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Heavy Haul Corridor Selection and Service Design Models

by

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Abstract: Heavy haul corridors are capital intensive and are relatively expensive to maintain. It is therefore imperative that heavy haul corridors are chosen with care, such that sufficient traffic is available on the corridors to ensure adequate returns. The strategic choice will be dictated by projected pattern and volume of freight traffic, projected pattern of passenger traffic and terminal facilities. Various choices may be obtained with different rolling stock and locomotive capacity to obtain scenarios with existing and future fleet characteristics, as well as future terminal facilities.

Further, tactical operating plans for networks with heavy haul corridors should be designed properly to ensure maximum utilization of such corridors with a given set of customer demands, rolling stock and locomotive size and capacity, terminal facilities and capacity of peripheral networks. Such operating plans which might span from a fortnight to three months, include decisions regarding routes, frequency of services, aggregation and disaggregation policies, empties repositioning policies and direct or consolidating train service policies. These operating plans may also depend on the service level committed to a customer, which is again tied to a particular pricing.

This paper proposes two operations research based models: (i) a model for choosing a heavy haul corridor(s) within an existing network and (ii) a model for design of an optimal operating plan for an existing network with a designated heavy haul corridor(s). The models are further demonstrated on a hypothetical railroad network with test data.

The contributions of the proposed models are manifold, few of which are: scenario analysis with various combinations of demand patterns, fleet size and characteristics and terminal facilities; enabling investment decisions for up gradation of track, fleet or terminal facilities through comparative analysis of scenarios; and enabling service design to meet specific customer needs.

1.Introduction

1.1   Heavy Haul corridors generally have the following characteristics: (a) corridors have entirely freight traffic movement with little or no passenger traffic (b) corridor tracks capable of handling high axle load wagons (c) corridor stations/yards are capable of handling long train lengths and (d) corridor track side power carriers and equipment are capable of catering to multiple locomotives with high horsepower. Thus heavy haul corridors have higher capital cost of (i) tracks which must be capable of handling high axle load wagons, (ii) high axle load wagons, and (iii) locomotives with higher horse power and better braking systems. The operating costs of heavy haul corridors are also higher due to increased maintenance costs of tracks and fuel costs incurred by high horse power locomotives. However the favorable economics of heavy haul corridors lie in the reduction of unit costs due to longer trains and higher payload wagons [1] as well as higher average speeds than mixed freight and passenger train corridors. Thus heavy haul corridors are economical through extension of all the three major limiting factors of railway transport- axle load, train length and speed [2].

1.2   It is therefore imperative that heavy haul corridors are chosen with care, such that sufficient traffic is available on the corridors to take advantage of longer and heavier trains and thereby ensure adequate returns. The strategic choice will be dictated by projected pattern and volume of freight traffic, projected pattern of passenger traffic and terminal facilities. Various choices may be obtained with different rolling stock and locomotive capacity to obtain scenarios with existing and future fleet characteristics, as well as future terminal facilities.

Selections of optimal routes have so far been studied in the context of passenger railways. The maximum covering and shortest path problem has been studied extensively to determine the railway route which caters to the maximum population and has the shortest path [3] [4]. However the author has not come across any research on the optimal selection of freight routes.

1.3 Further, tactical operating plans (or service designs) for networks with heavy haul corridors should be designed properly to ensure maximum utilization of such corridors with a given set of customer demands, rolling stock and locomotive size and capacity, terminal facilities and capacity of peripheral networks. Such operating plans which might span from a fortnight to three months, include decisions regarding routes, frequency of services, aggregation and disaggregation policies, empties repositioning policies and direct or consolidating train service policies. These operating plans may also depend on the service level committed to a customer, which is again tied to a particular pricing.

Various aspects of tactical operating planning of rail transportation networks have been researched extensively since the last three decades [5]. However the author has not come across an integrated model which takes into account all the factors related to tactical operating planning of heavy haul corridors.

1.4 This paper proposes two operations research based models: (i) a model for choosing a heavy haul corridor(s) within an existing network and (ii) a model for service design or optimal operating plan for an existing network with a designated heavy haul corridor(s). The models are further demonstrated on hypothetical railroad networks with test data.

The paper is organized as follows: Section 2 describes the model for choosing a heavy haul corridor(s) within an existing network; Section 3 describes the model for service design or optimal operating plan for an existing network with a designated heavy haul corridor(s); followed by discussions and conclusion in Section 4.

2. Heavy Haul Corridor Selection Model

2.1 The cost function associated with a heavy haul corridor is different from the cost function of a normal railway corridor. The capital cost and operating costs of a heavy haul corridor will be higher than that of a normal railway corridor, due to (a) higher capital costs of track, wagons and locomotives and (b) higher operating costs of maintenance of track and fuel charges. However since the heavy haul corridors accommodate longer trains with heavier axle load wagons, the total cost will be lower for routes having higher traffic. This aspect has been used for the heavy haul corridor selection model described in this section.

2.2 The following integer programming model is proposed for Heavy Haul Corridor selection:

Indices used:
s this index is used for sections
r this index is used for routes

We define a section as a network connection between two contiguous origin/destination yards. A route is defined as a collection of sections, which comprise the path of shortest length between an origin and a destination yard.

Notation for data elements:
R total number of routes; thus $r=1,…,R$
P_r set of sections comprising route r
D_r average annual traffic (in million tons) forecasted over route r
CCN wagon carrying capacity (in tons) for normal routes
CCH wagon carrying capacity (in tons) for heavy haul routes
TN maximum number of wagons on trains plying on normal routes
TH maximum numbers of wagons on trains plying on heavy haul routes
FN_s fixed annual cost of a normal section s
FH_s fixed annual cost of a heavy haul section s
VN_s cost of hauling a train on a normal section s
VH_s cost of hauling a train on a heavy haul section s

Decision variable:
x_s =1, if the section s is retained as a normal section
    =0, if the section s is upgraded to a heavy haul section

The objective function to minimize is the cost of transportation C, which is given by the following expression as a summation of fixed and operating annual costs of normal and heavy haul sections:

$$C = \sum_{r=1}^{R} \sum_{s \in P_r} \left(x_s \left(FN_s + VN_s \left(\frac{D_r}{(CCN)(TN)} \right) \right) + (1 - x_s) \left(FH_s + VH_s \left(\frac{D_r}{(CCH)(TH)} \right) \right) \right)$$

2.3   The model is demonstrated with a network given in Figure 1 containing 9 yards A,B,C,D,E,F,G,H and I.
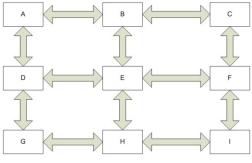
Fig.1

Each bi-arrow in Figure 1 indicates an existing rail network connecting a pair of major traffic origins and/or destinations. Table 1 gives the sections (indicated by 'x') comprising the shortest path for any route; thus the shortest path connecting the origin A and destination I comprises the sections AD, DG, GH and HI (obtained by reading the 'x's in column AI).

R	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	C	C	C	C	C	C	D	D	D	D	D	E	E	E	E	F	F	F	G	G	H
S	B	C	D	E	F	G	H	I	C	D	E	F	G	H	I	D	E	F	G	H	I	E	F	G	H	I	F	G	H	I	G	H	I	H	I	I
AB	X	X											X																							
BC		X							X						X																					
AD			X	X	X	X	X	X					X																							
DE				X	X					X						X						X	X													
EB										X	X	X		X																						
EF					X							X				X	X						X				X									
FC															X	X	X	X	X	X	X															
DG						X	X	X					X											X	X	X										
GH							X	X											X						X	X		X			X			X	X	
HE														X														X	X	X						
HI								X											X	X						X				X	X	X			X	X
IF															X				X	X	X										X	X	X			

Table 1

The annual traffic flows (in million tons) for each route (origin-destination pair) are given in the Table 2. Thus the annual traffic on route BG is 1000 million tons.

	A	B	C	D	E	F	G	H	I
A	-	500	400	10	10	30	50	10	20
B	300	-	10	500	200	600	1000	300	20
C	300	50	-	10	20	70	20	10	30
D	10	600	20	-	10	30	50	20	50
E	10	300	100	20	-	40	70	80	10
F	200	20	1	10	50	-	3	30	40
G	40	20	10	40	200	50	-	10	100
H	100	10	500	2	30	100	20	-	50
I	20	80	700	100	30	200	10	80	-

Table 2

2.3.1   We use the model for the network in Figure 1 along with shortest routes given by Table 1 and annual traffic flows given by Table 2 for two different scenarios, with different cost functions for heavy haul corridor and normal railway corridor. We assume the following data for both the scenarios: CCN=70, CCH=100, TN=60,TH=120.

In the first scenario, we assume that FN=10, FH=30, VN=7, VH=12 for all sections. Solving the model with first scenario data, we obtain that sections AB and EB should be upgraded as heavy haul sections.

The second scenario assumes that fixed cost and variable costs are higher for certain sections. We assume that FN=10, FH=20, VN=7, VH=11 for section BC; FN=10, FH=30, VN=7, VH=15 for section EB; FN=10, FH=30, VN=7, VH=11 for section GD; FN=10, FH=15, VN=7, VH=12   for section HE;and   FN=10, FH=30, VN=7, VH=12 for remaining sections. Solving the model for the second scenario data, we obtain that sections AB, BC and HE should be upgraded as heavy haul sections.

The integer programming model requires approximately 4 seconds for solution for both the scenarios using IBM-ILOG CPLEX software on a 1.33 GHz laptop.

3. Service Design Model

3.1   Service Design (or tactical operating plan) is the optimum scheduling of services for a given traffic demand pattern, a set of resources and a set of business environment constraints, in order to maximize both the customer service indices as well as the transporter's profits. Scheduling of services involves planning (a) when to run a service (say a freight train departing Shalimar yard on Mondays and Wednesdays at 5 pm), (b) origin and destinations of the service (say from Shalimar yard to Nagpur), (c) the route of the service (through Rourkela-Bilaspur or through Bhubaneswar-Vijaywada-Kazipet) , (d) the resource deployment for the service (say a BOXN or BOY wagon, a Bondamunda Loco Shed or Bhilai Loco Shed locomotive, Kharagpur based crew or Chakradharpur based crew), (e) the customer(s) serviced (say 20 wagon loads of cement of customer X from Bilaspur to Nagpur or 30 wagon loads of finished steel of customer Y from Visakhapatnam to Nagpur); here Service Design attempts to optimize the process of traffic consolidation, (f) the terminal operations involved for the service (say commencing the train run with 50 wagons (30 of customer P and 20 of customer Q) at Shalimar, or dropping off 30 wagons of customer P at Chakradharpur) and (g) balancing and positioning operations to correct resource imbalances and ensure proper positioning over the network by moving empties, dead-heading locomotives and crew. A traffic demand pattern is the forecasts of demands for transportation over different O-D pairs during each day over the planning horizon; say, 20 wagons of rice from Kharagpur to Nagpur on Mondays and Thursdays. The set of resources is the resources (say wagons, locomotives, crew) at the disposal of the transporter which can be deployed for meeting the transport needs of the customers. This set of resources would be determined after taking into account the maintenance and repair/overhaul requirements of track, signals, wagons, coaches and locomotives. Business environment constraints would involve issues such as maximum train lengths, speed restrictions, bridge loading restrictions, crew working rules, compulsory brake

certification of wagons after accruing certain mileage, restrictions on maximum traction power drawn (thus limiting maximum traffic on certain routes) , terminal operation hours (say 16 hours operations in a yard necessitating all wagon pickup and drop off exercises to be restricted within those 16 hours) and terminal constraints (say only four lines in the reception yard, resulting in limits on maximum number of trains that can be received).

Service Design is a tactical planning exercise carried out for the entire network-wide movement for all customers [1]. This is generally done on a fortnightly or weekly basis, taking into consideration the latest information on (a) traffic demand patterns (b) resource availability (considering track, wagon and locomotive maintenance schedules and forecasted availability) and (c) external influencers (say forecasted inclement weather which might slow down train movement in certain sectors). It must be distinguished from strategic planning, in the sense that the planning is done considering existing resources over a medium time frame (say one to three weeks), which rules out long-lead options such as augmentation of resources (say doubling of track or adding wagons to the fleet). A service design is similar to a passenger train timetable which allows the dispatcher to form appropriate trains and dispatch them at the proper time.

3.2   In order to appreciate the complexity of network design let us take a linear network consisting of four consecutive stations P,Q,R and S spaced 200 km apart. Let us assume that the traffic forecasts for the following few weeks are as follows: (a) 20 wagons of customer A are to be transported from P to Q on Monday, Wednesday and Friday (b) 10 wagons customer B are to be transported from P to S on Tuesday, Thursday and Sunday (c) 40 wagons of customer C are to be transported from Q to S on Friday and Saturday (d) 30 wagons of Customer D are to be transported from Q to R on Thursday and Sunday (e) 30 wagons of customer E are to be transported from R to S on Monday and Sunday (f) 50 wagons   of customer F are to be transported from S to Q on Friday and Sunday (g) 20 wagons   of customer G are to be transported from R to P on Wednesday and Friday. Customers are prioritized as X, Y and Z, with X being lowest priority, Y as intermediate priority and Z as highest priority. Customers A,E and G have priority X; B and D have priority Y; and customers C and F have the highest priority Z.

If we analyze the problem, we come across a wide range of options of service network design. For example, if we take customer A alone, there are numerous options available. Few of the options for Monday's indent of customer A would be (i) run a train with only 20 wagons from P to Q on Monday (ii) run a train on Wednesday with 40 wagons from P to Q combining Wednesday's indent of customer A (iii) run a train on Friday with 60 wagons from P to Q combining Wednesday's and Friday's indent of customer A (iv) run a train on Tuesday with 30 wagons from P to S combining Tuesday's indent of customer B; the train will drop off 20 wagons of customer A at Q (v) run a train on Tuesday with a maximum of 40 wagons from P to S combining Tuesday's indent of customer B and earlier Sunday's indent of customer E; the train will drop off 20 wagons of customer A at Q and pickup 30 wagons of customer E at R. Each option has its advantages and disadvantages. In option (i) we are under utilizing section capacity by running a train of very small length; however the advantage is that the average time of transit (including waiting time for train formation) is the lowest. In options (ii) and (iii) we have tried to improve the section capacity utilization, but the average time of transit increases (since Monday's indent is kept waiting till Wednesday or Friday). In options (iv) and (v) we have tried to improve the section capacity utilization, but at the cost of increase of transit time due to terminal operations of dropping off or picking up wagons.

The model developed for service design minimizes the costs associated with (a) number of trains being operated, (b) delays in formation and dispatch of customer indents; the costs associated with the delay will vary with customer priorities (c) train pickup and/or dropping off wagons at intermediate yards on the route.

3.3   An integer programming model was developed for service design of heavy haul railway networks:

Indices used:
r   this index is used for routes on which trains are run
s   this index is used for routes on which customer requires transportation

w   this index is used for day of week, on which a train is operated with $w=1,2,....,7$ and $w=1$ denoting Monday

v   this index is used for day of week, on which an indent is raised by customer or wagon is loaded by the customer

j   this index is used for customers

Notation for data elements:

Q total number of customers; there are 8 customers in the example

C_R cost of running a train

C_j cost of wagon waiting for train formation and dispatch, for each day for customer j

C_T cost of picking up and dropping each wagon at terminals en route

R total number of routes; thus $r=1,...,R$ and $s=1,....,R$
the total number of routes in the example is 12, wherein routes are PQ,PQR,PQRS,QR,QRS,RS, SRQP,SRQ,SR,RQP,RQ and QP

$h_{rs}=1,$ if route r is included in route s (for example route QR is included in route PQRS)
  $=0,$ if route r does not include route s

p_{rs} number of pick up and drop off terminals for train run on route s for customer demand for transport on route r (for customer demand of transport on route QR, the train operated on route PQRS has a pickup at Q and a drop off at R; thus $p=2$ for $r=QR$, $s=PQRS$)

D_{jvs} indent raised (in terms of wagons) by customer j on day v for transport on route s

M maximum number of wagons in a train

Decision variables:

$x_{wrjvs}=1$, if freight train is operated on day w on route r with customer j's load indented on day v on route s
    $=0$, if freight train is not operated on day w on route r with customer j's load indented on day v on route s

$y_{wr}=1$, if freight train is operated on day w on route r
    $=0$, if freight train is not operated on day w on route r

We wish to minimize the sum of cost of running the trains, cost of wagon waiting for train formation and dispatch for each day for different priority customers and the cost of picking up and dropping each wagon at terminals en route. The objective function is thus given by the summation of three expressions pertaining to the three costs:

$$\left\{\sum_{w=1}^{7}\sum_{r=1}^{R}(C_R y_{wr})\right\}+$$
$$\left\{\sum_{w=1}^{7}\sum_{r=1}^{R}\sum_{j=1}^{Q}\sum_{v=1}^{7}\sum_{s=1}^{R}\left(D_{jvs}x_{wrjvs}h_{rs}C_j(|w-v|)\right)\right\}+$$
$$\left\{\sum_{w=1}^{7}\sum_{r=1}^{R}\sum_{j=1}^{Q}\sum_{v=1}^{7}\sum_{s=1}^{R}(D_{jvs}x_{wrjvs}h_{rs}p_{rs}C_T)\right\}$$

Subject to the constraints,

$$\sum_{w=1}^{7}\sum_{r=1}^{R}x_{wrjvs}=1, \text{for all j=1,....,Q, v=1,....,7,s=1,....,R} \tag{1}$$

$$100000*y_{wr}\geq\sum_{j=1}^{Q}\sum_{v=1}^{7}\sum_{s=1}^{R}x_{wrjvs}, \text{for all w=1,....,7,r=1,....R} \tag{2}$$

$$\sum_{j=1}^{Q}\sum_{v=1}^{7}\sum_{s=1}^{R}\frac{x_{wrjvs}D_{jvs}}{M}\leq1, \text{for all w=1,....,7,r=1,....,R} \tag{3}$$

Explanation of the constraints: Constraint (1) ensures that each customer indent is transported by a train. Constraint (2) ensures that a train is operated on a route r on a particular day w (or $y_{wr}=1$) whenever, at least one of the customers' indents is transported on that route on that particular day (or any $x_{wrjvs}=1$). Constraint (3) ensures that any train that is operated, has a maximum of M wagons on the train.

3.4   Table 3 lists the optimal service designs obtained using the integer programming model for the example described in section 3.2 with three different scenarios of these costs and

assuming maximum number of wagons in a train M=70. The service design given below omits the movement of empties required for wagon balancing. The integer programming model requires approximately 4 seconds for solution using IBM-ILOG CPLEX software on a 1.33 GHz laptop.

Scenario	Costs	Optimal Service Design
1	C_R=1, C_j=4,6,8 for priority X,Y,Z C_T=10	**16 trains** operated as follows: (a) 3 trains from P to Q on Mon, Wed and Fri with 20 wagons of A (b) 3 trains from P to S on Tue, Thur and Sun with 10 wagons of B (c) 2 trains from Q to S on Fri and Sat with 40 wagons of C (d) 2 trains from Q to R on Thur and Sun with 30 wagons of D (e) 2 trains from R to S on Mon and Sun with 30 wagons of E (f) 2 trains from S to Q on Fri and Sun with 50 wagons of F (g) 2 trains from R to P on Wed and Fri with 20 wagons of G.
2	C_R=500, C_j=4,6,8 for priority X,Y,Z C_T=10	**9 trains** operated as follows: (a) 1 train from P to Q on Wed with 40 wagons of A's Mon & Wed indents (b) 1 train from P to S on Sat with 20 wagons of A's Fri indent and 40 wagons of C's Sat indent (c) 1 train from P to S on Fri with 30 wagons of B's Tue, Thur & Sun indents and 40 wagons of C's Fri indent (d) 1 train from Q to R on Thur with 30 wagons of D's Thur indent (e) 1 train from Q to R on Sun with 30 wagons of D's Sun indent (f) 1 train from R to S on Mon with 60 wagons of E's Sun and Mon indents (g) 1 train from S to Q on Fri with 50 wagons of F's Fri indent (h) 1 train from S to Q on Sun with 50 wagons of F's Sun indent (i) 1 train from R to P on Fri with 40 wagons of F's Wed and Fri indents
3	C_R=500, C_j=4,6,8 for priority X,Y,Z C_T=200	**9 trains** operated as follows: (a) 1 train from P to Q on Fri with 60 wagons of A's Mon, Wed and Fri indents (b) 1 train from P to S on Fri with 70 wagons of B's Tue, Thu and last Sun indents and C's Fri indent (c) 1 train from P to S on Sat with 40 wagons of C's Sat indent (d) 1 train from Q to R on Thur with 30 wagons of D's Thur indent (e) 1 train from Q to R on Sun with 30 wagons of D's Sun indent (f) 1 train from R to S on Mon with 60 wagons of E's Sun and Mon indents (g) 1 train from S to Q on Fri with 50 wagons of F's Fri indent (h) 1 train from S to Q on Sun with 50 wagons of F's Sun indent (i) 1 train from R to P on Fri with 40 wagons of F's Wed and Fri indents

Table 3

It will be observed from the results that the service design changes depending on the relative costs of train running, delays and terminal operations.

3.5   The above model can be extended further to include aspects such as (i) section capacity or maximum number of trains that can be run in a section, (ii) terminal constraints in terms of maximum number of wagons that can be handled per day, (iii) crew scheduling considering crew availability and working rules, (iv) scheduled maintenance of resources, (v) different resources with different capacities, say locomotives with different hauling capacities (thus limiting the maximum trailing loads) or wagons with different carrying capacities; such resources will also have different cost functions comprising fixed and variable cost components, and/or (vi) reliability of resource performances (say probabilities of track fracture, locomotive failure or wagon brake binding on specific sections) . Inclusion of such aspects optimizes all aspects of railway operations ensuring maximum utilization of all resources at a minimum cost and maximization of customer satisfaction.

4. Discussion and conclusion

The contributions of the proposed models are manifold, few of which are: scenario analysis with various combinations of demand patterns, fleet size and characteristics and terminal facilities; enabling investment decisions for up gradation of track, fleet or terminal facilities through comparative analysis of scenarios; and enabling service design to meet specific customer needs.

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