



2011 RAS Problem Solving Competition

Train Design Optimization
(Updated March 2012)

DISCLAIMER: The problem presented here exemplifies one of several opportunities for Operations Research application in the Railway industry. We have simplified a real-life problem for this competition. More general problems and related literature is available on the competition web-site under the section Related Literature. Best of luck for the competition.



Definitions

Block: A set of railcars that are being moved as a single group or lot from one rail yard to another, where the individual cars within the block can have a disparate set of origins and destinations. Rail yards assemble these blocks based on the final destinations of the railcars and other compatible attributes.

Blocking: Similar to airline and less-than-truck load industries, a set of cars can be aggregated to create a block at a yard, then separated into individual cars at a subsequent yard and again aggregated with different cars into a different block. This process of aggregation and separation of cars is variously referred to as Blocking, Classification, or Marshalling. Classification improves the efficiency of railcar transportation by providing a way to aggregate individual railcar movements into larger groupings, what can then be formed into trains. For an individual railcar, the classification process can happen multiple times at a sequence of intermediate yards before a car reaches its destination.

Block swap: A Block swap is defined as transferring a block between trains without re-classification of cars at yards. In effect, the entire block or lot of cars remains coupled together and is moved en masse to another train. This allows a block to use more than one train to reach its destination, while requiring less classification work when the railcars are moved from one train to another.

Crew segment: Railroad crews typically drive trains between a fixed pair of locations, called a “crew district” or “crew segment.” A North American freight train will generally cross multiple crew segments, and thus use multiple crews as it traverses its route. Thus, a crew segment is a link on the network between two nodes on which a crew can operate a train.

Single-ended territory: Crews are typically domiciled at a specified location at one end of the crew segment. The crew segments are designed such that it is a full day work to get from one end to the other. Thus crews typically work from the “home” terminal (where they are domiciled) to the “away” terminal one day, and then return the next day. A single-ended territory has crews domiciled at only one end of the crew segment, and thus has one home and one away location. As noted above, crews can take a train either from home to away location or away to home location on a pre-defined crew segment.

Railcar: In the railroad industry, a railcar is also referred as railroad car, railway car, car, or wagon. On a freight railroad, railcars are loaded with freight, coupled with other railcars to form a train. Subsequently, locomotive(s) are used to transport the train between required rail yards. For this competition, we assume only one type of railcar even though numerous types are used in practice.

Railroad Network: A railroad network can be abstractly represented by a set of nodes and links. Nodes represent physical locations on the network such as rail yards and reference points called mile posts, where as links correspond to the rail track connecting the nodes.

Trip Plan: A trip plan is the itinerary that a railcar will follow as it moves from its origin to its destination. This includes information on the sequence of blocks the railcar will use to move from its origin to its destination, the trains that are used to transport these blocks, and the timing of these movements. A railcar trip plan is analogous to a passenger itinerary in the airline industry.

Problem Description

While the freight railroad industry has been in existence for over two centuries, the fundamental concept of aggregating freight railcars based on different attributes to create blocks and subsequently combining blocks to create trains has not changed. Freight railroads receive requests from customers to transport cars. Upon receiving the request, based on each car's attributes (such as physical dimensions, freight type, etc.), the railway generates a trip plan detailing the movement of the car from the customer's origin location to the requisite final destination.

Trip plans are generated based on the operating plan. Two of the main components of an operating plan are:

- a) What blocks are to be made at each rail yard, and which railcars are to be placed into each block (Block Design)?

Please refer to [1] for more information about the Block Design Optimization.

- b) What trains are to be operated, including which blocks are to be transported by each train (Block-To-Train Assignment, BTA) and what routes are to be followed by each train (Train Routing)?

Please refer to [9] for additional information about BTA problem.

Train routing includes identifying the origin, destination and route for each individual train, such that these routings are consistent with the rail network and the blocks to be transported. Along its route, a train can visit different yards to perform work events like (a) pickup block(s), (b) set-off block(s), or (c) both set-off and pickup blocks. Depending on the work event, the train is required to stop for different amount of time. Thereby, train routing also includes determining arrival and departure schedules of the train at rail yards along the route.

Both of these elements of the operating plan are generally designed at a tactical level, which means that the plan is created a few weeks to a few months in advance of it being operated, and the plan is then followed and adjusted as necessary during actual operation.

In this competition, it is assumed that the blocks made at each of the yards have already been determined and cannot be changed. Hence, the block attributes such as origin, destination, number of cars, length and tonnage is given information.

The research problem to be addressed in this competition is related to addressing the second component of operating plan design, which includes Block-To-Train Assignment (BTA) and Train Routing. This component is also referred to as "Train Design".

Train design is one of the most fundamental and difficult problems encountered in the railroad industry. A Class I railroad can daily operate around 200 merchandise trains, which follow a pre-determined schedule. These trains transport close to 1,000 blocks by picking up or setting off blocks at 180 to 200 locations. Approximately, 400 to 500 crews are involved in moving the merchandise trains from corresponding origin to destination locations. This complex problem has huge potential for benefiting from the application of Operations Research. Identifying the optimal routes for the trains, and associated Block-To-Train assignments, subject to different capacity and operational constraints, is called Train Design Optimization. Operational and capacity constraints involved in this problem include:

- a) *Blocks per train*: A train is constrained by the maximum number of blocks it can carry. Assigning too many blocks to a train may result in an excessive number of train stops, which is discouraged for operational efficiency.
- b) *Block swaps per block*: Each block is constrained by the maximum number of times it can be block swapped. Even though theoretically block swaps are efficient, from a practical perspective, it requires additional time and resources.
- c) *Work events per train*: Each time a train is stopped en-route to either pickup or set-off blocks, it is called a work event. If a train performs both pickups and set-offs at an intermediate yard, then it is considered one work event. Work events are costly both in terms of carrying out the tasks of adding and removing the blocks, but also in terms of train delay (to the cars, locomotives, and crew that are on the train) and potential consumption of network capacity while the train is stopped. Work events as defined here are only the intermediate stops, and do not include the origination or termination events for the train.
- d) *Train length and tonnage restriction by link*: Depending on geographical and track attributes, certain sections of the railroad have limitations on the maximum train length and tonnage. Train tonnage refers to the weight of the train.
- e) *Number of trains passing through a link*: In order to avoid congestion on certain links of the rail network, links are constrained by the maximum number of trains passing through either by direction or for both directions on a combined basis.
- f) *Crew originating and terminating yards*: Crews can only travel on pre-determined crew segments and every train has to be assigned to a crew on each crew segment. As a result, all trains must originate at the start of a crew segment, and terminate at the end of a crew segment, even if this means that they have to move part of the way along a crew segment without carrying any blocks or railcars.

Different crew segments are governed by different union agreements in the railroad industry. At times, these union agreements get very complicated. For this competition, we assume a simplified version of the crew segments (which are called single-ended territories) across the whole network. Trains can travel across multiple crew segments. Crew Imbalance on a crew segment is considered as the absolute difference between number of trains going from A to B and number of trains going from B to A. Crew imbalance results in additional expense for repositioning the crews using an over-the-road taxi service.

The objective of Train Design Optimization problem is to minimize the sum of:

- a) Train start cost: Product of total number of trains created and each train start cost.
- b) Train travel cost: Product of train travel miles and train travel cost per mile
- c) Car travel cost: Product of car travel miles and car travel cost per mile (cars to be based on the number of cars specified to be in each block)
- d) Work events cost: When a train stops at an intermediate location to either pickup and/or set-off a block, it is considered as a work event. Sum of all the individual work events across all the trains multiplied by the cost per work event is considered as the work events cost.
- e) Blocks swap cost: Sum of block swap costs across all the blocks
- f) Crew imbalance cost: Product of number of imbalance crews and crew imbalance penalty
- g) Trains imbalance cost: Product of trains imbalance and train imbalance penalty
- h) Missed cars cost: A block is considered to be missed if the block is not transported from its origin to destination. Total number of missed cars is the sum of cars in each of the missed block. Missed cars cost is the product of total number of missed cars and missed cost per railcar.
- i) Car hire cost: The time difference between the arrival of a car at the destination yard and the departure at the originating yard is car trip time. The product of trip time and cost to hire a car per hour is the total car hire cost for the trip.

Train design problem is highly combinatorial in nature and a very complex optimization problem. Several attempts have been made in the past to solve special cases of the problem (Assad [2], Keaton [10, 11], Crainic and Rosseau [4], Haghani [7, 8], Gorman [6], Newman and Yano [12, 13], Carpara et. Al. [3, and Dorfman and Medanic [5]). These approaches vary in terms of cost and business constraints considered and the size of the underlying problem instances.

Example

This example considers a railroad network with four nodes as depicted in Figure 1. Block pickup and set-off cost information is provided for each of the nodes in Table 1.

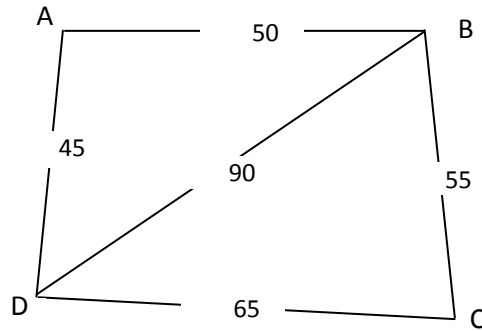


Figure 1. Railroad Network

Node	Block Swap Cost
A	30
B	50
C	50
D	70

Table 1. Pickup and set-off cost (\$) at different nodes in the network

In this example, five blocks are made and their corresponding information is presented in Table 2.

BlockID	Origin	Destination	# of Cars	Total Length (Feet)	Total Tonnage (Tons)	Shortest Distance (Miles)
Block1	A	C	50	3000	2500	105
Block2	A	D	25	1500	1250	45
Block3	B	D	40	2400	2000	90
Block4	D	A	28	1680	1400	45
Block5	D	B	16	960	800	90

Table 2. Blocks information

Origin	Destination	Distance (Miles)	Max Train Length(Feet)	Max Tonnage (tons)	Max # of Trains
A	B	50	8000	10000	3
A	D	45	5000	11000	4
B	C	55	9000	9000	5
B	D	90	8500	10000	4
C	D	75	9200	11000	4

Table 3. Network and Capacity information

Network and link capacity restrictions are provided in Table 3. All the distances are assumed to be symmetrical and all links bi-directional. For example, link B to A is 50 miles and subject to capacity constraints the same as link A to B.

Crew segments information is presented in Table 4. If a train's route is A->B->C, then a crew from crew segment (B – A) is assigned to the train from A -> B at A and subsequently a crew from crew segment (B – C) is assigned to the train from B -> C at B. While a train crosses over from one crew segment to the other, the onboard crew gets off the train and a new crew gets onboard. Further, crew segments are bi-directional. Hence, crews in crew segment A – D can take a train from either A to D or D to A. Furthermore, each crew has to either travel on the shortest path between Node1 and Node2 or incur atmost 15% out of route miles compared to shortest path while traveling on a crew segment. Also, a train can travel for atmost 10 hours before the crew has to change.

Node1	Node2
A	D
B	A
B	D
B	C
D	C

Table 4. Crew segments information

Other input parameters for this optimization problem are provided in Table 5.

Parameters	Values
Crew Imbalance Penalty per imbalance	\$600
Train Imbalance Penalty per imbalance	\$1000
Train travel cost per mile	\$10
Car travel cost per mile	\$0.75
Cost per work event	\$350
Maximum Blocks per train	8
Maximum Block swaps per block	3
Maximum intermediate work events per train	4
Train start cost	\$400
Crew start cost	\$200
Missed cost per railcar	\$5000
Car hire cost per hour	\$0.75
Time required for block pick up	40 Minutes
Time required for block set off	20 Minutes
Average speed of the trains (Miles/Hour)	20

Table 5. Other Optimization Parameters

Feasible solution

In this feasible solution, three trains are created to transport the blocks as displayed in Table 6. Train1 travels from yard A to yard D after picking up 75 cars at yard A. Later, Train1 arrives at yard D, drops off 75 cars and picks up 28 cars. Subsequently, Train1 travels from yard D to yard A with the 28 cars. Similarly, Train2 and Train3 travel between the rail yards to transport the cars. The total train miles in this example are 335 miles. Also, Train1 and Train 2 stop at the common intermediate node D. At node D, both the trains either pickup and/or set-off blocks and is collectively called as a work event. Hence, the total number of work-events done by all the trains is 2.

It is assumed that the same trains run on all days of the week. Hence, Train 1 departs yard A at 1000 on day 1 (represented as 1/1000) and arrives yard D at 1215 on the same day. Based on the average train speed input parameter of 20 miles/hour, it takes 2 hours 15 minutes to travel between yards A and D. Subsequently, Train1 has to wait for 60 minutes at yard D as one set-off (20 minutes) and one pick-up (40 minutes) work event happens. A train's journey can span over multiple days.

Train Name	Sequence	Node	Scheduled Arrival	Schedule Departure	Cumulative Miles	Set-off cars	Pick-up cars	Outbound cars	Crew Change Flag
Train1	1	A	--	1/1000	0	0	75	75	No
Train1	2	D	1/1215	1/1315	45	75	28	28	No
Train1	3	A	1/1530	--	90	28	0	0	No
Train2	1	B	--	1/1100	0	0	40	40	No
Train2	2	D	1/1530	1/1630	90	40	50	50	Yes
Train2	3	C	1/2015	--	165	50	0	0	No
Train3	1	D	--	1/1700	0	0	16	16	No
Train3	2	B	1/2130	--	90	16	0	0	No
Total Train Miles					345				

Table 6. Train Routes Solution

Block-To-Train Assignment information is provided in Table 7. For example, Block1 travels on Train1 from yard A to yard D. Car miles (2,250) for A to D segment for Block1 is the product of A to D segment miles (45) and the number of cars (50) in Block1. In other words, car miles for a block are the product of the block travel distance and the number of cars in the block. Subsequently, the total car miles is the sum of individual car miles of the blocks. In addition, this Block-To-Train Assignment solution satisfies the maximum number of block swaps constraint as presented in Table 5. For example, Block1 travels on two different trains resulting in one block swap. This feasible solution also satisfies the

constraint that a train can carry atmost 10 blocks. Block swap costs at the intermediate nodes for a block are presented in Table 7. For example, Train1 sets-off Block1, which is subsequently picked up by Train2 at node D. Hence a block swap cost at node D is assigned to Block1. Note that block swap cost is not assigned at the origin or destination of block.

Block	Sequence	Train	Start Node	End Node	Block Swap Cost	Segment Miles	# of Cars	Car Miles
Block1	1	Train1	A	D	70	45	50	2,250
Block1	2	Train2	D	C	0	75	50	3,750
Block2	1	Train1	A	D	0	45	25	1,125
Block3	1	Train2	B	D	0	90	40	3,600
Block4	1	Train1	D	A	0	45	28	1,260
Block5	1	Train3	D	B	0	90	16	1,440
Total costs					70			13,425

Table 7. Block-To-Train Assignment Solution

Table 8. presents crew to train assignment information. For Train1, a crew is assigned from A-D and the same crew takes Train1 from D-A. Hence, the forward and reverse directions values for Train1 are both 1. Similarly, for Train2, a crew is assigned from B-D and another crew is assigned from D-C.

Crew Dist	TrainID	Forward	Reverse
A - D	Train1	1	1
B - D	Train2	1	0
D - B	Train3	1	0
D - C	Train2	1	0

Table 8. Crew to Train Assignment

Table 9. presents the crew imbalance information, which is created using the information from Table 4. For example, Train1 travels from yard A to yard D, which is also a crew segment. Hence, A -> D can be considered as Direction I in Table 9. Subsequently, D -> A is considered as Direction II. Direction I # of trains represents the count of all the trains traveling from A -> D in Table 6 that require a crew change at yard A and yard D. Similarly, Direction II # of trains represents the count of all the trains traveling from D -> A that require a crew change at yard D and yard A. In Table 9, Crew Imbalance for the segment A -> D and D -> A is the absolute difference between Direction I and Direction II # number of trains. As we consider the absolute difference between the forward and reverse number of trains, it does not matter which direction is considered as the forward direction.

Direction I	Direction II	Direction I # of Trains	Direction II # of Trains	Crew Imbalance
A -> D	D -> A	1	1	0
B -> D	D -> B	1	1	0
D -> C	C -> D	1	0	1
Total Crew Imbalance				1

Table 9. Crew Imbalance Information

Table 10. presents the train imbalance information, which is extracted from Table 6. In Table 6. it can be observed that one train originates at each of the yards A, B and D. The intermediate stops of the trains are not considered in this calculation. Similarly, one train terminates at each of the yards A, B and C. As one train terminates at yard C but no train originates there, yard C has a train surplus or imbalance. Similarly, yard D has a train deficit or imbalance.

Yard	Originating Trains	Terminating Trains	Train Imbalance
A	1	1	0
B	1	1	0
C	0	1	1
D	1	0	1
Total Train Imbalance			2

Table 10. Train Imbalance Information

Block	Number of Cars	Trip Begin Time	Trip End Time	Trip Time (Hours)	Car Hire Hours
Block1	50	1/1000	1/2015	10.25	512.5
Block2	25	1/1000	1/1215	2.25	56.25
Block3	40	1/1100	1/1530	4.5	180
Block4	28	1/1315	1/1530	2.25	63
Block5	16	1/1700	1/2130	4.5	72
Total Car Hire Hours					883.75

Table 11. Car Hire Hours Information

Table 11 presents the car hire hours depending on the trip time for each of the blocks. Block1

departs its origin yard A on Train1 at 1/1000 (time 1000 on day 1) and arrives at its destination yard C on Train2 at 1/2000. Trip time is the difference between the block arrival at destination and departure at origin yard. Car hire hours are product of Trip time of a block and the number of cars in the block.

The objective function is composed of four different components

- a) Train start cost is 3 (Number of train) * 400 (Table 5) = \$1,200
- b) Crew start cost is 5 (Number of crews used) * 200 (Table 5) = \$1000
- c) Train travel cost is 345 (Table 6) * 10 (Table 5) = \$3,450
- d) Car travel cost is 13,425 (Table 7) * 0.75 (Table 5) = \$10,068.75
- e) Work event cost is 2 (Number of train work events) * 350 (Table 5) = \$700
- f) Block Swap cost is 70 (Table 7) = \$70
- g) Crew imbalance cost is 1 (Table 9) * 600 (Table 5) = \$600
- h) Train imbalance cost is 2 (Table 10) * 1000 (Table 5) = \$2,000
- i) Missed cars cost is 0 (Total number of missed cars) * 5000 (Table 5) = \$0
- j) Car hire cost is 883.75 (Table 11) * 0.75 (Table 5) = \$662.81

The final objective function value is \$19,751.56.

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