9th Urban Mobility India Conference & Expo 2016
Planning Mobility for City's Sustainability

Analyzing Urban Mass Rapid Transit Networks

Using Graph Theory

Ashwini Soman Ranade
(Architect, Urban Planner)

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2. Aim & Objectives of Thesis
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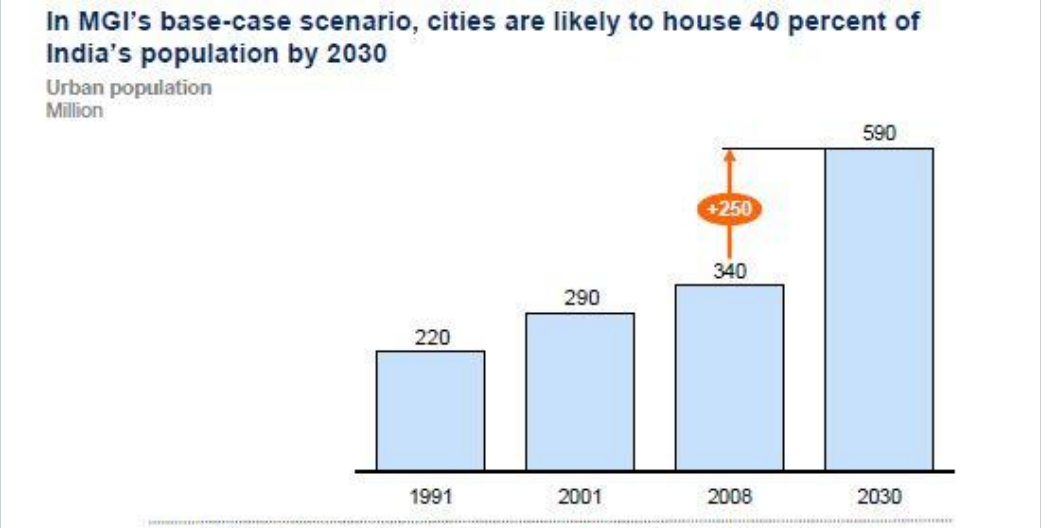
Transportation Networks are majorly planned with demand based approach

Alternative Network based approach

To study transport network characteristics, their Form and also assess their performance.



- Need is to understand the kind of network design and patterns being formed.
- Can network of Indian cities draw lessons from that of similar case city?

- Cities are planning high capacity public transport systems to cater to the growing transportation demands.

In planning these capital intensive systems seldom attention is paid to the kind of network being developed

To analyze Urban Mass Rapid Transit networks of different cities with a network based approach; Graph Theory.

Objectives

1. Review Urban Mass Rapid Transit Networks of different cities.

- Understand Transit Line Type and Network patterns.
- Study their Network Characteristics

2. To draw lessons from Network design Parameters and their Indicators for different cities.

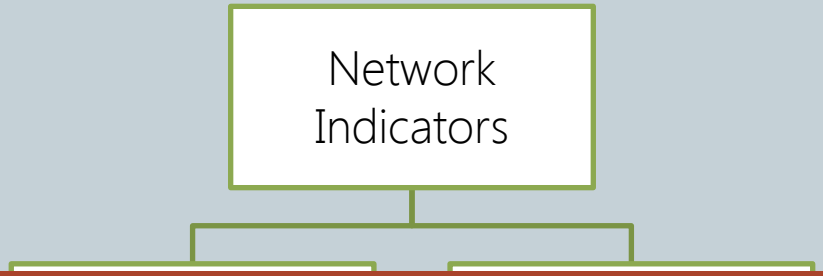
- Comparative analysis of network design parameters for case cities across the world.

3. To assess Network design Parameters of proposed networks for Indian cities.

- Analyze network design parameters of proposed networks of Indian cities (Delhi, Mumbai and Bengaluru)

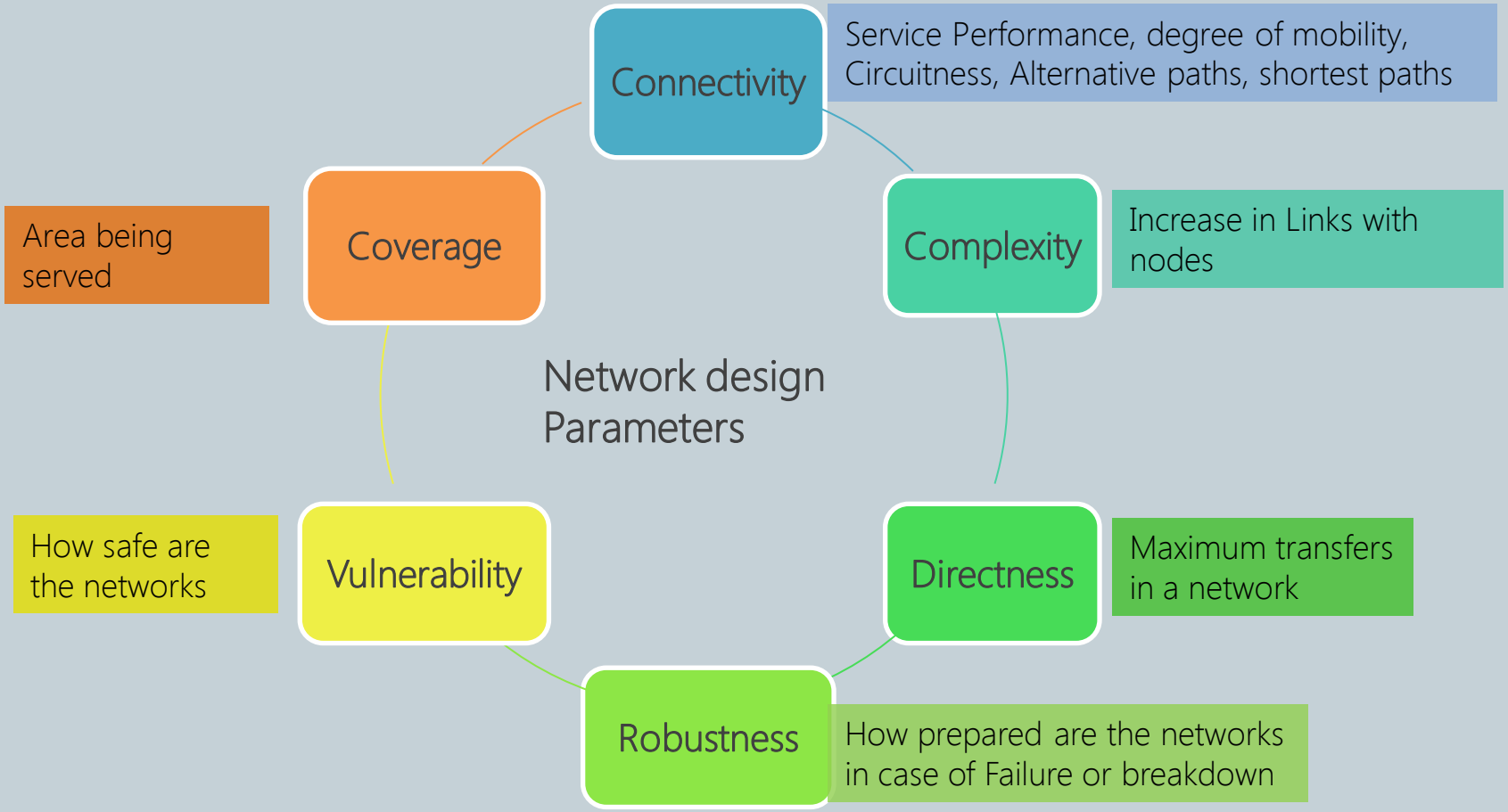
Various researchers › Developed and used Network Indicators to measure Performance of networks

Apart from the Social, Economic, Environment and System based indicators



What do these Indicators reflect?

They reflect upon the Network design Parameters and Performance



It becomes crucial to understand what these parameters mean.

Planning of Urban Mass Rapid Transit Network has two main objectives:
Service efficiency and Attract passengers.

For attracting Passengers Network design should be

Basic Network Design Parameters for better performing Networks

Well Connected

Simple Direct

Cover maximum area

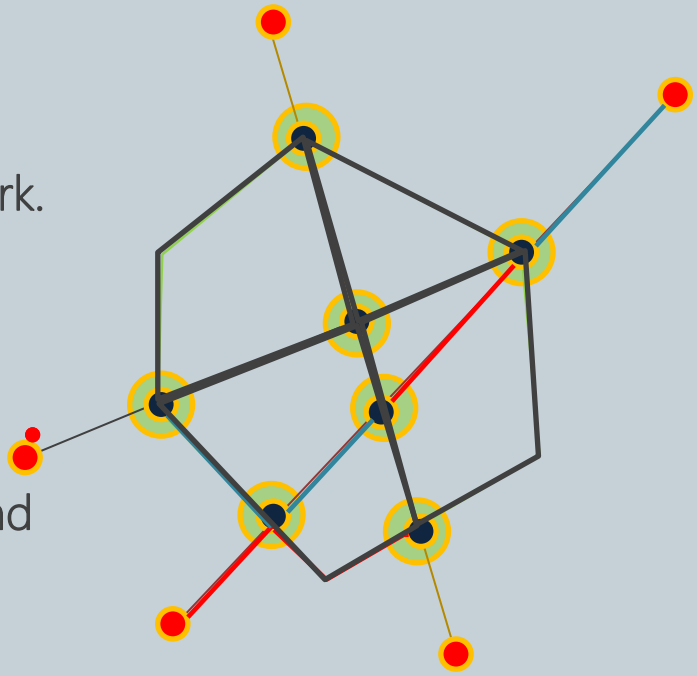
1. Connectivity
2. Coverage
3. Extensiveness

Adapted from various sources

1. Connectivity is the ease with which passengers can travel within a network.

This can be when;

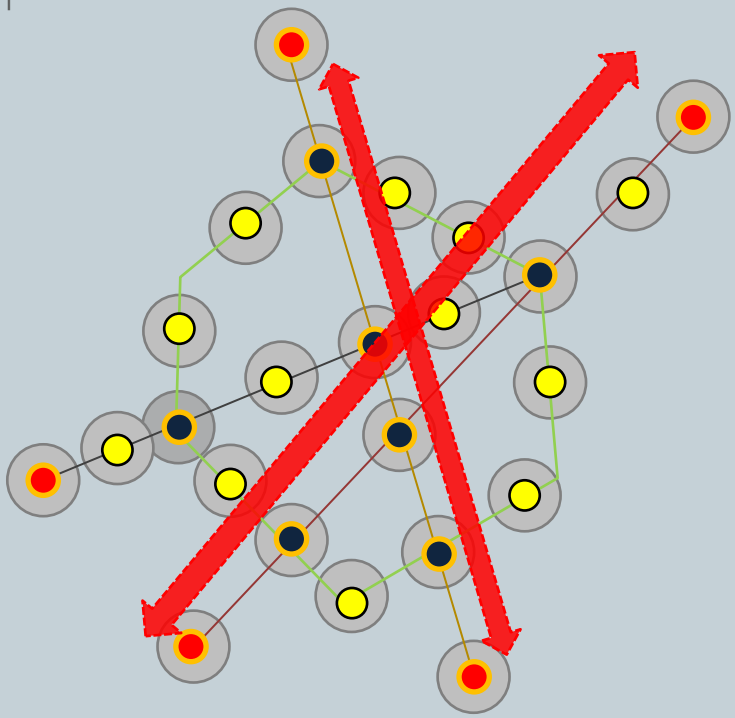
1. There are alternate paths to move in the network.
2. More nodes and links.
3. Transfers available in the network.
4. Network structure is has paths that start and end at the same node (circuits).
5. Proximity of a node



2. Coverage is how accessible is the network to public.

1. Area served by the network.

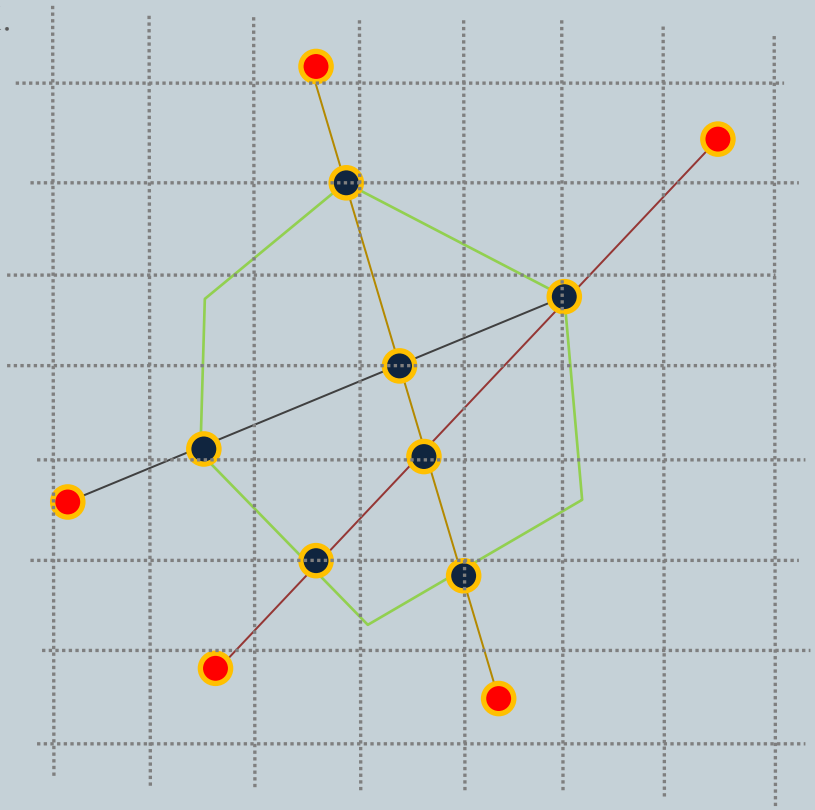
2. Extent of the network



3. Extensiveness is how intense is the network.
(Relating it to city characteristics)

Network laid per km area.

Network laid per Mn population



1km*1km Grid

	Network Measure	Indicates	Researcher
1.	Average Interstation Spacing	• Good Coverage (less value) • High operating speed (larger values) **Coverage**	Kansky,(1962-64)
2.	Line Overlapping	• More the value more are the common sections, More transit lines are connected	Gattuso & Miriello, 2005
3.	Beta Index	• Value increases with increase in Nodes and Links **Connectivity**	Kansky (1962-64)
4.	Alpha Index	• Existing circuits to possible circuits in the network	Gattuso & Miriello, 2005
5.	Gamma Index	• Relation Between observed and possible Links	Kansky (1962-64)
6.	Detour Index	• Straight distance/ Transport Distance **Directness**	Kansky (1962-64)
7.	Pi Index	• Ratio Between Expanse and Diameter **Coverage**	Kansky (1962-64)
8	Shimbel Index	• Shortest distance between two distant Nodes **Connectivity**	Shimbel
9	Eta Index	• Average length /link **Coverage**	Kansky (1962-64)
10	Theta Index	• Average amount of Traffic/ Intersection	Kansky (1962-64)

	Network Measure	Indicates	Researcher
11.	Cyclomatic No.	• Indicates the development of Network **Complexity**	Kansky,(1962-64)
12.	Net network Length	• Network length without overlapping links **Coverage**	Gattuso & Miriello, 2005
13.	Network Density	• Length of network laid per unit area	Jennifer Dill, 2004
14.	Connected Node Ratio	• Street Intersection	Jennifer Dill, 2004
15.	Percent 4 way intersections	• Percentage of 4 legged Intersection **Complexity**	Cervero, 1995-97
16.	Intersection Density	• Intersection per unit area	Cervero, 1995-97
17.	Block Density	• No. of Census blocks per area	Cervero, 1995-97
18	Network Weight	• No. of Concu... nodes **Connectivity**	Gattuso & Miriello, 2005
19	Network Loop	• Links –Nodes+... **Complexity**	Gattuso & Miriello, 2005
20	Network Length	• Total Network leng... **Coverage**	Gattuso & Miriello, 2005

Network Design Parameter	Indicators	Description	Norm
Connectivity (ability to move with ease)	1. Alpha Index	Existing Circuits / maximum possible circuits in the network	Value ranges from 0 to1
	2. Gamma Index	Existing paths/ maximum possible paths	Value ranges from 0 to1
	3. Beta Index	Link/node	Value is 0 for networks with no circuits.
	4. Degree of Transfer	Net transfer possibility per station / Transfer nodes	Value is 1 for networks that have nodes with possibility of 1
	5. Eta Index	Average Link length	Varies as per transit line lengths
Coverage (catchment area)	1. Transit Coverage Area	Area being served by the transit stations/ Urban area	Varies as per the no. of stations
	2. Average Interstation spacing	Extent of the networks	Varies as per different cities.
	3. Average Line lengths		
Extensiveness (Intensity of the network)	1.Network density	Km of network/ km area	Varies with different cities of similar sizes.
	2. Network pop. Density	Network/population	

- Principles of Graph Theory
- Application to Public Transport sector.
- Transit line type and network

1. Literature Review

2. Identification of suitable Indicators

1. Suitable indicators to evaluate Network design parameters.

3. Process

1. Data Collection
   - Transit maps
2. Converting maps to Planar graphs

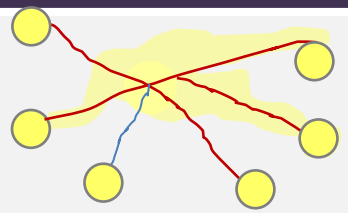
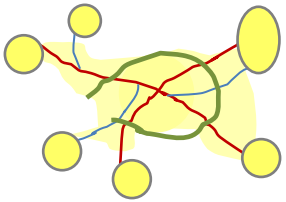
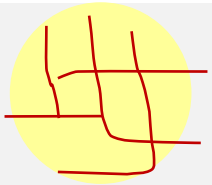
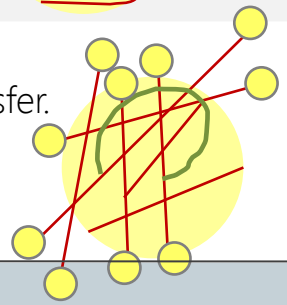
Understanding layout of Transit Line and pattern of the Network formed.

Computation of Indices

4.Comparative Analysis

5. Conclusions

Conceptual Framework

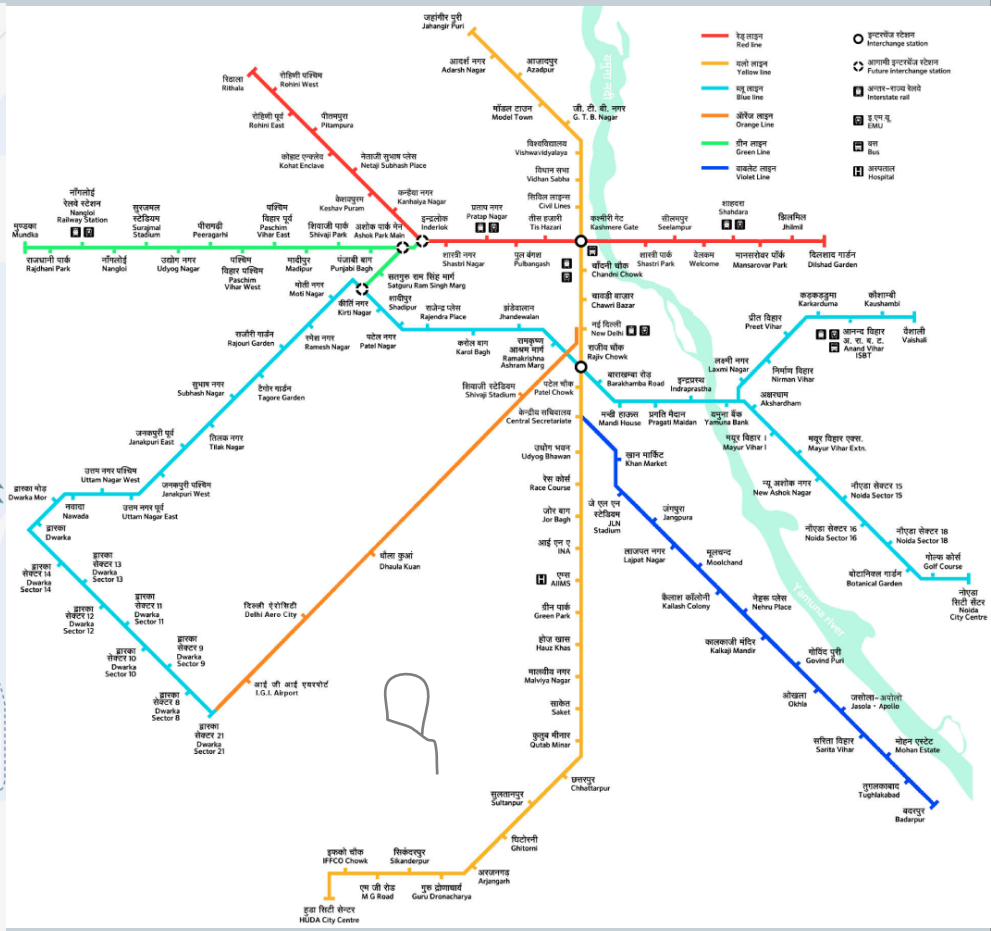
S.no.	Type	Description	
1.	Radial Networks (with or without branches)	• In cities with strong emphasis on the centre. • Lines follow major travel directions. • Does not cater to non-CBD oriented trips. • Lines majorly overlap giving less coverage.	
2.	Radial Circumferential Networks	• Consists of Radial, Diametrical, ring lines. • Typically serves busy corridors and many sub-centres. • Intersection creates transfer points and covers non-CBD trips as well. • Have greater coverage.	
3.	Rectangular / Grid Networks	• Transit lines follow geometric pattern. • Cities with uniform density. • Provides uniform coverage.	
4.	Ubiquitous Networks	• Service in all high demand corridors. • Good connectivity amongst transit lines requiring maximum one transfer. • Adequate coverage throughout the urban area. • Good connections to non-CBD oriented trips as well.	

(adapted from Vuchic,2005) To understand layout of **Transit network pattern** of the Network.

1st Objective: To Review networks of different cities

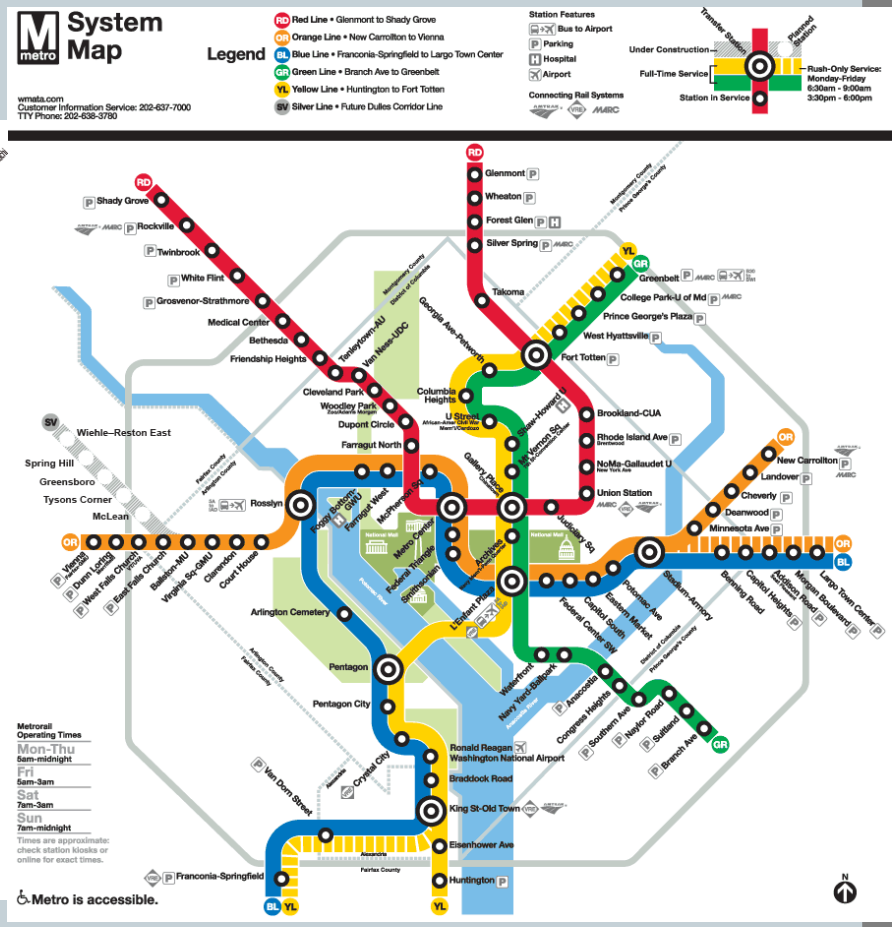
- Understand line type and pattern

Boston Network



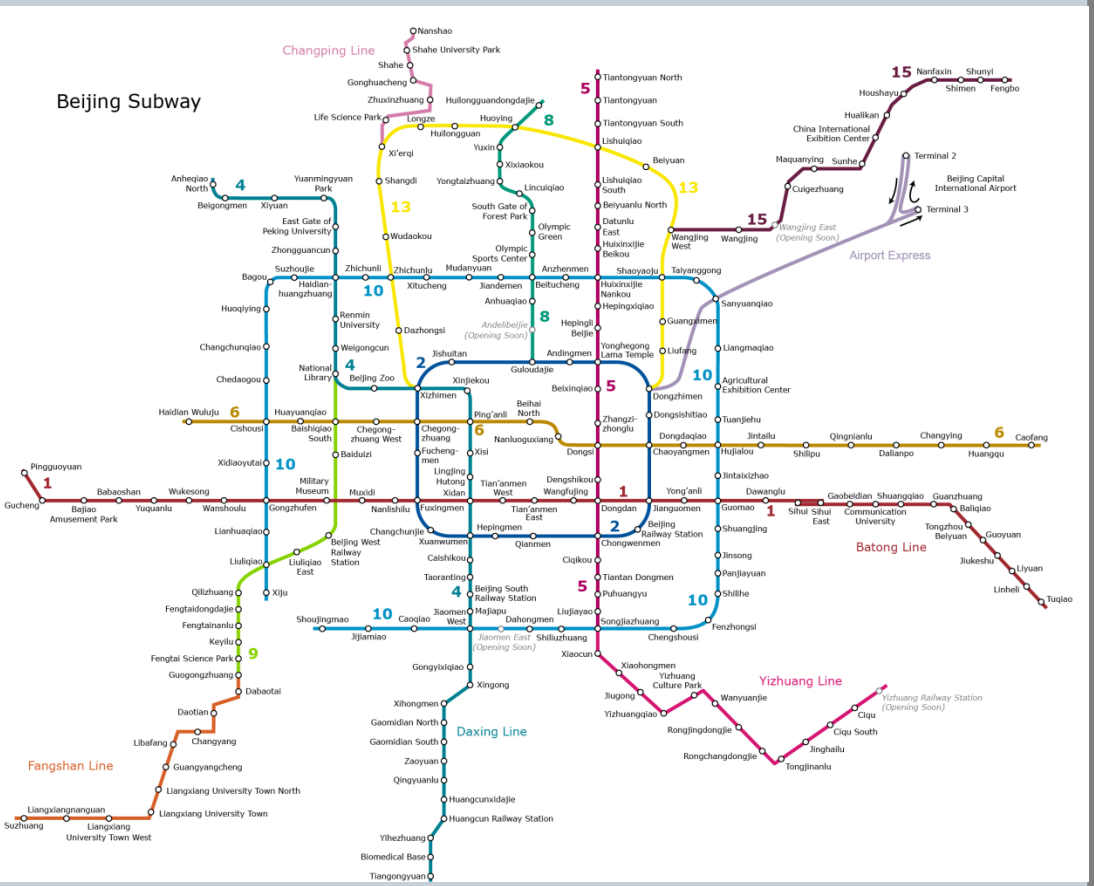
Delhi Network

Osaka Network

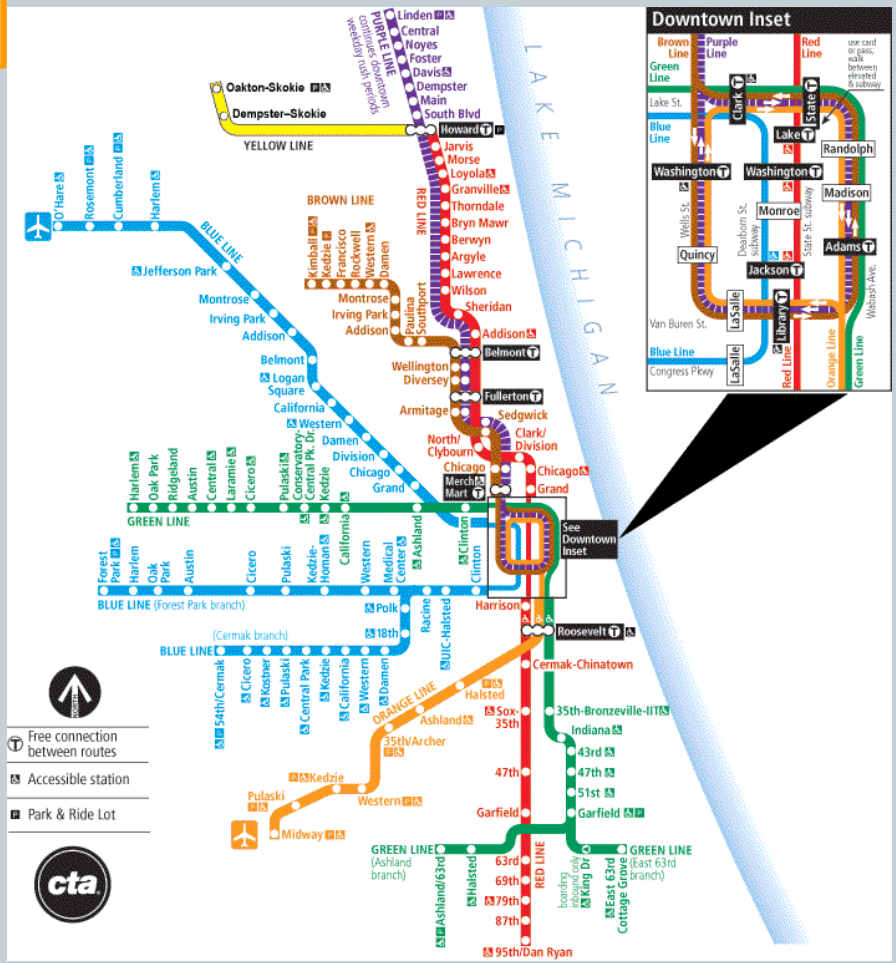


Washington Network

Shanghai Network

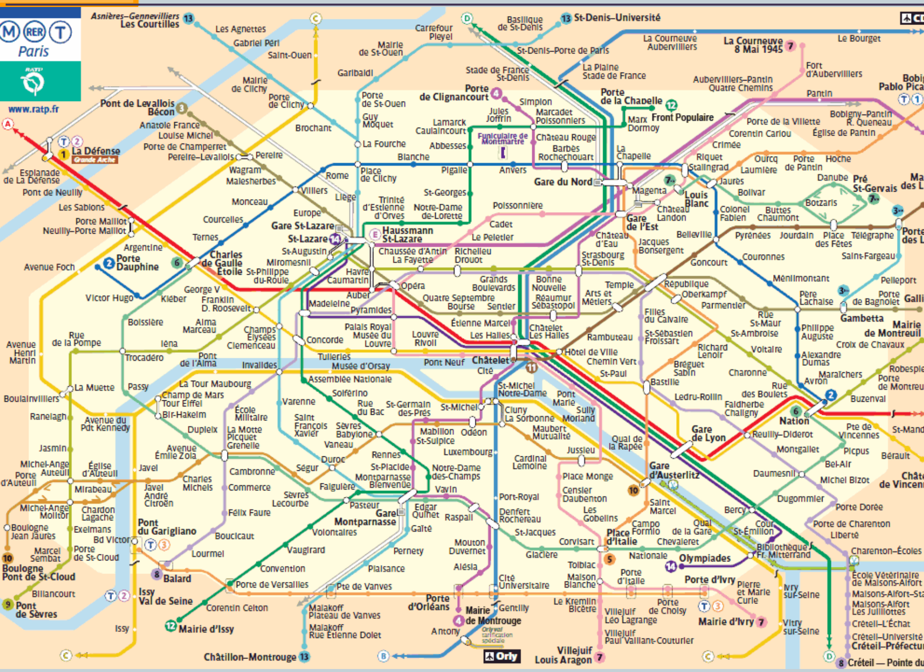


Beijing Network

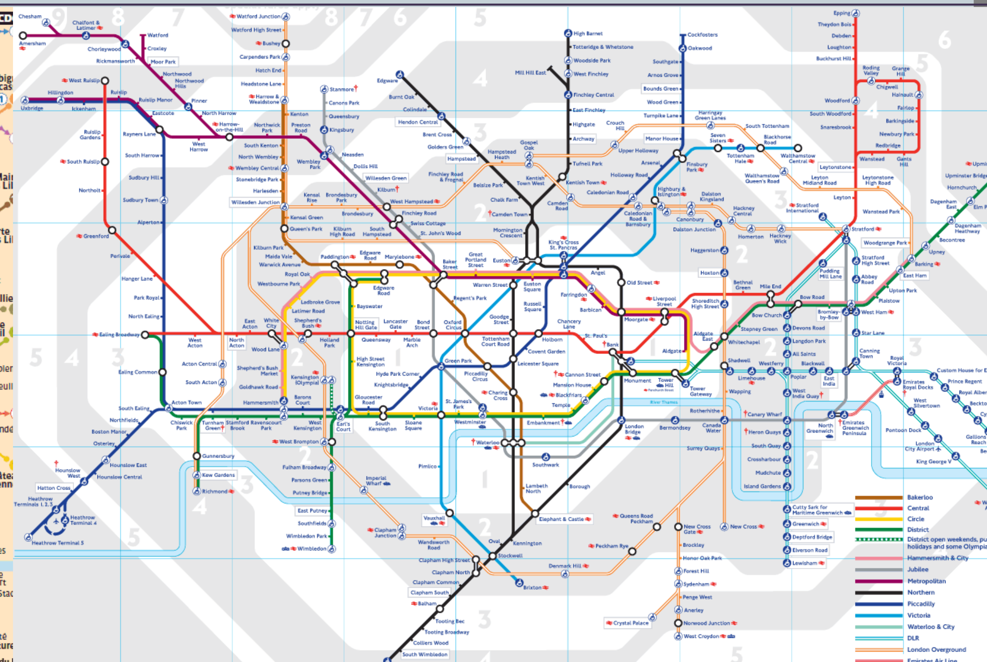


Chicago Network

New York Network



Paris Network



London Network

	City	No. of Lines (q)	Total Line Length (km)	Stations N_s	Radial	Diametrical	Tangential	Circumferential	Circle	Loop	Network
1	Paris	16	214	303	7	5	1	2	0	1	U
2	Beijing	16	442	262	6	3	4	2	1	0	RC
3	London	16	488	353	10	5	0	0	1	0	RC
4	Shanghai	12	533	284	6	4	1	1	0	0	RC
5	Singapore	5	152.9	95	2	1	0	2	0	0	RC
6	Chicago	8	165.5	145	0	3	1	0	0	4	R
7	Bengaluru*	2	42.3	40	2	0	0	0	0	0	R
8	Beunos Aires	6	51.4	83	6	0	0	0	0	0	R
9	Boston	6	103	117	4	2	0	0	0	0	R
10	Cairo	3	77.9	61	3	0	0	0	0	0	R
11	Delhi	7	196.15	143	3	3	0	0	0	1	R
12	Gangzhou	9	256.4	142	7	2	0	0	0	0	R
13	Honk kong	10	212.9	154	9	0	1	0	0	0	R
14	Milan	4	94.5	103	2	2	0	0	0	0	R
15	Mumbai	7	235	95	7	0	0	0	0	0	R
16	NewYork	9	368.05	422	7	2	0	0	0	0	R
17	Osaka	9	125.42	121	8	0	1	0	0	0	R
18	Prague	3	59.4	57	0	3	0	0	0	0	R
19	Tehran	5	152	89	2	3	0	0	0	0	R
20	Washington	6	188	91	1	4	0	1	0	0	R

Bengaluru As per phase-1 network*

1st Objective: To Review networks of different cities

- Understand Network characteristics

								No. of nodes Hosting Lines								
S.No.	City	Total Line Length	Stations Ns	Lines q	Nodes N	End N_e	Transfer N_t	2	3	4	5	6	A (Links)	As	Am	Network
1	Beijing	442	262	16	64	17	47	44	3	0	0	0	94	94	0	RC
2	Bengaluru *	42.3	40	2	5	4	1	1	0	0	0	0	4	4	0	R
3	Beunos Aires	51.4	83	6	18	11	7	7	0	0	0	0	19	19	0	R
4	Boston	103	117	6	29	16	13	10	3	0	0	0	32	31	1	R
5	Cairo	77.9	61	3	12	6	6	6	0	0	0	0	14	14	0	R
6	Chicago	165.5	145	8	35	11	24	11	4	4	4	1	57	36	21	R
7	Delhi	196.15	143	7	19	9	10	10	0	0	0	0	22	22	0	R
8	Guangzhou	256.4	142	9	32	11	21	21	0	0	0	0	44	44	0	R
9	Honk Kong	212.9	154	10	31	12	19	18	1	0	0	0	35	29	6	R
10	London	488	353	16	86	24	62	38	14	8	1	1	162	124	38	RC
11	Milan	94.5	103	4	16	10	6	6	0	0	0	0	18	18	0	R
12	Mumbai	235	95	7	38	4	34	28	5	1	0	0	41	12	29	R
13	NewYork	368.05	422	9	73	26	47	33	7	5	2	0	130	109	21	R
14	Osaka	125.42	121	9	35	11	24	21	3	0	0	0	47	45	2	R
15	Paris	214	303	16	104	42	62	45	13	4	3	1	178	178	0	U
16	Prague	59.4	57	3	9	6	3	3	0	0	0	0	9	9	0	R
17	Shanghai	533	284	12	51	17	34	24	9	1	0	0	74	65	9	RC
18	Singapore	152.9	95	5	20	4	16	15	1	0	0	0	30	28	2	RC
19	Tehran	152	89	5	19	9	10	10	0	0	0	0	22	22	0	R
20	Washington	188	91	6	51	7	44	40	3	1	0	0	52	11	41	R

Key Findings

- All cities have **predominantly Radial lines** (with/without branching) in their networks that connect their city centers to surrounding areas.

- **Radial Circumferential networks** have Circle or Circumferential lines binding other lines. Hence these networks have,

a) **More lines and nodes**.

b) **More transfer nodes** that offer transfer to multiple lines.

c) Maximum overlapping links are seen in Radial Networks

2nd Objective: To draw lessons from Network design Parameters and their Indicators of different cities

- Comparative analysis of Network design parameters of cities across the world.

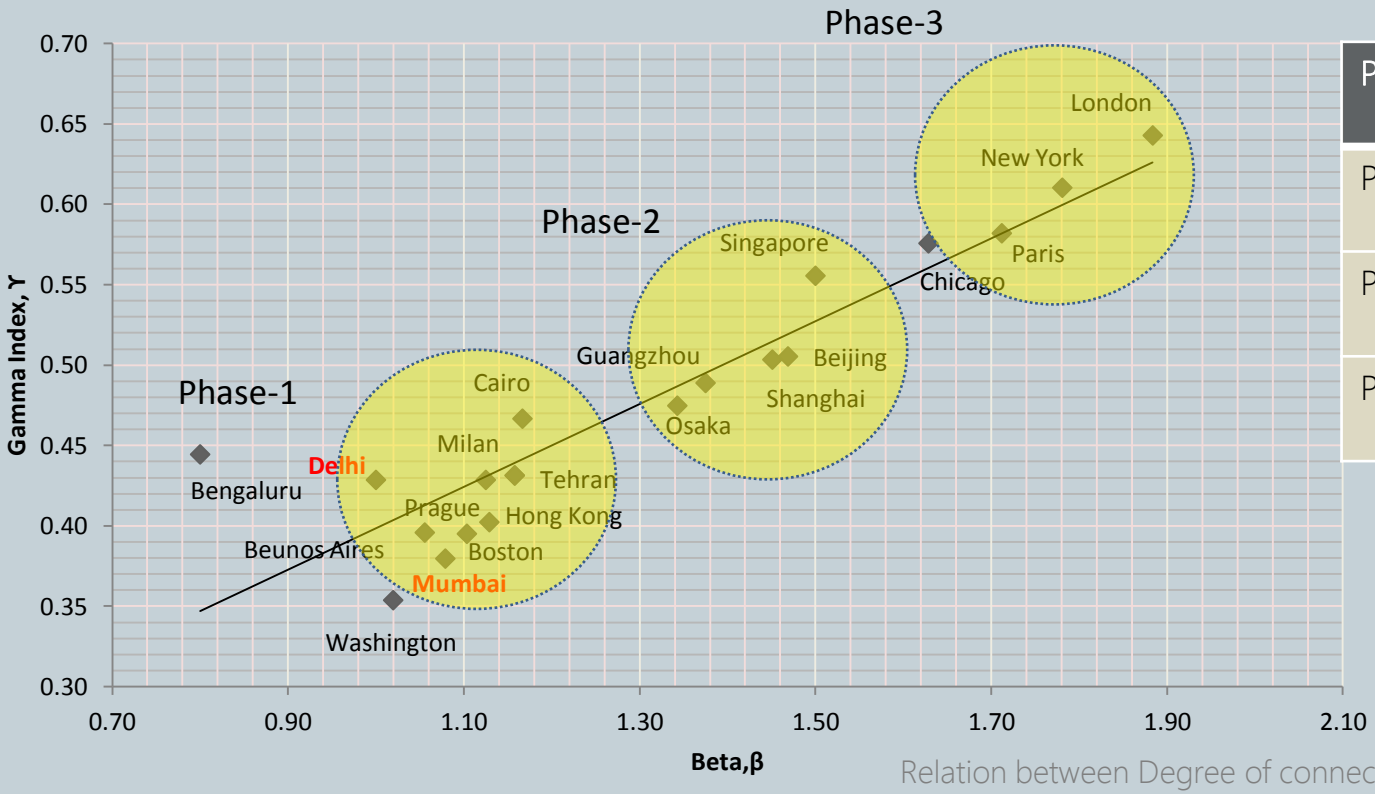
		Connectivity					Coverage			Extensiveness						
	City	Alpha α	Gamma ϒ	Degree of Transfer Nodes ρ	Beta β	Eta Index	Area Served	Avg. Line Length	Avg. Interstation Spacing	Network/Km²	Network /Mn Population	Population (Mn)	Urban Footprint Area	Annual Ridership (Mn)	Daily Ridership
1	Beijing	0.252	0.51	1.06	1.5	5.6	0.110	27.6	1.7	0.282	27.8	15.9	1869	2460	9.11
2	Bengaluru	0.000	0.44	1.00	0.8	10.6	0.031	21.2	1.1	0.042	5.0	8.5	1012	0.147	0.00
3	Beunos Aires	0.065	0.40	1.00	1.1	2.7	0.078	8.6	0.6	0.062	6.3	8.1	832	308	1.14
4	Boston	0.075	0.40	1.15	1.1	3.2	0.029	17.2	0.9	0.033	40.8	2.5	3158	147	0.54
5	Cairo	0.158	0.47	1.00	1.2	5.6	0.043	26.0	1.3	0.069	6.7	11.7	1125	837	3.10
6	Chicago	0.354	0.58	1.29	1.6	2.9	0.057	20.7	1.1	0.083	28.2	5.9	1986	222	0.82
7	Delhi	0.121	0.43	1.00	1.2	8.9	0.067	28.0	1.4	0.118	10.0	19.5	1667	606	2.24
8	Gangzhou	0.220	0.49	1.00	1.4	5.6	0.033	28.5	1.8	0.076	19.0	13.5	3380	1825	6.76
9	Honk kong	0.088	0.40	0.74	1.1	6.1	0.453	21.3	1.4	0.797	30.2	7.1	267	1444	5.35
10	London	0.461	0.64	0.98	1.9	3.0	0.189	30.5	1.4	0.332	54.1	9.0	1470	1171	4.34
11	Milan	0.111	0.43	1.00	1.1	5.3	0.044	23.6	0.9	0.052	10.2	9.2	1828	328	1.21
12	Mumbai	0.056	0.38	0.35	1.1	5.7	0.088	33.6	2.5	0.277	11.4	20.6	850	2640	9.78
13	NewYork	0.411	0.61	1.04	1.8	2.8	0.142	40.9	0.9	0.158	25.8	14.3	2334	1655	6.13
14	Osaka	0.200	0.47	1.04	1.3	2.7	0.084	13.9	1.0	0.111	12.7	9.8	1128	836	3.10
15	Paris	0.369	0.58	1.61	1.7	1.2	0.233	13.4	0.7	0.210	33.7	6.4	1020	1524	5.64
16	Prague	0.077	0.43	1.00	1.0	6.6	0.125	19.8	1.0	0.165	46.5	1.3	359	530	
17	Shanghai	0.247	0.50	1.06	1.5	7.3	0.063	44.4	1.9	0.150	24.2	22.0	3611	2276	8.43
18	Singapore	0.314	0.56	0.94	1.5	5.1	0.236	30.6	1.6	0.484	55.1	2.8	316	794	2.94
19	Tehran	0.121	0.43	1.00	1.2	6.9	0.033	30.4	1.7	0.072	14.4	10.6	2112	480	1.78
20	Washington	0.021	0.35	0.18	1.0	3.6	0.025	31.3	2.1	0.065	77.8	2.4	2888	218	0.81

Network Design Indicators

Population and Urban Footprint Data source: Demographia World Urban Area, 11th edition_ Jan 2015
Annual Ridership Data source: World metro database and other compiled sources.

	Design Parameter		
Strong co-Relation			Ridership increases as parameter is improved
Weak Relation			Ridership is less affected by the design parameter but still it improves the network design

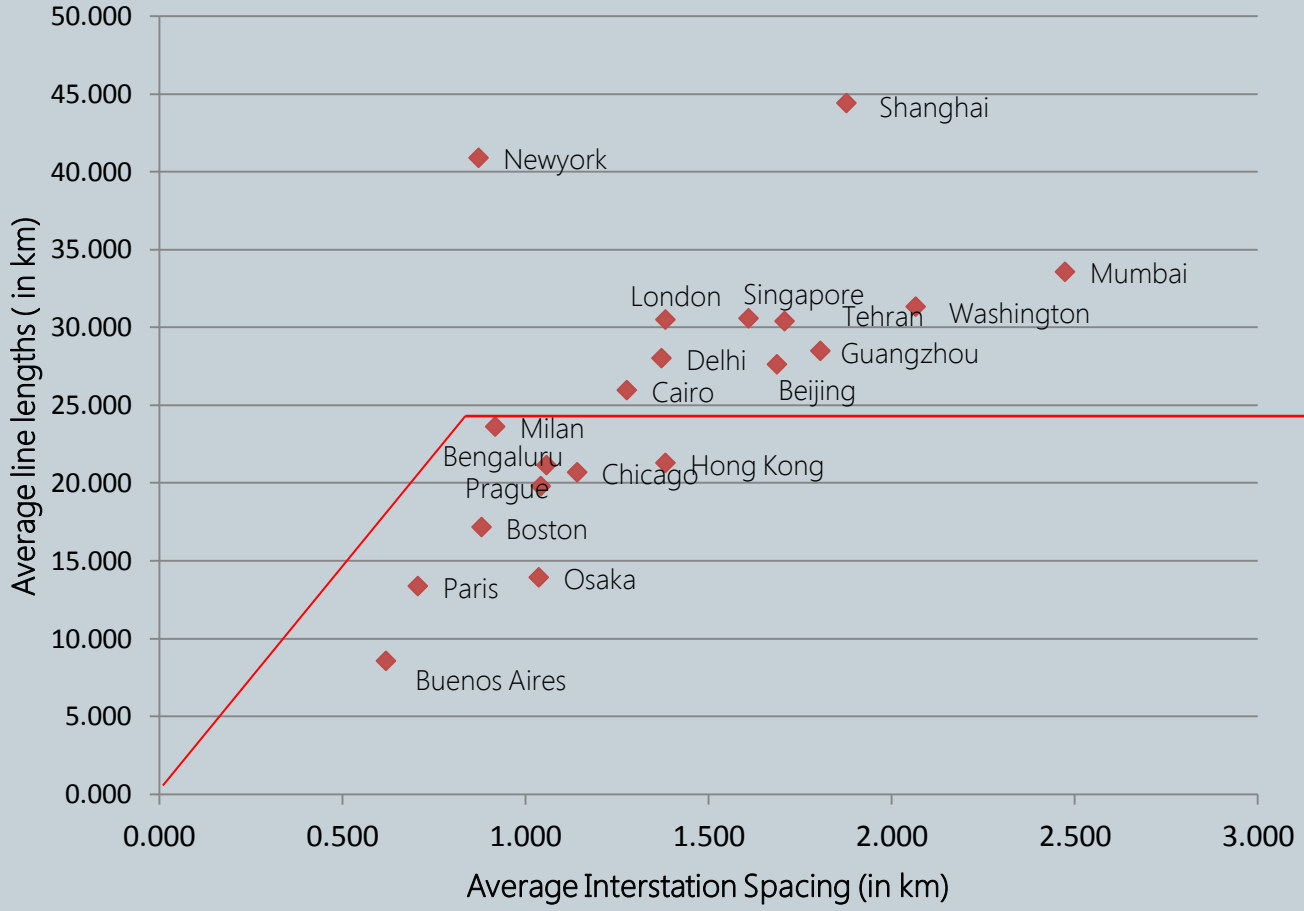
	Design Parameter and Ridership (Performance)	R^2
Strong co-Relation	1. Alpha Index – Completeness	0.81
	2. Gamma Index– Alternate paths	0.81
	3. Beta Index - Link –Node ratio	0.67
	4. Area Served- No. of Stations	0.64
	5. Network Density- Network laid/km	0.71
Weak Relation	1. Degree of transfer Nodes- Transfer possibilities per station	
	2. Eta -Index Length of the Link	
	3. Network laid per Mn pop.	



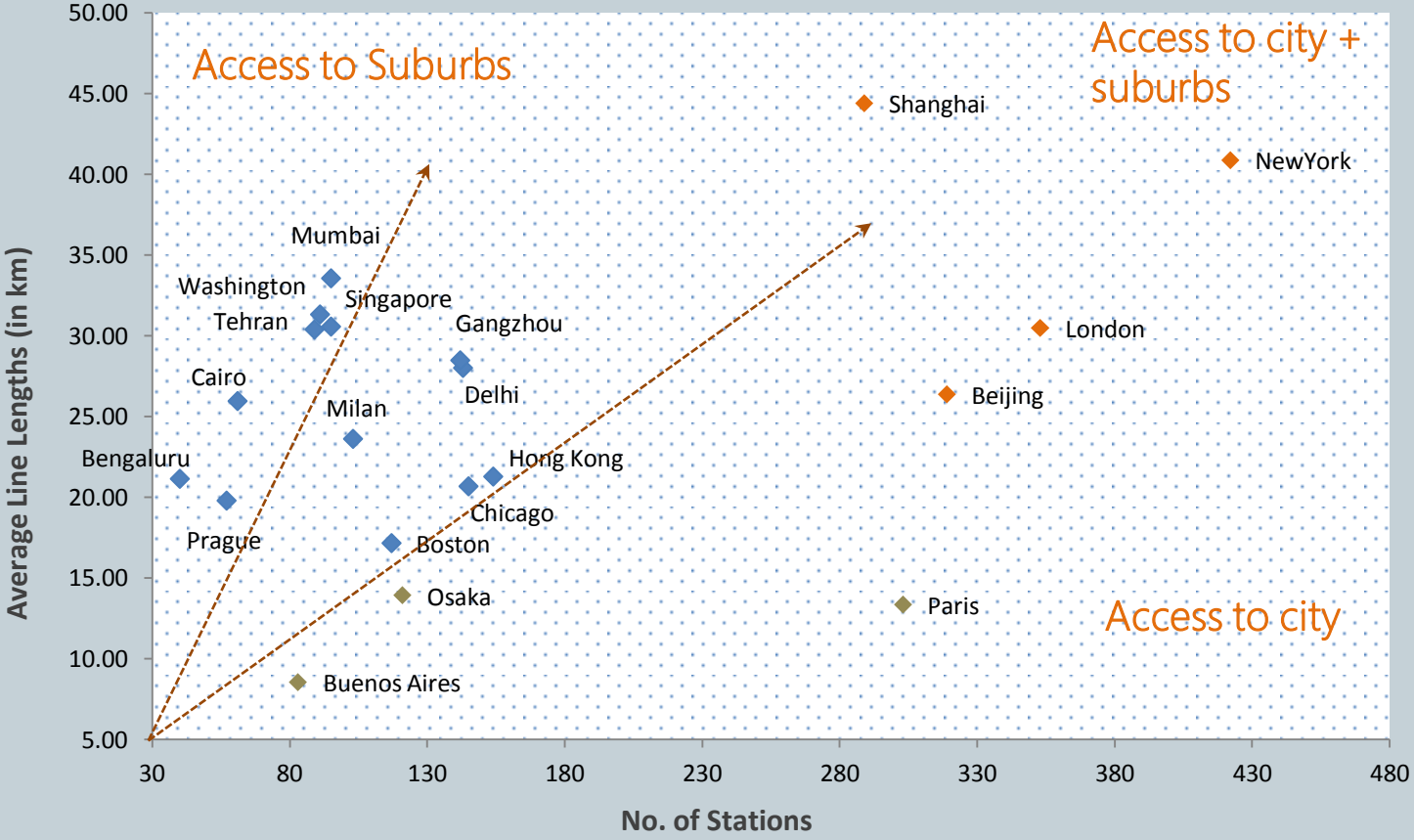
Phase	Link-Node relation and connectivity
Phase-1	Network is Weakly connected
Phase-2	Network is 50% connected
Phase-3	Network is 60% connected

Relation between Degree of connectivity and Link-node

Indian cities fall in phase one with low connectivity level.



Relation between Average interstation spacing and Average Line lengths



Relation between Average interstation spacing and Average Line lengths

Existing networks of Indian cities provide access to city center for people living in suburbs

Ridership and Coverage

	Alpha	Area served	Beta	Eta
Cities that hold relation	London, Paris, Singa	London, Paris, Singapore,	Paris, New York, Shanghai	Shanghai, Guangzhou, Beijing, Osaka
Possible Reason	End Nodes are l leading to a mo complete netwo	High number of stations and Low interstation spacing	More number of intersecting lines	
Outliers	Mumbai, Chinese ci HK	Mumbai, New York (Possibly because of Overlapping lines)	Beijing, Chicago, Mumbai, HK	London, New York, Paris
Sample Size	60%	75%	70%	55%
R^2	0.81	0.64	0.67	0.66

Key Findings

- Network analysis of various cities can be done on parameters of Connectivity, Coverage and Extensiveness.
- Strong Co-relation exists between few Network design Indicators and Ridership.
- Hence, improving the network design indicators wil help increase ridership.
- Connectivity can be increased by :

I. Increasing the link to node ratio (networks can achieve 66 % connected level)
II. Increasing the Transfer nodes that provide transfer to multiple lines.
III. Reducing the average link length. (Increasing proximity of a node)

- Coverage of the network increases with increasing number of stations and reducing interstation spacing.
- Networks can expand adopting any of the 3 broad categories: Access to public, Access to suburbs, Access to both.

- Extensiveness of the network can be improved by:
- Laying more of Transit lines will result in more Network density.

3rd Objective: To assess Network design of proposed UMRT networks for Indian cities.

- Analyze network design parameters of proposed networks of Indian cities (Delhi, Mumbai and Bengaluru)

For selected Indian case cities

- How have the Network pattern and design indicators changed?
- Is their any improvement?
- How design parameters can be improved?

Delhi Network

Line Extensions

New transit lines

New nodes

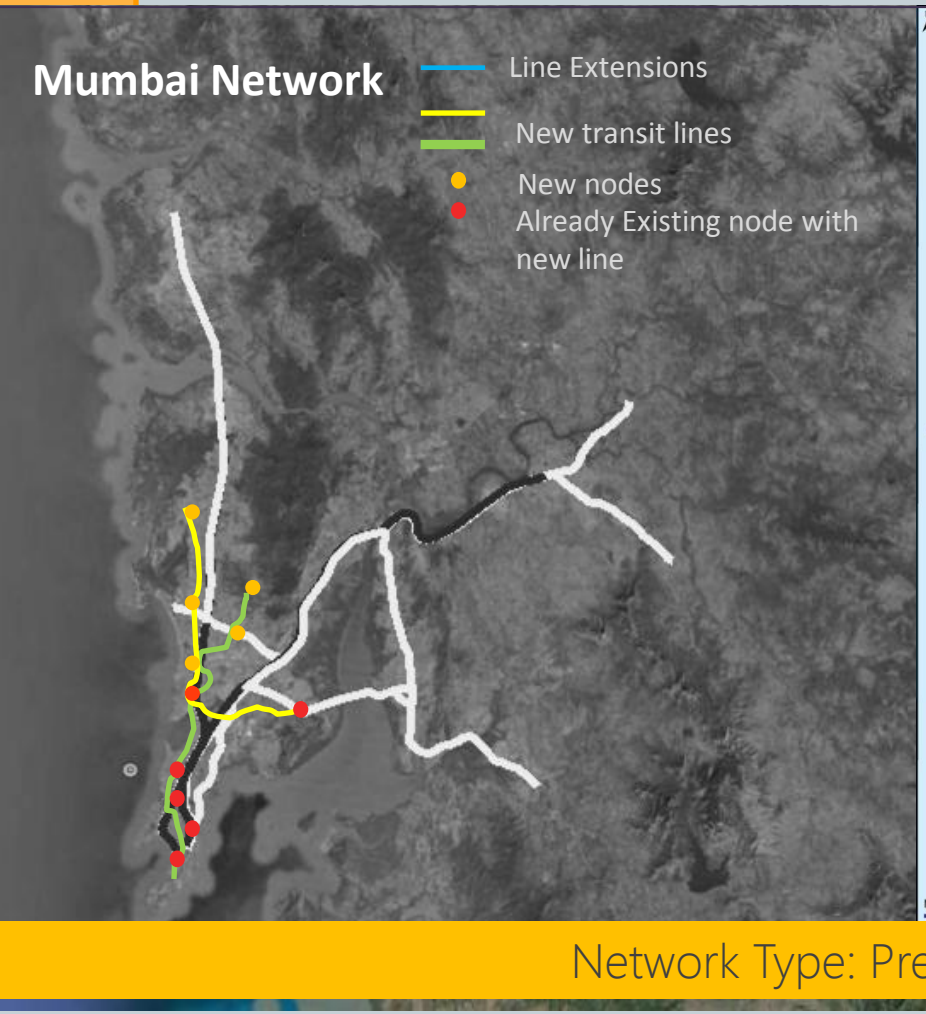
Already Existing node with new line

Proposed network

- Extension of lines
- One circumferential line
- Radial acting as half ring

Delhi Metro network Phase-3, DMRC

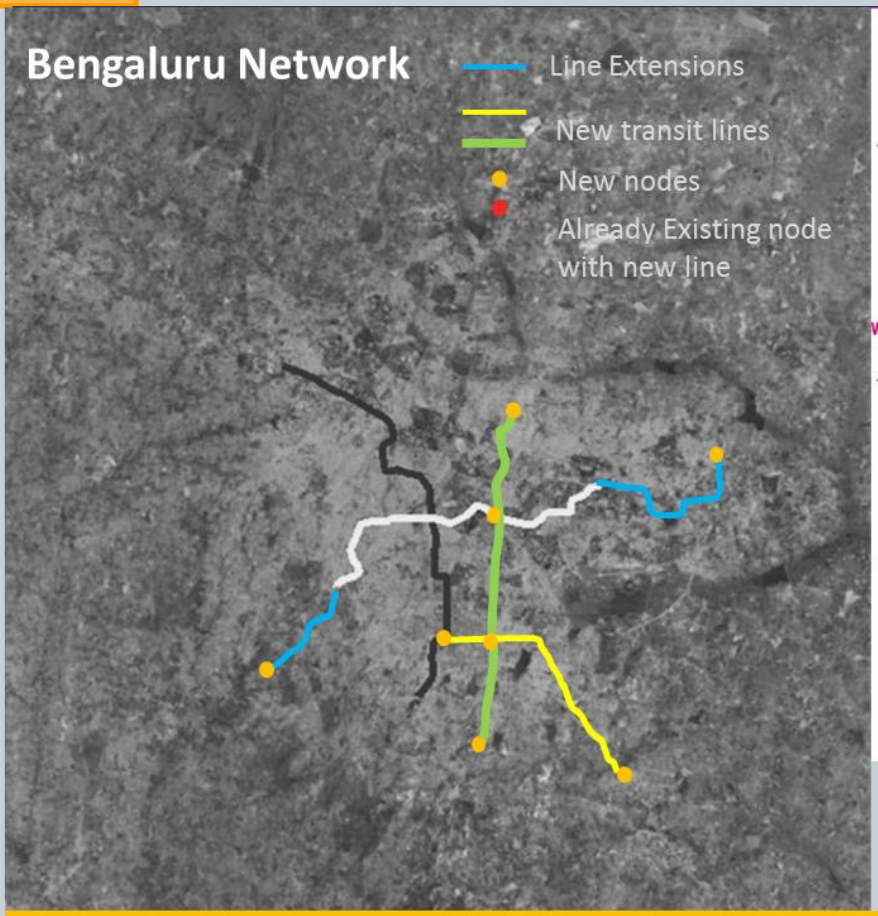
Network Type: Radial Circumferential

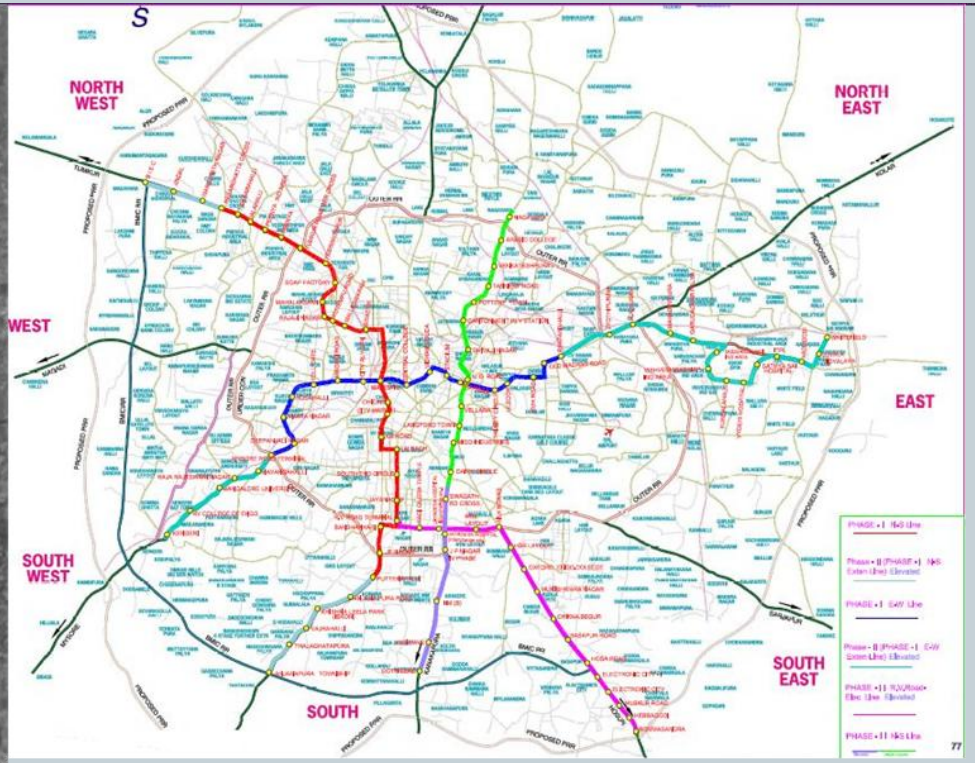


Proposed network

- 2 New transit lines intersecting the existing ones.

Network Type: Predominantly Radial





Bengaluru Metro network Phase-2, DPR

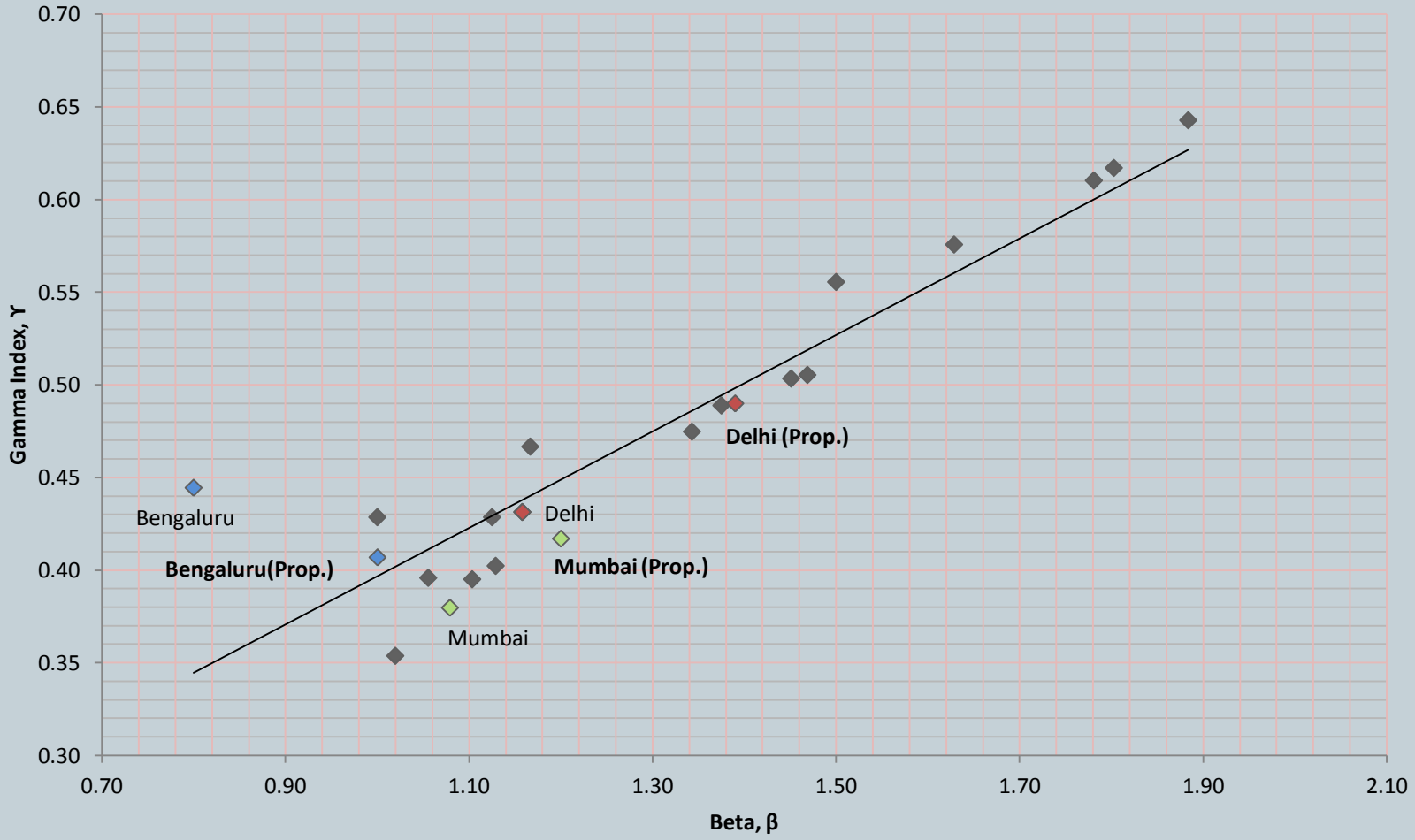
Network Type: Radial

								No. of Nodes hosting lines							
City	Urban Footprint area	No. of Transit Lines	Total Line Length	No. Of Stations	Nodes	End Nodes	Transfer Nodes	2	3	4	5	6	Links	Single Links	Multiple Links
Delhi (Prop.)	1667	9	347	234	36	12	24	23	1	0	0	0	50	49	1
Delhi	1667	7	196.15	143	19	9	10	10	0	0	0	0	22	22	0
Mumbai (Prop.)	850	9	279.4	139	46	7	39	32	4	3	0	0	55	25	29
Mumbai	850	7	235	95	38	4	34	28	5	1	0	0	41	12	29
Bengaluru (Prop.)	1012	4	113.5	97	11	7	4	4	0	0	0	0	11	11	0
Bengaluru	1012	2	42.3	40	5	7	4	4	0	0	0	0	4	4	0

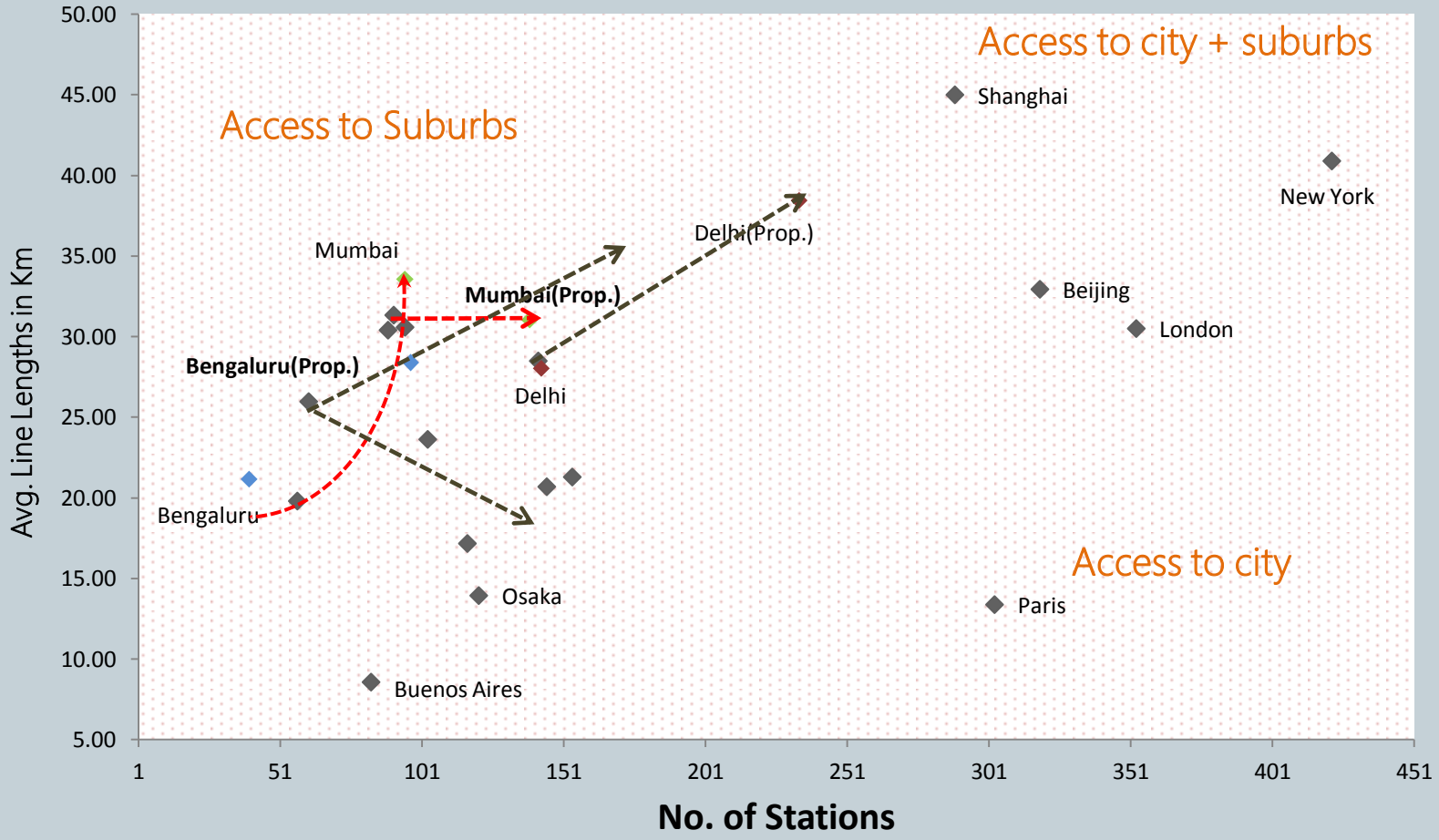
Network Characteristics of Proposed networks

	Connectivity					Coverage			Extensiveness
City	Alpha α	Gamma ϒ	Degree of Transfer Nodes	Beta β	Eta Index	Area Served	Avg. Line Length	Avg. Interstation Spacing	Network/Km2
Delhi (Prop.)	0.22	0.49	1.0	1.39	6.94	0.110	38.6	1.48	0.208
Delhi	0.12	0.43	1.00	1.16	8.92	0.067	28.0	1.37	0.118
Mumbai (Prop.)	0.13	0.42	0.51	1.22	4.98	0.128	31.0	2.01	0.328
Mumbai	0.06	0.38	0.35	1.08	5.73	0.088	33.6	2.47	0.277
Bengaluru (Prop.)	0.06	0.41	1.0	1.0	10.31	0.075	28.4	1.17	0.112
Bengaluru	0	0.44	1.0	0.8	10.575	0.031	21.15	1.06	0.042

Network Design Indicators



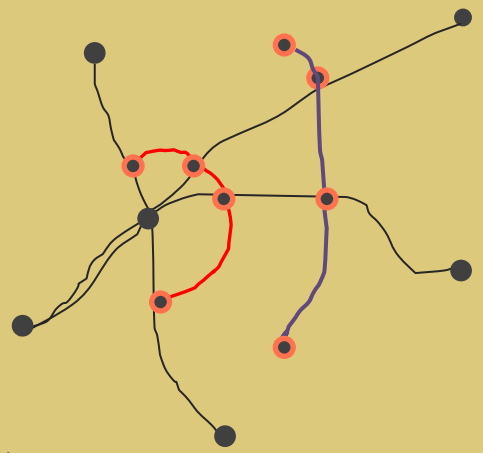
Connectivity levels have increased in the Proposed networks



- Indian cities can improve their connectivity levels by:

What are the possible ways in which Indian cities can improve their networks?

I. Introducing more transit lines .This will improve the link node ratio also the network density.



- By binding the radials with circumferential lines or circle lines.
- By introducing lines that reduce the link lengths.
- Having more stations with reduced interstation spacing.
- All these improvements will have positive implications on Ridership.

- Network based approach proves significant in analyzing Network design of the urban mass rapid transit networks for cities with varying metropolitan backgrounds.

- With the comparative analysis cities can draw lessons on the Network design parameters and adopt them for their network building.