System Headway on the slow corridor for suburban services (Western Railways - Mumbai)

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Summary

The section capacity of a rail section and the reliability of a planned timetable on the section depends upon the achievable section headway. Section headway in turn depends upon signal locations, signal aspects, train characteristics, platform allocation and turnaround times. We present a detailed analysis of section performance along the Churchgate-Borivali slow corridor of Western Railways. We show that the current section headway is slightly above 3 minutes, but we suggest how the section headway could be reduced to 2.5 minutes by adding a few signals and re-spacing a few signals, together with a small increase in traversal time. A systemic view is presented of train operation on the suburban corridor, considering all factors relevant to system performance.

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1 Introduction

The suburban railway timetable in Mumbai is a complex operating document which has a very direct impact on several decisions by Western Railway and the resulting service to commuters and the costs of operation. This report attempts to provide quantitative and analytical inputs to this process and validates certain choices being made by Western Railways and suggests some alternatives in operating practice. The suburban rail network in Mumbai, specifically the slow corridor on Western Ralway, is studied using a combination of simulation and analytical methods.

1.1 Initial motivation

The initial motivation for the study was that the current timetable may not have made adequate provision for certain types of patterns and movements on the network, specifically the increasing number of en-route crossovers at Borivali.

After discussions, the initial task was to assess and estimate the achievable headways on the various corridors and to suggest whether signal re-spacing would yield any benefits. This is driven by the fact that there is a continuous ongoing need to increase the number of trains because of an increase in number of passengers. Decreasing the headway and increasing the number of trains cannot be done until the headways are calculated accurately and bottleneck sections are identified. Other means of increasing carrying capacity such as introducing trains of larger length could also be considered.

Another task that was identified was that the timetable should be analysed to find out if the slack given for train movement on straight track is adequate for reliable performance, at least in the presence of small delays - which seem almost inevitable in daily running.

As far as we are aware, this is one of the first attempts at putting together a document that considers safety and the operational principles of signal placement and safety together with timetabling principles of headway and traversal times, in a unified way.

1.2 Summary of analysis

The main conclusions are as follows

- The current timetable is very close to theoretically achievable headway in the down direction and in fact, attempts to run trains slightly faster than the theoretical headway in the up direction.
- A combination of signal re-spacing and speed restrictions can result in a headway of 2.5 minutes. Even if trains are run at 3 minute frequency, the above respacing and speed restrictions can improve performance.
- As secondary outcomes, the use of a rail traffic simulation tool for analyzing suburban rail traffic was established and a system-wide study could be carried out. It permits further analysis and parametric study, for example, what happens if train characteristics are improved slightly.

2 Terminology

We begin by listing some of the major terms used in this report.

- Block or signal block is a section of track guarded by a signal.

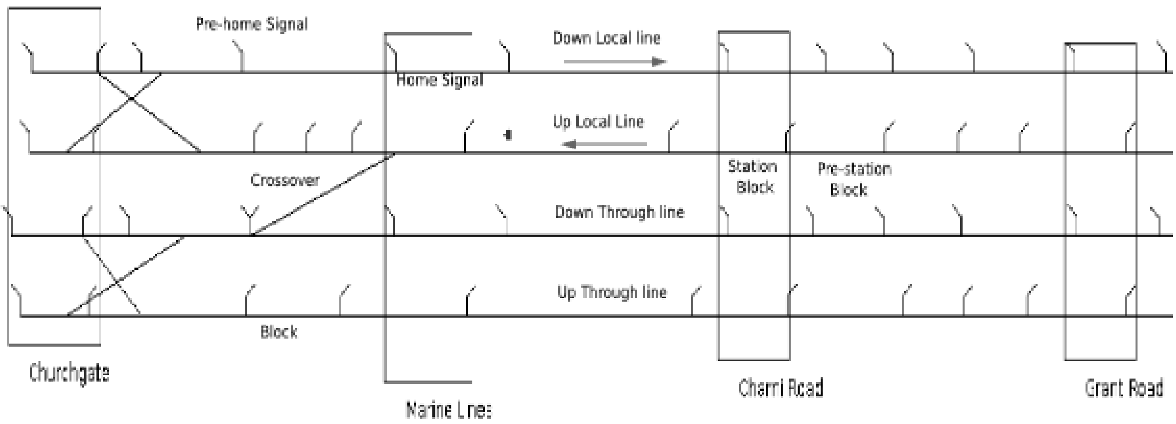

Figure 1: Section Terminology

- Station Block is a signaling block at a station, guarded by a home signal
- Pre-Station Block is the signaling block just before the station block, and is guarded by a pre-home signal.
- Starter Signal is the signal guarding the block just after a station.
- Section Headway is the time interval (frequency) at which we plan to run trains on a given corridor
- Signal Headway: The Y/YY/G headway of a signal is the time a signal takes to turn yellow/double yellow/green after a train has passed it. This is explained in more detail in section 6 below.

The schematic diagram in figure 1 illustrates all these terms.

3 Major objectives

The major objectives of the current study are the following

- To determine current achievable headway in the down and up directions on the Churchgate Borivali slow corridor and see whether the current timetable can be reliably operated.
- To see if a reduced headway along Churchgate-Borivali slow corridor is possible by addition and relocation of signals, if needed, without increasing the traversal time by much.
- To demonstrate a general methodology for signal spacing.
- To demonstrate a general purpose simulation tool for analyzing rail operations.

4 Data collected and data used in the study

Data was collected regarding the following aspects of rail infrastructure and train operations.

- Section data
  - The exact locations of signals are obtained from roll plans and measurements made by the Signaling Department.

  - The approximate locations of crossovers are got from roll plans.
  - The approximate locations of permanent speed restrictions are got from the Working Time Table.
  - The exact locations of station jurisdiction are got from roll plans.

- Rolling stock data

  - The main characteristic that we have had to use as per our best judgement is the acceleration and deceleration characteristic of the rakes on the suburban system. Values for these were obtained from the Operations and Electrical Engineering Department of WR.
  - The booked speed of 65 km is used in our analysis. The notional booked speed for timetabling is 70 kmph. We note that rakes are capable of operating even upto 105 kmph and this is in fact observed when there is a clear run available.

- Timetable and control chart data

  - The working timetable was used to understand the current practice and control charts were used to check the actual performance on a sample basis.

4.1 Rolling Stock Data

The physical operating characteristics of train running of suburban EMUs (12 car rakes) were decided on by using a variety of inputs. Western Railways provided us with one set of values (see Table 1 below).

The GPS plot obtained for a typical train run is shown in figure 2. This was repeated over more than a dozen different runs at different times of the day. Train running characteristics were inferred from these plots, averaged over several runs.

In addition, time measurements were made using actual observations at platforms, knowing the length of the platform and where the rake starts decelerating and also when it achieves full speed. These were done over many instances, including peak hour working.

We have observed by means of several measurements that the actual performance on the system is more conservative than the values given to us by Western Railways. The standard rakes that are used on the WR suburban section have a service braking of 0.28-0.3 m/s^2 and an acceleration of 0.5 m/s^2 upto 50 kmph.

The major conclusion, tabulated below in the summary table 2 below, is that the values provided by Western Railways are probably the maximum achievable values as per the manufacturer specifications and trials. What happens in practice is often more conservative and depends on rake condition, driver behaviour, weather and visibility conditions, trespassing and many other field conditions. We have chosen to work with these more conservative values for later analysis and conclusions. If the system is actually operated with the more ambitious values provided by the railways, the conclusions will actually more favourable.

Table 2 summarizes the train characteristics calculated using the GPS measurements over several runs.

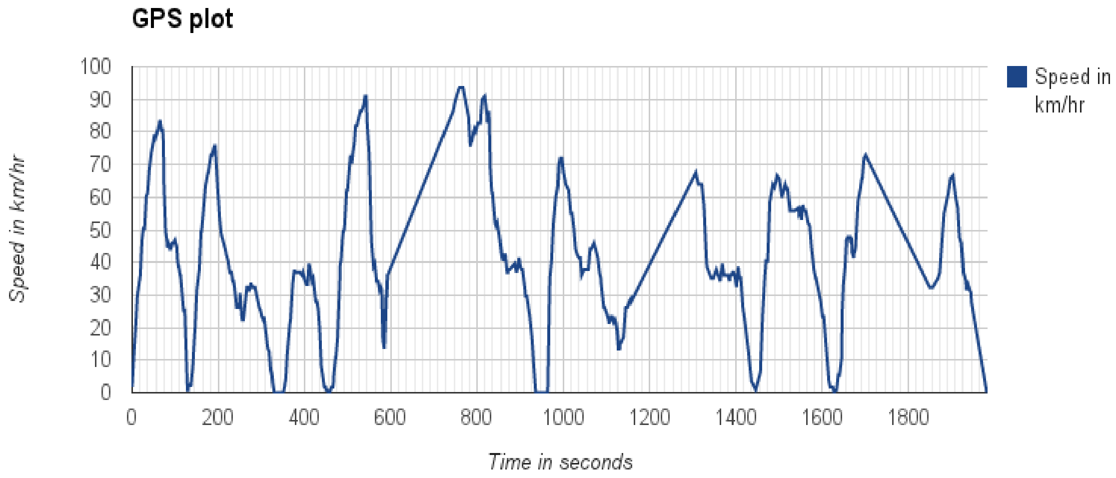

Figure 2: Speed vs Time Plot obtained from GPS measurements

Train no.	From	To	acceleration 0-50 kmph	acceleration 50-100 kmph	Deceleration
1	Dadar	Bandra	0.50	0.18	0.28
2	Bandra	Andheri	0.46	0.41	0.34
3	Andheri	Borivali	0.58	0.31	0.27
4	Borivali	Andheri	0.53	0.22	0.24

Table 1: Train characteristics calculated through GPS measurement

	Acceleration	**Deceleration**	**Speed**
Western Railway	0.54 m/s^2 for 0-50 kmph	0.84 m/s^2 for 100-50 kmph 0.76 m/s^2 for 50-0 kmph	Booked speed: 65 kmph between CCG-BVI 70 kmph between BVI-VR[1]
GPS based measurement	0.52 m/s^2 for 0-50 kmph 0.3 m/s^2 for 50-100 kmph	0.25 - 0.33 m/s^2 observed maximum	103 kmph for new rakes 81 kmph for old rakes (max observed)
Measurements on platform: 38-40 s to enter and 32-36 to leave	0.5 m/s^2 for new rakes, 0.4 m/s^2 for old rakes	0.33 m/s^2 for all rakes	
Values finally used in the study	0.5 m/s^2	0.30 m/s^2	Max speed: 65 kmph

Table 2: Summary Table for values of train characteristics

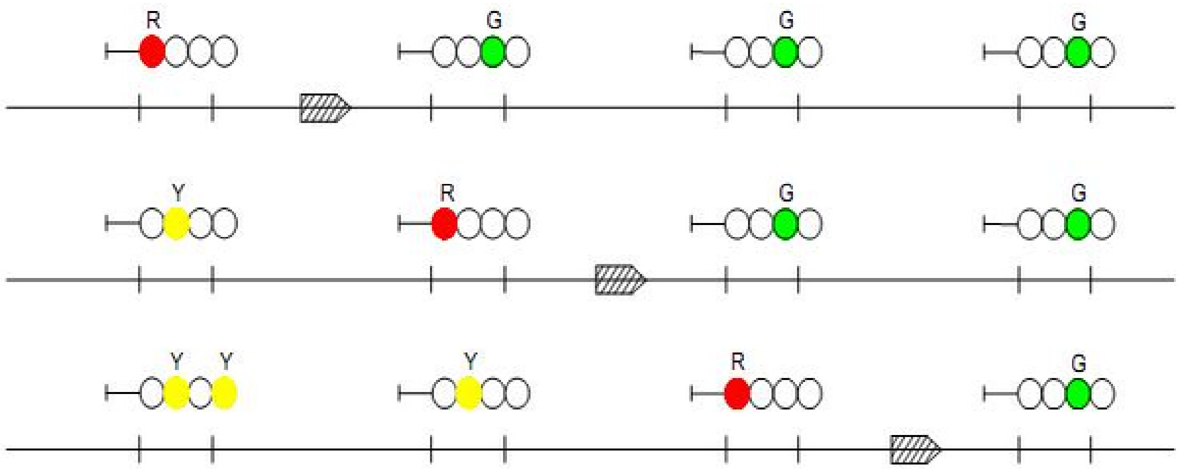

Figure 3: Operating behaviour of signals

4.2 Track data

We have taken station locations, signal block locations and track characteristics (location of speed restrictions) from various sources in Western Railway. Some of this data is available in the working timetable, some in the signaling plans of the S and T department and some in the civil engineering roll plans for the section.

4.3 Timetable data

The working timetable [1] is taken as the reference operating document.

5 Operating Rules and sectional headway

For the analysis of suburban traffic, the main operating rule is that only one train can occupy a signal block at one time. There are no planned overtakes of suburban trains.

The speed of trains on the section is guided by the use of fixed line-side signals which indicate the occupancy of block sections ahead of it.

The schematic view below demonstrates signal aspects vis a vis occupancy of block sections, for four aspect signaling. For three aspect signaling, only red, yellow and green aspects are used. The different signal aspects mean the following:

- Red aspect (R): the block ahead is occupied
- Yellow aspect (Y): only the next block is empty
- Double yellow aspect (YY) : only the next two blocks are empty
- Green aspect (G): at least the next 3 blocks are empty

The main operating rules are as follows

- Trains should not pass a red signal
- The time table and train speeds are fixed so that trains do not encounter a yellow signal by design.

- Train speed must be such that a yellow signal is not encountered, i.e. by design, trains encounter double yellow or green (in four aspect signaling) or green (in three aspect signaling).
- Yellow aspect must be entered only at 60 kmph, and the train must slow down to 38 kmph within 290 meters. This is ensured using speed restrictions and sighting distance where applicable.

5.1 Signal Headway

The schematic diagram in figure 4 shows the computation of signal headways in general. [adapted from the work of Dicembre and Ricci, see references]

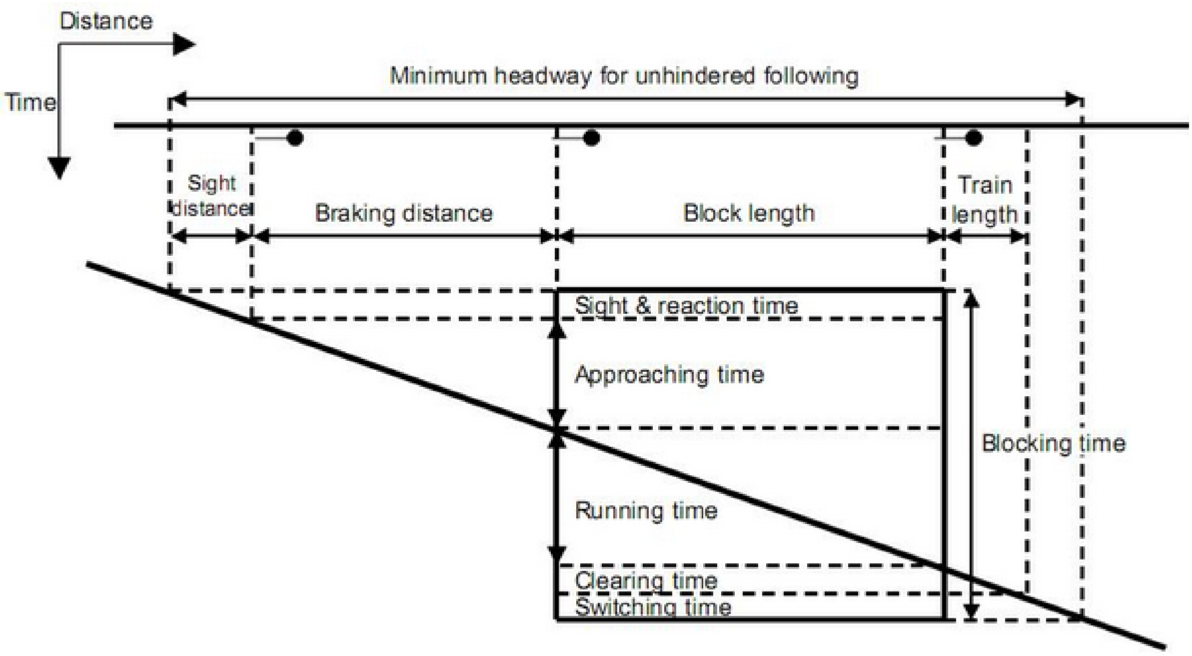

Figure 4: Headway

$H_{i,j}$ is denoted as the j^{th} signal aspect headway for the signal i. Formally,

$$\begin{aligned} H_{i,j} &= Time\ to\ cover\ sighting\ distance\ for\ signal\ i \\ &+ Time\ to\ cover\ j\ blocks\ from\ signal\ i \\ &+ Time\ to\ clear\ the\ the\ last\ block \end{aligned}$$

5.2 Section Headway

Section headway is the headway at which trains can move through the section and still maintain as fast booked speed as possible.

H_j will denote the j aspect headway by which rakes could move so that they will see at least j aspect at all but last $j-1$ signals between every pair of adjacent stations. For e.g., YY headway will denote the maximum over Y headways of home signals and YY headway of other signals.

6 Computation of Signal Headways

For a given infrastructure, the signal headway can be observed and the maximum of these on a corridor gives an indication of the achievable section headway.

The table 3 computes the time taken for each signal on the down slow corridor to turn double yellow. For home signals, we also compute the Y headway, which is the relevant number (as the train is anyway coming to a scheduled halt at the station block after a home signal).

Signal on down local line	YY Headway in minutes	Y headway in minutes, if Home signal	Signal on up local line	YY Headway in minutes	Y headway in minutes, if Home signal
S-5	2.14		S-42	1.55	
S-25	2.68		S-32	1.26	
S-45	2.63	2.1	S-22	1.41	
S-1	2.94		S-12	1.57	
A-304	2.62	2.18	A-489	2.52	
A-312	1.40		A-485	2.57	2.03
A-320	1.15		A-481	1.77	
A-324	2.40		A-477	1.58	
A-328	2.80	2.07	A-473	2.55	
S-1	2.81		A-469	2.79	2.07
S-11	2.42	2.03	A-465	1.78	
S-21	1.56		A-461	1.19	
S-31	2.87		A-459	1.31	
S-41	2.92	2.3	S-40	2.64	
S-51	2.17		S-42	2.51	2.12
S-1	2.94		A-457	1.82	
S-2	3.10	2.27	S-10	1.64	
S-3	2.36		S-26C	1.34	
A-356	2.73		A-455	1.70	
A-358	2.76	2.07	A-453	2.65	
A-360	1.94		S-	2.70	2.03
A-370	2.53		S-16	1.71	
A-372	2.75	2.04	S-61	1.37	
A-376	**3.08**		S-60	2.88	
A-378	2.58	2.16	S-59	0.10	2.44
A-380	1.41		S-48	1.78	
A-382	1.24		S-44	1.33	
A-385	2.43		S-43	1.58	
A-386	2.62	2.06	A-439	2.70	
S-51	1.59		A-433	2.72	2.04
S-390	1.43		S-21C	1.70	
S-11	2.56		A-421	1.51	
S-21	2.86	2.07	S-37	2.66	
S-51	1.87		S-36	2.60	2.06
S-71	2.76		S-33	1.66	
S-65	2.69	2.21	A-417	2.63	
A-410	1.63		A-411	2.59	2.15
A-414	2.65		S-82	1.49	
S-21	2.65	2.15	S-72	1.40	

S-24	1.49		S-62	2.46	
S-26	1.31		S-52	2.42	2.03
S-422	2.92		S-12	1.56	
A-428	3.10	2.31	A-393	1.37	
A-434	2.07		S-92	2.54	
S-26	1.62		A-387	2.63	2.14
S-27	2.43		S-42	1.58	
S-28	2.30	1.87	A-385	2.63	
S-35	1.29		A-381	2.74	2.17
S-37	1.50		**A-379**	**3.11**	
S-39	**2.96**		A-377	2.96	2.27
S-3	2.70	2.13	**A-373**	**3.35**	
S-446	1.86		A-365	3.01	2.37
S-450	1.80		A-361	1.84	
S-26A	2.09		A-357	2.55	
S-3	2.82		A-355	2.51	2.07
S-458	2.54	2.02	S-15	1.51	
S-39	1.77		S-16	2.91	
S-49	1.79		S-42	3.33	2.38
A-464	**2.95**		S-32	3.04	
A-468	2.70	2.18	**S-22**	**3.72**	
A-472	1.72		S-12	2.90	2.33
A-476	1.61		S-2	2.93	
A-480	2.76		A-333	2.47	2.09
A-482	2.66	2.15	A-329	1.28	
A-486	1.55		A-325	1.48	
S-11	1.23		A-321	2.69	
S-494	3.43		A-313	2.65	2.04
S-21	3.61	2.94	S-10	2.90	
			S-9	2.59	2.17
			S-58	1.52	
			S38	1.44	
			S-28	1.85	

Table 3: Headways for all signals [1]

In addition to the values obtained through simulation, 8 seconds has been added as a margin to account for sighting distance for signals other than starter and home signals and to account for reaction time for starter signals. These assumptions are discussed in a little more detail in 13.

Since, G headway for any signal additionally includes traversal time for another block, G headway will be greater than YY headway of the signal. Given that the YY headways of most of the signals are very close to 3 minute and YY headways of some signals are over 3 minutes, G headway will be greater than 3 minutes for most signals. At the same time, because the inter-stations distances are small and trains have to halt at all stations on slow corridors, the rakes will not be able to reach the high enough speeds on G headway protocol to achieve a substantial gain in the traversal times. Hence, G headway of the system will reduce the throughput of the system considerably. So, we have limited our analysis to YY headway only.

[1] Both Y headway and YY headway is computed for the home signals. The top 3 headways for signals that are not home signals are highlighted for the down and up local lines.

Down Local Line			Up Local Line		
Signal	**Location**	**YY Headway in minutes**	**Signal**	**Location**	**YY Headway in minutes**
A-376	Starter signal at DDR	3.03	S-22	Pre-home signal at BCL	3.67
S-39	Pre-home signal at JOS	2.91	A-373	Starter signal at DDR	3.30
A-464	Pre-home signal at MDD	2.90	A-379	Starter signal at MTR	3.06

Table 4: Bottleneck Sections

7 Numerical simulation

A rail simulator developed at IIT Bombay over many years was used for analyzing the CCG BVI slow corridor. The simulator was used for (a) numerically computing signal headways - by running a single train on the given infrastructure, as well as (b) the section headway - by running a group of trains at the proposed frequency.

The IIT Bombay simulator was validated using a variety of measurements and observations. For example, the interstation running times were compared with that of the working timetable and the results are shown in table 5 and table 6.

7.1 Inter-station running times - simulation vs timetabled

Stations	Timetable Inter-station running time MM:SS	Simulation Inter-station running Time MM:SS	Difference MM:SS
Churchgate			
Marine Lines	3:00	2:45	0:15
Charni Road	2:30	2:06	0:24
Grant Road	2:30	2:29	0:01
Bombay Central	2:00	1:58	0:02
Mahalakshmi	3:00	2:33	0:27
Lower Parel	3:00	2:45	0:15
Elphinstone road	3:00	3:04	-0:04
Dadar	2:00	2:34	-0:34
Matunga Road	2:30	2:14	0:16
Mahim	3:00	2:32	0:28
Bandra	3:30	2:51	0:39
Khar Road	3:00	2:50	0:10
Santacruz	2:30	2:29	0:01
Vile Parle	3:00	3:07	-0:07
Andheri	4:30	3:13	1:17
Jogeshwari	3:30	2:58	0:32
Goregaon	4:30	4:05	0:25
Malad	4:00	3:26	0:34
Kandivali	3:00	3:11	-0:11
Borivali	5:00	3:42	1:18

Table 5: Inter-station running times on down local line - simulation vs timetabled

Note : Section times are rounded off to half a minute in the Working Time Table. Section times before Bandra, Andheri and Borivali include some terminal slack in the working timetable.

Stations	Timetable Inter-station running time MM:SS	Simulation Inter-station running Time MM:SS	Difference MM:SS
Borivali	-	-	-
Kandivali	5:00	3:44	1:16
Malad	3:00	3:02	-0:02
Goregaon	3:30	3:27	0:03
Jogeshwari	4:30	4:04	0:26
Andheri	4:00	2:56	1:04
Vile Parle	3:30	3:31	-0:01
Santacruz	3:00	3:04	-0:04
Khar Road	2:30	2:32	-0:02
Bandra	4:00	2:39	1:21
Mahim	3:00	2:48	0:12
Matunga Road	3:00	2:28	0:32
Dadar	4:00	2:16	1:44
Elphinstone road	2:00	2:31	-0:31
Lower Parel	3:00	2:33	0:27
Mahalakshmi	3:00	2:42	0:18
Bombay Central	3:00	3:26	-0:26
Grant Road	2:00	2:05	-0:05
Charni Road	2:30	2:40	-0:10
Marine Lines	2:30	1:57	0:33
Churchgate	4:00	2:30	1:30

Table 6: Inter-station running times on up local line - simulation vs timetabled

Note : Section times are rounded off to half a minute in the Working Time Table. Section times before Bandra, Andheri and Borivali include some terminal slack in the working timetable.

8 Signal spacing

One of the major objectives of the exercise was to propose signal spacing to achieve the goals of improved headways and more reliable timetables.

8.1 Notation

- v_b : Booked speed of rakes is the speed assumed for timetabling various operations of rakes.
- $S_{standardBlock}$: Standard block length.
- $S_{minBlock}$: Minimum length of a block.
- $S_{maxBlock}$: Maximum length of a block.
- v_{aws} : AWS speed of the train is the speed of the train allowed by the auxiliary warning system (AWS) when a train enters a block section on yellow aspect.

8.2 Standard Block Length

The major consideration for the standard size of a signaling block is that the train should be able to come to a halt at the end of a block, if it enters with a yellow signal. We would also check that two consecutive blocks should be long enough that the train should come to a halt when it enters the block on a double yellow signal (in four aspect signaling) or a green signal (in two aspect signaling). This depends on the permissible speeds which the train can have which are taken to be 60 kmph for yellow entry and maximum speed for other signal aspects. Some possible rules for standard size of blocks are listed below

- From figure 5 on page 13 of AWS manual[2],
  $Block\ Size \geq emergency\ braking\ distance$
- $Block\ Size \geq servicebrakingdistance$
- $Block\ size + sighting\ distance \geq service\ braking\ distance$

We chose the following conditions, for speeds of 65 kmph, and deceleration parameter of 0.3 m/s^2:

$$S_{standardBlock} + sighting\ distance = service\ braking\ distance + reaction\ distance \quad (1)$$

$$v_{max}^2 = 2 * emergency\ braking * S_{standardBlock} \quad (2)$$

The plot of graphs using the emergency braking and service braking principles is shown in figure 5. Braking distance is directly proportional to square of initial velocity of rake. But, since the service braking is smaller than emergency braking, so the service braking distance is greater than the emergency braking distance. In figure 5, standard block length (thick curve) is taken as the maximum of service braking distance minus the sighting distance (dashed curve) and the emergency braking distance (dotted curve).

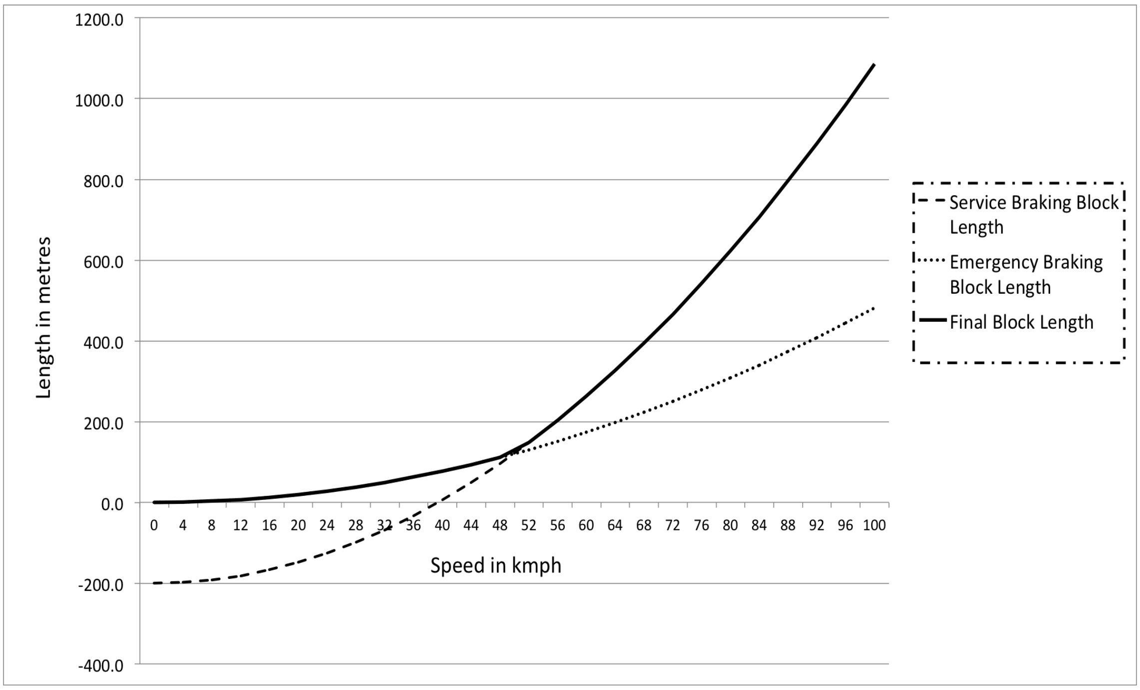

Figure 5: Standard Block Length vs Speed

Using these principles, the standard block size is 400 m, for normal running of trains at the desired speed.

For the station block, an additional principle is used to determine the block length because a train will be occupying the station block for the maximum amount of time. The principle is as follows

$$S_{stationBlock} = Train\ length + overlap\ distance \tag{3}$$

The length of a rake used in Western Railways is approximately 258 m for a 12 car rake and 310 m for 15 car rake and the overlap distance is generally taken to be 120 m. Hence, the block size calculated by this principle comes out to be 378 m for 12 car rake and 430 m for 15 car rake. However, currently only 12 car rakes are used on the slow corridor. Therefore, the station block size is taken to be 400 m which is same as standard block size.

Some other considerations are as follows.

- The AWS (Auxiliary Warning System) manual specifies that inter-signal spacing should be 400 m. This agrees with the parameter set max speed = 90 kmph and emergency braking = 0.8 m/s^2 and the train being able to come to a halt in one block, if required.
- We can also keep the block length lower, $S_{minBlock}$, about 300 m, but then
  - speed limit of 57.6 kmph should be imposed. Refer equation 6
  - YY headway : 2 min 15 s

  If this is done, the consequence are as follows.
  - The CCG-BVI traversal time will become 64 min. Even so, it is less than the currently timetabled time
  - This requires additional equipments like reduced braking magnets on some sections. This already exists in the current infrastructure.

The given parameters are AWS speed, emergency braking, service braking, acceleration, maximum speed, sighting distance, reaction time and minimum separation of rakes. The derived variables are overlap distance, standard block length, booked speed, velocity profile of the rakes and the signal headways.

8.3 Equations

From the AWS manual [2],

$$\begin{aligned}\text{overlap distance} = &\frac{(AWS\ speed)^2}{2 * emergency\ braking} \\ &+ minimum\ rake\ separation\end{aligned} \tag{4}$$

We calculate booked speed using the following quadratic equation.

$$v_{booked}^2 - v_{booked} * reaction\ time\ = S_{standardBlock} + sighting\ distance \tag{5}$$

From acceleration (given), service braking (given) and v_{booked} (calculated), we determine the velocity profile. From velocity profile, we determine the signal headways.

Sometimes, shorter blocks will be needed to be used because of short-inter station distance. A speed limit would be required to impose on those blocks given by following equation.

$$v_{limit}^2 - v_{limit} * reaction\ time\ = S_{shortBlock} + sighting\ distance \tag{6}$$

8.4 Signal spacing principles

Based on the above discussion, and using the parameters a = 0.5 m/s^2, d = 0.3 m/s^2, speed = 65 kmph, we arrive at the following guidelines for signal spacing.

- The station block should be 400 m long - note that this section involves both acceleration and deceleration.
- The pre-station block should be 400 m long - note that this section involves a deceleration.

We, now, provide a method for signal spacing (assuming no speed restrictions).

We chose maximum block size $S_{maxBlock} = 800$ m. If block size is greater than 800 m, in case of delays, the system's punctuality is affected and can lead to cascading delays. Longer blocks would require additional use of equipments like advanced track magnets. Use of advanced track magnets for blocks longer than 700 m is mentioned in the AWS manual [2]. Also, if first two blocks are of size 800 m and 800 m, YY headway of the starter signal comes out to be 145 s. Use of blocks of sizes 850 m and 850 m will increase the headway beyond desired 2.5 minute headway (150 s).

So, here is how to achieve signal spacing for desired headway. Let S be the inter-station distance.

Case 1: Inter-station distance greater than 1200 m ($S \geq 1200$)

Station block and pre-station block will be of length 400 m. Remaining available distance is $S - 800$. This distance will require at least $\frac{S-800}{S_{maxBlock}}$ blocks. Number of blocks cannot contain a fraction. So the remaining distance will need to be covered by $\lceil \frac{S-800}{S_{maxBlock}} \rceil$ where $\lceil x \rceil$ represents ceiling function where x is rounded to integer just greater than x.

Let $M = \lceil \frac{S-800}{S_{maxBlock}} \rceil$.

Thus, there will be $M + 2$ blocks. The station block and pre-station block should be of 400 m each and the remaining M blocks should be of length $\frac{S-800}{M}$ for the remaining inter-station distance.

For example, if S = 1700. Then $M = \lceil \frac{1700-800}{800} \rceil = \lceil \frac{900}{800} \rceil = 2$, and $\frac{S-800}{M} = \frac{1700-800}{2} = 450$. Thus, there will be 4 blocks of lengths 450, 450, 400 and 400 m.

Case 2: Inter-station distance less than 1200 m but greater than 960 m ($960 \leq S \leq 1200$)

Construct 1 block of size 320 m and 2 blocks (station and pre-station block) of size $\frac{S-320}{2}$ each and a speed restriction of at least 57.6 kmph should be imposed. As the block lengths increase, the speed restriction value will also increase. We should note that we could have created 3 blocks of size $\frac{S}{3}$ as well. But, this leads to smaller station block requiring lower speed restriction value which will increases the traversal time required.

Case 3: Inter-station distance less than 960 m but greater than 800 m ($800 \leq S \leq 960$)

Construct 2 blocks of size $S/2$. The Y headway of starter and home signal will be less than 2.5 minutes as desired. We cannot split this region into 3 blocks. Note that when the inter-station distance can contain only two blocks, the pre-home signal and starter signal are the same. Hence, no matter where we place the home signal (with block size restrictions holding true), the system headway may be governed by the headway of this pre-home signal. The reason being, YY headway calculation of this pre-home signal will also include the additional acceleration profile of the rake.

A general procedure for doing this for any set of values of acceleration, deceleration, signal aspects and inter station distances can be developed. This is part of the academic work that is being done in this area at IIT Bombay.

9 Performance analysis

We give below the performance of the CCG-BVI section for different operating parameters, in particular, minimum lengths of blocks and different acceleration deceleration combinations.

9.1 Performance metrics for different block lengths

The table below gives the impact of minimum block size on the headway and also the traversal time on the CCG-BVI section. We note that smaller block lengths will involve speed restrictions for safe operation, and will lead to (small) increases in traversal times.

Block Lengths in metres	**Max speed in kmph**	**YY headway in minutes**	**CCG-BVI Traversal time in minutes**
300	57.6	2:16	60
400	65	2:30	58
500	68.4	2:39	57
600	75.6	2:44	56

Table 7: Headway and traversal time vs block lengths

9.2 Performance metrics for different train characteristics

The table below gives the impact of different acceleration and deceleration characteristics on the achievable YY headway and traversal time on the CCG-BVI section. The impact on achievable headways and traversal time is significant.

The values of 0.5 m/s^2 for acceleration and 0.8 m/s^2 for deceleration actually lead to potential instability (growth of delays) against minor disturbances. This is not analysed further in this report, but is studied separately as part of this project.

Acceleration (in m/s^2)	**Deceleration (in m/s^2)**	**Maximum Speed (in kmph)**	**Headway (in minutes)**	**CCG-BVI traversal time (in minutes)**
0.5	0.3	65	2:30	57
0.5	0.4	72	2:15	54
0.5	0.5	83.8	2:10	50
0.6	0.6	90	2:00	47

Table 8: Headway, maximum speed and traversal time vs acceleration and deceleration

10 Move towards a 2.5 minute headway

Using the principles above, we propose that on the up and down local lines, some number of inter station sections be modified and some signals added, which will achieve a target headway of 2.5 minutes. The complete list comes at the end of this section, but we provide the logic for this with the examples below.

10.1 Illustrative actions

We list three examples of what needs to be done on critical sections in the up and down directions and provide the details of the analysis.

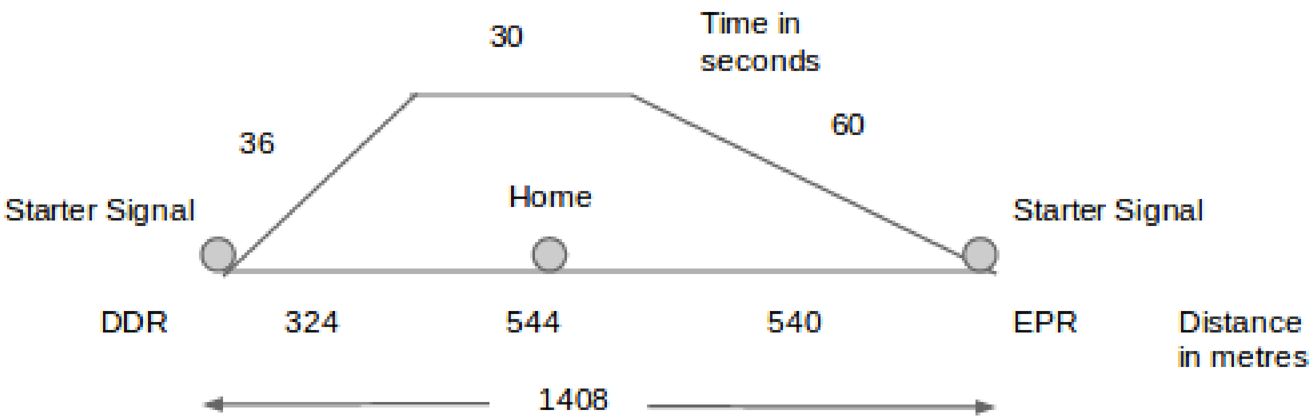

Figure 6: Train profile along up local line between Dadar-Elphinstone Road

Case 1: Up local line on the Dadar (DDR) - Elphinstone Road (EPR) section (refer figure 6)
$Traversal\ time = 36 + 30 + 60 = 126\ s$
$Halt\ time + clearing\ time = 25 + 40 = 65\ s$
$YY\ headway\ (starter\ signal\ DDR) = 126 + 65 = 191\ s = 3.20 min$

We are looking at train traversal from DDR to EPR. The home signal in figure 6 is Elphinstone Road home signal. The current YY headway for starter signal at DDR as computed above is 3.20 min. Instead, if we have three blocks of size 608, 400 and 400 m, we get YY headway of starter signal as 126 s (traversal time between DDR-EPR) and YY headway of pre-home signal as 147 s. We similar top bottleneck sections at starter signal of MTR on up local line and starter signal of DDR on down local line.

Case 2: Down local line on the Lower Parel (LP) - Elphinstone Road (EPR) section

The starter signal at LP is 2-aspect because it is guarding a block of length 525 m having speed restriction 30 kmph. Inter-station distance between LP and EPR is 1485 m. So, the remaining distance after speed restriction to EPR station is 960 m. Since, the LP starter signal is 2-aspect, extending the starter block section to 685 m, will force to run trains at lower speed for longer distance which is not desirable. And, having station and pre-station blocks of 480 m each will make YY headway go above desired 2.5 minutes headway. Hence, 4 blocks of size, 525, 320, 320, 320 m respectively and a speed restriction of 57.6 kmph helps achieve desired headway.

Case 3: Up local line on the Goregaon (GMN) - Malad (MDD) section

The YY-headway of pre-home signal on down local line at MDD has a YY headway of 2.99 minutes. This is because of long pre-station block and station block of 720 m and 583 m. Changing the lengths of these blocks to 400 m and 400 m will give a YY headway of 147 s. Other blocks can be adjusted accordingly.
Building on these case studies, the table below has suggested signal spacings between all stations on the CCG-BVI slow corridor.

Station 1	**Station 2**	**New Block Lengths in meters**	**Speed Restrictions for shorter blocks**
CCG	MEL	437, 400, 400	
MEL	CYR	323, 320, 320	57.6 kmph
CYR	GTR	571, 400, 400	
GTR	BCL	422, 400	
BCL	LP	646, 400, 400	
LP	EPR	525, 322, 320, 320	57.6 kmph
EPR	DDR	666, 400, 400	
DDR	MTR	400, 311, 400	57.6 kmph
MTR	MM	633, 400, 400	
MM	BA	572, 400, 400, 400	
BA	KHR	400, 397, 380, 380	
KHR	STC	581, 400, 400	
STC	VLP	632, 400, 400	
VLP	ADH	567, 400, 400, 400, 400	
ADH	JOS	600, 500, 400, 400	
JOS	GMN	600, 600, 600, 516, 400, 400	
GMN	MDD	604, 600, 400, 400, 400	
MDD	KILE	538, 400, 400, 400, 400	
KILE	BVI	500, 500, 490, 400, 400, 400	

Table 9: Suggested block lengths on slow corridor

Note : The above table describes the ideal block lengths without considering any other constraints. The block lengths for the up local line will be the same as those along the down local line, but in the reverse order.

11 Delay Analysis

We would like the timetable to be able to recover from minor disturbances. A small disruption that affects one train should not (a) affect too many other trains and (b) should not cause more and more delay to subsequent trains.

11.1 Control chart analysis

- From the control chart we can see trains which are 3 minutes apart according to the timetable, and also trains which are just 2 minutes apart because of one of the trains being late, in these cases it can be seen that the subsequent trains are also delayed by even more time. No sign of delay explosion can be seen in the control charts, all though a delay in one train causing several other trains to be delayed can be seen but is not amplified.

- The exact reason for delays can not be inferred from the control charts, since the source of delay in the control charts can be AWS failure, terminal movements or extra time spent on a platform etc. but on simulation of some trains from the charts that are being late, easily schedules the trains without any delay.
- There are some errors in the control charts that we observed. For example trains are always making up time of 1-6 minutes from KILE to BVI which is not possible. In the down direction most trains gain delay between Bandra and Andheri, the reason can be the through to local or vice versa movements. Trains are normally making time between Andheri and Borivali.
- Between CCG and BCT the trains are on average gaining delay of 1-3 minutes and the delay is maintained or reduced till Bandra. This strengthens our belief that MEL-CYR is one of the bottleneck sections.

12 Utility of the work

There are two possible courses of action for Western Railway, which are suggested through our analysis

- Reduce headway to 2.5 min, run more trains
  - This is achieved by adding and/or respacing a few signals and putting a few additional speed restrictions on a few sections.
- Run at 3 minute timetable headway, but improve robustness by reducing system headway to 2.5 min or so
  - Currently, the operation of trains close to the section headway leads to slow running of trains. This necessitates a bigger slack in traversal time, and leads to inefficient operations.

13 Additional points

In a presentation regarding the study, the following points were raised.

- **Neutral section** The present scheme forbids locating a signal 350 m before and a 270 m after of a neutral section. This makes it a total signal block of 620 m which if it is a station or a pre-home block, with a limit of 400m, affects the headway of the section. This calls for a review of the locations of the neutral section. For example, despite a neutral section between DDR-EPR, there exist 3 blocks along the down local line. But, there exist only 2 blocks along the up local line which lead to YY headway of more than 3 minutes.
- **Terminal effects at Borivali, Andheri and Bandra:** At Borivali and Andheri, terminal effects are likely to be significant. This needs more detailed study. The effect also depends on the turnaround times planned at these terminals as well as the scheduling strategy at the terminals, especially in case of late running. An observation is that small delays in through trains at Borivali are often amplified because of trying to preserve the order of trains departing at Borivali.
- **MRVC simulator:** MRVC is likely to use a simulator for its own analysis and this can be compared with our analysis, if the opportunity arises.

- **15 car rakes:** Headway of 2.5 minutes is still possible, but station blocks now need to be 430 m long.
- **Variety in rolling stock:** Different types of rolling stock are used by Western Railway on its suburban services. Till standardization is achieved, it is recommended to use conservative values for timetabling.
- **Sighting distance:** Sighting distance is taken into account in the definition of headway. It is not relevant in station blocks as the train is stationary and in sight of the starter signal anyway.
- **Reaction times:** Reaction time is relevant in starter signals (i.e. station blocks) and for yellow and red, it is not that relevant as the motorman is already warned of this (by the previous signal). In summary, one of (a) sighting distance and (b) reaction time is relevant for all signals, and a time of 8 seconds is added to the headway to account for this.
- **Age of rakes:** The older rakes take 7-9 seconds more than the newer rakes to decelerate and accelerate at every station. This becomes very crucial to headway calculations on the slow corridor. Further, the old rake takes 3 minutes more than new rake in terms of traversal time between CCG and BVI. This results in 6 minute increase in round trip time, and since the headway is 3 minutes, 2 more rakes need to be used in the CCG-BVI pattern. Using the newer and faster rakes on slow corridor and older and slower rakes on the fast corridor can help in maintaining lower YY headway on the slow corridor.

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