# Principles of operations management for metro rail

Narayan Rangaraj
IEOR, IIT Bombay

# Metro operations in India

In a growing phase - Delhi metro network well developed and expanding, others still in the initial phase of operations with 2-3 lines

Currently self contained systems, integration with other transit modes is partly achieved, and will need to be more tight in future

Pricing and ticketing currently self contained - in future will be expected to be part of unified transport authority in relevant city

Schedules may need co-ordination, but since metro operations are very frequent, this is not much of an issue

# Recent headlines …

## Charkop full, second depot essential if more rakes are added to new Metro lines

An MMRDA official said the original plan was to have separate depots for both lines before starting the services. However, as land for the depot for line 7 (Dahisar East to Andheri East) could not be finalised, it was decided to use the depot for line 2A (Dahisar to DN Ngaar) for line 7 also.

Written by **Sweety Adimulam**



## Mumbai: Metro One ridership increases after integration with newly started lines

As per Metro One, both interchange stations – Western Express Highway (WEH) and DN Nagar – saw a total increase in ridership by nearly 15,000 per day.

Written by **Sweety Adimulam**
Mumbai | January 25, 2023 18:49 IST

# In this workshop

Presentations, discussions and experience sharing on metro rail operations

All aspects of operations, including

- demand assessment
- service planning and timetabling
- rolling stock management, including maintenance
- crew planning
- ticketing
- pricing
- integration with other modes,
- energy management …

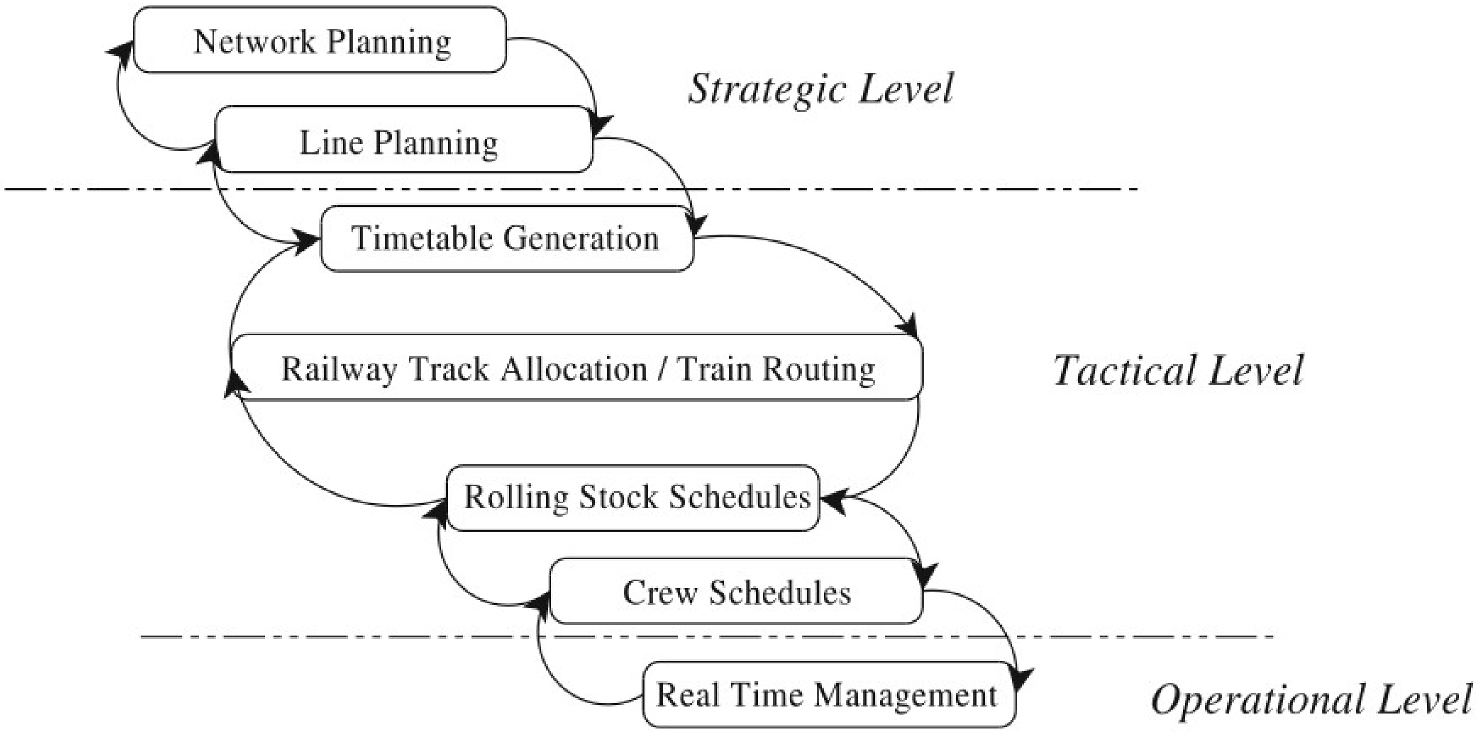
Active participation requested

Some exercises planned

Your own experiences and thoughts may please be shared

If agenda identified for collaborative work in the area, …

# Generic Planning Process (Source-Lusby et al.)



# Some specific concepts that we will try to elaborate in this workshop

Line plan options for a single (long) physical line

Cyclic timetabling and acyclic timetabling

Planning options for Y shaped or double Y shaped networks

The relationship between vehicle planning and timetabling

Presentation of timetable and commuter information

Maps and query based systems

Planning of operations during maintenance regimes and during disruptions

# Tabular and other views of a timetable

Typical view

Rows: Stations (locations) - sometimes with arrival and departure rows

Columns: Services (with service number and timings)

Bottom row may have linkage information (on connecting rakes)

These are required for detailed operations planning - including rake planning and crew planning

Customers may require only abstracted information

# U U3 S+U Warschauer Str. ◄► U Krumme Lanke

Die Linie U3 verkehrt zusätzlich in den Nächten Fr/Sa, Sa/So und vor Feiertagen auf dem Streckenabschnitt U Nollendorfplatz ◄► U Krumme Lanke. In den übrigen Nächten verkehrt die Nachtbus-Linie N3.

Tarifbereich Berlin Teilbereich A | A | B

| Station | durchschn. Fahrzeit | Umsteigen |
|---|---|---|
| S+U Warschauer Str. | | S3, S5, S7, S75, S9, U1, Tram M10, Bus 300, 347 |
| U Schlesisches Tor | 2 | U1, Bus 165, 265, N60, N65 |
| U Görlitzer Bahnhof | 4 | U1, Bus M29 |
| U Kottbusser Tor | 5 | U1, U8, Bus 140 |
| U Prinzenstr. | 7 | U1, Bus 140 |
| U Hallesches Tor | 9 | U1, U6, Bus M41, 248, N42 |
| U Möckernbrücke | 11 | U1, U7 |
| U Gleisdreieck | 12 | U1, U2 |
| U Kurfürstenstr. | 14 | U1, Bus M48, M85 |
| U Nollendorfplatz | 16 | U1, U2, U4, Bus M19, 106, 187, N26 |
| U Wittenbergplatz | 18 | U1, U2, Bus M19, M29, M46, N26 |
| U Augsburger Str. | 20 | |
| U Spichernstr. | 21 | U9, Bus 204 |
| U Hohenzollernplatz | 23 | Bus 249 |
| U Fehrbelliner Platz | 24 | U7, Bus 101, 115, 143, N43 |
| S+U Heidelberger Platz | 26 | S41, S42, S46, Bus 249, 310 |
| U Rüdesheimer Platz | 28 | Bus 186 |
| U Breitenbachplatz | 29 | Bus 101, 248, 282 |
| U Podbielskiallee | 31 | |
| U Dahlem-Dorf | 32 | Bus M11, X83 |
| U Freie Universität (Thielplatz) | 34 | Bus 110 |
| U Oskar-Helene-Heim | 36 | Bus X10, 110, 115, 285, 623, N10 |
| U Onkel Toms Hütte | 38 | Bus 118 |
| U Krumme Lanke | 40 | Bus X11, 118, 622 |

| | Mo - Do ca. | | | | | | Fr ca. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4:00 - 4:30 | 4:30 - 6:00 | 6:00 - 6:30 | 6:30 - 20:00 | 20:00 - 21:30 | 21:30 - 0:30 | 4:00 - 4:30 | 4:30 - 6:00 | 6:00 - 6:30 | 6:30 - 20:00 | 20:00 - 22:30 | 22:30 - 0:30 |
| S+U Warschauer Str. ▸ U Nollendorfplatz | - | | 10 | 5 | 10 | - | - | | 10 | 5 | 10 | - |
| U Nollendorfplatz ▸ U Krumme Lanke | 10 | | | 5 | 10 | | 10 | | | 5 | 10 | |
| | | | | | | | | | | | | |
| U Krumme Lanke ▸ U Nollendorfplatz | - | 10 | | 5 | 10 | | - | 10 | | 5 | 10 | |
| U Nollendorfplatz ▸ U Warschauer Str. | - | | 10 | 5 | 10 | - | - | | 10 | 5 | 10 | - |

| | Sa ca. | | | | | So ca. | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0:30 - 5:00 | 5:00 - 5:30 | 5:30 - 10:00 | 10:00 - 22:30 | 22:30 - 0:30 | 0:30 - 6:30 | 6:30 - 7:00 | 7:00 - 10:00 | 10:00 - 21:30 | 21:30 - 0:30 |
| S+U Warschauer Str. ▸ U Nollendorfplatz | - | | | 10 | - | - | | | 10 | - |
| U Nollendorfplatz ▸ U Krumme Lanke | 15 | | 10 | | | 15 | | 10 | | |
| | | | | | | | | | | |
| U Krumme Lanke ▸ U Nollendorfplatz | 15 | 10 | | | | 15 | 10 | | | |
| U Nollendorfplatz ▸ U Warschauer Str. | - | | | 10 | - | - | | | 10 | - |

Headway on same line: Inequality
Tdep_Rk:2 – Tdep_Rk:1 >= 3 min

Frequency across services

Traversal Time: Equality

eg: Tarr_VSH – Tdep_PNVL = 31 min

Halt Time: Inequality

Eg: 0.5 min <= Halt at VDRD <= 1.5 min

| Services | PNVL-VDRD | PNVL-CST | PNVL-CST | BEPR-CST | GMN-CST | PNVL-CST |
|---|---|---|---|---|---|---|
| *ServiceNum* | *PLVDGMN:2* | *PL:2* | *PL:4* | *BR:2* | *GMN:2* | *PL:6* |
| *RakeNum* | *Rk:1* | *Rk:2* | *Rk:3* | *Rk:11* | *Rk:18* | *Rk:7* |
| GMNd | | | | | 07:22 | |
| BAd | | | | | 07:47 | |
| PNVLd | 06:43 | 06:46 | 6:49.5 | | | 06:58 |
| BEPRd | 6:58.5 | 7:01.5 | 07:05 | 07:08 | | 7:13.5 |
| NERd | 7:05.5 | 7:08.5 | 07:12 | 07:15 | | 7:20.5 |
| VSHa | 7:14 | 7:17 | 7:20.5 | 7:23.5 | | 7:29 |
| VSHd | 7:14.5 | 7:17.5 | 07:21 | 07:24 | | 7:29.5 |
| MNKDd | 7:23.5 | 7:26.5 | 07:30 | 07:33 | | 7:38.5 |
| CMBRd | 7:29.5 | 7:32.5 | 07:36 | 07:39 | | 07:45 |
| VDRDa | 07:45 | 07:48 | 7:51.5 | 7:54.5 | 7:57.5 | 8:00.5 |
| VDRDd | | 7:48.5 | 07:52 | 07:55 | 7:58.5 | 8:01.5 |
| CSTa | | 08:06 | 8:09.5 | 8:12.5 | 08:16 | 08:19 |
| *Rake will work as* | *Contd_PLVD GMN:2* | *PL:15* | *B:5* | *PL:17* | *PL:19* | *V:5* |
| | *7:47.5* | *08:09* | *8:12.5* | *8:15.5* | *08:19* | *08:22* |

Turn around time at the terminal: Inequality

3 min <= Tdep_PL:15 – Tarr_CST <= 10 min

# Feasible timetables

Mathematical relationship between entities are (simple) equations or inequalities

Can be captured as a set of conditions that indicate feasible sets of values that can be satisfied

This allows us to compute valid timetables efficiently, and exhaustively search for good options if needed

Not easy to verify feasibility of all desired conditions (headway, frequency and perhaps others) and also not easy to find the optimal solution among all possible feasible solutions

Many good, approximate procedures available and an active area of research to find good formulations (including track/platform considerations) and solution techniques

# Different ways of constructing timetables

**Constructive**

Start with small number of services and plan rakes for them and incrementally increase the services with a given target frequency

Adjust turn around times at terminals and check for platform availability

**Integrative**

Specify a system of conditions to be satisfied by timings

Use a solver or a heuristic to compute timings of all services in one go

Adjust as per local terminal conditions

# Line planning options for a single, long line

Basic question - do all services need to run end-to-end

Convenient for short lines with homogeneous spread of demand at all locations

For very long lines (beyond 20 km), it is quite likely that demand at the edges is not as much as demand

(a) to and from certain locations or

(b) between locations towards the center of the network

Best use of rolling stock, crew and energy resources may be to run some short services

Could also be required because of locations of depots or other operational reasons

**In a later session, these options will be explored in some detail**

# Cyclic timetabling and acyclic timetabling

Since metro services are quite frequent and meet regular requirements of commuters, it is seen that frequency of service is what customers look for

Takt or Takt-time is a term used in Japanese and German systems to describe cycle times

Headway = min time between two consecutive services (from safety point of view)

Frequency = number of services in some time unit (e.g. one hour)

Takt = time gap between services implied by some frequency

E.g. 12 services an hour → Takt of 5 mins

Takt often written as 4 or 5 or 4/5 (gap of 4 minutes followed by gap of 5 minutes)

# Example

If we have services A → B → C and we want services from A → C every 10 mins and we introduce short running services from B → C

If we introduce 2 more services every 20 mins, we get a uniform frequency of B → C services

If we introduce one more short service from B → C over a 20 min period, we cannot get a uniform frequency from B → C

If we want uniform frequency from B → C, then uniform frequency at A has to be sacrificed

# Options

Uniform at B

| | | | | |
|---|---|---|---|---|
| A | 5:45 | 5:51 | – | 6:05 |
| B | 6:00 | 6:06 | 6:13 | 6:20 |
| C | 6:30 | 6:36 | 6:43 | 6:50 |

Uniform at A

| | | | |
|---|---|---|---|
| 5:45 | 5:55 | – | 6:05 |
| 6:00 | 6:10 | 6:15 | 6:20 |
| 6:30 | 6:40 | 6:45 | 6:50 |

At A : 6, 14, 6, 14, 6, 14, …
At B: 6, 7, 7, 6, 7 ,7, …

At A: 10,10,10,...
At B: 10, 5, 5, 10, 5, 5,...

## Cyclic schedules

Compact to plan and convey timetable information

Easy to compute overall requirements (rakes/rolling stock and crew) and service levels to passengers

## Acyclic schedules

Need to be planned in detail

Needs more effort to compute overall requirements (rakes/rolling stock and crew) and service levels to passengers

# Example of cyclic plan

On a line A → B → C, with headway = 7 mins, can we plan the following?

A → B → C services 4 times an hour (equally spaced), i.e. one service after every 15 mins - call it type 1 service

A → B service 3 times an hour (equally spaced), i.e. one service after every 20 mins - call it type 2 service

Headway of 7 mins easily permits 7 services an hour, but difficult to achieve exact frequency of services

Even if we have a headway of 5 mins, it is difficult to achieve this? ‘

What is the least headway that will permit this?

Another option is to relax the periodicity a little, and say that time between two services of type 1 is 20 +- 2 minutes, e.g k = 2, i.e. between 18 and 22 mins

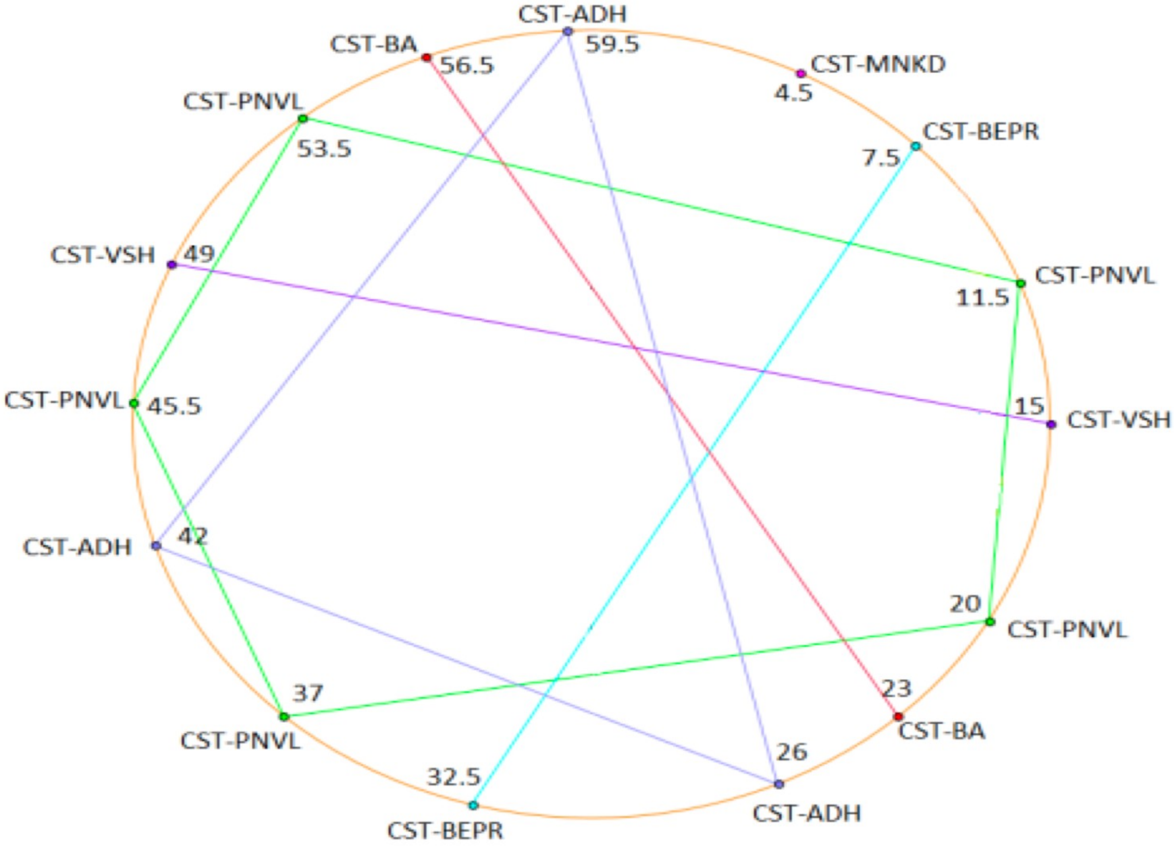
What is the smallest k that will permit this?

# Cycle plan - PESP

The formal version of this decision is the Periodic Event Scheduling Problem - PESP

Constraints are between events and everything is relative to a predetermined period T (which can be 60 mins, 30 mins, 20 mins etc)

Costs can be put on any choices of times, e.g. waiting costs for passengers, changeover costs for passengers




**Departure Times for CST**

# Planning options for Y and double Y shaped sections

Examples

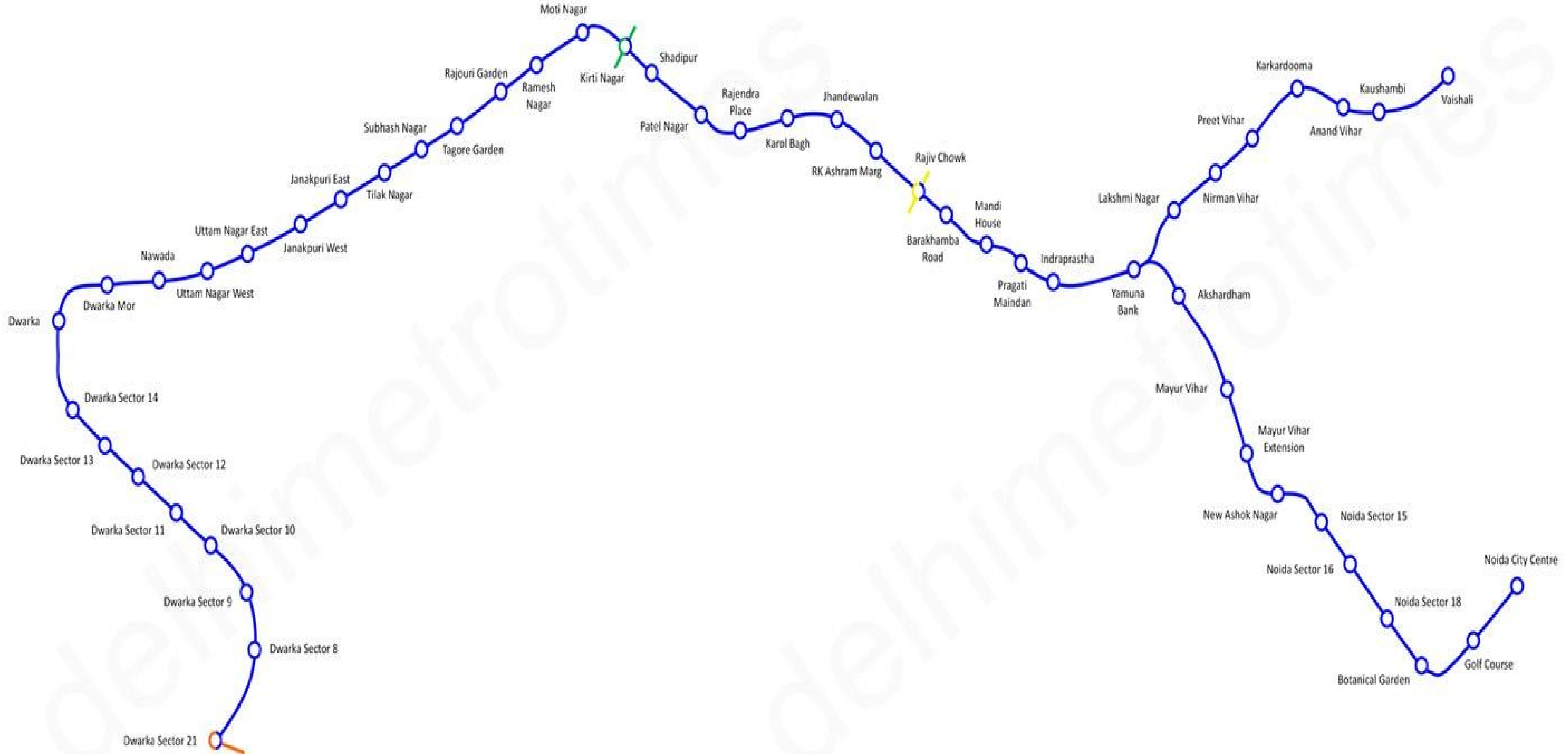
Delhi Metro Blue Line

Mumbai suburban - Central Railway

Sealdah south suburban services

Berlin S Bahn network

# Delhi Metro Blue LIne



# Relationship between timetabling and vehicle planning

Timetables for metro and suburban operations are done in a very integrated manner along with vehicle schedules

Unlike

Long distance rail - where there is a delinking possible at terminals (maintenance, rake linking options with other services)

Buses - may not have as much of a constraint at terminals

# Disruption management - special case

What to do if the services on ONE line at some point in a linear network are disrupted for 30-60 mins?

- General principle: Keep up services in both directions for the parts of the subnetwork it is possible to do so
- Question: Do we wish to run through services on the single line?

Number of rakes in each subpart of network should be close to steady state occupation of each part of the network so that services with appropriate frequency can continue on that part of network

- General strategy is to stop services in both directions and operate from nearest available crossovers in each subpart of network
- Principle is that in steady state, the number of rakes in each subpart of the network is in keeping with the number of services that can be operated there

# Presentation of timetable and commuter information

Maps are useful in concise communication of travel options and coverage of metro system

Coloring and design of maps is a very important aspect and requires great care

Query based systems are very important (including complementary modes of transport), see, for example

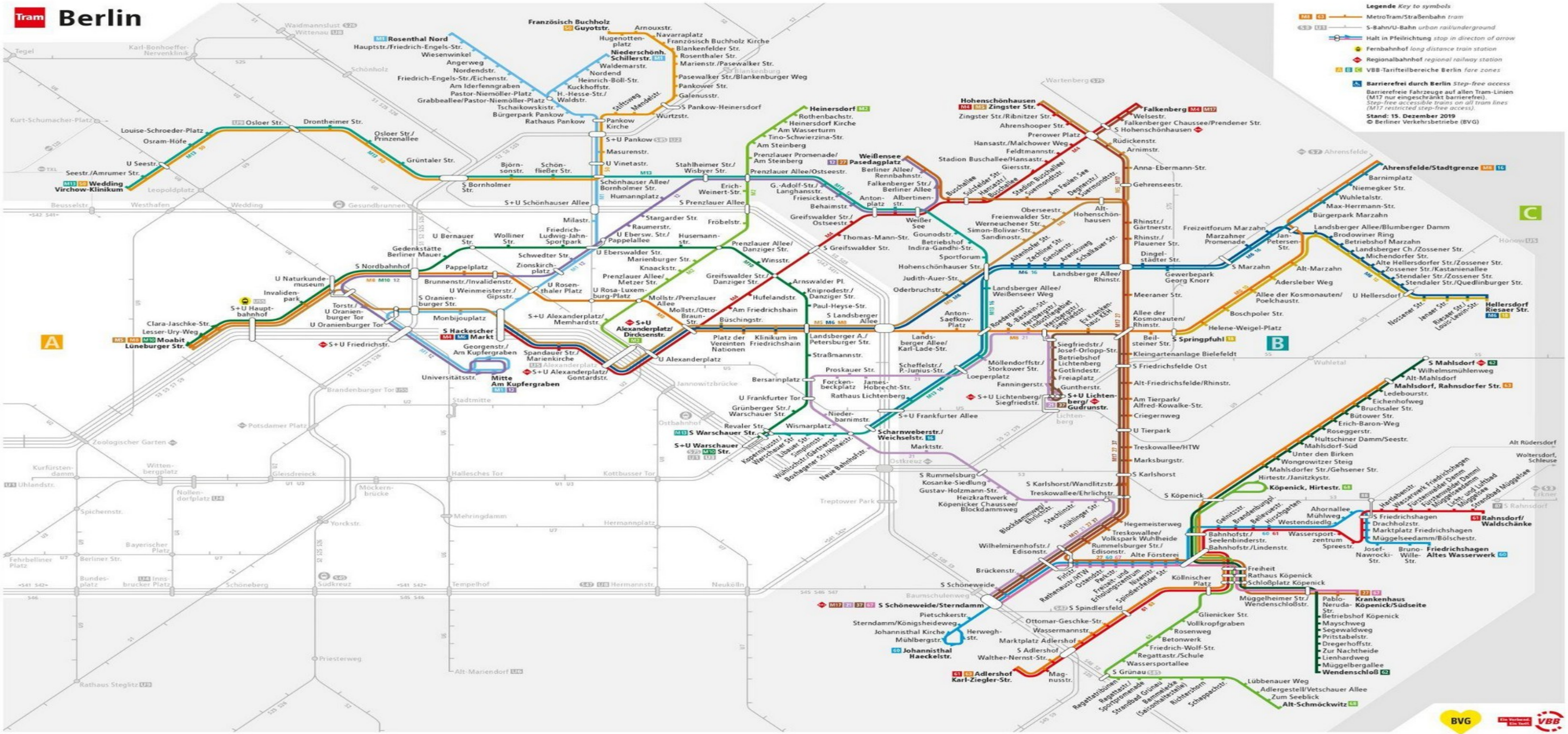
https://www.bvg.de/en/connections/connection-search

Need to make Passenger Itinerary Network based queries available, including connecting modes of transport

General idea: Shortest path (or cheapest or with least number of changes or …) on a network with nodes being time/space co-ordinates and arcs being possible waits and moves

- Approximate algorithms available for efficient computation of such paths

# Example - Berlin tram network




https://www.bvg.de/en/connections/network-maps-and-routes

https://www.bvg.de/en/connections/network-maps-and-routes

# Example of a decision support system

LinTim

https://lintim.net/

Number of utilities for planning of public transport systems

Research based effort and still managed in the academic sphere

Originally developed at the Univ of Göttingen, Germany, then at Tech Univ Kaiserslautern, now hosted at Aalto Univ, Finland

Benchmark examples and test data sets welcome

Open source and available for trial

# Summary of efforts of our group

Work with Indian Railways

- Rationalized timetable construction on Golden Quadrilateral and Diagonals on Indian Railway mainline network
- Rail traffic simulator development
- Rolling stock management - coaching, suburban as well as freight
- Crew planning for suburban as well as mainline services

Attempt initiated with Delhi Metro on line planning and timetabling

Research work in technical aspects of timetabling and vehicle planning

See ***https://www.ee.iitb.ac.in/%7Ebelur/railways/*** for more information

Many other studies in the areas of logistics and transportation for various agencies

# Conclusion

A lot of expectation in the country regarding metro rail - has already changed the mobility pattern in Delhi and similar impact expected in other areas

Needs to be integrated with overall mobility patterns and needs of the city, in conjunction with other modes

Many challenges in the years to come and a lot of scope for innovative and meaningful work for all of us