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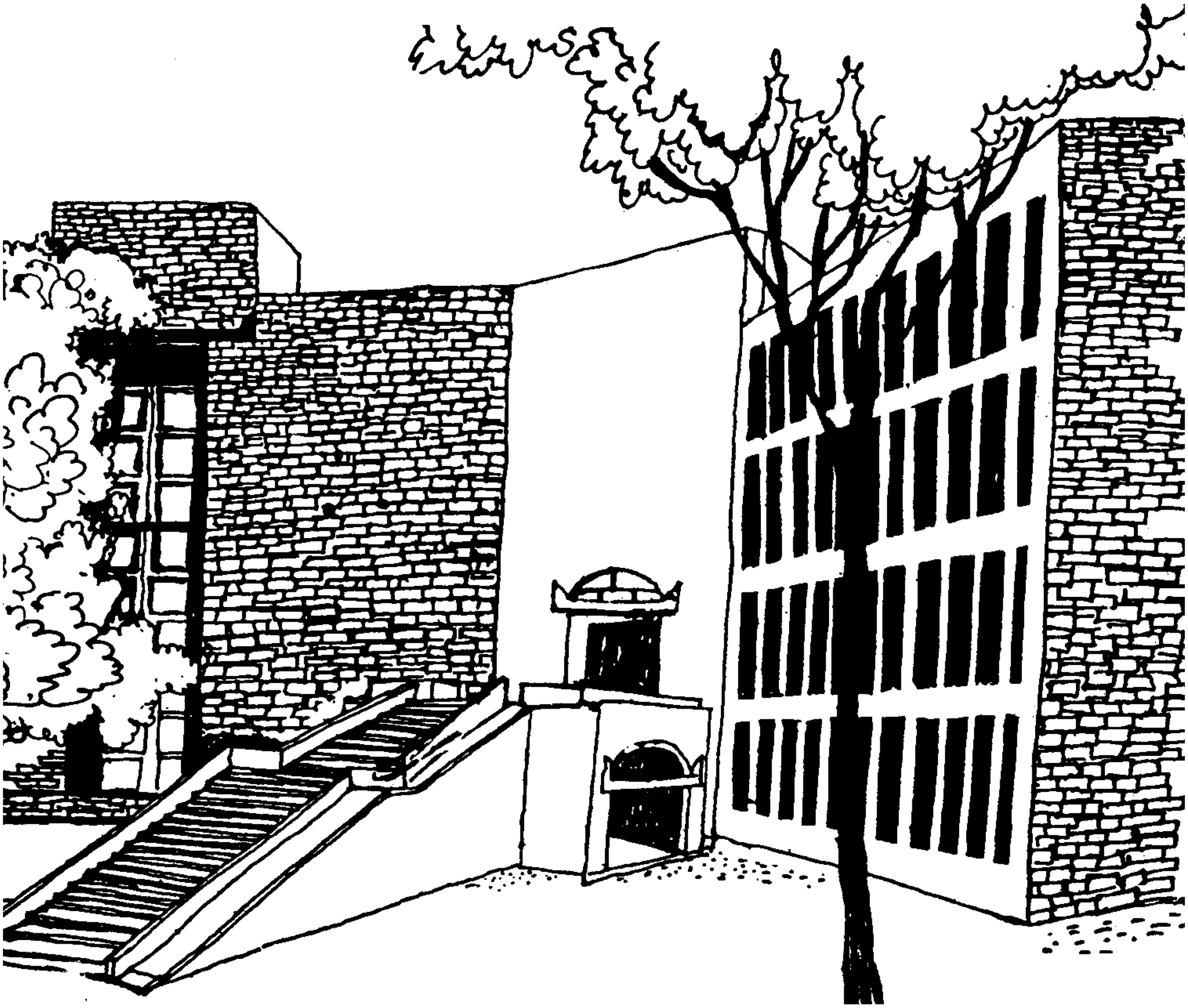

SIMULATION MODELS TO EVALUATE RAILWAY OPERATING POLICIES

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Abstract

In this paper, we describe two applications of simulation models to evaluate the following railway operating policies: 1. Loco assignment at a junction, and 2. Twin single line versus orthodox double line operation. The models are developed as a part of a project for improving resource utilization in a zonal railway of the Indian Railways.

Loco assignment at a junction: At a junction, a large number of iron ore trains go loaded in one direction and return empty in the other. These trains form a major proportion of a stream of trains, consisting of a few non-iron trains also. For this stream, the track on one side of the junction is electrified while the other side is not. Diesel traction is used on the non-electrified side, with double heading in the loaded direction, (which is towards the junction for iron ore trains), and single heading in the empty direction, (away from the junction for iron ore trains). This creates a surplus of diesel locos at the junction, which are sent light for other uses. The simulation model evaluates the rules for assignment of locos for light running.

The operating rule considered is for how much time an incoming diesel loco should wait for being assigned to a train. If no train is expected within the stipulated time, the loco is sent light. The criterion used for evaluating different values of the above parameter is the minimization of the total waiting costs of locos and trains. This is derived by first computing the waiting time incurred by all locos and trains, and then finding the weighted sum by using relative weights of loco and train waiting costs.

Twin single line versus orthodox double line operation: A 43 km, orthodox double line section of a busy main line, apart from catering to through traffic, has five originating/terminating stations for coal and cement movements. These movements further necessitate empty train movements, light engine movements, and movements for maintenance. Some of the facilities such as coal loading points and wagon maintenance depot are so located that the trains accessing these facilities cause cross movements, resulting in detention. A suggested solution to this problem is to convert the section to a twin single line operation, which provides flexibility in scheduling cross movements. An added advantage of twin single line operation could be in better utilization of track capacity during a period when there are successive trains in the same direction.

Since, the above proposal involves high capital investment, it is essential to evaluate the effect of the proposed conversion on line capacity and average section travel time. For this, an existing simulation model, developed to measure line capacity on a different section, is being extended. The paper summarizes the existing model and its extension.

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INTRODUCTION

The South Central Railway (SCR), located in the south central part of India, is one of the nine zonal railways of the Indian Railway system. The SCR has a route length of approximately 7,200 kms, amounting to 11.4% of the total route kms of the Indian Railways. The originating freight traffic handled by SCR is about ten percent of the total amount handled by the Indian Railways. Three commodities, coal, export iron ore, and cement account for 75% of the total originating freight traffic in SCR. Of the total commoditywise originating traffic in the Indian Railways, SCR handles 10% of coal, 45% of export iron ore, and 14% of cement. As these three commodities are carried over only 30% of the SCR route length, the corresponding sections are highly congested. Further, the demand for transport of these commodities over SCR is expected to grow significantly. In this context, identification of bottlenecks and improvements in resource utilization are important.

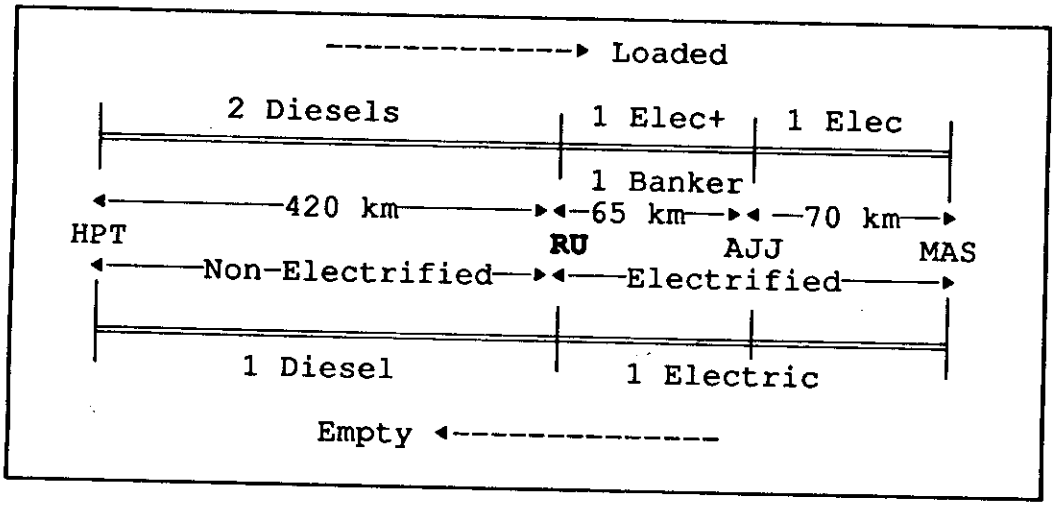
After an analysis of commoditywise traffic streams, we identified various bottlenecks [1]. Suggestions were made to improve some of the bottlenecks based on a simple cost benefit analysis of alternatives. For other bottlenecks, where the variables were many, and the nature of interaction complex, simulation models were used for the analysis. In this paper, we describe two of these simulation models. The first is a loco assignment model which deals with interaction between locos and freight trains at a junction in the iron ore circuit, the problem being to estimate the detention of locos and trains under various operating policies. The second deals with interaction between track and station layout and train movements in a section where the coal and cement traffic originate, the problem being to measure line capacity and average travel time for two systems of operation. These two systems are twin single line operation and orthodox double line operation. The need for simulation in both these situations is accentuated by the fact that the train arrivals into the system of interest are uncertain.

1. LOCO ASSIGNMENT MODEL

1.1. Context Description

Iron ore is transported from mines in Hospet (HPT) area to Madras (MAS) port for export [2]. The annual export is about 7 million tons, which is carried through six trains daily in a closed circuit movement. There are six loading points in the HPT area. Figure 1 shows a line diagram of this circuit. A train weighs 1300 tons while empty, with a carrying capacity of 3400 tons of iron ore. The distance between HPT and MAS is 555 kms, split as 420 kms of non-electrified track between HPT and Renigunta (RU), and 135 kms of electrified track between RU and MAS.

Figure 1
Iron Ore Circuit



Loaded trains move to RU from HPT area with two diesel locos. After changing the traction to electric at RU, one electric loco and a banker loco haul the train till Arakkonam (AJJ) over a 65 km graded section, after which the train proceeds to MAS without the banker. The banker itself returns light to RU. After unloading at MAS, the empty train returns with a single electric loco to RU, after which a single diesel loco hauls the train to loading points.

Under the above scheme of loco usage, a surplus of diesel locos is built up at RU. These are sent light to the loading points, usually performing other tasks such as shunting on the way. Sometimes, an empty train is hauled by two diesel locos, whenever the departure time of the train is convenient for return of a surplus loco.

Loco related decisions at RU have a significant impact on the performance of the iron ore circuit. Three important decision areas are:

1. Whether to run the loaded and empty trains on the RU-MAS section with diesel locos so that detention due to traction change at RU is avoided.
2. Whether to run each empty train with two diesel locos to reduce the train detention incurred in waiting for a second loco at loading points.
3. Under the current situation of diesel loco surplus at RU, what should be the maximum permissible waiting time (MAXWAIT) for a diesel loco to be used with a train leaving RU towards HPT; that is, if the waiting time is expected to exceed MAXWAIT, then the loco is sent light.

The simulation model described in this section deals with the third decision area.

MAXWAIT is determined by the trade off between the loco detention cost and train detention cost. This decision is also influenced by the non-iron ore trains running on the same non-electrified section to and from RU. Table 1 gives a summary of the train and diesel loco movements on the non-electrified section to and from RU over a ten day period.

Table 1
Summary of Movements

Type of movement	TO RU		FROM RU	
	No. of movements	No. of locos	No. of movements	No. of locos
Loaded iron ore needing 2 locos	55	110	0	0
Empty iron ore using 1 loco	0	0	45	45
Empty iron ore using 2 locos	0	0	6	12
Non iron ore needing 1 loco	55	55	45	45
Non iron ore needing 2 locos	4	8	19	38
Light single loco	8	8	5	5
Light double loco	0	0	5	10
Total	123	181	125	155

Notes:
1. The total number of loaded and empty iron ore trains do not match since data is for a ten day period.
2. Six empty iron ore trains use a double loco just to facilitate light movements.
3. The loco movements to and from RU do not match, since some of the light movements from RU take place into the electrified section.

As can be derived from the above table, the percentage of non-iron ore trains towards RU is 52, and from RU is 56. Hence the loco assignment model considers the loco requirements of both these types of trains.

1.2. Model Description

1.2.1. Inputs

1. Arrival times of trains at RU from the non-electrified side, along with the number of locos per train. This defines the supply pattern of diesel locos.
2. Arrival times of trains at RU from the electrified side, to continue their journey into the non-electrified side, along with the number of locos per train. This defines the demand pattern of diesel locos.
3. The costs of train waiting and loco waiting. These depend on the investment costs as well as the opportunity costs of detention. While the investment costs are readily available, the opportunity costs are difficult to measure. In this model, we parameterize the relative train waiting costs, by considering the cost of waiting time of a single loco as one unit. For this purpose, the trains from RU are classified as follows: (a) iron ore empty trains, (b) non-iron ore trains needing two locos, and (c) non-iron ore trains needing one loco. The investment costs of trains in (a) and (b) categories being close to each other, their costs of waiting are treated as equal. The cost of waiting of trains in category (c) is estimated to be 90% of the other two categories, based on the investment costs.

1.2.2. Decision Rule

The criterion to determine MAXWAIT is the sum of the costs of loco waiting and train waiting. We find the optimum MAXWAIT by evaluating different values of MAXWAIT within a specified range.

For a given value of MAXWAIT, the costs of detention are evaluated as follows: The locos and the trains are maintained as separate lists, each sorted in the ascending order of arrival time. Initially, none of the trains have loco(s) assigned to them. The model considers each loco from the list successively to decide if it is to run light; if not, the detention of the loco and the detention of the train to which it is assigned are computed. The pseudocode for this procedure is given in Table 2.

The procedure assigns locos to trains needing a double head only if both the locos satisfy the MAXWAIT criterion. This is captured in the *italicised* statement of the pseudo code:

```
IF TDTF-LATC ≤ MAXWAIT THEN
```

Under a modified procedure, locos are assigned to trains needing a double head even if just the second loco satisfies the MAXWAIT criterion. The modified pseudo code is the same, but for the above statement. The modified statement is:

```
IF TDTF-LATN ≤ MAXWAIT THEN
```

We refer to the first procedure as LATC rule and the modified procedure as LATN rule.

Table 2
Pseudocode for Computing Detention

```
Let LATC be the arrival time of C, the loco under consideration
Let LATN be the arrival time of N, the next loco
( If the loco under consideration arrives into RU as the lead loco of a double headed train, then LATC = LATN)
Let Q be the queue of trains which do not have the required number of locos completely assigned
Let TATF be the arrival time of the first train, F, in Q
Let TATS be the arrival time of the first train, S, in Q which requires to go as a single headed train.
Let TDTF be the departure time of train F, if C were to be assigned to F
Let TDTS be the departure time of train S, if C were to be assigned to S

IF  F has to leave RU as a single headed train THEN
    TDTF <-- max(LATC, TATF)
    IF TDTF-LATC ≤ MAXWAIT THEN
        assign C to F
        detention of C <-- TDTF-LATC
        detention of F <-- TDTF-TATF
    ELSE
        assign C to light running
        detention of C <-- 0
    END IF
ELSE
    IF F has no loco assigned to it THEN
        TDTF <-- max(LATN, TATF)
        IF TDTF-LATC ≤ MAXWAIT THEN
            assign C to F
            detention of C <-- TDTF-LATC
            detention of F <-- TDTF-TATF
        ELSE
            TDTS <-- max(LATC, TATS)
            IF TDTS-LATC ≤ MAXWAIT THEN
                assign C to S
                detention of C <-- TDTS-LATC
                detention of S <-- TDTS-TATS
            ELSE
                assign C to light running
                detention of C <-- 0
            END IF
        END IF
    ELSE
        TDTF <-- max(LATC, TATF)
        detention of C <-- TDTF-LATC
    END IF
END IF
```

1.3. Results

The simulation was run with actual arrival data of trains over the ten day period mentioned above, for values of MAXWAIT ranging from zero to ten hours. The average detention of trains and locos obtained, along with those for the existing assignments are given in Table 3.

Table 3
Average Detention (Hrs) to Trains and Locos

	Train (Single head)		Train (Double head)		Loco	
Existing assignment	4.23		5.28		2.00	
MAXWAIT (Hrs)	LATC Rule	LATN Rule	LATC Rule	LATN Rule	LATC Rule	LATN Rule
0	4.22	4.43	6.85	4.95	0.00	0.23
1	3.00	3.10	4.32	3.33	0.12	0.22
2	1.82	1.68	2.25	1.70	0.30	0.40
3	1.35	1.35	1.30	1.30	0.62	0.63
4	1.05	0.82	1.25	1.10	0.93	1.08
5	0.40	0.43	0.40	0.40	1.68	1.65
6	0.35	0.38	0.40	0.40	1.92	1.85
7	0.33	0.20	0.20	0.20	2.20	2.38
8	0.33	0.20	0.20	0.20	2.62	2.87
9	0.10	0.12	0.18	0.00	3.70	3.65
10	0.12	0.10	0.18	0.00	4.45	4.27

From this table, it can be seen that the existing practice of assignments is not in line with the simulation results for any of the MAXWAIT values. This is because, in reporting the values of detention of locos and trains, the existing practice is to include the time spent in operations like shunting and in other delays such as waiting for crew and path. In the model, such factors are not included. According to our discussions with railway officials, at least one hour can be attributed to these factors for trains, and a little more for locos. Taking this into consideration, the MAXWAIT value that comes closest to the existing performance is one hour, when used with LATC rule. This reinforces the current principle that "a train should wait for a loco and not vice versa", as stated by railway officials.

The MAXWAIT value of zero provides an upper bound for train detention.

The simulation also provides a comparison between the LATC rule (where for double head trains, both locos have to satisfy the MAXWAIT criterion) and LATN rule (where for double head trains, only the second loco should satisfy the MAXWAIT criterion). As expected, the detention of double head trains in the LATC rule is greater than or equal to that in the LATN rule. For single head trains, neither rule dominates.

As MAXWAIT increases, the train detention comes down while the loco detention goes up in general. The reduction in train detention is significant for smaller values of MAXWAIT. Correspondingly loco detention goes up significantly for higher values of MAXWAIT.

The optimum value of MAXWAIT obviously depends on the relative costs of waiting of locos and trains. Figure 2 shows the total cost curve under LATC rule, for one set of relative costs, which for a loco, a single head train and a double head train are 1, 0.9, and 1 respectively. It can be seen from the figure that the optimum MAXWAIT is 3 hours. It should also be noted that the curve is relatively flat around the optimum. The optimum values of MAXWAIT based on different sets of relative costs are given in Table 4.

Table 4
Optimum Values of MAXWAIT

	Relative weights of costs			Total Weighted Detention (Hrs)		MAXWAIT (Hrs) [Interval]	
S.No.	Loco	Train (single head)	Train (double head)	LATC Rule	LATN Rule	LATC Rule	LATN Rule
1	1	1.80	2.00	364	365	5	[4,5]
2	1	1.35	1.50	310	313	3	3
3	1	0.90	1.00	241	241	3	2
4	1	0.45	0.50	149	154	2	2
5	1	0.18	0.20	88	102	1	[1,2]
6	1	0.09	0.10	50	70	0	1

Figure 2
Total Weighted Detention (LATC Rule)
Weights. Loco:1, Single Head Train:0.9, Double Head Train:1

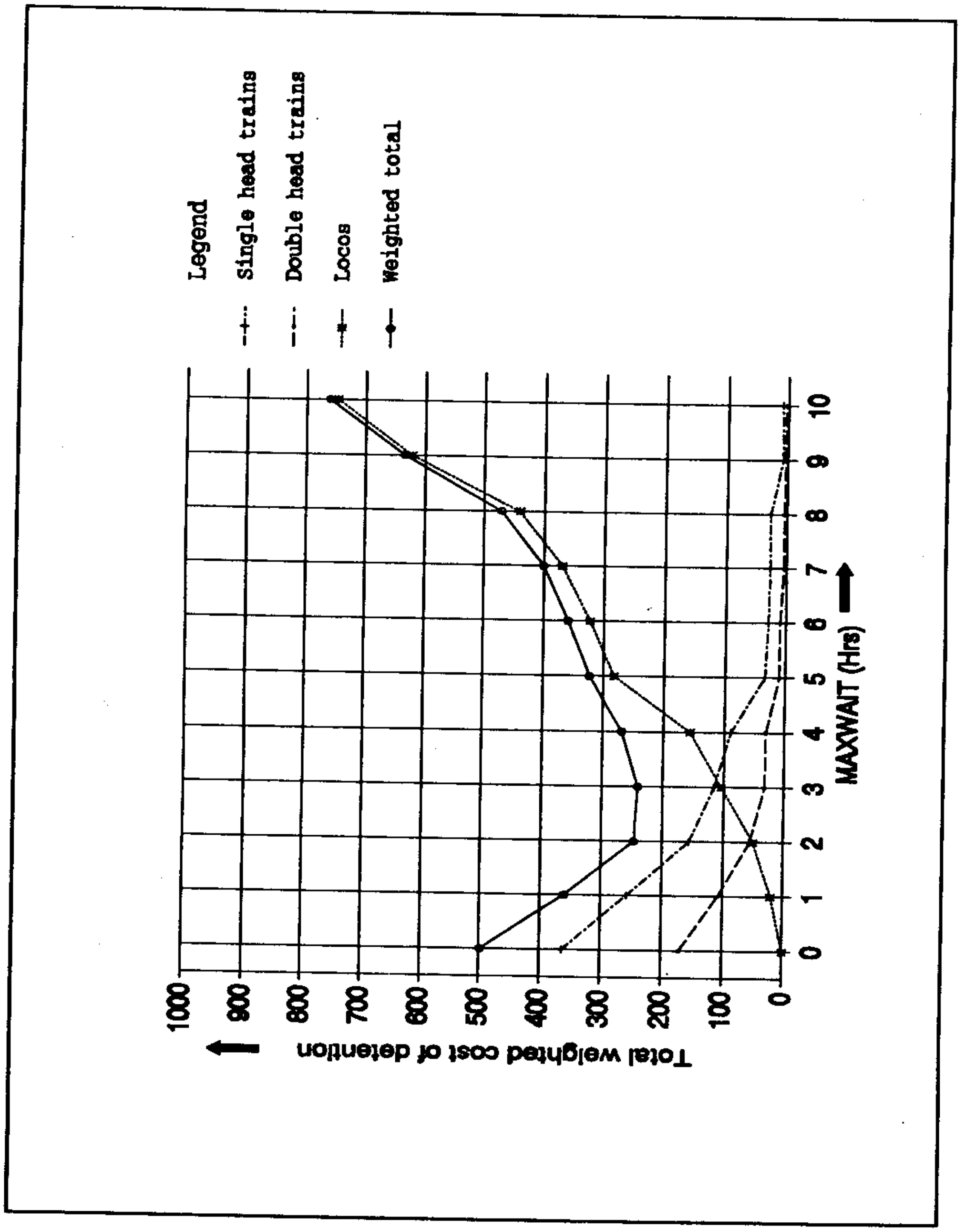


Table 4 shows that the total detention under the LATN rule is larger than that under the LATC rule, especially when the loco cost is relatively significant. As the relative cost of trains decreases, the optimum MAXWAIT decreases. As deduced from Table 3, the existing MAXWAIT used is one hour or less, which implies that the relative cost of trains is less than 20%. *This is surprising given that the investment costs of a loco and a freight train are approximately equal.* The opportunity costs of detention alone cannot account for this difference.

2.4 Extensions

The model described above is useful to develop a rule for loco assignment at a tactical level, especially when the cost of waiting does not differ significantly between the trains. If the costs differ significantly, then a better approach would be to use the "transportation" model for optimal assignments. In the transportation model, each loco, whose arrival time is known is one unit of supply, and each train whose arrival time is known is a demand with one or two units as the case may be. In this case, the model has to be run dynamically, whenever information on a future train or loco arrival becomes known.

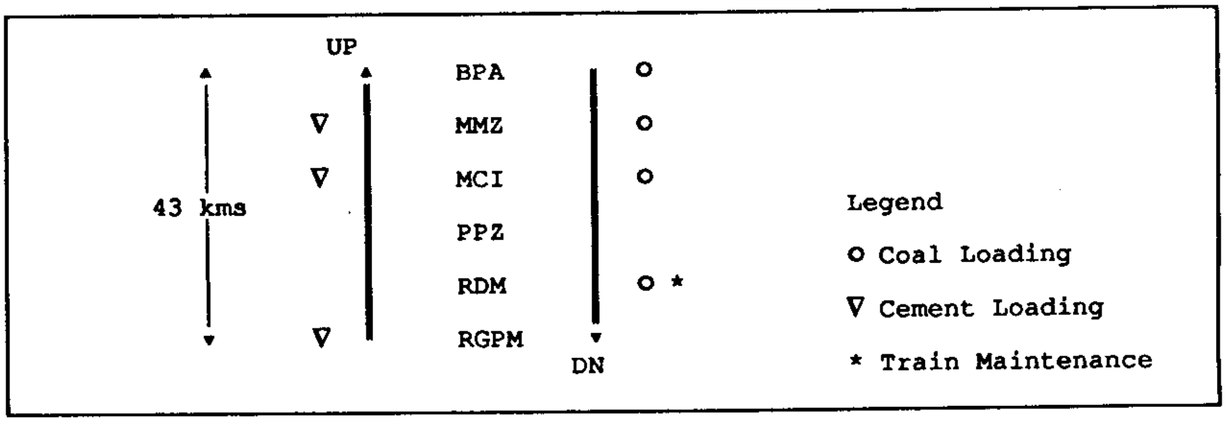
3. TWIN SINGLE LINE EVALUATION MODEL

3.1. Context Description

Coal and cement, amounting to 40% of the total originating traffic of SCR get loaded in a 43 km section of a busy main line from five loading points. Figure 3 is a line diagram [3, 4] of the section between the stations Bellampalli (BPA) and Raghavapuram (RGPM). The direction from BPA to RGPM is called down (DN), and that from RGPM to BPA up (UP).

In this section, over 14 trains originate per day, and an equal number of empty trains terminate. Further, there are light loco movements between loading points, and empty train movements for maintenance. This traffic combined with the through traffic on the section leads to congestion and detention. The problem is further complicated by the cross movements caused by (a) the location of loading areas and other facilities, and (b) the orthodox double line operation requiring trains to use one track only (that on the left side, as per the convention of Indian Railways) in a given direction. For example, an empty train entering the section in the UP direction bound for loading at BPA, after maintenance at Ramagundam (RDM), would require three cross movements: one into RDM, the second out of RDM, and the third into BPA. Certain trains and loco movements which originate and terminate within the section cause double cross movements.

Figure 3
Location of Facilities on BPA-RGPM Section



From an analysis of train movements over a five day period, it was evident that the problem of cross movements was more severe at Ramagundam (RDM) and BPA than at other stations.

A suggested solution to this is to convert the section from the existing orthodox double line operation to a twin single line operation, which permits movements in both directions on both tracks. The benefit of the proposed operation needs to be evaluated on the criteria of detention and throughput, using a simulation model. An existing line capacity evaluation model [5], which was developed primarily to study an orthodox double line section, is being extended to study the above problem.

3.2. Existing Model

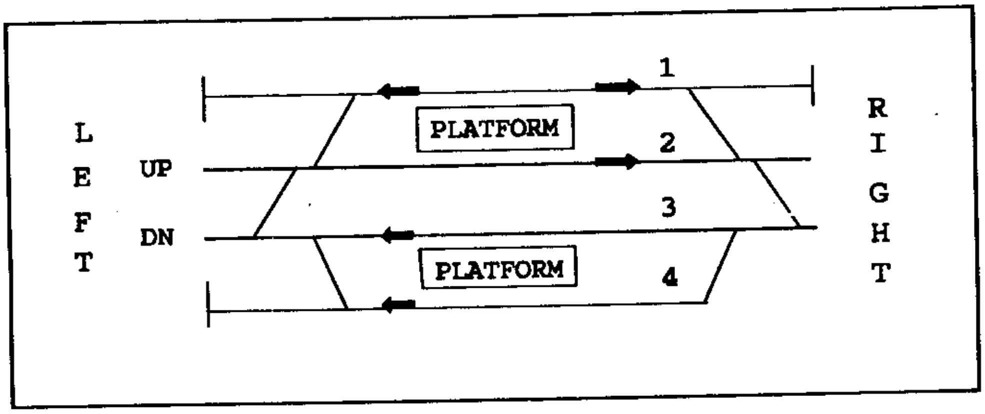
The objective of this model is to evaluate the line capacity and the average section travel time for freight trains, given a set of scheduled passenger services. The reason for this objective is that the Indian Railways, who earn most of their revenue through freight operations, seek to maximize the freight throughput.

The key inputs to this model are: (a) station and track layouts, and (b) passenger train schedules. The model develops freight train paths successively in each direction, avoiding the prohibited time intervals caused by the passenger trains and the previously scheduled freight trains.

The station and track lay outs are coded as three matrices, ACL, ACR, and STR, for each station. The matrices contain the following information:

1. Which of the tracks within the station can be accessed from the left side (Matrix ACL) and which from the right side (Matrix ACR), by assigning '1' indicating accessibility and '0' for no access in the corresponding matrix cell.

Figure 4
Representation of a Typical Station



Matrix ACL	Matrix ACR	Matrix STR
Track No: 1 2 3 4 UP 1 1 0 0 DN 1 1 1 1	Track No: 1 2 3 4 UP 1 1 0 0 DN 1 1 1 1	Track No: 1 2 3 4 B U D D S M M S P P P P

2. For each track in the station, whether it is a main line ('M') or siding ('S'), whether there is a platform facing it ('P') or not ('N'), and in which direction(s) it is signalled ('U' for UP, 'D' for DN, and 'B' for both), (Matrix STR). Figure 4 shows the diagram of a typical station along with the three matrices.

This model has been used for evaluating different operating policies like impact of increase in freight train speed, improvements in signalling, double tracking an existing single track bridge, and starting times for freight trains from a major yard.

3.3. Extension for Twin Single Line Evaluation

The data representation of station layouts remains the same, taking into account the additional cross overs and signalling that would be provided for twin single line operation. In addition to this, as the possibility of interfering movements increases considerably, an explicit consideration through interference matrices is required. For a proposed movement into or out of a station, the interference matrix indicates which other movements are not permissible 'simultaneously' (within a small time interval, determined by the signalling technology).

In the scheduling procedure, the concept of prohibited intervals is generalized to consider train movements in both directions on a section of track between two stations. For various decisions concerning interactions between trains, the priorities between trains have to be considered. Further, the number of crossings by a train from one main line to another is a significant issue in this context. Since the crossings take place at a slow speed, acceleration and deceleration times are to be explicitly incorporated. These were not considered in the existing model.

The model will be used to study the following factors which significantly influence the benefits of the twin single line operation:

1. The operating rules for using the 'wrong' line (that on the right side!) by exception or by type of train etc.
2. The length of the section which needs to be converted to twin single line operation. For example, only the two sections on either side of RDM (the most congested station), the section between BPA to RGPM, or one or two sections before BPA to one or two sections after RGPM.

4. CONCLUDING REMARKS

a. As railway operations deal with a large number of interacting elements, simulation models are useful for evaluating railway operating policies. An approach to developing such models is to identify major traffic streams and to define problems focused on a stream.

b. Being a very large organization, the Indian Railways is generally trapped into a quagmire of issues. In this context, it is important for the modeller to understand the hierarchy among the problems and to define them accordingly.

c. In both the models discussed, the relative costs of different categories of rolling stock play a crucial role. Due to non availability of proper costs, the operating policies are usually governed by thumb rules. According to the above models, the costs have a significant impact on the operating policies, and hence it is essential to assess the costs realistically.

d. While the models described in this paper are planning tools, they can be also used for operational decision making, by building around them decision support systems to be used by the operating personnel.

e. Since track is an important resource, and major infrastructural investments are not possible, it is helpful to build and use models that quantify line capacity for various intermediate forms of investment, or for alternate operating policies.

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