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

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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).

![Conceptual framework for OPSM](image)

Figure 2 : Illustration of basic indices

Table 2 : Indices, sets and parameters used in OPSM

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

<table>
<thead>
<tr>
<th>Sets</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b^+)</td>
<td>Set of any two trains with same direction</td>
</tr>
<tr>
<td>(b^-)</td>
<td>Set of any two trains with opposite direction</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>Set of existing and prospective siding nodes</td>
</tr>
<tr>
<td>(\epsilon_i)</td>
<td>Set of origins to train (i)</td>
</tr>
</tbody>
</table>
Train dispatching variables are used to ensure the logic behind train dispatching mechanism in OPSM.

\[ x_{ij}^p = \begin{cases} 1 & \text{if train } i \text{ passing through segment } p \text{ before train } j, \text{ 0 otherwise} \\ a_{ij}^q = \begin{cases} 1 & \text{if train } i \text{ stays on siding } q \text{ during the dispatching period}, \text{ 0 otherwise} \\ \theta_{ij}^q = \begin{cases} 1 & \text{if and only if train } i \text{ stays on siding } q \text{ before train } j, \text{ 0 otherwise} \\ \end{cases} \\ \end{cases} \]

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 \( \beta \) for investment cost can be determined by following the principle mentioned in the study by Lai and Barkan [9]. Since \( W \) is the delay cost for different type of trains, the dispatching result could reflect the business objectives of North American railroads [10].

**Objective:**

\[
\min \beta \sum_{c \in C} \sum_{q \in Q^c} U^{qc}(z^{qc} - g^{qc}) + \\
\sum_{i \in N} \sum_{q \in Q} W^i(D_i^q - A_i^q) + \\
\sum_{i \in N} \sum_{q \in Q} W^i(D_i^q - e_i^q) \\
\]

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.

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

\[ \forall (i,j) \in b^+, i \neq j, q \in \delta^p, p \in P \]

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

\[ \forall (i,j) \in b^+, i \neq j, q \in \delta^p, p \in P \]

\[ Mx_{ij}^p + D_i^p \geq D_j^p + h_{ij}^p \]
\[ \forall (i,j) \in b^+, i \neq j, q \in \delta_p, p \in P \tag{4} \]

\[ Mx^q_j + A^q_j \geq A^q_i + h^q_j \tag{5} \]

\[ \forall (i,j) \in b^+, i \neq j, q \in \delta_p, p \in P \]

\[ M(1 - x^q_i) + D^q_j \geq A^q_i + h^q_q \tag{6} \]

\[ \forall (i,j) \in b^+, i \neq j, q \in \delta_p, p \in P \]

\[ Mx^q_j + D^q_i \geq A^q_j + h^q_j \tag{7} \]

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

\[ e^+_i \leq D^q_i \leq e^-_i \quad \forall i \in N, q \in \pi \tag{8} \]

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.

\[ M_{o^q} \geq D^q - A^q \quad \forall i \in N, q \in Q \tag{9} \]

\[ \theta^q_i \geq \theta^q_i + o^q_j + x^q_i^o - 2 \quad \forall i \in N, j \in N, i \neq j, q \in \delta_p, p \in P \tag{10} \]

\[ 3\theta^q_i \leq \theta^q_i + o^q_j + x^q_i^p \quad \forall i \in N, j \in N, i \neq j, q \in \delta_p, p \in P \tag{11} \]

\[ A^q_i \geq D^q_j + h^q_j - M(1 - \theta^q_i) \quad \forall i \in N, j \in N, i \neq j, q \in \kappa \cap \delta_p, p \in P \tag{12} \]

\[ \psi^q_i \leq \sum_{c \in C} \ell(c) (z^q + g^q) \quad \forall i \in N, q \in \kappa \tag{13} \]

\[ D^q_i \geq A^q_i + o^q_i(f_i + t^q_i) \quad \forall i \in N, q \in Q \tag{14} \]

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 have 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.

\[ \sum_{c \in C} g^q c \leq \sum_{c \in C} z^{o^q} c \quad \forall q \in Q \tag{15} \]

\[ \sum_{i \in N} q^a_i \leq M \sum_{c \in C} z^{o^q} c \quad \forall q \in Q \tag{16} \]

\[ \sum_{c \in C} z^{o^q} c \leq 1 \quad \forall q \in \eta^+ \tag{17} \]

\[ \sum_{c \in C} z^{o^q} c = 1 \quad \forall q \in \eta^- \tag{18} \]

\[ \sum_{c \in C} z^{o^q} c = 0 \quad \forall q \in \eta^- \tag{19} \]

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.

\[ \sum_{c \in C} U^c z^{o^q} c \leq B \tag{20} \]

\[ \hat{A}^q_i \leq E \quad \forall i \in N, q \in k_i \tag{21} \]

\[ A^q_i - D^q_i = \sigma^q_i \quad \forall i \in N, (q, s) \in \delta_p, p \in P \tag{22} \]

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.
The departure times of the trains from 1, q1, q5, q9 5 years

Short freight trains: 100 cars                     
Long freight trains: 150 cars

Average train speed
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,
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.

7 REFERENCES


