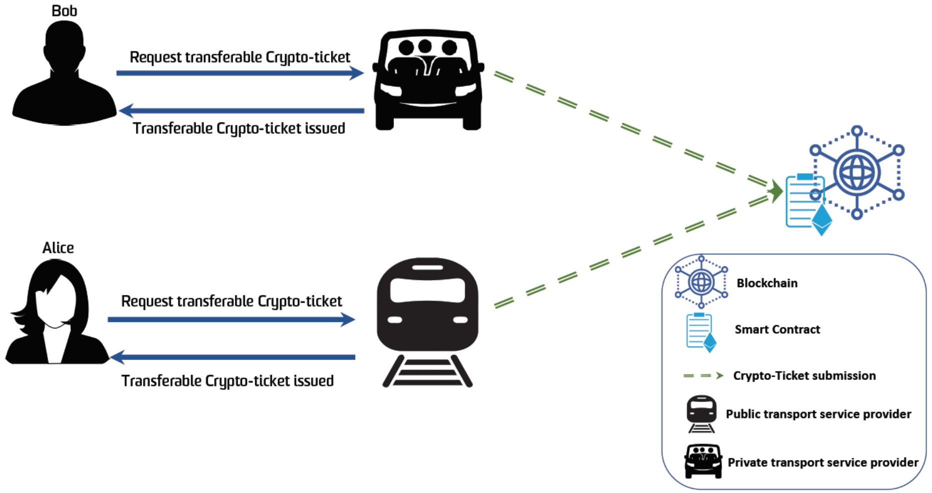


Fig. 2. Simple model for crypto-ticket issueing.

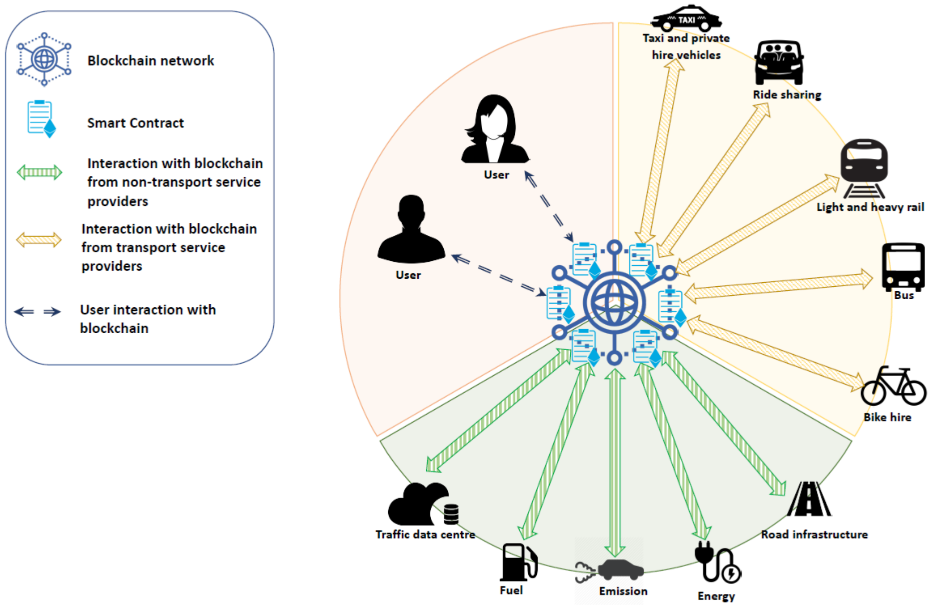


Fig. 6. Market for asset trading in a blockchain-based MaaS network

ERC-20 Smart Contract Implementation

Blockchain implementation

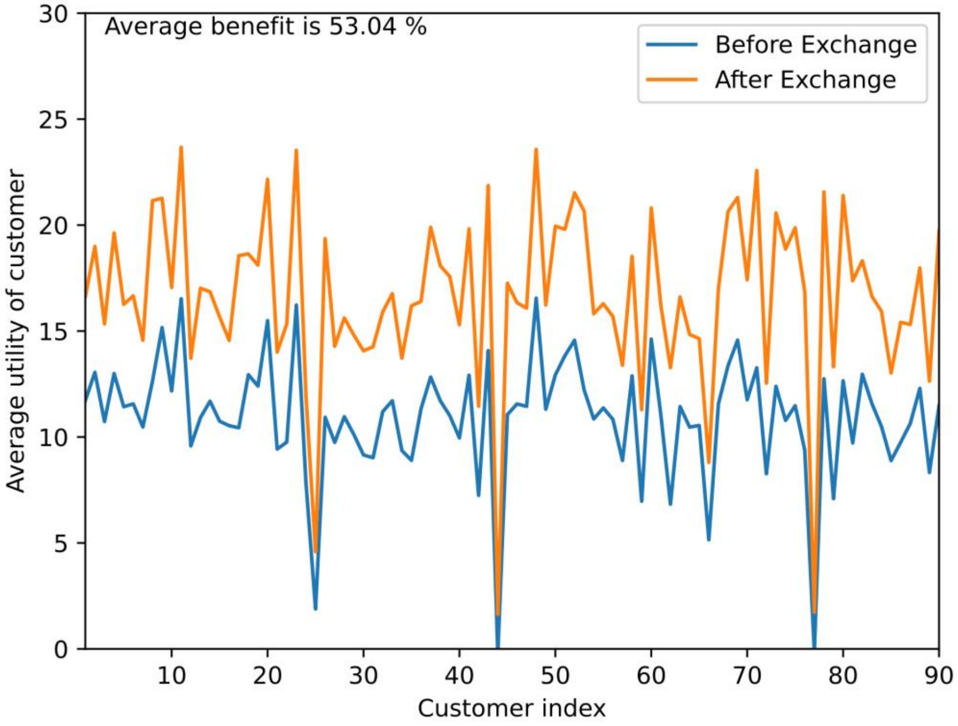
Simulated decentralised exchange

Examined bounds of operation

Random start

Users exchange mobility links

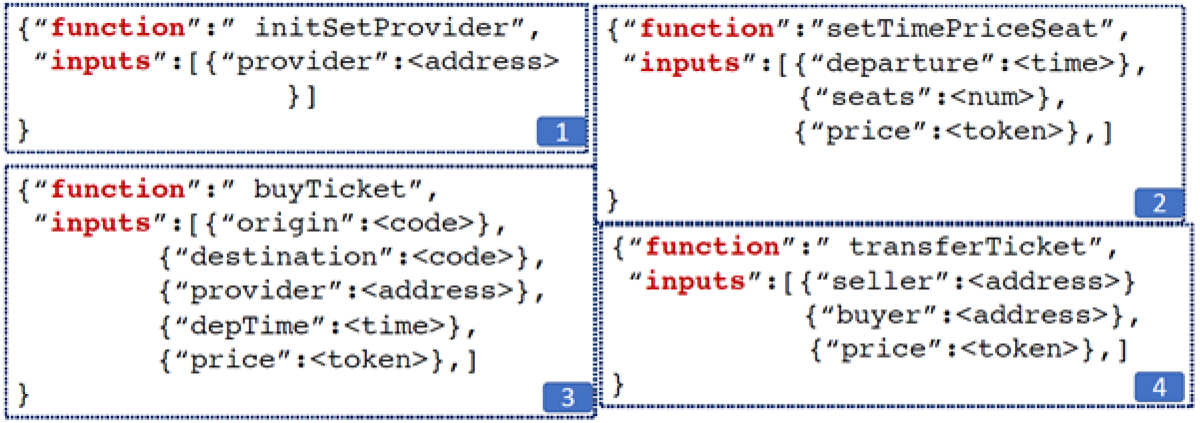
Simulated user and system benefit



Explored typical bounds from random start

10,000 simulation runs

Currently, exploring analytical bounds and communication costs



```
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           }]
}
```

```
{"function":"setTimePriceSeat",
 "inputs":[{"departure":<time>},
           {"seats":<num>},
           {"price":<token>},]

}
```

```
{"function":" buyTicket",
 "inputs":[{"origin":<code>},
           {"destination":<code>},
           {"provider":<address>},
           {"depTime":<time>},
           {"price":<token>},]
}
```

```
{"function":" transferTicket",
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           {"buyer":<address>},
           {"price":<token>},]
}
```

Fig. 3. Functions of the contract in the market stage

Model Scope – Health Interaction

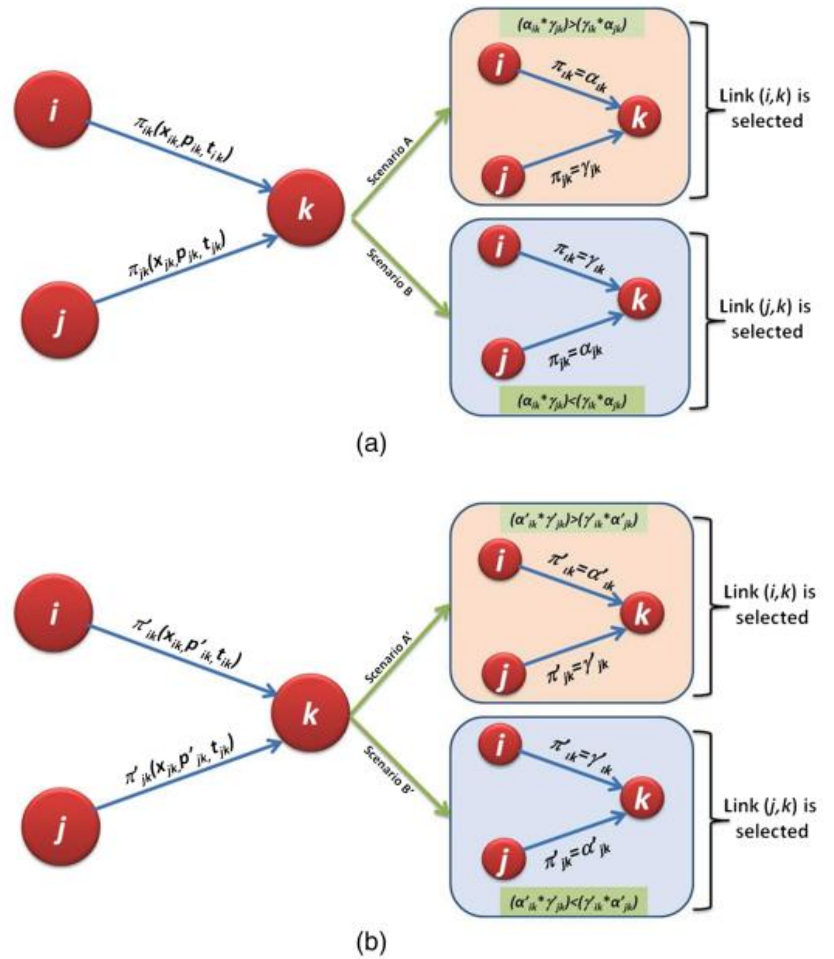

Fig. 6. (a) Example network with link costs and possible infection link selections for a network with accurate transmission probabilities, p; (b) example network with link costs and possible infection link selections for a network with inaccurate transmission probabilities, p'

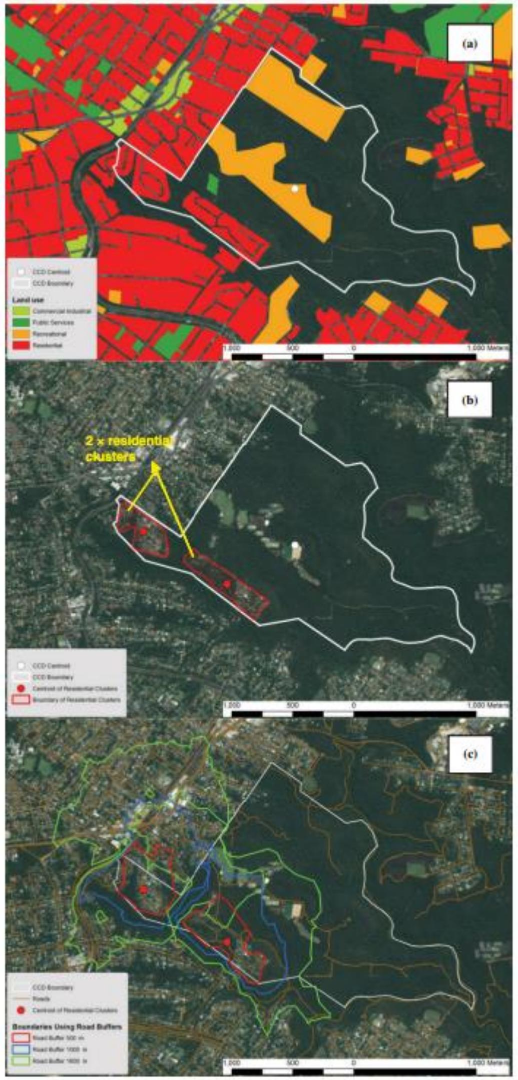

FIGURE 2 Aggregation clustering: (*a*) residential land use areas within CCD boundary (land use layer obtained from Office of Environment and Heritage, New South Wales, Australia); (*b*) two residential clusters within CCD boundary; and (*c*) proposed boundaries using three road buffer distances.

L Gardner;D Fajardo;ST Waller;O Wang;S Sarkar (2012) '**A predictive spatial model to quantify the risk of air-travel-associated dengue importation into the United States and Europe**', J of Tropical Medicine, vol. 2012, pp. 1-11.

L Gardner;D Fajardo;ST Waller (2014) '**Inferring Contagion Patterns in Social Contact Networks Using a Maximum Likelihood Approach**', ASCE Natural Hazards Rev., vol. 15(3).

L Gardner;D Rey;AE Heywood;R Toms;J Wood;ST Waller;CR MacIntyre (2014) '**A scenario-based evaluation of the Middle East respiratory syndrome coronavirus and the Hajj**', Risk analysis : an official publication of the Society for Risk Analysis, vol. 34, pp. 1391 - 1400.

N Amini;T Rashidi;L Gardner;ST Waller (2016) '**Spatial aggregation method for anonymous surveys: Case study for associations between urban environment and obesity**', Tr. Research Record, vol. 2598, pp. 27 - 36.

D Rey;L Gardner;ST Waller (2016) '**Finding Outbreak Trees in Networks with Limited Information**', Networks and Spatial Economics, vol. 16, pp. 687 – 721

M Saberi;H Hamedmoghadam;M Ashfaq; SA Hosseini;Z Gu;S Shafiei;DJ Nair;V Dixit;L Gardner;ST Waller;MC González (2020) '**A simple contagion process describes spreading of traffic jams in urban networks**' Nature Communications 11, Article number: 1616, pp. 1-9.

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

Some of our Relevant Papers

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)

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

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

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

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

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

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

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

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

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

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

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

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

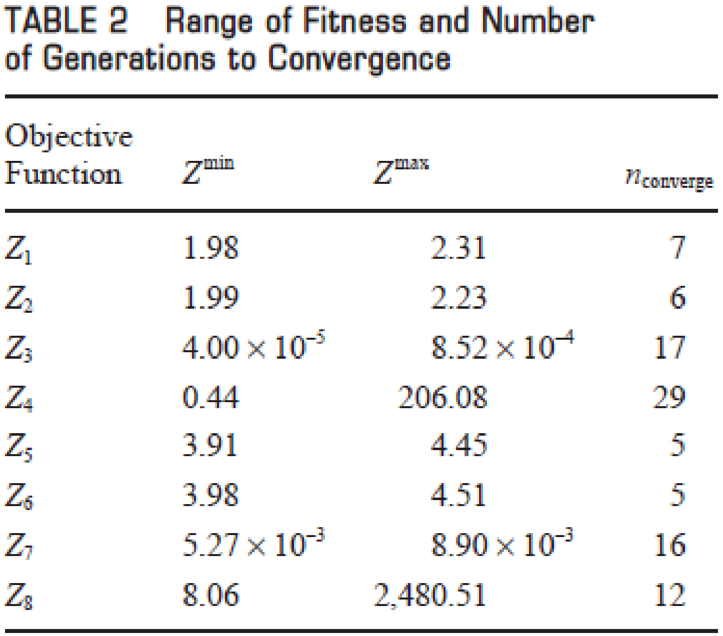

TABLE 2 Range of Fitness and Number of Generations to Convergence

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

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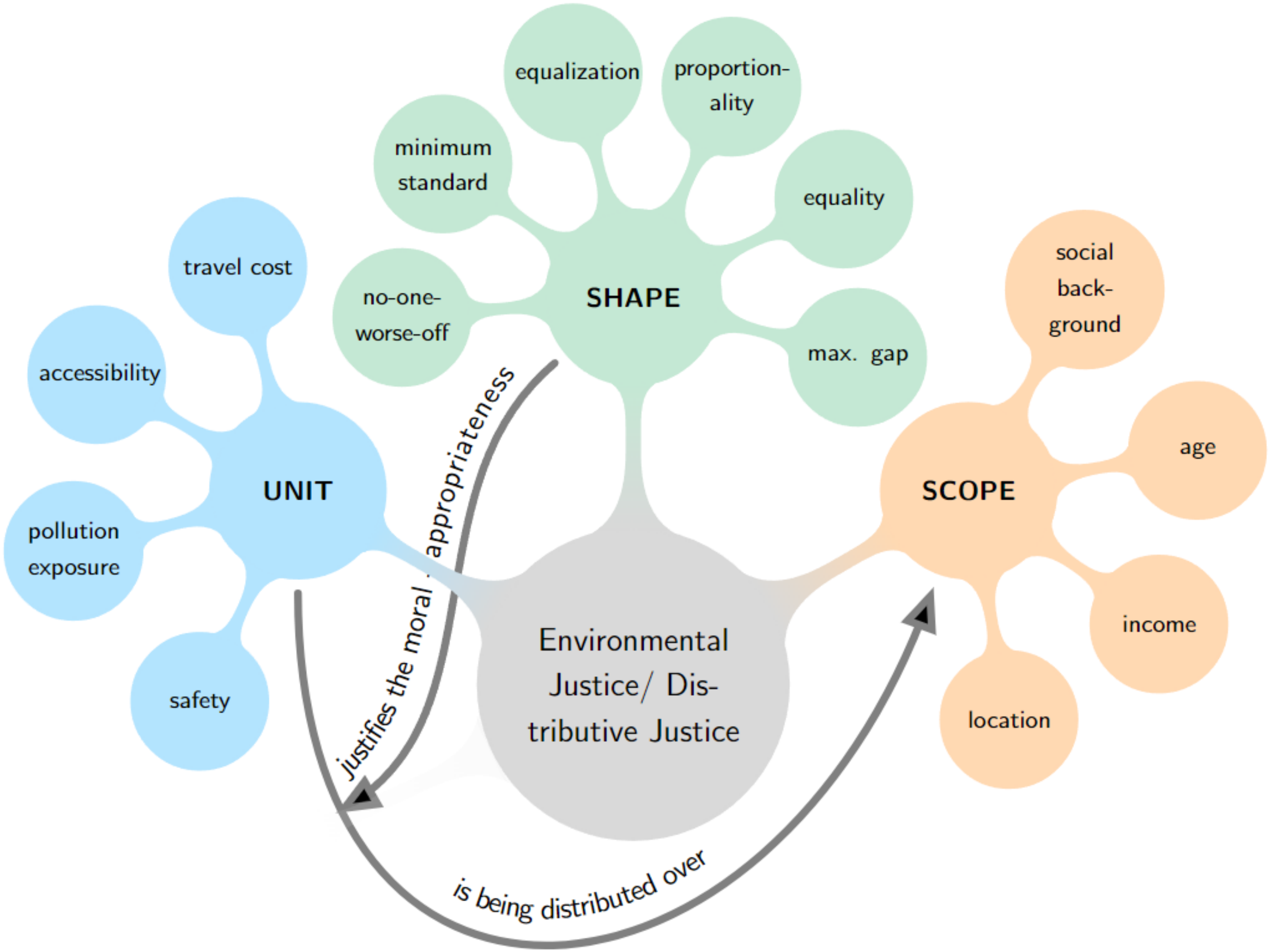
Ethics Metrics – Current Ongoing Work (Current ARC Discovery Grant)

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

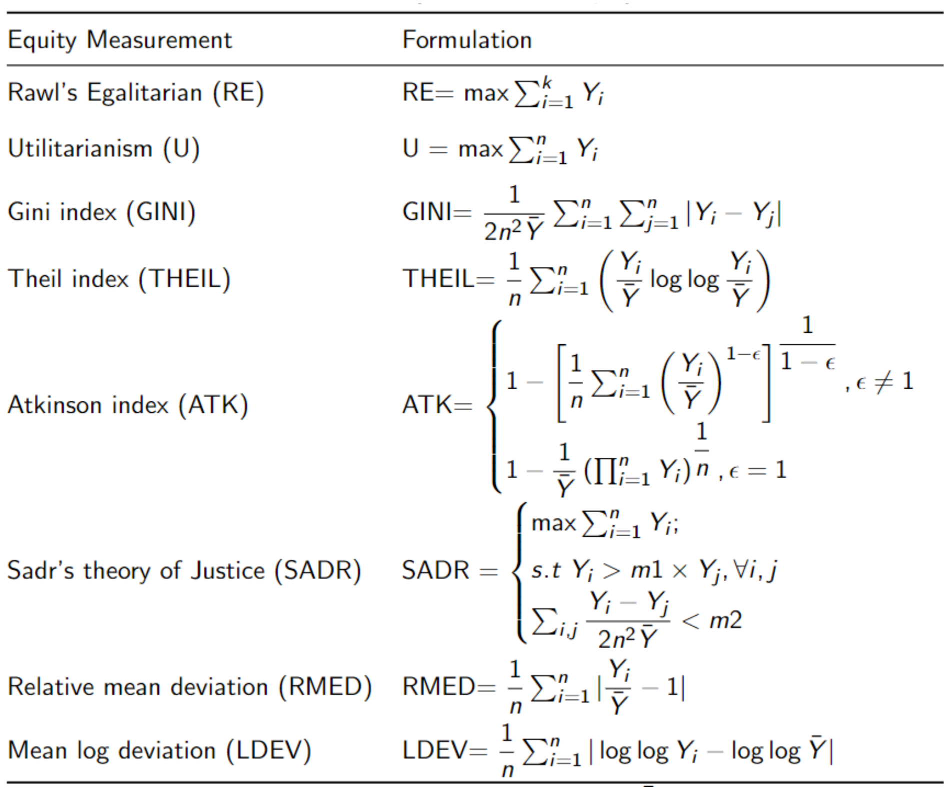
Metric	Ethical theory	Type	Target impact
Utilitarian	Consequentialism/ Distributive justice	Equity	Maximizes the welfare of all user groups
Rawl's Egalitarian	Deontological/ Distributive justice	Equity	Maximizes the welfare of the least advantaged user group
CBA with distributive weights	Consequentialism/ 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)	$\text{RE} = \max \sum_{i=1}^{k} Y_i$
Utilitarianism (U)	$\text{U} = \max \sum_{i=1}^{n} Y_i$
Gini index (GINI)	$\text{GINI} = \frac{1}{2n^2 \bar{Y}} \sum_{i=1}^{n} \sum_{j=1}^{n} \lvert Y_i - Y_j \rvert$
Theil index (THEIL)	$\text{THEIL} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{Y_i}{\bar{Y}} \log \log \frac{Y_i}{\bar{Y}} \right)$
Atkinson index (ATK)	$\text{ATK} = \begin{cases} 1 - \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{Y_i}{\bar{Y}} \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}, \epsilon \neq 1 \\ 1 - \frac{1}{\bar{Y}} \left(\prod_{i=1}^{n} Y_i \right)^{\frac{1}{n}}, \epsilon = 1 \end{cases}$
Sadr's theory of Justice (SADR)	$\text{SADR} = \begin{cases} \max \sum_{i=1}^{n} Y_i; \\ s.t\ Y_i > m1 \times Y_j, \forall i, j \\ \sum_{i,j} \frac{Y_i - Y_j}{2n^2 \bar{Y}} < m2 \end{cases}$
Relative mean deviation (RMED)	$\text{RMED} = \frac{1}{n} \sum_{i=1}^{n} \lvert \frac{Y_i}{\bar{Y}} - 1 \rvert$
Mean log deviation (LDEV)	$\text{LDEV} = \frac{1}{n} \sum_{i=1}^{n} \lvert \log \log Y_i - \log \log \bar{Y} \rvert$

Road Vehicle Carbon and Emission Modelling (Ongoing Work)

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

Example: Road vehicle carbon

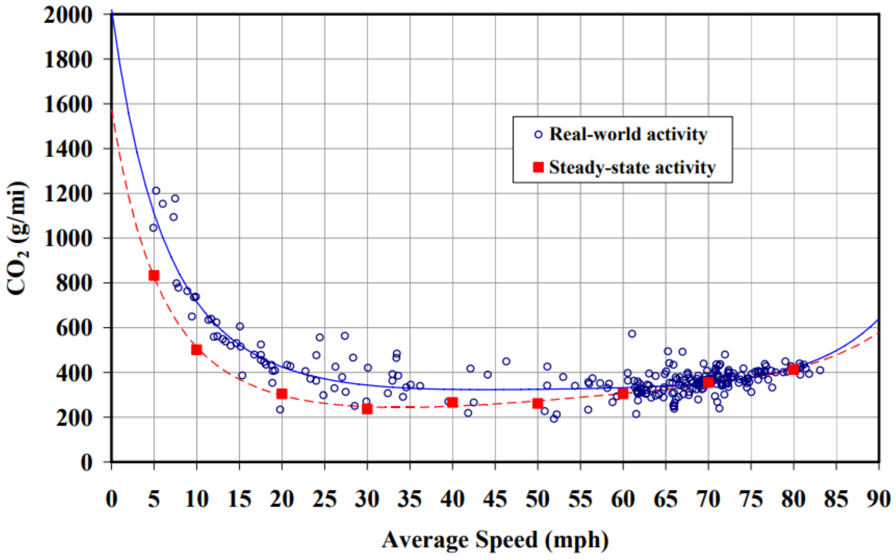
3 Methods examined including:

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.



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

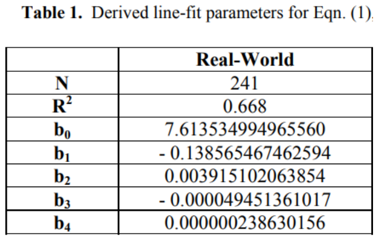


Table 1. Derived line-fit parameters for Eqn. (1).

	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.

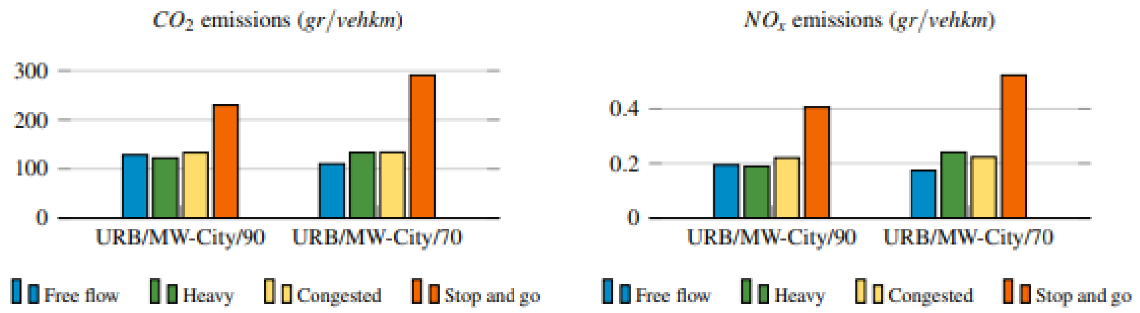


Figure 1. HBEFA emission factors; (a) CO_2 (b) NO_x.

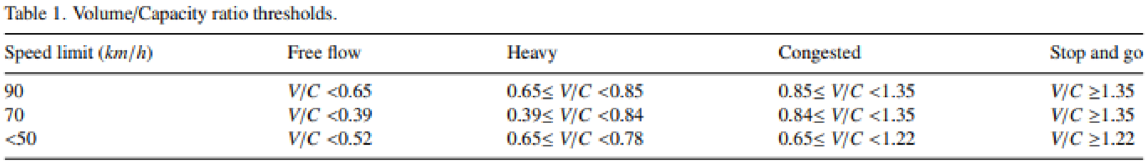
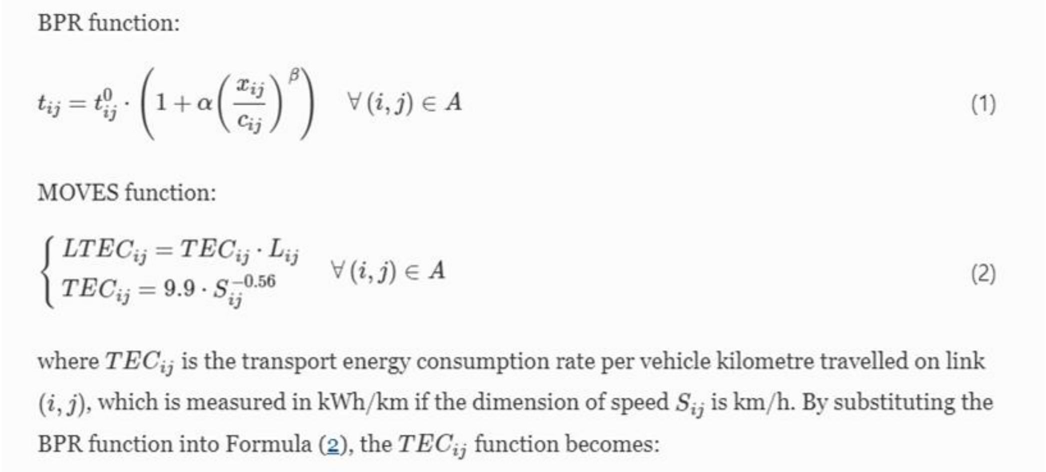


Table 1. Volume/Capacity ratio thresholds.

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

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

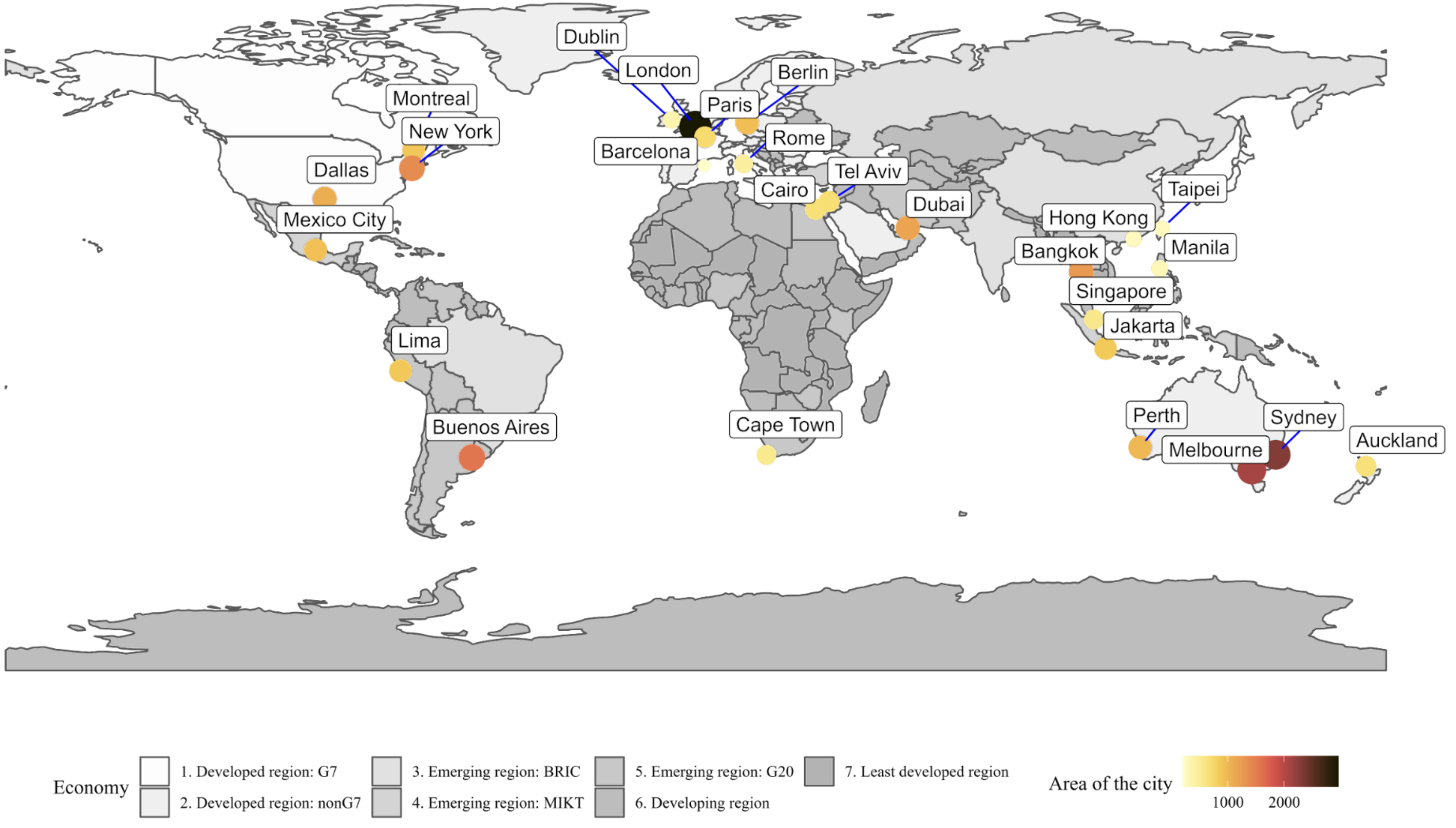
Considered World Cities

City	Region	[1] Economic Representation	[2] Area of city [km^2]
Auckland	Oceania	Developed : Non G7	645
Bangkok	Asia	Emerging : G20	1267
Barcelona	Europe	Developed : G7	201
Berlin	Europe	Developed : G7	954
Buenos Aires	South America	Emerging : G20	1571
Cairo	Africa	Emerging : G20	657
Cape Town	Africa	Emerging : G20	540
Dallas	North America	Developed :G7	1091
Dubai	Middle East	Developing	1159
Dublin	Europe	Developed :G7	360
Hong Kong *	Asia	Emerging : BRIC	281
Jakarta	South East Asia	Emerging : MIKT	860
Lima	South America	Emerging : G20	880
London	Europe	Developed : G7	2961
Manila	South East Asia	Emerging : G20	313
Melbourne	Australia	Developed : Non G7	2103
Mexico City	South America	Emerging : MIKT	931
Montreal	North America	Developed : G7	890
New York	North America	Developed : G7	1388
Paris	Europe	Developed : G7	717
Perth	Australia	Developed : Non G7	1008
Rome	Europe	Developed : G7	452
Singapore *	Asia	Developing	556
Sydney	Europe	Developed : Non G7	2305
Taipei	Asia	Developed : Non G7	273
Tel Aviv	Middle East	Developed : Non G7	681

[1] Data Source: World Bank [4]

[2] Area of the city considered in the study through GIS mapping

* Considered as developed economies based on the high GDP



Data source: World Bank

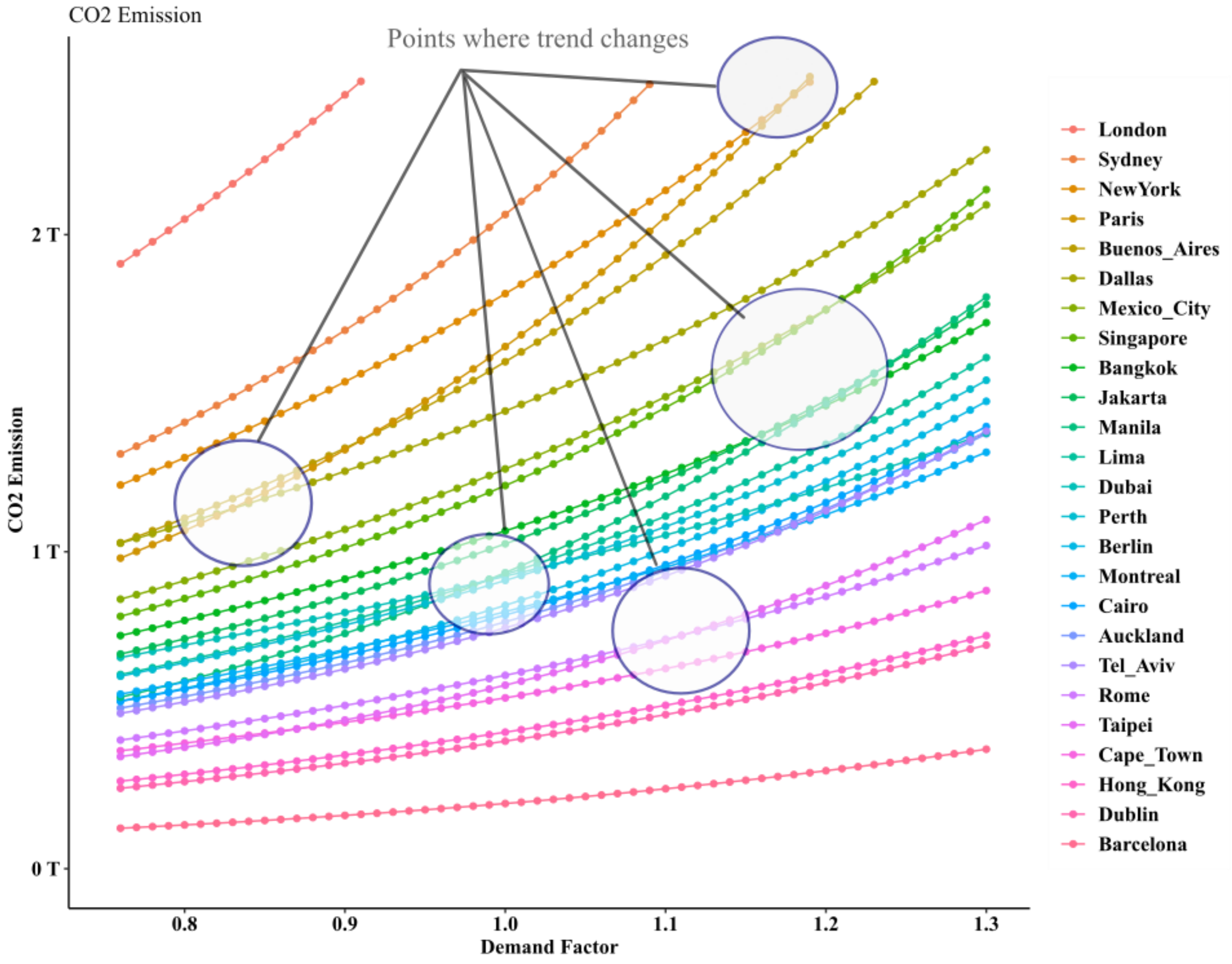
Preliminary Quantification of the Gradient of Road Traffic Carbon (Carbon Sensitivity)

Current work - in draft for illustration

- **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



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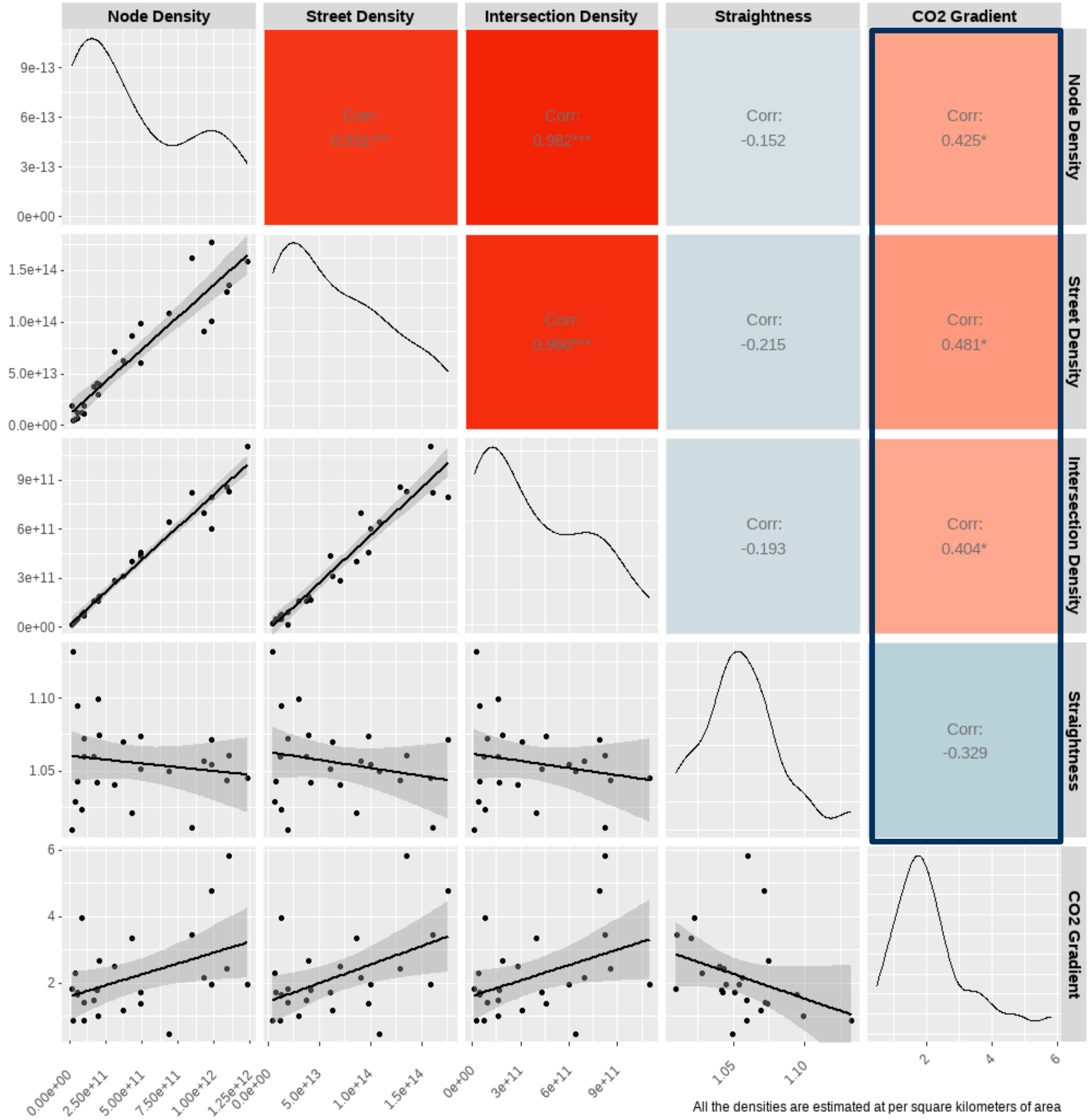
Do network parameters have any influence on gradient of emissions?

Current work – in draft for illustration

More than 25 different networks parameters were investigated

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

- <u>Preliminary Analysis</u>: 4 are found to have significant relation with gradient of emission
  - (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

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Inferring network capacity reduction and demand variation after disruptions for rapid system evaluation

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1. Introduction

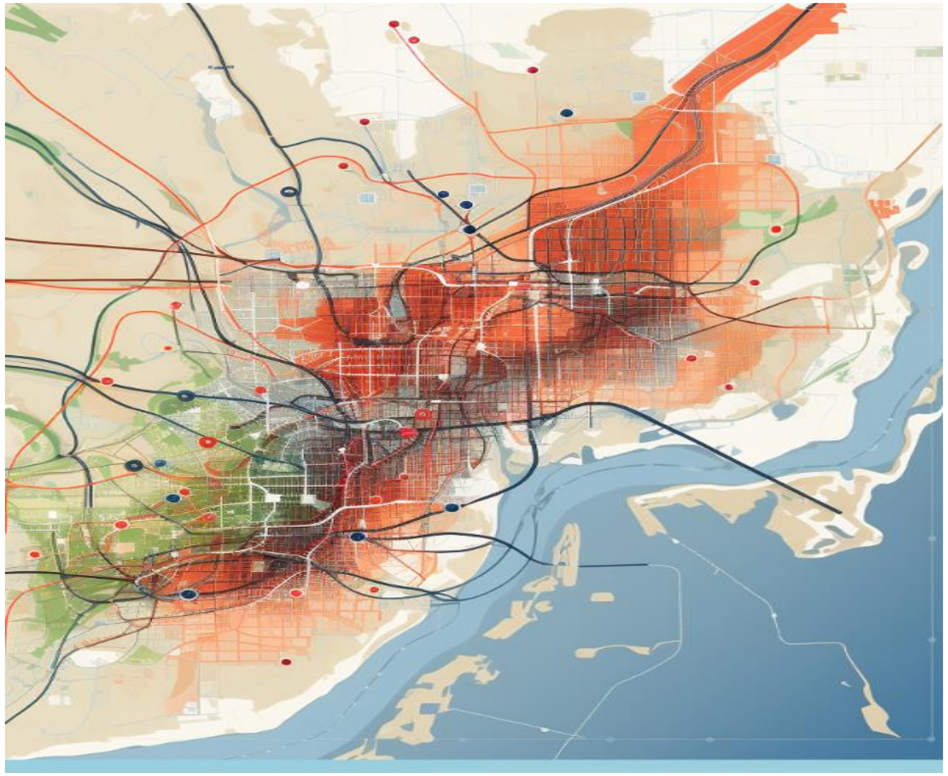


Fig.1. An abstract illustration of transportation network

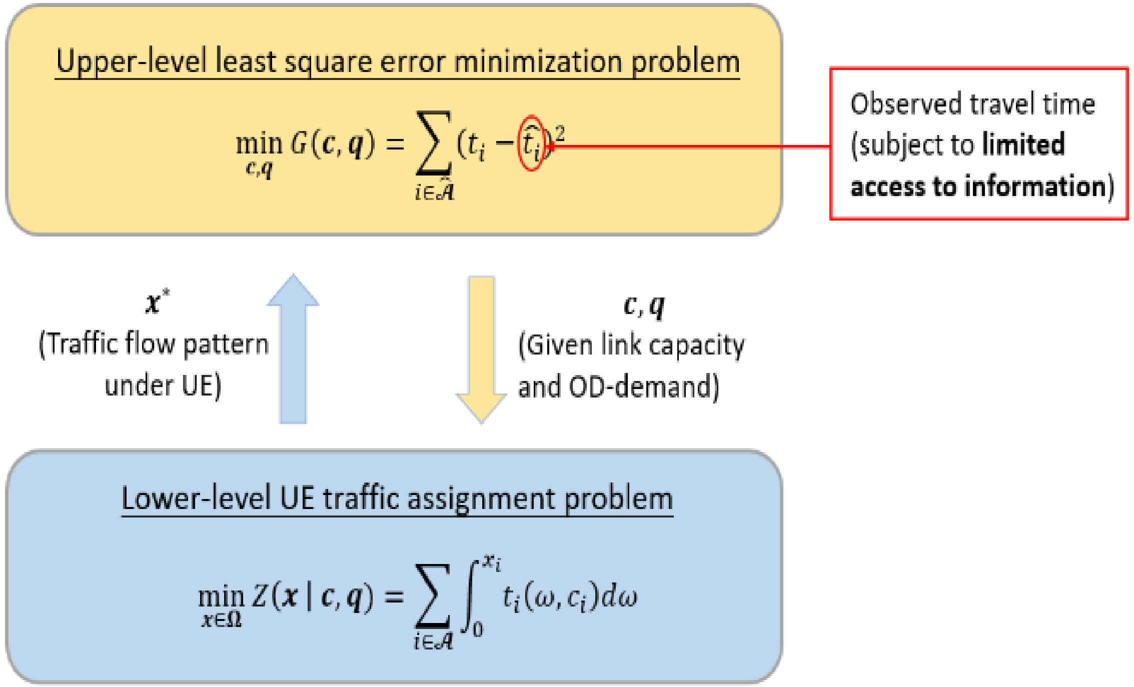
- Transportation disruptions have **significant social and economic impacts**, but obtaining detailed data during the early stages of disruptions is challenging.
- Existing studies on transportation network disruption have primarily focused on **analyzing network properties and quantifying performance measures**, but they often **overlook the impact on travel behavior and assess the state of disrupted networks**.

1. Introduction

Fig.2. An illustration of disrupted transportation network

- We propose a network assessment methodology, called CRDM, which **estimates the network-level capacity reduction and OD demand variation**, enabling **quick and informed decision-making** by transportation operators and decision-makers.

2. Problem description



Upper-level least square error minimization problem

$$\min_{\boldsymbol{c},\boldsymbol{q}} G(\boldsymbol{c},\boldsymbol{q}) = \sum_{i\in\hat{\mathcal{A}}} (t_i - \hat{t}_i)^2$$

Observed travel time (subject to **limited access to information**)

$\boldsymbol{x}^*$ (Traffic flow pattern under UE)

$\boldsymbol{c},\boldsymbol{q}$ (Given link capacity and OD-demand)

Lower-level UE traffic assignment problem

$$\min_{\boldsymbol{x}\in\Omega} Z(\boldsymbol{x}\mid\boldsymbol{c},\boldsymbol{q}) = \sum_{i\in\mathcal{A}} \int_0^{x_i} t_i(\omega,c_i)d\omega$$

Fig.3. Bi-level framework for the joint estimation of network-scale capacity reduction and OD demand matrix (CRDM)

- Consider a fully connected and directed graph represented by $G(N,A)$, where N denotes the set of nodes and A represents the set of links.
- We aim to estimate network capacity reduction/loss based on limited information, i.e., OD demand distribution is unknown and some observations of link travel times are available.
- We propose a network assessment methodology, called CRDM, which estimates the network-level capacity reduction and OD demand variation.

2. Model formulation

2 . 1 The generalized least squares model for CRDM (GLS-CRDM)

- In the upper-level: $\min_{\mathbf{c},\mathbf{q}} G(\mathbf{c},\mathbf{q}) = \sum_{i\in\hat{\mathcal{A}}} (t_i(x_i^*, c_i) - \hat{t}_i)^2$

- In the lower-level: UE traffic assignment

$$\min_{\mathbf{x}\in\Omega} Z(\mathbf{x} \mid \mathbf{c},\mathbf{q}) = \sum_{i\in\mathcal{A}} \int_0^{x_i} t_i(\omega, c_i)\,d\omega$$

with

$$\Omega = \left\{ \mathbf{x} = (x_i,\ i \in \mathcal{A}) \middle| x_i = \sum_{r\in\mathcal{R}_w} f_r\delta_{ir},\ \forall i \in \mathcal{A};\ \sum_{r\in\mathcal{R}_w} f_r = q_w, \forall w \in \mathcal{W};\ f_r \geq 0, \forall r \in \mathcal{R}_w \right\}$$

$\boldsymbol{c}$: The remaining link capacity vector
$\boldsymbol{q}$: OD demand matrix
$\boldsymbol{x}$: The link flow vector

$\hat{t}_i$: The observed link travel time of link i
t_i: The link travel time under UE condition, given $\boldsymbol{c}, \boldsymbol{q}$

$\mathcal{A}$: The set of links
$\tilde{\mathcal{A}}$: The set of links with available link travel time data.
$\mathcal{R}_w$: The set of available paths given OD demand q_w
W: The set of OD demand pairs.

Remark 1: The CRDM problem reduces to the OD demand estimation problem if it only optimizes OD demand matrix $\boldsymbol{q}$, subject to given link capacity $\boldsymbol{c}$.

2.1 The generalized least squares model for CRDM (GLS-CRDM)

2 . 1 . 1 Characteristics of solutions to the GLS-CRDM

- **Optimality conditions of the GLS-CRDM**

$$(t_i - \hat{t}_i)\left[\frac{\partial t_i}{\partial c_i} + \frac{\partial t_i}{\partial x_i^*}\frac{\partial x_i^*}{\partial c_i}\right] + \sum_{k \in \hat{\mathcal{A}} \backslash i} (t_k - \hat{t}_k)\left[\frac{\partial t_k}{\partial x_k^*}\frac{\partial x_k^*}{\partial c_i}\right] = 0, \quad \forall i \in \hat{\mathcal{A}}$$

$$\sum_{i \in \hat{\mathcal{A}}} (t_i - \hat{t}_i)\frac{\partial t_i}{\partial x_i^*}\frac{\partial x_i^*}{\partial c_j} = 0, \quad \forall j \in \hat{\mathcal{A}}^c \cap \mathcal{A} \qquad \text{(FOCs)}$$

$$\sum_{i \in \hat{\mathcal{A}}} (t_i - \hat{t}_i)\left[\frac{\partial t_i}{\partial x_i^*}\frac{\partial x_i^*}{\partial q_w}\right] = 0, \quad \forall w \in \mathcal{W}$$

$\boldsymbol{\frac{\partial t_i}{\partial c_i} + \frac{\partial t_i}{\partial x_i^*}\frac{\partial x_i^*}{\partial c_i}}$: combined effect of the marginal increase in the remaining capacity c_i of the observable link i on the link travel time of link i.

(i) $\frac{\partial t_i}{\partial x_i^*}\frac{\partial x_i^*}{\partial c_i}$:the marginal link travel time induced by changes on UE based traffic flow due to the capacity variation

(ii) $\frac{\partial t_i}{\partial c_i}$: the direct effect of capacity variation on the link travel time.

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2.1 The generalized least squares model for CRDM (GLS-CRDM)

2 . 1 . 1 Characteristics of solutions to the GLS-CRDM

- **(Solution uniqueness)**: the solution non-uniqueness to the GLS-CRDM model is illustrated
And examined under a simple two-link single-OD network.

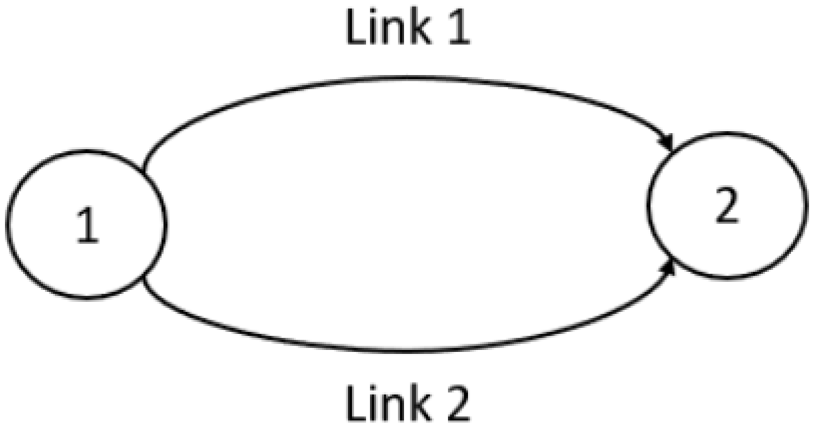


Fig.4. A two-link single-OD network

Remark 2: For the two-link single-OD network in Fig.2, given that realized travel times on links 1 and 2 are observed,

(i) when only the remaining capacities of the two links are both estimated, the optimal (c_1^*, c_2^*) is not unique;
(ii) when only the OD demand is estimated, the optimal q^* is unique;
(iii) when only estimating the remaining capacity of either link, the optimal c_1^* (or c_2^*) is unique;
(iv) when the remaining capacity and OD demand are simultaneously estimated, the optimal (c_1^*, c_2^*, q^*) is not unique;

2.1 The generalized least squares model for CRDM (GLS-CRDM)

2.1.1 Characteristics of solutions to the GLS-CRDM

Remark 3: For the two-link single-OD network in Fig.2, if a solution (c_1^*, c_2^*) is obtained, for any given $\widetilde{c_1} \in \left(0, \frac{\hat{t}_1 - t'_{1,x_1} q}{t'_{1,c_1}}\right)$ with $\boldsymbol{\tilde{c}}_1 \neq c_1^*$, one can always find $\tilde{c}_2$ based on Eq.(1) such that $(\tilde{c}_1, \tilde{c}_2)$ is also solution.

$$\tilde{c}_2 = (c_1^* - \tilde{c}_1)\frac{t'_{1,c_1}}{t'_{2,c_2} t'_{1,x_1}} + c_2^* \ (1)$$

where $t'_{i,c_i} = \frac{\partial t_i}{\partial c_i}$, $t'_{i,x_i} = \frac{\partial t_i}{\partial x_i}$ are all exogenous inputs and the exact values are dependent on (c_1^*, c_2^*).

Remark 3 indicates **the existence of multiple solutions to the GLS-CRDM model.**

Remark 4: Following Remark 3, under given OD demand q and with the consideration of constant $t'_{i,x_i}(>0)$ and $t'_{i,c_i}(<0)$

where $t_i = t'_{i,x_i} x_i + t'_{i,c_i} c_i$, **the solution set for the remaining capacities** can be written as follows:

$$S^* = \left\{ (c_1^*, c_2^*) \middle| \, c_1^* \in \left[0, \frac{\hat{t}_1 - t'_{1,x_1} q}{t'_{1,c_1}}\right]; c_2^* = -\frac{c_1^* \left(c_2^0\right)^2 \left(\hat{t}_2 - t'_{2,x_2} q\right) t'_{2,c_2}}{(c_1^0)^2 \left(\hat{t}_1 - t'_{1,x_1} q\right) t'_{1,c_1}} + \frac{\hat{t}_2 - t'_{2,x_2} q}{t'_{2,c_2}} \right\}$$

where $t'_{i,c_i} = \frac{\partial t_i}{\partial c_i}$, $t'_{i,x_i} = \frac{\partial t_i}{\partial x_i}$ and $\hat{t}_i$ $(i \in \{1,2\})$are all exogenous inputs.

2. Formulation of Model #2

2 . 2 The maximum entropy-least squares model (MELS-CRDM)

There exist multiple solutions based on the GLS-CRDM model. Such solution variability creates uncertainties in estimating the network capacity loss.

$$\min_{\boldsymbol{c},\boldsymbol{q}} S(\boldsymbol{c},\boldsymbol{q}) = \sum_{i \in \mathcal{A}} (c_i ln c_i - c_i) + \sum_{w \in W} (q_w ln q_w - q_w) \tag{2.1}$$

Subject to

$$\sum_{i \in \hat{\mathcal{A}}} (t_i^*(x_i^*, c_i) - \hat{t}_i)^2 \le \epsilon \tag{2.2}$$

Constrains the difference between the observed link travel times and the estimated link travel times

$$x_i^* - \sum_{w \in W} \sum_{r \in R_w} f_r^w \, \delta_{i,r}^w = 0, \forall i \in \mathcal{A} \tag{2.3}$$

$$\sum_{r \in R_w} f_r^w - q_w = 0, \forall w \in W \tag{2.4}$$

$$0 \le c_i \le c_i^0, \forall i \in \mathcal{A}; 0 \le q_w \le Q, \forall w \in W \tag{2.5}$$

The MELS model incorporates the GLS objective from the GLS model into a constraint. By fine-tuning the value of ϵ, the MELS model can yield the same minimum discrepancy between observed and estimated link travel times as that in the GLS-CRDM model.

2.2 The maximum entropy-least squares model for CRDM (MELS)

2 . 2 . 1 Characteristics of solutions to the MELS-CRDM

- **Lagrangian relaxation of the MELS model:**

$$\min_{\boldsymbol{c},\boldsymbol{q}} L(\boldsymbol{c},\boldsymbol{q},\mu,v,\beta) = \sum_{i\in\mathcal{A}}(c_i lnc_i - c_i) + \sum_{w\in W}(q_w lnq_w - q_w) + \mu\left(\sum_{i\in\tilde{\mathcal{A}}}(t_i^*(x_i^*,c_i) - \hat{t}_i)^2 - \epsilon\right) + \sum_{i\in\mathcal{A}} v_i\left(x_i^* - \sum_{w\in W}\sum_{r\in R_w} f_r^w\,\delta_{i,r}^w\right) + \sum_{w\in W}\beta_w\left(\sum_{r\in R^w} f_r^w - q_w\right)$$

- **Uniqueness of the optimal solution:** The solution to the Lagrangian dual is unique. Note that the existence of the solution can be guaranteed by adjusting the value of ϵ .

3. Numerical studies

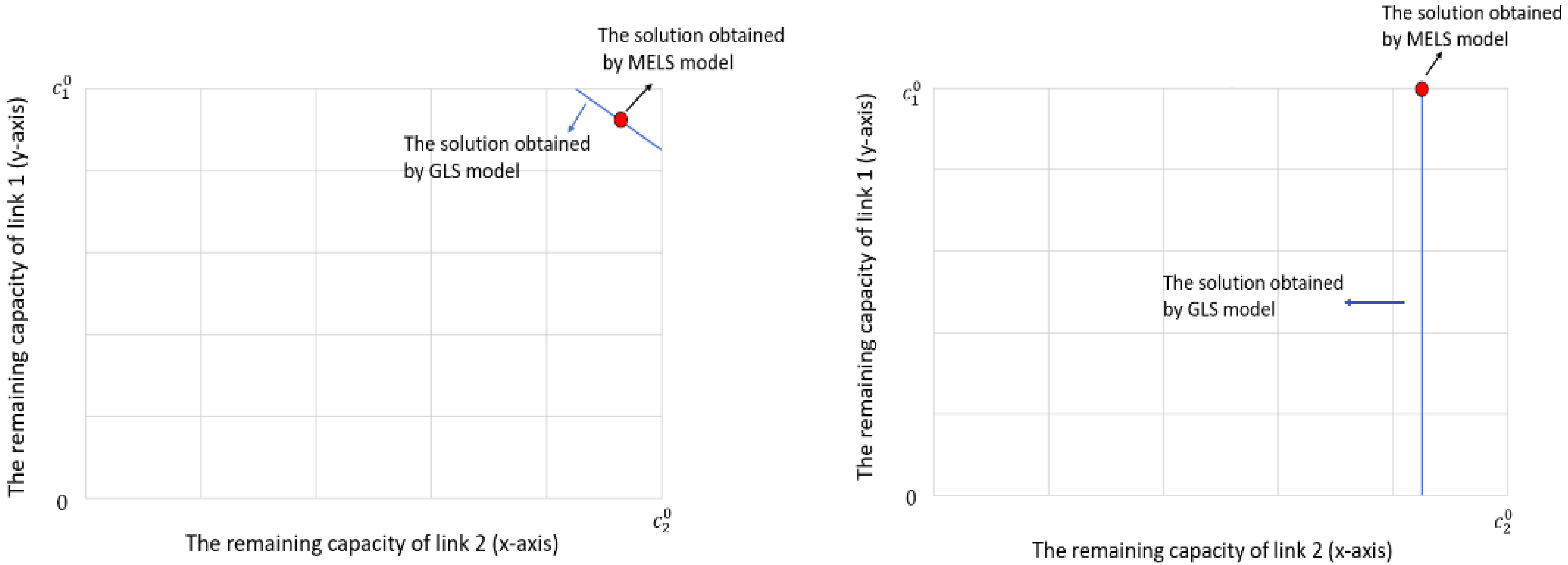
- **Relative difference in network capacity reduction:**

$$r_d = \left| \frac{n_e - n_r}{n_0} \right| \times 100\%$$

n_e: the estimated network capacity reduction
n_r: the actual network capacity reduction
n_0: the initial network overall capacity

3. Numerical studies

3 . 1 The two-link single-OD network



(a) The first scenario (Both links have traffic flows)

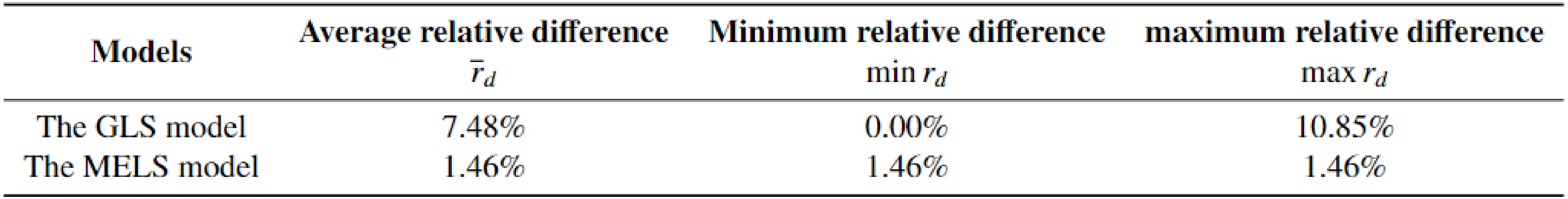
(b) The second scenario (Only one of the links has traffic flow)

Fig.5. Comparison of solutions for the optimal remaining link capacities: the GLS model vs. the MELS model

3. Numerical studies

3 . 1 The two-link single-OD network

Table 1. Comparison of network level capacity reduction estimation between the GLS model and the MELS model



Models	**Average relative difference** $\bar{r}_d$	**Minimum relative difference** $\min r_d$	**maximum relative difference** $\max r_d$
The GLS model	7.48%	0.00%	10.85%
The MELS model	1.46%	1.46%	1.46%

3. Numerical studies

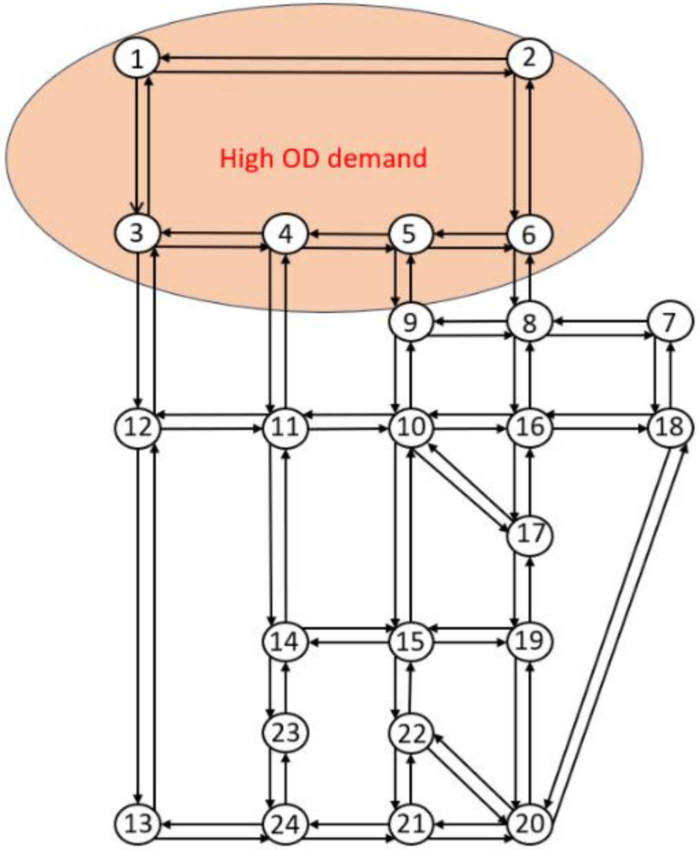


Fig.6. A Sioux-Falls network for numerical example

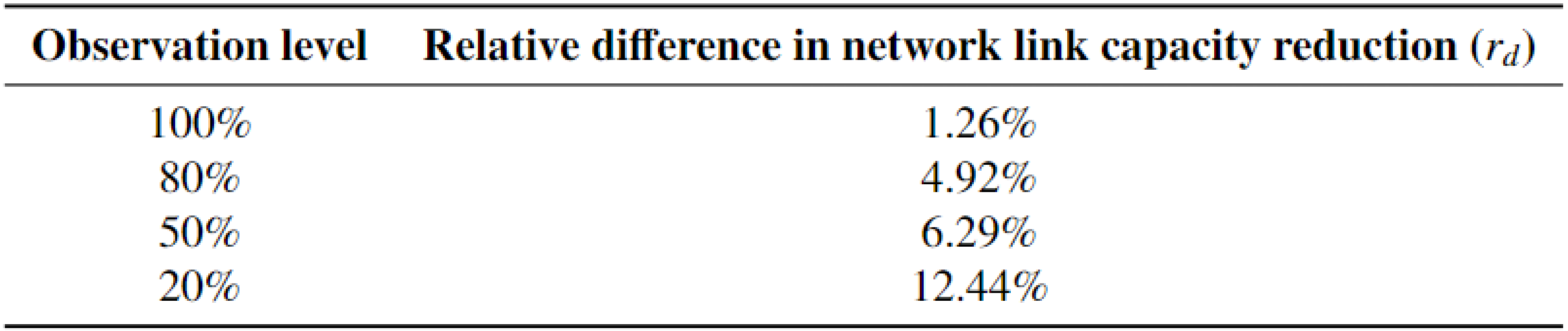
Table 2. Estimation results for network capacity reduction using the proposed MELS method

Metrics	**Description**	**Values**
r_d	The relative difference between the estimated and real network capacity reduction (calculated as a percentage of the original network capacity)	1.26%

3. Numerical studies

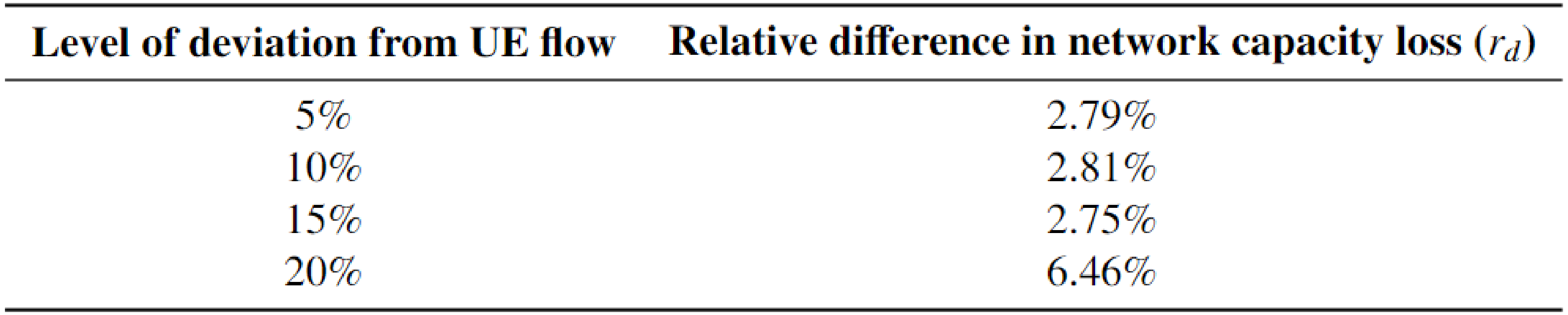
3 . 2 The Sioux-Falls network

Table 3. Estimation accuracy under different observation levels/coverages



Observation level	Relative difference in network link capacity reduction (r_d)
100%	1.26%
80%	4.92%
50%	6.29%
20%	12.44%

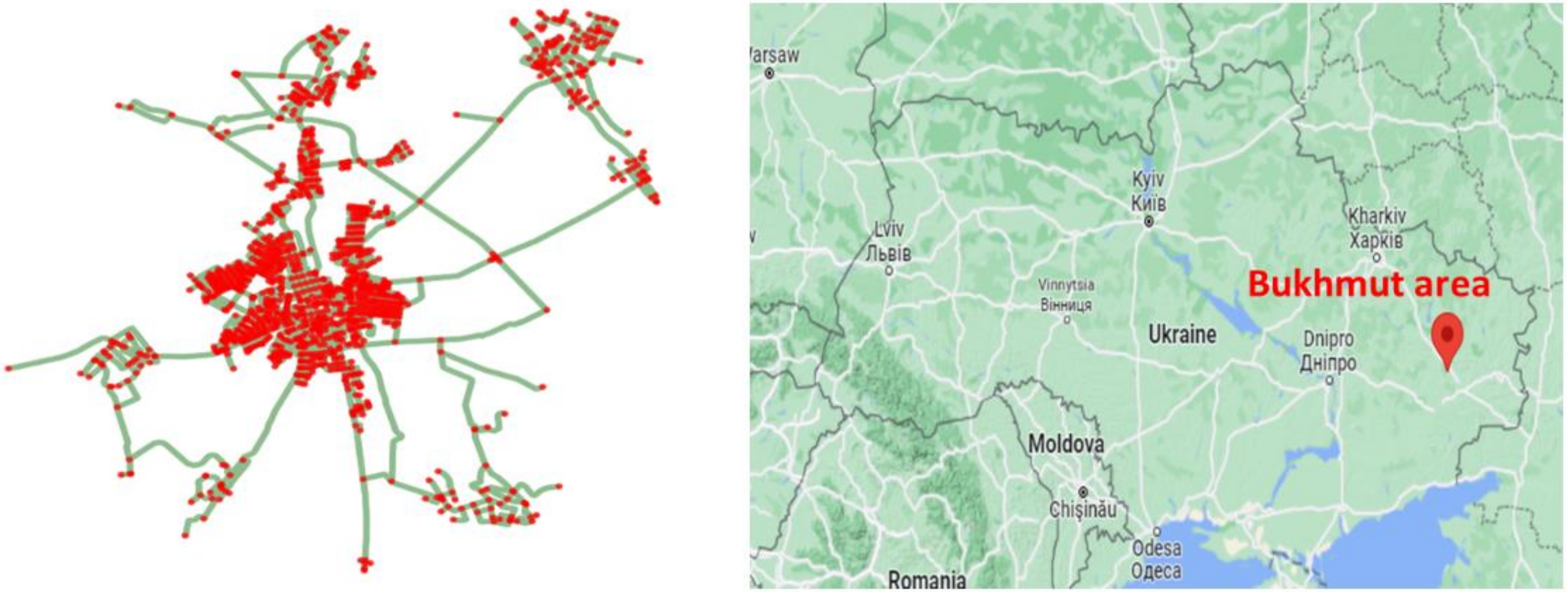
Table 4. Comparison of estimation results for link capacity reduction



Level of deviation from UE flow	Relative difference in network capacity loss (r_d)
5%	2.79%
10%	2.81%
15%	2.75%
20%	6.46%

3. Numerical studies

3 . 3 Bukhmut network



(a) A part of transportation network in Bukhmut area

(b) The map of Ukraine

Fig.7. A part of transportation network in Bukhmut, Ukraine

Table 5. Estimation results for network capacity reduction

Cases	Average relative difference $\bar{r}_d$	Minimum relative difference $\min r_d$	maximum relative difference $\max r_d$	Variance for relative difference $\sigma^2(r_d)$
OD demand is unknown	6.87%	4.21%	16.19%	1.05%
OD demand is known	3.28%	2.82%	8.14%	0.12%

4. Conclusions

- This paper is the first study to propose the **rapid estimation** of network-scale capacity reduction and OD demand matrix for disrupted networks **under limited information**

- This study develops **a tailored bi-level modeling framework** for the studied post-disruption network assessment problem, involving UE traffic assignment in the lower-level and minimization of discrepancy between observed and estimated link travel times in the upper-level.

- Numerical experiments on several transportation networks, including a two-link single-OD network, the Sioux-Falls network, and a real-world network in Bukhmut, further demonstrate **the effectiveness of the proposed method**.

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