Multi-Objective Timetable Design in Suburban Rail Transport

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July 11, 2018

Introduction

Suburban Timetable

A suburban timetable can be characterized by five parameters

- Buffer headway (time between trains)
- Slack (in traversal time) and its distribution across various sections
- Punctuality of services
- Number of scheduled services
- Rakes (rolling stock units) required to run scheduled services

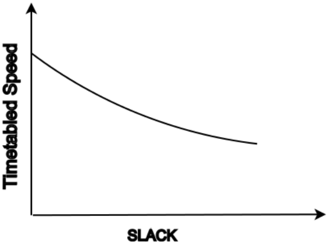
If buffer headway and slack are given as inputs to generate a timetable, the other three parameters can be used to measure the quality of timetable.

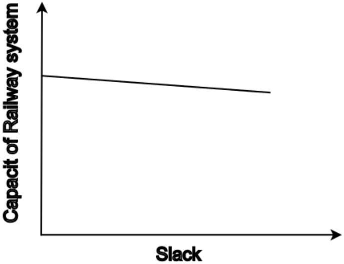
Suburban Timetabling - summary

- From all feasible timetables (i.e. combination of slack and buffer headway), a good timetable can be selected, based on objectives that one chooses.
- For fixed # of services - multiple timetables (combination of slack and buffer headway) requiring different
  - different # of rakes
  - different punctuality
- Depending on whether a level of punctuality or providing services with certain number of rakes is the objective, a unique timetable is selected.

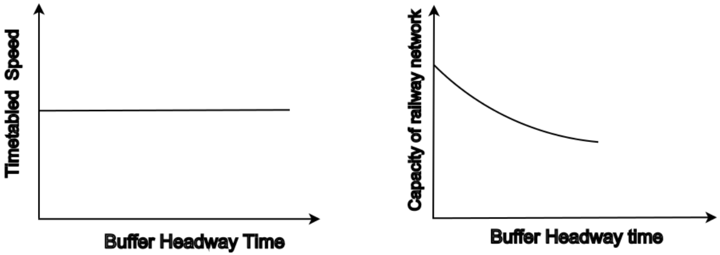
Relation between Slack, Headway and Punctuality

Slack vs Timetabled speed and capacity





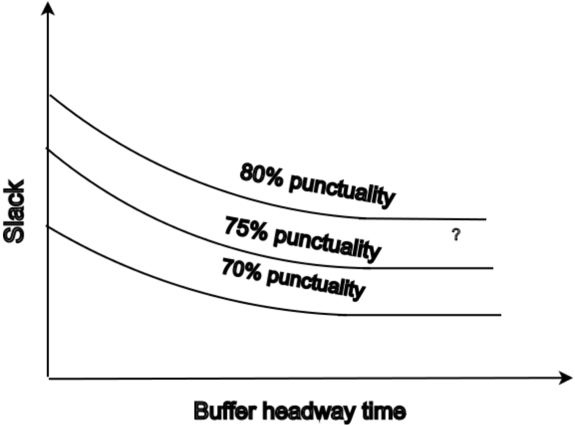
Headway vs Timetabled speed and capacity



Relation between Slack, Headway and Punctuality

- For a given level of punctuality, combinations of slack and headway can be used
- Equi-punctuality curves are those combinations of slack and headway that achieve a certain punctuality (for a given number of services or rakes)
- Also, if one wants to achieve certain punctuality level, then equi-punctuality curve of that level provide multiple timetable that will have same punctuality. Now based on whether one wants to have more services (less buffer headway) or less rakes (more buffer headway), an optimal timetable is selected.

Relation between Slack, Headway and Punctuality



Western Railway, Mumbai

Western Railway

12 car train
In Mumbai

Close to 5000
passengers

Super Dense
Crush Load

Photo : Chaitanya Gokhale – through IRFCA

Western Railway (WR) Simulation

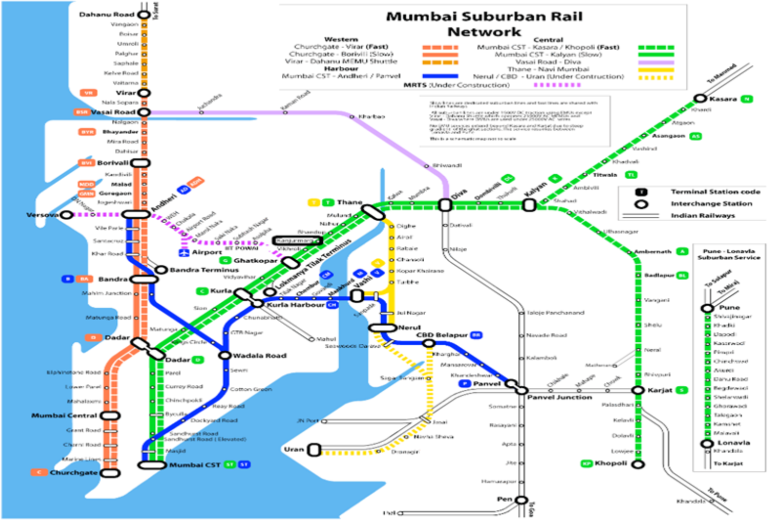
To explore Equi-punctuality curves, simulation of the Western Railway line, Mumbai suburban railway is done using an LP

Multiple timetables have been generated using different combination of buffer headway, slack and its distribution and Equi-punctuality curves are generated.

Further, these timetables are compared based on their three main characteristics

- Punctuality of timetable
- Number of scheduled services
- Number of rakes required

Mumbai Suburban Map



Slack, Buffer, Punctuality in Western Suburban Railway

- Morning peak, average headway = 3.5 minutes and average slack = 10% of prescribed run-time
- Slack distributed throughout all stations based on judgement of railway officials
- Train arrival punctual if it is late by no more than 5 minutes at the terminal station from its scheduled arrival time
- Trains which are canceled are not considered while calculating punctuality!!
- Western suburban railway has punctuality of around 95%.

Experiment Design

WR Simulation

- Slow Locals considered for CCG- BVI (33km) and CCG-ADH (21km) services considering operational and infrastructural constraints
- Minimum runtime: CCG - BVI service is 52.5 mins, CCG - ADH 36.5 minutes
- Disturbances simulated based on actual run time of slow trains for a period of 4 days

Simulation

- Analyze the effect of adding slack and buffer headway on other parameters like number of scheduled services, rakes required to run scheduled services and punctuality of railway system.
- A given level of punctuality can be achieved by different combinations of slack and buffer (Equi-punctuality curves)

Western Railway (WR) Services

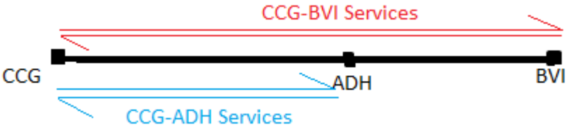


Figure: Schematic diagram showing terminal stations of Churchgate-Borivali (CCG-BVI) and Churchgate-Andheri (CCG-ADH) services.

Infrastructure modeling in the WR Simulation

- Western Railways have dedicated tracks for slow and fast services. Simulation experiments are with slow services.
- We have considered 2 terminating platforms at CCG, BVI and ADH and two through platforms at ADH.

Operational consideration for WR Simulation

- Halt time at each station = 30 seconds, added to nominal run time given in the working timetable
- Minimum arrival headway at all stations = 3 minutes
- The minimum platform headway = 3 minutes
- It is assumed that no train will leave the station before its scheduled time.

Realized Run Time consideration for WR Simulation

- Though nominal run time is given, realized run time needs to be generated for simulating the trains.
- Actual train running data of arrivals at stations during morning peak at major station for 4 weekdays (3rd, 4th, 7th and 8th May, 2018) is used
- Traversal time distributions constructed from this data and used in the simulation

Other Considerations for WR Simulation

- Zero Slack-Buffer timetable - with nominal run time and minimum headway.
- Multiple timetables generated by adding different values of slack and buffer headway and also by changing distribution of Slack at various stations.
- All services start from Churchgate, go to Andheri/Borivali and then come back to Churchgate and thus complete one cycle
- Simulation is done for two cycles to consider the effect of late arrival of rake at source station on the next services

Turnaround Slack Considered for WR Simulation

- Apart from minimum turnaround time which is 3 minutes, turnaround slack is given at terminating stations (BVI, ADH, CCG in our study) in working timetable
- In our simulation, turnaround slack of 3 minutes at ADH and BVI terminals
- To avoid platform assignment complications at CCG, we have added 3 minutes to the run time between the previous major station and CCG

Measure of punctuality

- Punctuality measured at all stations.
- Train arrival is punctual if it is late by no more than 3 minutes from its scheduled arrival time.
- Punctuality of timetable is calculated as

$$\text{Timetable Punctuality} = \frac{\#\text{ of punctual arrival/departure events}}{\text{Total }\#\text{ of events}} * 100 \tag{1}$$

Services offered in Timetable

- In our study, the number of services offered in a timetable is calculated for a fixed time duration of 240 minutes (peak period is 180 minutes)
- Services which start and end in this time are considered in the simulation

Western Railway Simulation

The Simulation is done in three steps

- Target timetable is created based on desired buffer time, slack and its distribution. All operational rules are not considered, so may or may not be feasible.
- A feasible timetable is generated using an Mixed Integer Linear Programming (MILP) Model which ensures that all the infrastructural and operational constraints are satisfied
- Realized run time of trains are generated by using actual run time data and then trains are simulated using the MILP model used in previous step with some modifications

Multiple simulations are done to generate multiple timetables by varying slack from 5% to 25% and buffer headway from 0 minute to 3 minutes in small increments.

Operational Strategies

Trains at terminal can be handled in different ways.

- Fixed Sequence - the overall sequence of trains departing from all stations is as per the schedule timetable irrespective of delays incurred by CCG-ADH or CCG-BVI trains
- Partially flexible sequence - the order of trains is not fixed and depends on the actual arrival time of trains at Churchgate and Andheri stations. Because of this the secondary delay may reduce.

Results are reported for the fixed sequence case. Punctuality and other measures likely to be better for the flexible sequence case.

Model Definition

MILP formulation of Caprara et al. [2002] is modified with infrastructure and rake linking constraints

- I - set of services
- S - set of station or events.
- J^i be set of events in each service $i \in I$
- A^s be set of events at station $s \in S$
- $T_{i,j}$ - desired arrival time of service i at its *jth* event i.e $i \in I$, $j \in J^i$

Model Definition

- $t_{i,j}$ is the decision variable and denotes scheduled arrival time of service i at its jth event i.e $i \in I$, $j \in J^i$
- $x_{i,j,h,k}$ is the binary decision variable that is 1, if $t_{i,j}$ is less than $t_{h,k}$, otherwise 0.
- $time_{i,j}$ denotes minimum run time of service i from event $j - 1$ to j.
- N1 is the no. of services departed from CCG till the time first service (CCG-BVI-CCG) return to CCG.
- N2 is the no. of services departed from CCG till the time second service (CCG-ADH-CCG) return to CCG.

MILP Model for Generation of Feasible Timetable

Objective

$$Min \sum_i ((t_{i,len(J_i)} - t_{i,0}) - (T_{i,len(J_i)} - T_{i,0}) + (t_{i,0} - T_{i,0}))$$

$+\sum_{i,j}(t_{i,j} - T_{i,j}) \quad \forall i \in I, j \in J^i (2)$

subject to

$$t_{i,j+1} - t_{i,j} \geq time_{i,j+1} \quad \forall \imath \in I, j = 1, .., len(J^i) - 1 \qquad (3)$$

$$t_{i,j} - T_{i,j} \geq 0 \quad \forall i \in I, j \in J^i \qquad (4)$$

$$t_{i,j} - t_{h,k} \geq 3 - Mx_{i,j,h,k} \quad \forall t_{i,j}, t_{h,k} \in A^s, \forall s \in S \qquad (5)$$

$$t_{h,k} - t_{i,j} \geq 3 - Mx_{h,k,i,j} \quad \forall t_{i,j}, t_{h,k} \in A^s, \forall s \in S \qquad (6)$$

$$x_{i,j,h,k} + x_{h,k,i,j} = 1 \qquad (7)$$

MILP Model

$$x_{i,j,h,k} = x_{i,j+1,h,k+1} \tag{8}$$

$$t_{i,J^i-1} \leq t_{N1+i,0} \quad \forall i = 0, 2, 4, ...len(I) - N1 \tag{9}$$

$$t_{i,J^i-1} \leq t_{N2-1+i,0} \quad \forall i = 1, 3, 5, ...len(I) - N2 \tag{10}$$

$$t_{i,J^i-1} \geq t_{N1+i-2,0} + 3 \quad \forall i = 2, 4, ...len(I) - N1 \tag{11}$$

$$t_{i,J^i-1} \geq t_{N2-1+i-2,0} + 3 \quad \forall i = 3, 5, ...len(I) - N2 \tag{12}$$

$$t_{i,J^i/2} \geq t_{i-4,J^i/2+1} + 3 \quad \forall i = 2, 4, 6...len(I) \tag{13}$$

$$t_{i,J^i/2} \geq t_{i-4,J^i/2+1} + 3 \quad \forall i = 3, 5, 7...len(I) \tag{14}$$

Model Explanation

- Objective 2 tries to reduce the difference between desired and scheduled traversal time, desired and scheduled firing time at CCG station and schedule and desired time arrival time at all stations.
- Constraint 3 impose time difference between two consecutive arrivals of same train
- Constraint 4 ensures that no train departs a station before time
- constraints 5, 6, 7, 8 help to maintain a minimum headway of 3 minutes between arrival of consecutive trains at a station
- Constraints 9, 10 does the rake linking at Churchgate station.

Model Explanation

- Constraint 11 and 12 make sure that there should be a minimum time difference of 3 minutes between departure of one train and arrival of next train on same platform
- Constraints 13 and 14 ensure that there are no more than 2 trains standing at Andheri and Borivali terminating platforms at a given point of time i.e there are only two terminating platforms at Borivali and Andheri stations

MILP Model for Simulation

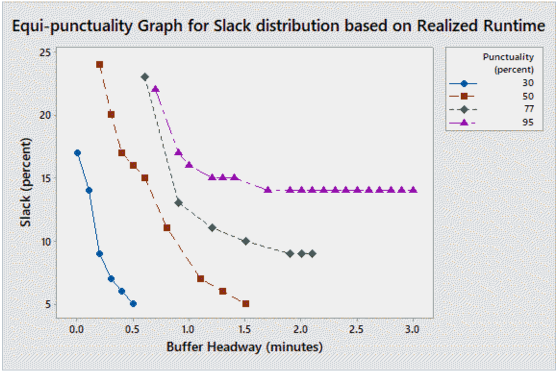
Once the Schedule Timetable is prepared, the simulation is done using same LP model with some slight modification in objective function and input data.

- $T_{i,j}$ denotes Scheduled arrival time which has been generated in last step described above.
- $t_{i,j}$ is the decision variable and denotes realized arrival time of service i at its *jth* event i.e $i \in I$, $j \in J^i$
- $time_{i,j}$ denotes realized run time of service i from event $j-1$ to j.
- The model is the same except for the objective

$$Min \sum_{i,j} (t_{i,j} - T_{i,j}) \quad \forall i \in I, j \in J^i \tag{15}$$

Results

Equi-Punctuality Curves for CCG-BVI services

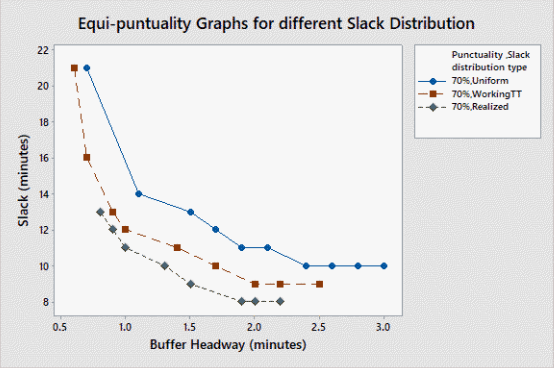


Effect of slack distribution on Equi-Punctuality curves

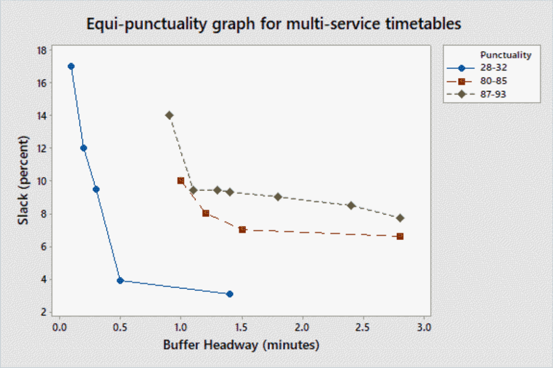
Once total headway and total slack that need to be given in schedule timetable is set, slack distribution at all station need to be specified. Slack distribution is done in three different ways.

- Uniform Slack distribution
- Slack can be distributed as in current Working Timetable of Western Railway (suburban) during morning peak hours
- Weightage of slack determined using run time difference between (average) realized and minimum run time

Effect of slack distribution on Equi-Punctuality curves



Equi-Punctuality Curves for two service timetable



Effect of Buffer Headway on timetable parameter

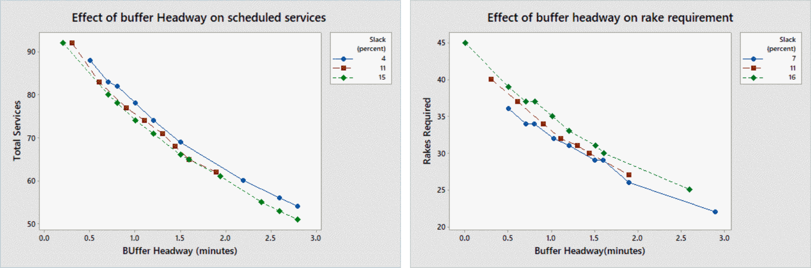


Figure: Effect of Buffer Headway on schedule Services and Rake Requirement

Effect of Buffer Headway on timetable parameter

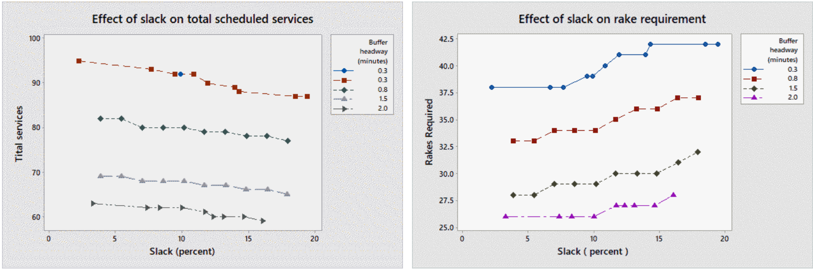


Figure: Effect of Slack on schedule Services and Rake Requirement

Inference

- The total services and the required rakes reduce by increasing the buffer headway, keeping constant slack.
- Also, rake requirement increase but total services that can be offered decrease with increase in slack, keeping constant buffer headway.
- But the rate of decrease in rake requirement and services with increase in slack is much less than rate of decrease in rake requirement and services w.r.t increase in buffer headway.
- Thus, the parameters: Rakes required and total scheduled services are more sensitive with buffer headway as compared to slack.

Simulation Results:CCG-BVI & CCG-ADH Services

Total services	Rakes required	Scheduled Headway	Scheduled slack	Punctuality
60	30	4.80	20.06	99.80
60	27	5.00	12.36	98.04
60	27	5.00	13.15	99.25
60	27	5.00	14.67	99.47
60	24	5.20	3.87	63.09
60	24	5.20	5.41	65.62
60	29	4.90	19.32	99.80
60	29	4.91	18.56	99.31
60	26	5.10	9.98	84.63
60	26	5.10	11.15	91.84

Inference

- For a fixed no. of services, say 60, multiple timetables, with different combination of slack and buffer headway, and with different number of rakes and punctuality are available
- If the objective is to maximize or to achieve certain punctuality, say 90%, then timetable with 11.15% slack and 2.1 minutes buffer headway need to selected and it will require 26 rakes
- For the minimal number of rakes i.e 24, optimal timetable has 2.2 min buffer headway and 5.41% slack and the punctuality will be 65%.

Simulation Results:CCG-BVI & CCG-ADH Services

Rakes required	Total services	Scheduled Headway	Scheduled slack	Punctuality
31.00	70.00	4.33	12.53	87.28
31.00	71.00	4.20	10.18	91.58
31.00	71.00	4.30	9.40	89.80
31.00	71.00	4.30	10.92	95.71
31.00	72.00	4.20	7.05	76.03
31.00	72.00	4.20	8.58	83.81
31.00	72.00	4.30	7.80	69.12
31.00	73.00	4.20	5.46	42.84
31.00	75.00	4.10	4.70	57.56
31.00	75.00	4.10	6.24	62.00
31.00	75.00	4.10	7.83	68.57
31.00	76.00	4.10	3.12	26.08
31.00	77.00	4.00	5.48	36.48
31.00	78.00	4.00	3.90	34.19
31.00	80.00	3.90	3.13	26.66

Inference

- For fixed number of rakes, say 31, then there are multiple timetables with different combination of slack and buffer headway that require same number of rakes but with different number of services and punctuality levels
- For 90% punctuality, a timetable with 10.18% slack and 1.2 minutes buffer headway is an option and 71 services will be provided
- To maximize number of services (80), the optimal timetable has 0.9 min buffer headway and 3.13% slack and the punctuality will be 26.7%.

Conclusions

- Study quantifies different performance measures on a complex, real timetable
- Framework discussed with railway authorities and they seem interested.
- Is traversal time slack better or buffer headway slack better?
    - Traversal time slack required for guarding against primary delays
    - Traversal time slack adds to passenger travel time
    - Buffer time and traversal time can both address secondary delays
    - Terminal constrains may put some bounds on buffer headway
- More input data analysis and output analysis needed

Acknowledgements

- **Shamit Monga**, Divisional Operations Manager, Western Railway, Mumbai
- **M. K.Jagesh**, Chief Train Controller, Western Railway, Mumbai
- **N. Hemachandra**, Industrial Engineering and Operations Reasearch, IIT Bombay

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Thanks for your attention!