Type-based Analysis of Road Networks

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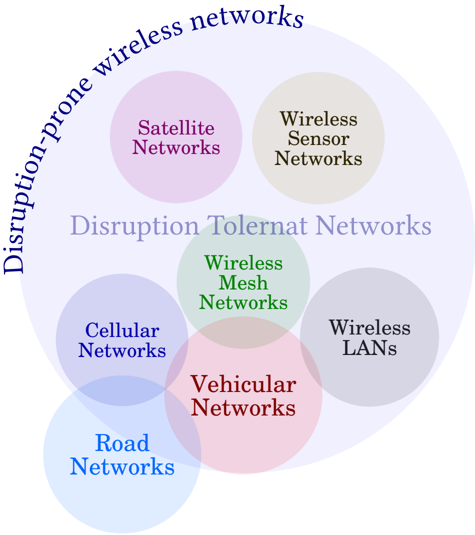
Happy Teachers Day

Dr. S. Radhakrishnan
(1888–1975)

> *"True teachers are those who help us think for ourselves."*

> *"A life of joy and happiness is possible only on the basis of knowledge and science"*

Where road networks fit in our research?



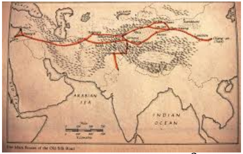
Outline

Road networks

- Important component in the development of any nation
- History traces their roots to the human civilization
- Primary platform of transportation and logistics over the land
- Dominate over other types of transportation modes
- Study on road network can characterize nature of human evolution

(a) Mohenjo-daro[1].

(b) London[2].



(c) Ancient Silk Road[3].

Figure 1: Ancient road networks in the world.

[1] *The Lower Town*. [Accessed 17-November-2015]. URL: http://www.ancientindia.co.uk/indus/explore/town_b1.html

[2] *David Rumsey Map Collection*. [Accessed 17-November-2015]. URL: http://www.davidrumsey.com/blog/categories/recent-additions?blog_full_view=1

[3] *Silk Road*. [Accessed 17-November-2015]. URL: http://www.theorientalcaravan.com/images/silk_road/mapasia.jpg

Road networks of present era

- Either self-evolved or planned in nature
- **Self-evolved networks**
  - Characterized by natural evolution of human mobility
  - Feature of developing and least developed countries
  - Ex. India, European cities, and Brazil

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  - Ex. cities in USA, Japan, and Chandigarh in India

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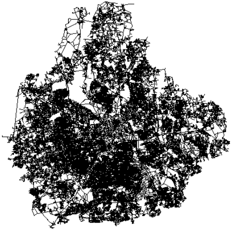
- **Planned networks**
  - Characterized by efficient planning before construction
  - Nature of developed countries
  - Ex. cities in USA, Japan, and Chandigarh in India
- Crucial in the development of intelligent transportation systems
- Should adapt modern technological requirement such as smart and green cities

Example cities from India, Europe, and USA



(a) Bangalore.

(b) Paris.

(c) Detroit.

Figure 2: Maps of cities with entire administrative area.

Example cities from India, Europe, and USA

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Figure 3: Maps of cities with area 10 km × 10 km.

Why analyze road networks?

Find out the reasons for the existing problems.

[4] Vipin Jain, Ashlesh Sharma, and Lakshminarayanan Subramanian. "Road traffic congestion in the developing world". In: *Proceedings of the 2nd ACM Symposium on Computing for Development.* 2012, pp. 1–10.

[5] Jerome Buhl et al. "Topological patterns in street networks of self-organized urban settlements". In: *The European Physical Journal B-Condensed Matter and Complex Systems* 49.4 (2006), pp. 513–522.

[6] Sergio Porta, Paolo Crucitti, and Vito Latora. "The network analysis of urban streets: A primal approach". In: *Environment and Planning B: Planning and Design* 33.5 (2006), pp. 705–725. doi: 10.1068/b32045.

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  - Inefficient traffic patterns
  - More travel time
  - Absence of efficient alternate paths

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  - Inefficient traffic patterns
  - More travel time
  - Absence of efficient alternate paths
- City road networks are analyzed using
  - Structural properties of road-networks[5]
  - Complex networks[6]
  - Geographical properties
  - Vehicle traffic characteristics

[4] Vipin Jain, Ashlesh Sharma, and Lakshminarayanan Subramanian. "Road traffic congestion in the developing world". In: *Proceedings of the 2nd ACM Symposium on Computing for Development.* 2012, pp. 1–10.

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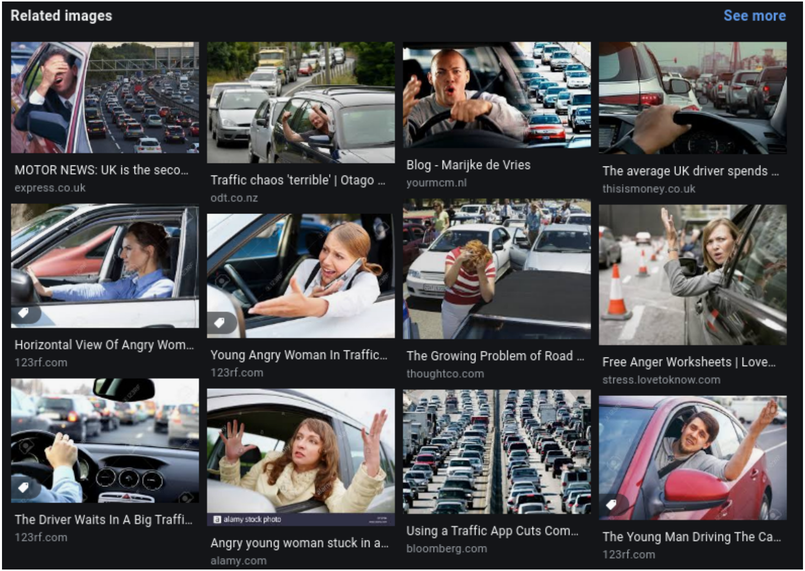
Congestion and inefficient driving patterns

Figure 4: Inefficient driving behavior in Xi'an, China[7].

[7] *Can public transport investment really fix traffic congestion? — CityMetric.* https://www.citymetric.com/transport/can-public-transport-investment-really-fix-traffic-congestion-1870. (Accessed on 09/03/2020).

Real-world road traffic: Some expressions



Is road-type a reason?

DO PEOPLE LIKE TO COMPLAIN ABOUT THE NARROW ROADS IN YOUR COUNTRY?

“For sure. People complain all the time. The roads, especially in the older parts of big cities are often extremely congested. But, in my opinion, people make the situation much worse by not following the traffic rules, which cause even more traffic jams. They think that they have the right to go through a red light or drive the wrong way down the road, which makes the situation worse for everyone. I don’t know why. I guess they must think they’re very important.”

Figure 5: Article on the influence of narrow roads[8].

[8] *Traffic Congestion — IELTS UNLOCKED.* https://ieltsunlocked.wordpress.com/tag/traffic-congestion/. (Accessed on 09/03/2020).

Type-based Analysis of Road Networks

Road-types

- Attributes indicating the quality of roads
- Determinants of road quality in terms of
  - Width of the road
  - Number of lanes
  - Maximum allowed speed limit
  - Paving
- Examples of road-types: *Motorways, trunk roads, primary roads, residential roads*, and *footways.*

(a) Motorway. **(b)** Primary. **(c)** Residential. **(d)** Foot/cycleway.

Figure 6: Example road-types[9]

- Important factor in users' **path selection** for a journey
- Influence journey comfort and travel time

[9] *Key:highway - OpenStreetMap Wiki.* https://wiki.openstreetmap.org/wiki/Key:highway. (Accessed on 09/03/2020).

Classification of road-types

- Made use of OpenStreetMap highway classification scheme[10]
- We consolidate and classify road-types into 12.
  - **Type 1** represents the highest quality road types
  - **Type 12** represents the least quality road types

Table 1: Road-type classification.

Road-type value	Road-type(s) specified in OpenStreetMap
1	*Motorway, motorway_link*
2	*Trunk, trunk_link*
3	*Primary, primary_link*
4	*Secondary, secondary_link*
5	*Tertiary, tertiary_link*
6	*Unclassified*
7	*Residential/business*
8	*Service*
9	*Living_street*
10	*Pedestrian*
11	*Cycleway*
12	*Track, footway, bridleway, steps, path*

[10] *Key:highway - OpenStreetMap Wiki.* https://wiki.openstreetmap.org/wiki/Key:highway. (Accessed on 09/03/2020).

Example cities from India, Europe, and USA

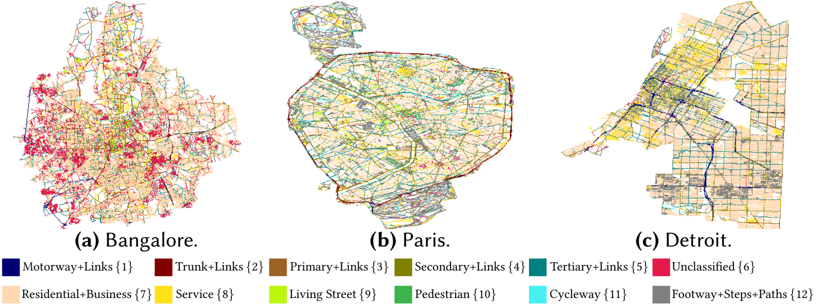


Figure 7: Maps of cities with entire administrative area.

Example cities from India, Europe, and USA

(a) Bangalore. **(b)** Paris. **(c)** Detroit.

Motorway+Links {1} Trunk+Links {2} Primary+Links {3} Secondary+Links {4} Tertiary+Links {5} Unclassified {6}
Residential+Business {7} Service {8} Living Street {9} Pedestrian {10} Cycleway {11} Footway+Steps+Paths {12}

Figure 7: Maps of cities with entire administrative area.

(a) Bangalore. **(b)** Paris. **(c)** Detroit.

Figure 8: Maps of cities with area 10 km × 10 km.

Road network model

We consider road network as a graph $G = (V, E)$

- V: Set of junctions (vertices/nodes), $N = |V|$
- E: Set of roads (edges/links) connecting two adjacent junctions, $M = |E|$

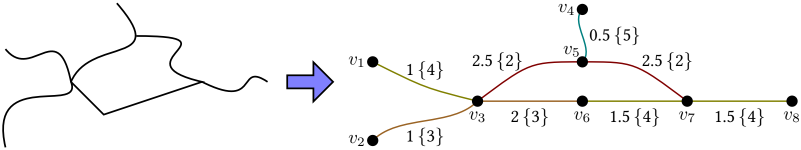


Figure 9: Road and its corresponding graph.

$$V = \{v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8\}$$

$$E = \{(v_1, v_3), (v_2, v_3), (v_3, v_5), (v_3, v_6), (v_4, v_5), (v_5, v_7), (v_6, v_7), (v_7, v_8)\}$$

Each edge $(u, v) \in E$ is associated with two attributes

- $l_{u,v}$: Length of the road connecting the junctions, $l_{u,v} \in \mathbb{R}^+$
- $t_{u,v}$: Type of the road, $t_{u,v} \in \{1, 2, \ldots, 12\}$

Known as **primal graph** approach[11]

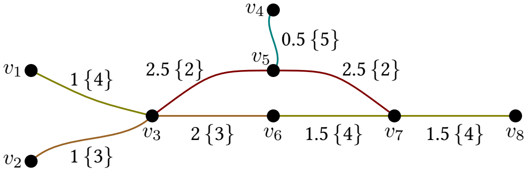
[11] Sergio Porta, Paolo Crucitti, and Vito Latora. "The network analysis of urban streets: A primal approach". In: *Environment and Planning B: Planning and Design* 33.5 (2006), pp. 705–725. doi: 10.1068/b32045.

Link-type proportion ($\mathcal{P}_i$)

Represents the proportion of each road-type in the network

$$\mathcal{P}_i = \frac{\ell_i}{M} \times 100$$

- ℓ_i: Number of links of type i
- M: Number of edges



$\mathcal{P}_2 = \mathcal{P}_3 = \frac{2}{8} \times 100 = 25$

$\mathcal{P}_4 = \frac{3}{8} \times 100 = 37.5$

$\mathcal{P}_5 = \frac{1}{8} \times 100 = 12.5$

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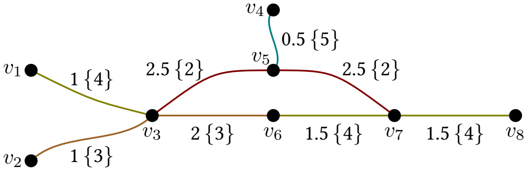
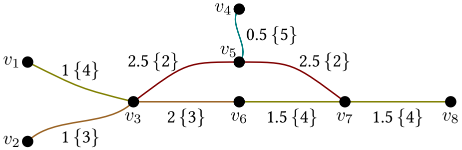


$\mathcal{P}_2 = \mathcal{P}_3 = \frac{2}{8} \times 100 = 25$ | $\mathcal{P}_4 = \frac{3}{8} \times 100 = 37.5$ | $\mathcal{P}_5 = \frac{1}{8} \times 100 = 12.5$

Indicates the availability of road-type i in the network

Link-type distribution (φ_i)

Measures the contribution of road-type *in the shortest paths*



SHORTEST PATH$(v_1, v_8) = v_1 \rightarrow v_3 \rightarrow v_6 \rightarrow v_7 \rightarrow v_8$

$\tau_3^G(v_1, v_8) = \frac{1}{4} \times 100 = 25$ $\tau_4^G(v_1, v_8) = \frac{3}{4} \times 100 = 75$

Link-type distribution φ_i of road-type i is computed **over all-pair shortest paths**

$$\varphi_i = \frac{\sum_{u,v,u \neq v} \tau_i^G(u, v)}{N(N-1)}$$

Indicates the requirement of road-type i in terms of shortest path traffic

Link-type demand (χ_i)

- Ideal shortest path is not feasible always if the path contains a low quality road

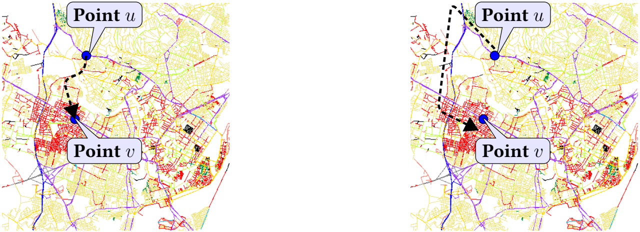


Figure 10: Infeasibility of shortest path.

- User has **preference/demand** toward specific road-types

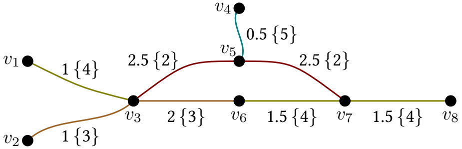
We define the link-type demand ϱ_u at junction u as

$$\varrho_u = \min(t_{u,w} \mid u, w \in V \wedge (u, w) \in E)$$

Link-type demand (χ_i)

The demand $\Gamma_{u,v}$ for a journey from node u to node v

$$\Gamma_{u,v} = \max(\varrho_u, \varrho_v)$$



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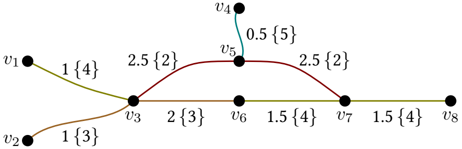

Assume a journey from v_2 to v_7, $\varrho_{v_2} = 3$, $\varrho_{v_7} = 2$

$$\Gamma_{v_2,v_7} = \max(2, 3) = 3$$

Link-type demand (χ_i)

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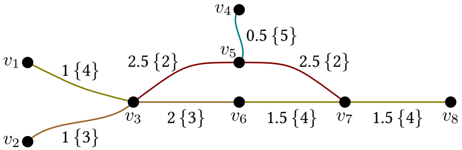
$$\Gamma_{u,v} = \max(\varrho_u, \varrho_v)$$



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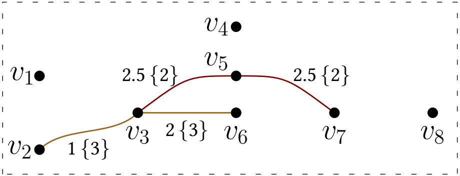
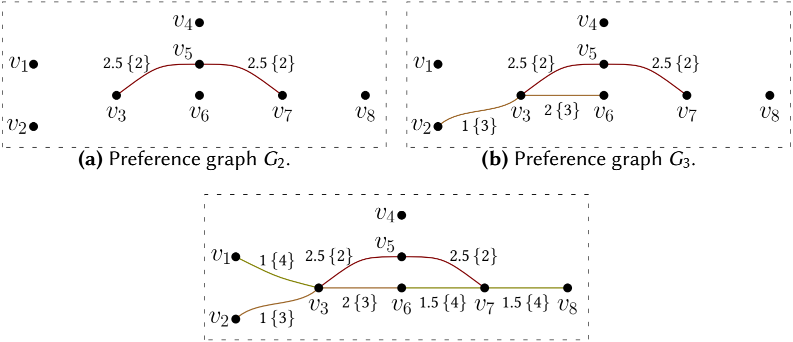


Figure 11: Restricted graph.

Link-type demand (χ_i)

We define **Preference Graph** $G_n = (V, E_n)$ as

$$E_n = \{(u, v) | (u, v) \in E \land t_{u,v} \leq n\}$$



(a) Preference graph G_2.

(b) Preference graph G_3.

(c) Preference graph G_4.

Figure 12: Preference graphs derived from the example network for different link-type demands.

Link-type demand (χ_i)

Link-type demand measures the distribution of road-types in shortest path on the **preference graphs**.

$$\chi_i = \frac{\sum_{u,v \in V, u \neq v, \mathbb{P}_{u,v}^{G_n} \neq \varnothing} \tau_i^{G_n}(u,v)}{\|\{(u,v) \mid u,v \in V \wedge \mathbb{P}_{u,v}^{G_n} \neq \varnothing\|}$$

- $n = \Gamma_{u,v}$
- $\tau_i^{G_n}(u,v)$: Contribution of type i in the shortest path from node u to v in G_n
- $\mathbb{P}_{u,v}^{G_n}$: Shortest path from node u to v in G_n

Indicates the requirement of road-type i in terms of user demand.

- More realistic measure to analyze road networks

Link-type index ($\mathcal{S}_i^{\chi}$)

Primary question

Whether there exists sufficient road-types to meet the user demand?

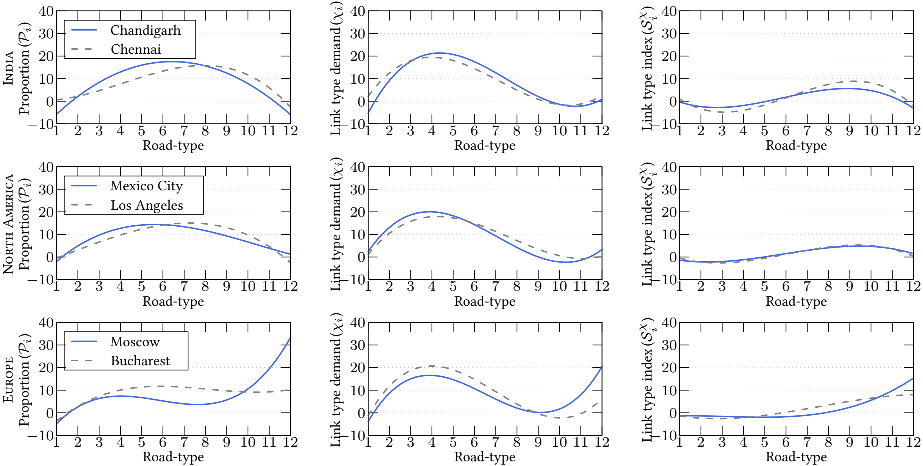
Measures the **mismatch** between link-type proportion $\mathcal{P}_i$ and link-type demand χ_i.

$$\mathcal{S}_i^{\chi} = \frac{i}{T}(\mathcal{P}_i - \chi_i)$$

Shows how much better the road network in terms of shortest-path based traffic considering user demand.

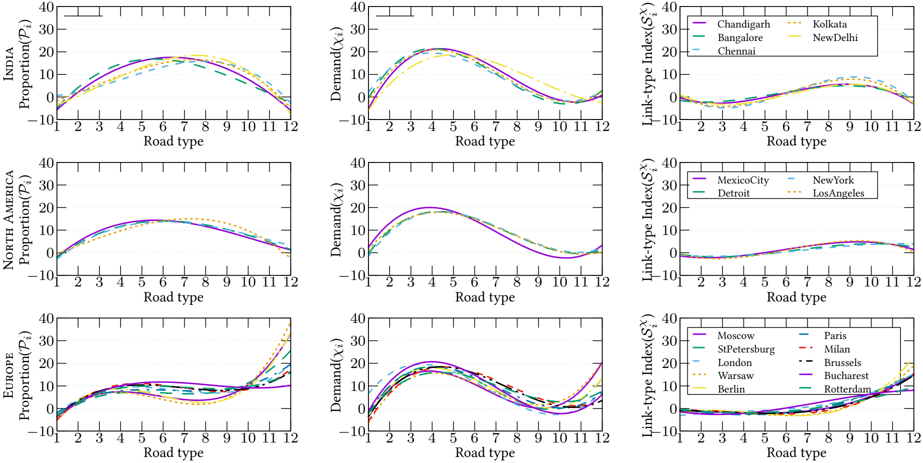
- $\mathcal{S}_i^{\varphi} \geq 0$: **Link-type surplus**
  - Indicates existence of sufficient road-types to meet the user demand.
- $\mathcal{S}_i^{\varphi} < 0$: **Link-type deficit**
  - Indicates deficiency of roads of type *i* to handle the traffic due to shortest paths based on user demand.

Proportion vs. Demand vs. Index



- Indian and USA share similar behavior in terms of proportion
- Europe shows more affinity toward footways
- Indian cities provide high deficits for more demanded types and surplus for less demanded types

Proportion vs. Demand vs. Index



Preference cost (Δ_G)

The additional cost (in terms of distance) incurred by user by choosing high quality road-types.

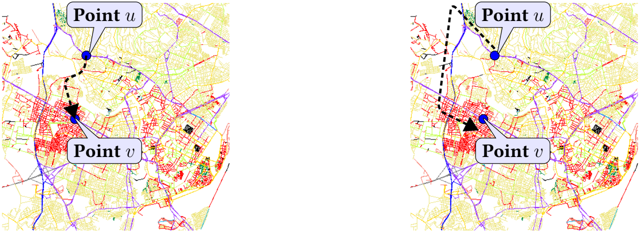


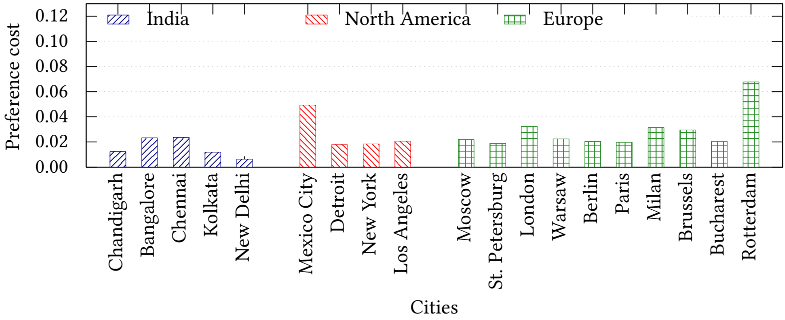
Figure 13: User's preference of high quality road-types.

The preference cost for traveling from node u to v is $\delta_{u,v} = \frac{d^{G_n}(u,v) - d^{G}(u,v)}{d^{G}(u,v)}$

Preference cost Δ_G for the graph G can be computed as

$$\Delta_G = \frac{\sum\limits_{u,v \in V, u \neq v, \mathbb{P}^{G_n}_{u,v} \neq \varnothing} \delta_{u,v}}{\|\{(u,v) \mid u,v \in V \wedge \mathbb{P}^{G_n}_{u,v} \neq \varnothing\|}.$$

Preference cost



- Lower the preference cost, more efficient the road network will be
- **New Delhi** being the least among the 57 cities studied
- USA keeps the preference cost $\Delta_G \leq 0.02$
- European cities keep $0.02 \leq \Delta_G \leq 0.03$

Preference cost is an important metric for planning and designing future **green cities**.

Type closeness (Ω_G^i)

Measures how much each junction is closer to the preferred road-type

- Users search for the nearest best quality road before the journey starts

Type closeness of a junction u toward road-type i is defined as

$$\omega_u^i = \min\left(d^{G_{\varrho_u}}(u, v) \mid \forall v, w \in V \wedge t_{v,w} = i\right)$$

The type closeness of the city graph toward a road-type i

$$\Omega_G^i = \frac{\sum\limits_{u \in V, \varrho_u > i} \omega_u^i}{\|\{u \mid \varrho_u > i\}\|}.$$

Important metric while constructing and positioning new high quality roads in an existing road network.

Type closeness of example cities

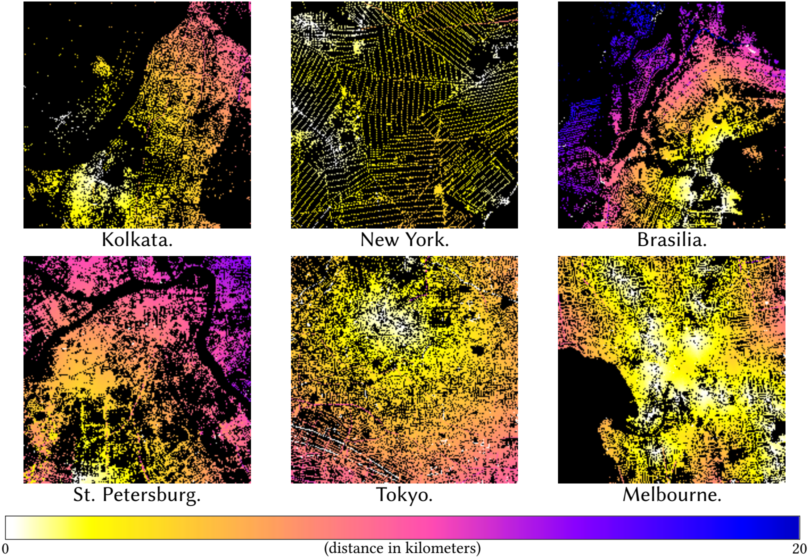


Figure 14: Type closeness toward *Motorways* of type value 1.

Questions raised

1. Whether sufficient road-types are available to meet our demand?
   - No. Deficits exist in higher demanded road-types.
2. How cities in India are different from cities of USA and Europe?
   - India is similar to USA in terms of link-type proportion and demand.
   - India exhibits different behavior with Europe in $\mathcal{P}_i$ and $\mathcal{S}_i^{\mathcal{X}}$.
3. What are the reasons for congestion in terms of road-types?
   - High demanded road-types are served with type deficits.
4. Whether we need to consider the road-types in the design of future cities?
   - Yes, preference cost and type closeness offer suitable candidate metrics for designing smart and green cities.

Conclusions

1. Road-types play a crucial role in our path selection for any journey
2. Analyzed road networks through the lens of road-types using five metrics
3. Type analysis shows the degree of insufficiency of road-types in Indian cities resulting in problems such as congestion
4. Quantified the additional cost due to high quality path selection, an important factor in designing green cities
5. Effort for reaching preferred road-type is captured using type-closeness
6. Analysis can be extended by including vehicle traffic characteristics and nature of hotspots within the city

Reference materials

Figure 15: Locations of 57 cities considered for our analysis.

1. Sarath Babu and B. S. Manoj, "**Toward a type-based analysis of road networks**," in *ACM Transactions on Spatial Algorithms and Systems*, August 2020, vol. 6, no. 4, ISSN 2374-0353.
2. Sarath Babu and B. S. Manoj, "**On the topology of Indian and Western road networks**," in 2016 8th *International Conference on Communication Systems and Networks (COMSNETS)*, January 2016, pp. 1-6.

Questions?

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Thank you.