OPTIMIZING LOCATION AND LENGTH OF PASSING SIDINGS ON SINGLE-TRACK LINES FOR LONG HEAVY-HAUL FREIGHT TRAINS

Mei-Cheng Shih

Graduate Research Assistant

University of Illinois, Urbana-Champaign, IL, USA

P.E. C. Tyler Dick

Senior Research Engineer

University of Illinois, Urbana-Champaign, IL, USA

Dr. Yung-Cheng Lai

Associated Professor

National Taiwan University, Taiwan

SUMMARY

Operation of long freight trains in heavy haul service can help improve the operation efficiency and reduce the unit cost, but the current rail infrastructure in North American can't fully support this type of operation. In North American, which the majority of rail network is single-track lines, the potential benefits of long freight trains are constrained due to the insufficient length of many passing sidings on many existing single-track lines. As a response to the infrastructure condition, railroads can operate long trains in a single direction [1] or fleet the long freight trains. However, increasing the length of existing short sidings is a more fundamental solution for the growing number of long freight trains. Constructing additional sidings with sufficient length is also a solution to facilitate the long freight operation. The trade-off between extending lengths of existing sidings and constructing new sidings with sufficient length could be very complicated when the budget is limited and alternatives are numerous. This study proposed an Optimal Project Selection Model (OPSM) to help the railroad planners select the most effective combination of available projects in order to maximize the return from the investment of railroads. Moreover, the developed tool is demonstrated by a hypothetical single-track scenario in the case study. The result of case study also proved the benefits from operation of long freight trains.

1 INTRODUCTION

The intention of long train operation of railroad industry as well as the associated economic and operation efficiency has been covered in a previous study. Newman et. al. [2] explained the economic and operational benefits of longer unit trains on one Class 1 Railroad. There is also a literature done by Martland [3] which stated the benefits of siding extension projects. He indicated the potential contributions of siding extension projects by showing a conservative estimation that 2/3 of the unit trains in operation are limited by the length passing sidings. On the other hand, constructing additional sidings with sufficient length on the existing single-track lines can also facilitate the operation of long freight trains. This strategy is used by at least one Class 1 railroad to accommodate long train operation and reduce traffic congestion [4]. Since the overall budget available for infrastructure improvement is always limited, a comprehensive planning process to balance the investment allocated to each type of projects is an essential element to help railroads maximize their return from investment.

Currently, railroad industry in North American relies on the experienced practitioners to find the solutions for the infrastructure constraints. This applies to the case to find solution for long freight train operation too. However, the experienced practitioners can identify feasible and effective infrastructure projects, but may not be able to consider all the related factors before determine an optimal selection of projects. In this study, an Optimal Project Selection Model (OPSM) is proposed to help railroad planners determine the optimal selection of available projects under limited budget. The result from OPSM, an optimal siding construction and extension plan which indicates the optimal selection of available projects, can help rail network to accommodate the operation of long freight trains. This can help the railroads to boost their economic and operation efficiency.

2 PROBLEM DESCRIPTION

Using the mathematical programing techniques, OPSM focuses on the determination of the optimal siding construction and extension plan. OPSM coordinates the ideas of both capacity planning and train dispatching models through a series of constraints [6] to achieve this goal. For the capacity planning part, the infrastructure constraints consider the construction cost, length and the capacity of the sidings [7]. In addition to the infrastructure constraints, those related to operation issues are considered through traffic constraints. Traffic constraints guarantee the necessary headway between two adjacent trains [8] and take the effect of train speed, length and commercial schedule into consideration.

Figure 1 below shows the conceptual framework for OPSM together with the inputs and outputs. The input parameters of the optimization model are track infrastructure properties and traffic characteristics. Based on the input parameters, the feasible projects will be identified and the travel time of each segment will be calculated, these data will then be use by the OPSM. OPSM follows the principles mentioned to generate two types of output (train paths and an optimal siding location plan) that depend on three cost categories (equivalent investment cost, meet and pass delay cost, and late departure cost).
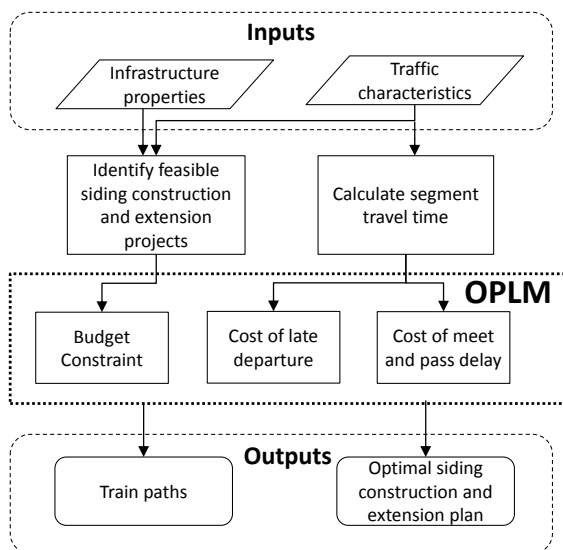

Figure 1 : Conceptual framework for OPSM

The details of the input data are displayed in the following list:

- Infrastructure properties
  - Mileposts of siding construction or extension projects (mile)
  - Total length of mainline (mile)
  - Construction costs associated with siding construction or extension projects (USD)
  - Locations and lengths of existing sidings (mile)

- Traffic characteristics
  - Average speed of trains on mainline in each segment (mph)
  - Average speed of trains on each existing and prospective siding (mph)
  - Scheduled departure time for trains (hr)
  - Lost time per acceleration and deceleration (hr)
  - Safety headway for adjacent trains (hr)

Infrastructure properties are associated with the existing track configuration, grade, and curvature. Traffic characteristics include the traffic mixture, train speed, commercial schedule, and the lengths of trains. Moreover, the effect of grade and curvature can be considered by adjusting the average speed of trains. OPSM uses these two different types of data to generate an optimal siding construction and extension plans.

3 NOTATION

In this study, the original track configuration and the relative locations of available projects are represented by three basic types of indices. Figure 2 below illustrates the relationship of these three types of indices. In this figure, notation q represents all the nodes, notation p stands for the segments between any two adjacent nodes, and notation c indicates the type of sidings. A more detailed notation list is displayed in Table 2.
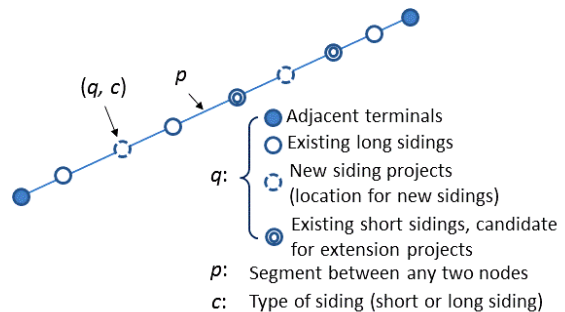

Figure 2 : Illustration of basic indices

Table 2 : Indices, sets and parameters used in OPSM

(a) Indices and sets

Indices	Description
$(i, j) \in N$	Indices referring to trains running through the line
$(p, r) \in P$	Indices representing sections of the line
$(q, s) \in Q$	Indices stand for sidings and stations (nodes)
$c \in C$	Index referring to standards of siding length (short or long)

Sets	Description
b^+	Set of any two trains with same direction
b^-	Set of any two trains with opposite direction
κ	Set of existing and prospective siding nodes
ε_i	Set of origins to train i

(b) Sets and parameters

Sets	Description
η^+	Set of prospective sidings
η^-	Set of existing sidings (potential objective for extension)
k_i	Set of destinations to the trains
ψ	Set of short sidings
δ_p	Set composed of all section p and the adjacent node q to enter the section
θ_p	Set composed of all section p and the adjacent nodes (q, s)
π	Set of origins and their adjacent sections

Parameters	Description
β	Equivalent weight for investment cost
t_i^q	Extra travelling time for train i to across siding q than a parallel section on mainline (hr)
f_i	Lost time due to an acceleration and a deceleration of train i (hr)
σ_i^p	Running time of train i on segment p
$U^{q,c}$	Cost of constructing siding q with type c *length standard* (USD)
$g^{q,c}$	The type of standard length of the existing siding
φ^q	Location of existing and prospective sidings q (milepost)
e_i^+	Earliest possible departure time of train i (hr)
e_i^-	Latest possible departure time of train i (hr)
h_{ij}^p	Safety headway between adjacent train i abd j on section p (hr)
L^c	Ability for siding q with type c legnth standard to accommodate trains, equal to 1 if c is long siding type, 0 if short siding type
v^i	Length standard of train i, equal to 1 if i is a long train, equal to 0 if i is a short train
W^i	Delay cost, the cost generated by an idling train-hour , it also reflects the priority of train i
M	An arbitrary big number
E	Total dispatching duration (hr)
B	Available budget (USD)

4 MODEL FORMULATION

Three basic types of decision variables are used in OPSM: train time variables, infrastructure variables and train dispatching variables. Train time variables represent the arrival and departure time of trains. Obtaining the values of time variables is equal to obtaining the train paths.

D_i^q = departure time of train i at node q

A_i^q = arrival time of train i at node q

y = time for last train to arrive its destination

The infrastructure variables determine the selection of feasible projects. An optimal siding construction and extension plan can be derived from the values of infrastructure variables.

z^{qc} = equal to 1 if siding q is in the standard length of type c

Train dispatching variables are used to ensure the logic behind train dispatching mechanism in OPSM.

x_{ij}^p = equal to 1 if train i passing through segment p before train j, 0 otherwise

o_i^q = equal to 1 if train i stays on siding q during the dispatching period, 0 otherwise

θ_{ij}^q = equal to 1 if and only if train i stays on siding q before train j, 0 otherwise

Equation (1) shows the objective function of OPSM. It minimizes the total cost during the planning horizon, which includes equivalent investment cost, meet and pass delay cost, and the late departure cost. The equivalent weight β for investment cost can be determined by following the principle mentioned in the study by Lai and Barkan [9]. Since W^i is the delay cost for different type of trains, the dispatching result could reflect the business objectives of North American railroads [10].

Objective:

$$Min\ \beta \sum_{c \in C} \sum_{q \in \eta^+} U^{qc}(z^{qc} - g^{qc}) +$$

$$\sum_{i \in N} \sum_{q \in \kappa} W^i(D_i^q - A_i^q) + \tag{1}$$

$$\sum_{i \in N} \sum_{q \in \varepsilon_i} W^i(D_i^q - e_i^+)$$

This objective is subject to a set of constraints (equations (2)~(24)), including dispatching constraints, commercial schedule constraints, siding length and capacity constraints, track configuration constraints and environmental constraints. The train dispatching constraints maintain a reasonable logic of the train dispatching process. They are shown in equations (2) to (7). The basic principle followed by this type of constraint to dispatch trains is to ensure a reasonable headway between any two adjacent trains. Equations (2) and (4) maintain a headway between the departure times of any adjacent trains toward the same direction and equations (3) and (5) maintain a headway between the arrival times of any two adjacent trains. Equations (6) and (7) guarantee the headway between two adjacent trains in opposite directions.

$$M(1 - x_{ij}^p) + D_j^q \geq D_i^q + h_{ij}^p$$

$$\forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{2}$$

$$M(1 - x_{ij}^p) + A_j^q \geq A_i^q + h_{ij}^p$$

$$\forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{3}$$

$$Mx_{ij}^p + D_i^q \geq D_j^q + h_{ij}^p$$

$$\forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \qquad (4)$$

$$Mx_{ij}^p + A_i^q \geq A_j^q + h_{ij}^p$$
$$\forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \qquad (5)$$

$$M(1 - x_{ij}^p) + D_j^q \geq A_i^q + h_{ij}^p$$
$$\forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \qquad (6)$$

$$Mx_{ij}^p + D_i^q \geq A_j^q + h_{ij}^p$$
$$\forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \qquad (7)$$

Based on the commercial freight train schedule, equation (8) enforces that trains depart from the origin before their latest allowable times.

$$e_i^+ \leq D_i^q \leq e_i^- \quad \forall i \in N,\ q \in \pi \qquad (8)$$

Equations (9) to (14) are siding length and capacity constraints. Equation (9) ensures that a dwell of a train link to variable o_q^i. Equations (10) and (11) identify the stopping sequence of trains on the same siding. Equation (12) helps eliminate all possible conflicts between two trains on the same siding. Equation (13) is the siding length constraint. It forbids a train to use a siding if the length of the train is longer than the standard length of the type of the siding. Equation (14) captures the extra travel time experienced by trains due to acceleration, deceleration, siding speed limit while traveling on sidings.

$$Mo_i^q \geq D_i^q - A_i^q \quad \forall i \in N,\ q \in Q \qquad (9)$$

$$\theta_{ij}^q \geq o_i^q + o_j^q + x_{ij}^p - 2$$
$$\forall i \in N,\ j \in N,\ i \neq j,\ q \in \delta_p,\ p \in P \qquad (10)$$

$$3\theta_{ij}^q \leq o_i^q + o_j^q + x_{ij}^p$$
$$\forall i \in N,\ j \in N,\ i \neq j,\ q \in \delta_p,\ p \in P \qquad (11)$$

$$A_j^q \geq D_i^q + h_{ij}^p - M(1 - \theta_{ij}^q)$$
$$\forall i \in N,\ j \in N,\ i \neq j,\ q \in \{\kappa \cap \delta_p\},\ p \in P \qquad (12)$$

$$v^i o_i^q \leq \sum_{c \in C} L^c (z^{qc} + g^{qc}) \quad \forall i \in N,\ q \in \kappa \qquad (13)$$

$$D_i^q \geq A_i^q + o_i^q(f_i + t_i^q) \quad \forall i \in N,\ q \in Q \qquad (14)$$

The following constraints are the track configuration constraints. Equation (15) maintains the lengths of the original long sidings. Equation (18) maintains the location of existing sidings at their original locations. Equation (16) prevents trains from meeting or passing at a non-existing

siding. Equation (17) ensures that a prospective siding can only has one type and equation (18) ensures the model to select one type for all present sidings. Moreover, since the current siding construction projects are usually designed as long siding type. Equation (19) enforces the type of new constructed sidings to be long siding. The reason to have this constraint is because long siding is the new standard length of new constructed sidings in North American.

$$\sum_{c \in C} v^c g^{qc} \leq \sum_{c \in C} v^c z^{qc} \qquad \forall q \in Q \qquad (15)$$

$$\sum_{i \in N} o_i^q \leq M \sum_{c \in C} z^{qc} \qquad \forall q \in Q \qquad (16)$$

$$\sum_{c \in C} z^{qc} \leq 1 \qquad \forall q \in \eta^+ \qquad (17)$$

$$\sum_{c \in C} z^{qc} = 1 \qquad \forall q \in \eta^- \qquad (18)$$

$$\sum_{c \in \psi} z^{qc} = 0 \qquad \forall q \in \eta^+ \qquad (19)$$

Equation (20) is the budget constraint. Equation (21) ensures OSLM to complete the dispatching process within a time period. Equation (22) fixes the train running time between any two adjacent nodes as average train running time along the section.
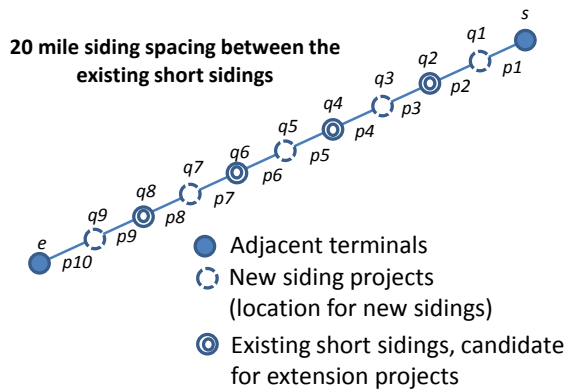
$$\sum_{c \in C} \sum_{q \in \eta^+} U^c z^{qc} \leq B \qquad (20)$$

$$A_i^q \leq E \qquad \forall i \in N,\ q \in k_i \qquad (21)$$

$$A_i^q - D_i^s = \sigma_i^p \quad \forall i \in N,\ (q,s) \in \vartheta_p,\ p \in P \qquad (22)$$

5 CASE STUDY

The use of OPSM is demonstrated in a hypothetical case (Figure 3) in the case study. It is a 100 miles long single-track line with 5 existing short sidings for siding extension projects and 4 locations of prospective siding projects. There is a 20 mile spacing between any two existing and adjacent sidings. Furthermore, the distance between an existing siding and a prospective siding project is 10 miles. The result of this case study not only show the capability of the tool to determine an optimal siding construction and extension plan, but display the potential benefits of using long freight trains.

20 mile siding spacing between the existing short sidings

● Adjacent terminals
◌ New siding projects (location for new sidings)
◎ Existing short sidings, candidate for extension projects

Figure 3 : Hypothetical case used in the case study

The values of the important parameters used in the case study are listed in Table 3. The priority of freight trains denoted by delay cost, is set according to Dingler [10]. These parameters in Table 3 reflect the advantages and disadvantages of short and long train operations. Long train operation requires fewer trains to fulfil the traffic demand, but decreases the average train speed. Short train operation need to run more trains to fulfil the demand, but the average train speed is higher than the long trains.

Table 3 : Input parameters

Parameter	Value
Train length (car)	Short freight trains: 100 cars
	Long freight trains: 150 cars
Average train speed (mph)	Short freight trains: 40 mph
	Long freight trains: 32 mph
Total traffic demand per day (car)	1200 cars per direction
Priority of trains (delay cost per hr, in USD)	Short freight trains: 586 USD/hr
	Long freight trains: 879 USD/hr
	(1.5 times as short trains)
Commercial schedule	The departure times of the trains are evenly distributed in 20 hours
Maximum track speed	40 mph
Safety headway between two trains	6 min
Planning horizon	5 years

To evaluate the effect of different traffic mixture of short and long freight trains, four traffic scenarios were tested. The details are listed below, noted that the total number of cars through the mainline maintains the same (1200 cars in total) in all scenarios.

- Scenario 1: 9 short trains, 0 long trains
- Scenario 2: 6 short trains, 2 long trains
- Scenario 3: 3 short trains, 4 long trains
- Scenario 4: 0 short trains, 6 long trains

OPSM was coded into GAMS and solved by CPLEX. Depending on the scenarios, the number of variables ranges from 3,500 to 7,000, the number of equations ranges from 10,500~20,400,

and the solution time ranges from 1 to 3 hours. Two types of outputs were generated from OPSM: the train dispatching result and the optimal siding construction and extension plan. Figure 4 shows the train dispatching result of scenario three as an example. Since there are no conflicts, the train dispatching mechanism in OPSM is logically reasonable.
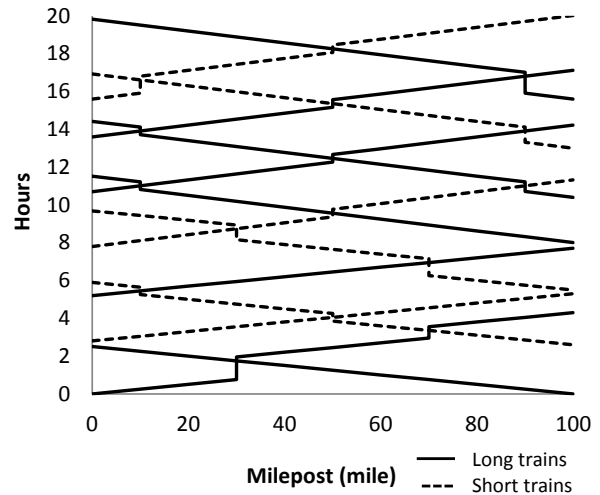

Figure 4 : Traffic dispatching result

Table 4 is the optimal siding construction and extension plans for all scenarios. It shows that the increase in ratio of long train in traffic decreases the number of siding construction projects and increases the number of siding extension projects. An explanation for this fact is that long train operation requires the existence of long sidings to execute meet and pass process. Also, the use of long trains decreases the number of trains that needs to be dispatched per day. The original track configuration with some siding extension projects is capable enough to handle the traffic under this circumstances.

Table 4 : Optimal siding construction and extension plans

Scenarios	Selected siding construction projects	Selected siding extension projects	Total investment cost (million
1	q6, q8		16.0
2	q6	q3	11.5
3		q1, q5, q9	10.5
4		q1, q5, q9	10.5

Figure 5 shows the equivalent investment cost, delay cost and total cost of all scenarios. For all scenarios, the total cost is less if the ratio of long trains is increased. This proves that the operation of long trains helps save the capital investment and reduces the total traffic delay. For this reason, the benefits of the long freight train operation are further strengthened.
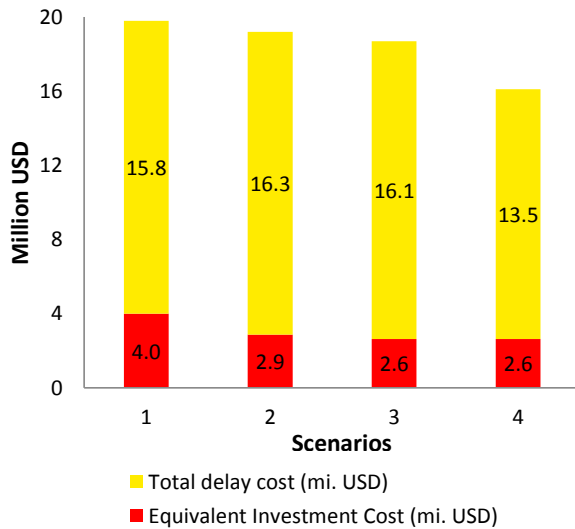
Figure 5 : Equivalent investment, delay, and total cost in all scenarios

6 CONCLUSION

The use of longer freight trains benefits both economical and operational efficiencies. However, the operation of long freight trains is constrained by the length of existing sidings. Railroads rely on the experienced practitioners to identify some effective and feasible projects as the solutions but may not be able to select the optimal collection of the solutions to solve the problems. Since human decision may not fully evaluate all the related factors while selecting the projects that need to be conducted, this study presents an OPSM to help railroads determine the optimal siding construction and extension plan. A case study was used to demonstrate the ability of OPSM. Result from the case study indicates that the increase in use of long freight trains can reduce investment and delay cost thus can help the railroads to maximize their return from investment and enhance the freight service quality.

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