Optimization of Siding Location for Single-Track Lines

Mei-Cheng Shih, Yung-Cheng (Rex) Lai, C. Tyler Dick, and Ming-Hsuan Wu

The demand for rail transportation in North America is expected to increase significantly in the coming decades. Additional capacity will be required to accommodate the new traffic demand for both passenger and freight services. The majority of the network is single track with passing sidings, which trains use for meets and passes; therefore, allocating sidings properly can significantly increase line capacity and reduce train delay. Railroads usually rely on experienced personnel to determine new siding locations to improve line capacity through infrastructure upgrades. Experienced railroaders often identify good solutions; however, this method does not guarantee that all good alternatives have been evaluated or that the best one is implemented. In this research, an optimal siding location model is developed with consideration of infrastructure and traffic characteristics to determine the optimal number and locations of sidings. The empirical results demonstrate that this model is able to generate an optimal plan for the number of additional sidings and their respective locations. This tool can therefore help railroads maximize their return on investment from capacity expansion projects and achieve the service quality desired by customers.

The demand for rail transportation in North America is expected to increase significantly in the coming decades (*1, 2*). Additional capacity will be required to accommodate the new traffic demand for both passenger and freight services. The capacity of a line can generally be increased through operational strategies or infrastructure upgrades (*3, 4*). As compared with infrastructure upgrades, operational strategies are less expensive and can be implemented quickly; however, this type of approach is relatively short-sighted and can only handle slight increases in traffic demand. The projected long-term increase in traffic demand is unlikely to be satisfied solely by changing operating strategies. Consequently, determining how to upgrade the infrastructure to accommodate future demand is an urgent task for all Class I railroads (*5, 6*).

In North America, the majority of the railway network is single track with passing sidings, which trains use for meets and passes. A proper allocation of sidings can increase capacity considerably, whereas poor decisions on passing siding location and spacing can lead to inefficient operations and significant train delay. For example, if two trains on a route between two adjacent terminals depart at the same time, each heading to the opposite terminal, it is clear that (assuming homogeneous train speed and acceleration) a passing siding must be placed halfway between the terminals to minimize delays due to train meets. However, for actual railroads, where territories of interest may be hundreds of miles long with an uneven distribution of speed restrictions and a heterogeneous traffic pattern, a systematic planning process is needed that determines the optimal number and location of sidings.

Railroads usually rely on established guidelines (*7*) and experienced personnel to determine new siding locations during the process of infrastructure upgrades (*5, 6, 8*). Experienced railroaders often identify good solutions; however, this method does not guarantee that all beneficial alternatives have been evaluated or that the best one is implemented (*9, 10*). Petersen and Taylor used simulation analysis to determine the optimal positions of sidings for a line with homogeneous traffic (*11*). Pawar used an analytical model to investigate the relationship between the length of sidings and the delays in meets (*12*). These two studies focused only on the effect of siding length and location instead of a siding planning problem with heterogeneous traffic. Higgins et al. developed the first optimization model to determine optimal siding locations (*13*).

The Higgins model is capable of determining the number and locations of sidings, but it does not take into account siding capacity constraints, construction costs, or the existing pattern of passing sidings. Infrastructure construction cost and practical construction concerns can reposition sidings away from optimal locations near bridges, grade crossings, tunnels, and narrow rights-of-way in urban areas. Decisions to avoid these locations are often made without full consideration of the trade-off between the increased construction cost of a particular optimal location and the long-term operating inefficiencies of a suboptimal location that is less costly to construct. Consequently, this research developed an optimal siding location model (OSLM) that considers infrastructure, construction cost, and traffic characteristics to determine the optimal number and location of sidings automatically. Through more informed decisions on siding location, railroads can use this tool to both maximize their return on investment from capacity expansion projects and achieve the service quality desired by customers.

OPTIMAL SIDING LOCATION MODEL

Problem Description

The siding planning problem focuses on the determination of the optimal number and location of additional sidings to be constructed on a single-track railway line. Although part of the problem is similar to a capacity planning problem, the solution also requires an

M.-C. Shih and C. T. Dick, Rail Transportation and Engineering Center, Department of Civil and Environmental Engineering, University of Illinois at Urbana–Champaign, 205 North Mathews Avenue, Urbana, IL 61801. Y.-C. (Rex) Lai and M.-H. Wu, Railway Technology Research Center, Department of Civil Engineering, National Taiwan University, Civil Engineering Building, Room 313, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan. Corresponding author: M.-C. Shih, mshih2@illinois.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2448, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 71–79.
DOI: 10.3141/2448-09

analytical approach to establishment of traffic flow through the network, especially for lines with heterogeneous traffic. As a result, the siding planning problem incorporates the ideas of both capacity planning and train dispatching through a series of constraints (*13*). The first type of constraint guarantees the necessary headway between two adjacent trains to avoid conflicts (*14–16*). The length and the capacity of the sidings need to be considered to avoid conflicts on sidings (*17, 18*). The effect of train characteristics, composition, and commercial schedule must also be taken into account to capture the impact of traffic heterogeneity (*19–23*).

In addition to these operational constraints, those related to infrastructure issues must be considered. The possible number and location of prospective sidings must first be identified according to the existing track configuration. The properties of the current track configuration, such as the location of existing sidings and stations, must be considered along with variation in construction cost in order to obtain a practical result that is applicable to railroads. The traditional method used by the rail industry usually takes into account only a subset of the concepts just mentioned. Thus the traditional method may be inadequate in generating the most effective siding location plan as a means of increasing line capacity. The OSLM is developed in this study to assist the siding planning process by factoring in a wide range of related parameters that ultimately generate an optimal siding location plan.

Figure 1 shows the conceptual framework for the OSLM and its inputs and outputs. The input parameters of the optimization model include track infrastructure properties, traffic properties, and operational parameters. On the basis of these input parameters, the optimization framework will follow the principles mentioned to deliver 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.

The detailed input data required by the OSLM are given in the following list.

- Traffic characteristics:
  - Average train traveling speed (mph),
  - Train direction (inbound–outbound),
  - Lost time due to acceleration and deceleration (h), and
  - Safety headway (h);
- Infrastructure properties:
  - Construction cost variation (milepost and US$),
  - Existing track configuration (miles and milepost),
  - Maximum speed along corridor (mph), and
  - Minimum siding spacing (mi); and
- Operational parameters:
  - Priority of trains (delay cost in US$ per h),
  - Turnout switching time (h),
  - Commercial schedule for passenger trains (h), and
  - Freight operating schedule (h).

Traffic characteristics depict the condition of traffic. Infrastructure properties are associated with the existing track configuration, terrain, and curvature along the line. Operational factors are the other parameters that affect the train dispatching process. In addition, the effect of grade can manifest itself in the maximum speed of trains, and the effect of curvature can be reflected in the average speed limit of a particular line. These three different types of parameters are used by the OSLM to generate an optimal siding location plan.

Data Preprocessing

Most of the data given above can be used directly by the OSLM but some of the infrastructure inputs need to be preprocessed. Figure 2 is an example of the result from preprocessing, where q represents nodes or sidings and n is the number of nodes or sidings. The notation p_n represents the segments between each pair of adjacent nodes (sidings, stations, yards) on a line, and n is the number of each segment. The notation c_n stands for construction zone, and n is the number of each construction zone. From the number and location of existing nodes, the maximum number and relative location of prospective sidings can be determined.

The maximum number of possible sidings between two existing sidings can be calculated by $\lfloor d/g \rfloor - 1$, where d is the segment length between two adjacent sidings and g is the minimum siding

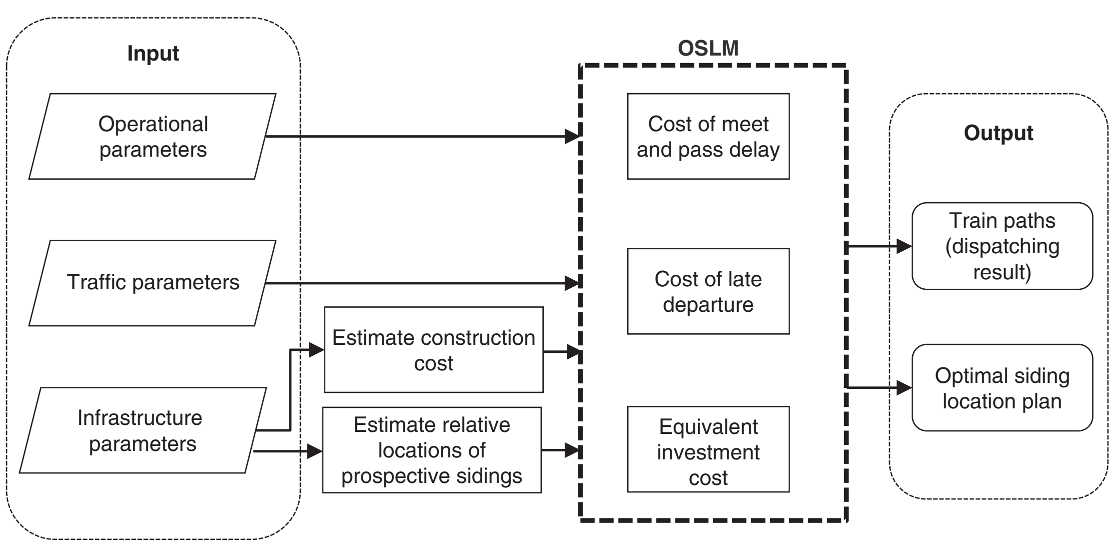

FIGURE 1 Decision support process of OSLM.

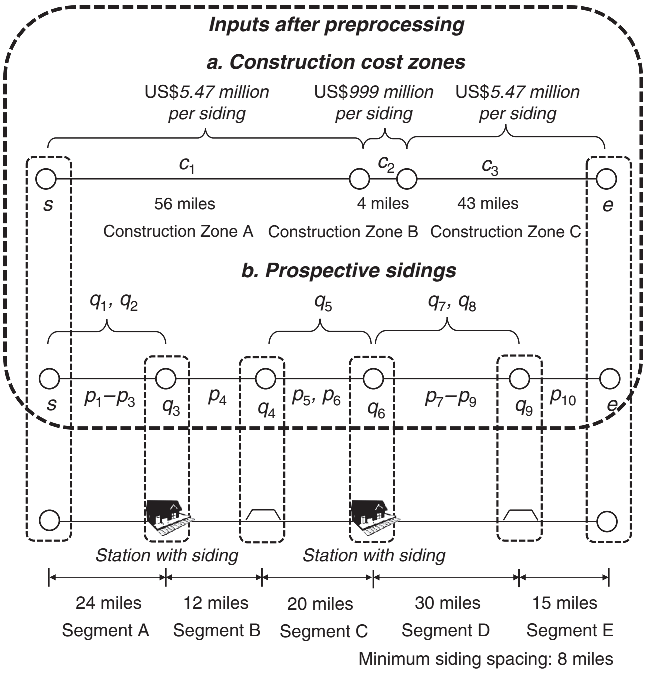

FIGURE 2 Example of preprocessing for infrastructure data.

spacing. For example, the spacing between the first existing siding and the starting node is 24 mi. Since the minimum siding spacing is assumed to be 8 mi in this study, the maximum number of prospective sidings is $\lfloor 24/8 \rfloor - 1 = 2$. Therefore, two possible sidings, q_1 and q_2, are identified between the first siding and the starting node. Both q_1 and q_2 can be built anywhere between the two existing sidings if the minimum siding spacing constraint is not violated. This fact holds for all sidings q_1–q_n throughout the model.

Following this process, several possible sidings (q_1, q_2, q_5, q_7, q_8) were identified and labeled in the example network shown in Figure 2. Moreover, the boundaries of each construction zone and the associated cost of siding construction can be either referenced from similar projects on other lines or obtained with simple estimation methods. If there are particular locations where siding construction is undesirable (e.g., sections with multiple grade crossings or a narrow right-of-way), an arbitrarily high construction cost can be assigned to these inappropriate sites, much like the c_2 zone illustrated in Figure 2, which was given a US$999 million cost of construction.

Mixed Integer Programing Model for OSLM

An optimization model for the siding planning problem can be seen as the combination of capacity planning and train dispatching models (*13*). Past studies usually focused on just one of these two models and were therefore incapable of solving the complete siding planning problem. By combining the two models, the OSLM can generate an optimal siding location plan to minimize the total cost (including investment cost, delay cost, and late departure cost) while satisfying a set of practical constraints (e.g., train separation, construction cost, siding capacity). In Table 1, all of the indexes, sets, and parameters used in the OSLM are defined.

TABLE 1 Indexes, Sets, and Parameters Used in OSLM

Symbol	Description
Indexes	
$(i, j) \in N$	Trains running through line
$(p, r) \in P$	Segments of line
$(q, s) \in Q$	Sidings and stations (nodes)
$c \in C$	Order of construction zones
Sets	
b^+	Any two trains with same direction
b^-	Any two trains with opposite direction
κ	Existing and prospective siding nodes
ε_i	Origins to train i
η^+	Prospective sidings
η^-	Existing sidings and stations
k_i	Destinations to the trains
δ_p	All segment p and adjacent node q to enter segment
ϑ_p	All segment p and adjacent nodes (q, s)
π	Origins and their adjacent segments
Parameters	
v_M^i	Average train traveling speed (mph)
β	Equivalent weight for investment cost
t_i^q	Extra traveling time for train i to cross siding q than parallel section on main line (h)
τ_i^q	Scheduled dwell time for passenger train i on station q
g	Minimum siding spacing (mi)
f_i	Lost time due to acceleration and deceleration of train i (h)
σ^c	Boundary of construction cost zone c (milepost)
U^c	Cost per siding in construction cost zone c (US$)
φ^q	Location of existing siding q (milepost)
e_i^+	Earliest possible departure time of train i (h)
e_i^-	Latest possible departure time of train i (h)
λ_q^{i+}	Earliest allowable arrival time for train i at station q
λ_q^{i-}	Latest allowable arrival time for train i at station q
h_{ij}^p	Safety headway between adjacent train i and j on segment p (h)
ς	Turnout processing time (h)
L_i^q	Ability for siding q to accommodate train i; if length of siding q is longer than length of train i, then $L_i^q = 1$, otherwise 0
W^i	Delay cost, cost generated by idling train hour (also reflects priority of train i)
M	Arbitrary big number
E	Total dispatching duration (h)
B	Available budget (US$)

There are three different types of decision variables in the OSLM: time variables, infrastructure variables, and train dispatching variables. Time variables are associated with the arrival and departure time of trains at each node. The train paths can be obtained by obtaining the value-of-time variables:

D_i^q = departure time of train i at node q, $D_i^q \geq 0$, and
A_i^q = arrival time of train i at node q, $A_i^q \geq 0$.

The infrastructure variables determine the need for and location of additional sidings. An optimal siding plan can be derived from the values of infrastructure variables:

d_p = positive variable, length of segment p, $d_p \geq 0$, and
z_c^q = 1 if siding q exists in construction zone c, 0 otherwise, $z_c^q \in \{0, 1\}$.

Train dispatching variables are included in the OSLM to ensure that all trains run efficiently through the network with no conflicts:

x_{ij}^p = 1 if train i passes through segment p before train j, 0 otherwise, $x_{ij}^p \in \{0, 1\}$;
o_i^q = 1 if train i stays on siding q to meet or pass another train during dispatching period, 0 otherwise, $o_i^q \in \{0, 1\}$; and
θ_{ij}^q = 1 if and only if train i stays on siding q to meet or pass before train j stays on same siding, 0 otherwise, $\theta_{ij}^q \in \{0, 1\}$.

Equation 1 is the objective function of the OSLM. It aims to minimize the total cost during the planning horizon, defined by the summation of equivalent investment cost, meet and pass delay cost, and late departure cost. The equivalent weight for the investment cost can be obtained by the method proposed by Lai and Barkan (*24*). Since W^i is the delay cost for different types of trains, this objective function has the flexibility to reflect the business objectives of North American railroads (*21, 22*).

Objective:

$$\min \beta \sum_{c \in C} \sum_{q \in \eta^+} U^c z_c^q + \sum_{i \in N} \sum_{q \in \kappa} W^i \left(D_i^q - A_i^q\right) + \sum_{i \in N} \sum_{q \in \varepsilon_i} W^i \left(D_i^q - e_i^+\right) \tag{1}$$

The objective is subject to a set of constraints (Equations 2–24), including constraints on train dispatching, train schedule, siding capacity, construction cost, and track configuration. The constraints on train dispatching ensure the accuracy of the dispatching process and are shown in Equations 2 through 7. The basic principle followed by this particular type of constraint is to separate the arrival or departure times of two adjacent trains at each node with a reasonable headway. Equations 2 and 4 maintain an appropriate headway between the departure times of any adjacent trains heading in the same direction, and Equations 3 and 5 maintain a safe headway between the arrival times of any two adjacent trains. Equations 6 and 7 guarantee the headway between two adjacent trains in opposite directions.

$$M\left(1 - x_{ij}^p\right) + D_j^q \geq D_i^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i, j) \in b^+; i \neq j; q \in \delta_p; p \in P \tag{2}$$

$$M\left(1 - x_{ij}^p\right) + A_j^q \geq A_i^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i, j) \in b^+; i \neq j; q \in \delta_p; p \in P \tag{3}$$

$$M x_{ij}^p + D_i^q \geq D_j^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i, j) \in b^+; i \neq j; q \in \delta_p; p \in P \tag{4}$$

$$M x_{ij}^p + A_i^q \geq A_j^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i, j) \in b^+; i \neq j; q \in \delta_p; p \in P \tag{5}$$

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

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

Based on a given passenger and freight train schedule, Equations 8 and 9 are train schedule constraints that consider the effect of traffic pattern and demand. Equation 8 ensures that trains depart from their origin within a given time range. According to a given schedule, Equation 9 further ensures that all passenger trains arrive at stations at an acceptable time.

$$e_i^+ \leq D_i^q \leq e_i^- \qquad \forall i \in N; q \in \pi \tag{8}$$

$$\lambda_q^{i+} \leq A_i^q \leq \lambda_q^{i-} \qquad \forall i \in N; q \in \kappa \tag{9}$$

Equations 10 through 15 are siding capacity constraints. Equation 10 links the train dwelling variable o_q^i with the train meet and pass delay. Equations 11 and 12 identify the trains that stop on the same siding sequentially. Equation 13 keeps two trains from occupying the same siding. It works together with Equation 9 and helps maintain the stopping pattern of passenger trains. Equation 14 is the siding length constraint and forbids a train from using a siding if the length of the train is longer than the siding itself. Equation 15 captures the extra travel time experienced by trains due to acceleration, deceleration, siding speed restrictions, and turnout switching time while traveling on sidings. Equations 10 and 15 also work as part of the schedule constraints. The notation τ_i^q in Equations 10 and 15 ensures the minimum dwell time for passenger trains at stations.

$$M o_i^q \geq D_i^q - A_i^q - \tau_i^q \qquad \forall i \in N; q \in Q \tag{10}$$

$$\theta_{ij}^q \geq o_i^q + o_j^q + x_{ij}^p - 2 \qquad \forall i \in N; j \in N; i \neq j; q \in \delta_p; p \in P \tag{11}$$

$$3\theta_{ij}^q \leq o_i^q + o_j^q + x_{ij}^p \qquad \forall i \in N; j \in N; i \neq j; q \in \delta_p; p \in P \tag{12}$$

$$A_j^q \geq D_i^q + \varsigma + h_{ij}^p - M\left(1 - \theta_{ij}^q\right) \qquad \forall i \in N; j \in N; i \neq j; q \in \{\kappa \cap \delta_p\}; p \in P \tag{13}$$

$$o_i^q \leq L_i^q \qquad \forall i \in N; q \in \kappa \tag{14}$$

$$D_i^q \geq A_i^q + o_i^q \left(f_i + t_i^q + \varsigma\right) + \tau_i^q \qquad \forall i \in N; q \in Q \tag{15}$$

The variation in siding construction cost is taken into account by Equation 16. It links the construction zone with the location of sidings to determine how much capital investment implementation of an additional siding would require:

$$\sum_{c \in C} \sigma^{c-1} z_c^q - M\left(1 - \sum_{c \in C} z_c^q\right) \leq \sum_{r \in \{r \leq p\}} d_r \leq \sum_{c \in C} \sigma^c z_c^q + M\left(1 - \sum_{c \in C} z_c^q\right) \qquad \forall q \in \{\kappa \cap \delta_p\}; p \in P \tag{16}$$

The following constraints are the track configuration constraints. The constraint that ensures minimum siding spacing is Equation 17. Equation 18, meanwhile, maintains the existing sidings at their original locations, and Equation 19 prevents trains from meeting or passing at a nonexistent siding. Equation 20 ensures that a siding can only exist in a construction zone, and Equation 21 ensures that the model selects all current sidings.

$$d_p \geq g - M\left(1 - \sum_{c \in C} \sum_{q \in \psi^+} z_c^q\right) \qquad \forall p \in P \tag{17}$$

$$\sum_{r\in\{r\le p\}} d_r = \varphi^q \qquad \forall q \in \{\eta^- \cap \delta_p\};\ p \in P \tag{18}$$

$$\sum_{i\in N} o_i^q \le M \sum_{c\in C} z_c^q \qquad \forall q \in Q \tag{19}$$

$$\sum_{c\in C} z_c^q \le 1 \qquad \forall q \in \eta^+ \tag{20}$$

$$\sum_{c\in C} z_c^q = 1 \qquad \forall q \in \eta^- \tag{21}$$

Equation 22 is the budget constraint and Equation 23 ensures that the OSLM completes the dispatching process within a given time period. Equation 24 sets the train running time between any two adjacent nodes as the average running time between the two points.

$$\sum_{c\in C}\sum_{q\in\eta^+} U^c z_c^q \le B \tag{22}$$

$$A_i^q \le E \qquad \forall i \in N;\ q \in k_i \tag{23}$$

$$A_i^q - D_i^s = \frac{d_p}{v_M^i} \qquad \forall i \in N;\ (q, s) \in \vartheta_p;\ p \in P \tag{24}$$

CASE STUDY

To demonstrate the use of the OSLM, a case based on an actual Class I route (Figure 3) was developed and two scenarios were implemented: one without variation in siding construction cost and one with variation. The optimal solution was also compared with the results obtained from conventional guidelines (traditional or intuitive method) that add new sidings to a line as evenly as possible while simultaneously avoiding areas of high construction cost. The comparison between the OSLM and the intuitive method can demonstrate the advantages of the OSLM. Moreover, the results from the OSLM for the two scenarios can be used to display the importance of variation in construction cost in the siding planning problem.

The values of the important parameters used in the case study are shown in Table 2. The priority of freight trains in Table 3, denoted by delay costs, is set according to previous research (*21, 22*), and the priority of passenger trains is assigned an arbitrarily large value. The departure times of trains are set to be evenly distributed during the day without fleeting; that is, no adjacent trains are the same type. The original traffic volume is estimated to be 14 trains per day by using the Canadian National Railway parametric model and the given route characteristics (*25*). The future demand is assumed to be 20 trains per day at the end of the 5-year planning horizon. The question then becomes how to effectively add new sidings to accommodate the new demand.

TABLE 2 Input Parameters in Case Study

Parameter	Value
Average traveling speed	
Passenger	70 mph
Intermodal	55 mph
Bulk	35 mph
Number of train	
Passenger	6 trains/day
Intermodal	8 trains/day
Bulk	6 trains/day
Direction of train[a]	
Eastbound	10 trains/day
Westbound	10 trains/day
Priority of train[b]	
Passenger	US$ 5,000
Intermodal	US$ 1,392
Bulk	US$ 586
Required headway between trains	6 min
Planning horizon	5 years

[a]3 passenger, 4 intermodal, and 3 bulk train/day.
[b]delay cost/train h.

As mentioned earlier, some of the infrastructure input data must be preprocessed before it can be used by the optimization model. Figure 4 presents the preprocessing results and also shows the variation in siding construction cost for different zones. The possible locations of prospective sidings are identified and the locations of construction zones are labeled. For this case study, the zones with higher construction cost are associated with urban areas. In these urban locations, the cost of sidings is estimated on the basis of the summation of siding construction, grade separation, and land acquisition costs. Based on typical estimated construction costs for these components, the siding construction cost in an urban area is three times that of a siding in a rural area. The construction cost of a typical rural siding is US$8 million, and an urban siding is US$24 million.

The OSLM was coded into AIMMS optimization technology and solved by CPLEX (*26*). The model has 9,586 variables and 32,812 equations; this is a large-scale optimization problem. The solution time ranges from 1 to 8 h depending on the budget available. Two types of outputs are generated from the OSLM: the train dispatching result and the optimal siding location plan. Figure 5 shows an example of the dispatching result under a scenario with a US$40 million budget and no variable construction costs. Since there are no unresolved conflicts between any two train paths, and all passenger trains dwell at their scheduled stop at their scheduled

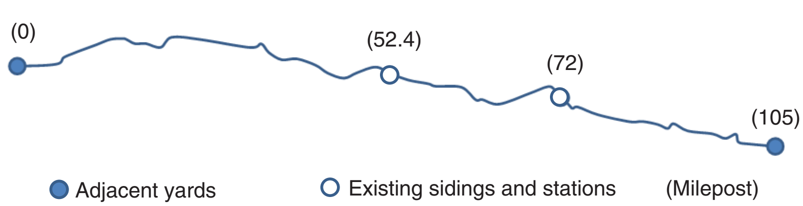

FIGURE 3 Rail line used in case study (station at Milepost 72 does not have siding).

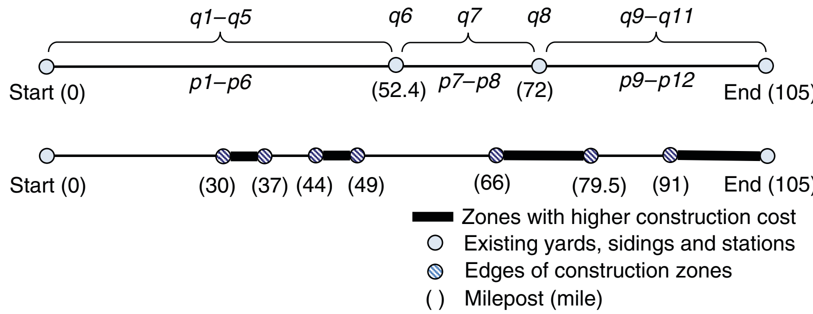

FIGURE 4 Infrastructure data after preprocessing.

time, the OSLM is proved to be a competent model for generating a reasonable dispatching result.

The performance of the OSLM optimal siding location plan is compared against the intuitive method in order to validate its effectiveness in the scenarios with and without variable construction costs. Figure 6*a* shows the optimal result of the first scenario, excluding siding cost variations under different budget levels. The delay cost of the two methods corresponding to different budget availability is displayed, which indicates that the OSLM can help save US$4 million to US$9.5 million during the 5-year planning horizon. Figure 6*b* shows the optimal result of the second scenario, which includes variations in siding costs. The results in Figure 6*b* indicate that the differences between the OSLM and the intuitive method for different budget levels are smaller when construction costs vary than in the first scenario, where costs are constant. This result is obtained because zones with higher construction cost restrict the possible locations of additional sidings, thereby closing the gap between the performance of the OSLM and that of the intuitive method. However, the performance of the OSLM is still better than the intuitive method, with savings from US$0.5 million to US$1.5 million in delay cost. The results demonstrate that the OSLM is an effective screening tool for determining optimal siding locations for further detailed engineering study.

The locations of sidings selected by the OSLM and the intuitive method under both cost scenarios are shown in Figures 7 and 8. The siding plans shown are not progressions from the original line to the improved line. Instead, they display the optimal final siding plans for an ultimate build-out to the specified budget level. If the sidings are to be phased in over time, additional analysis is required to determine the optimal order of construction. For expansion programs with a longer time frame, the model could be run iteratively to develop a progression of siding projects.

In general, for the scenario with constant construction costs, the locations of the additional sidings obtained by the OSLM are closer to the center of the line as opposed to being evenly distributed (Figure 7). This result suggests that the bottleneck on this line is near its middle, and therefore the limited resources should be allocated accordingly. Figure 8 is the result from the OSLM and the intuitive method under the second scenario, with higher siding construction costs in the urban areas. Even though zones with higher construction cost affect the selected siding locations, the distribution of sidings from the OSLM and the intuitive method still shows the same trend described for the previous constant-cost scenario. A reasonable explanation for this trend is that a line with a continuous portion of densely spaced sidings can decrease the total train waiting time on sidings compared with a line with evenly but more widely distributed sidings. In the former case, with shorter siding spacing, dispatchers can arrange complex meet and pass movements to occur in less time. Moreover, even though the trends are similar, the siding locations obtained by the OSLM under the two scenarios are very different. It is important for the OSLM to consider variability in construction cost in order to obtain a more practical optimal siding location plan.

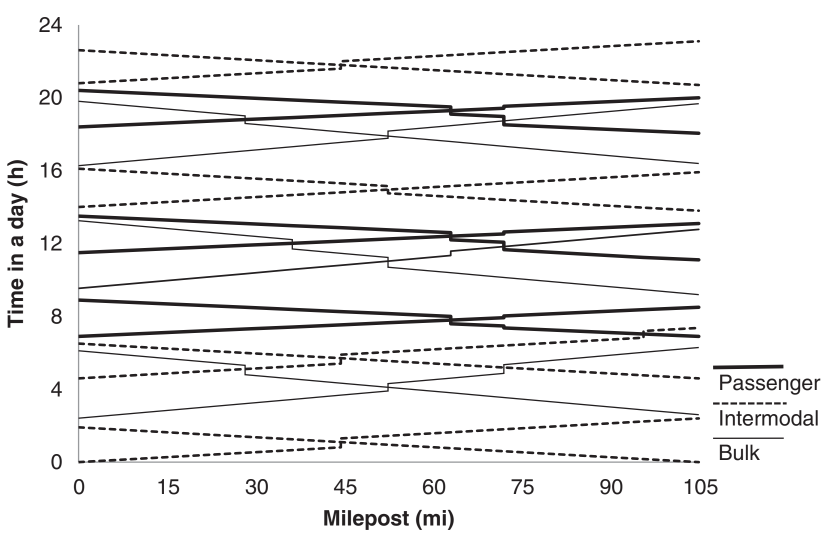

FIGURE 5 Example train dispatching result from OSLM.

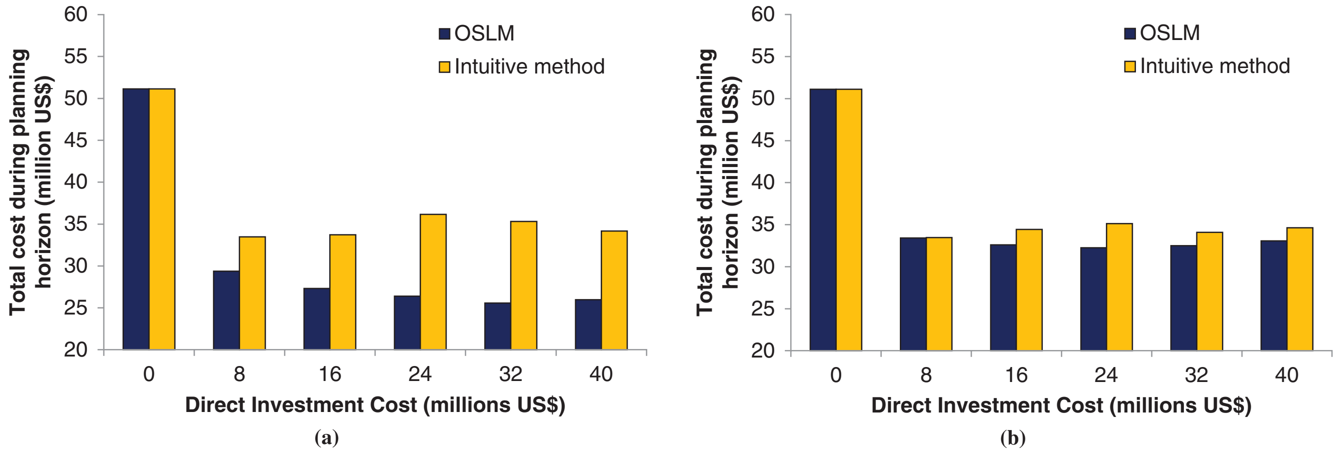

FIGURE 6 Performance of OSLM and intuitive method under different budget constraints corresponding to different scenarios: (*a*) without variable construction cost and (*b*) with variable construction cost.

CONCLUSIONS

Single-track lines with historically low traffic density are expected to reach the limits of practical capacity because of changes in traffic patterns and growing demand. As a response, this study developed a tool to help determine the optimal number and location of additional sidings to aid railways in planning capacity expansion projects. The case study demonstrates that the OSLM has better performance than traditional guidelines for setting siding locations. The ability of the OSLM to consider variable construction costs is crucial to obtaining a practical optimal siding location plan. This tool can therefore help railroads maximize their return on investment from capacity expansion projects while simultaneously achieving the service quality desired by customers. An effective solution algorithm for the OSLM to facilitate this process under multiple possible traffic patterns is planned. Another future direction for this work involves

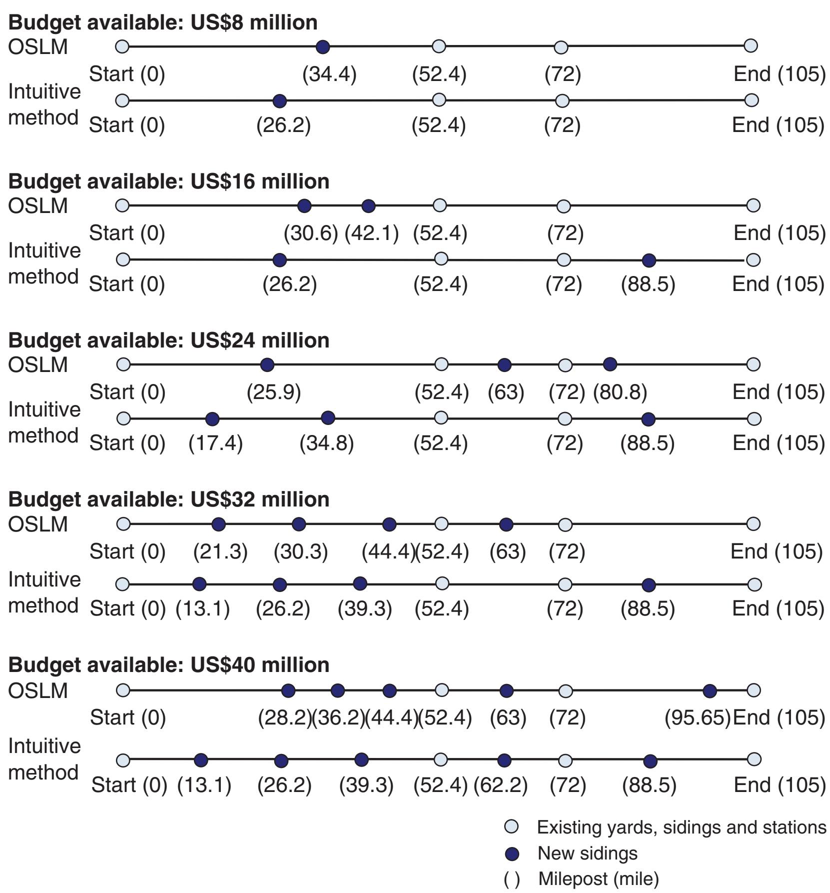

FIGURE 7 Comparison of selected siding locations without variable construction cost.

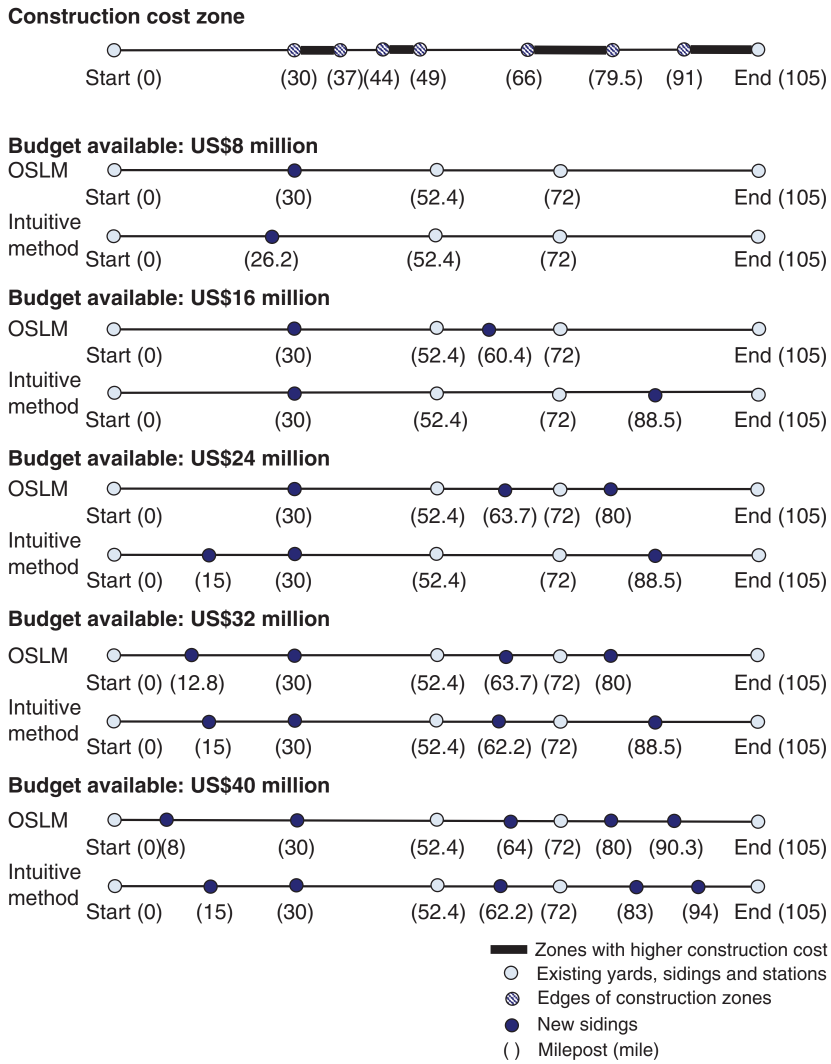

FIGURE 8 Comparison of selected siding locations with variable construction cost.

augmenting the OSLM with the capability to determine the optimal length and location of partial second main track along an existing single-track line.

ACKNOWLEDGMENTS

Partial support for this research was provided by grants from the Association of American Railroads and the National University Rail Center, a U.S. Department of Transportation University Transportation Center. The authors thank Paragon Decision Technology for the use of the AIMMS software for model optimization.

REFERENCES

1. *Transportation—Invest in Our Future: America's Freight Challenge.* AASHTO, Washington, D.C., 2007.
2. Cambridge Systematics, Inc. *National Rail Freight Infrastructure Capacity and Investment Study.* Association of American Railroads, Washington, D.C., 2007.
3. Lai, Y.-C., and M.-C. Shih. A Stochastic Multi-period Investment Selection Model to Optimize Strategic Railway Capacity Planning. *Journal of Advanced Transportation,* Vol. 47, 2013, pp. 281–296.
4. *I-5 Rail Capacity Study.* HDR, Portland, Ore., 2003.
5. Wanek-Libman, M. *Railway Track and Structure.* Simmons-Boardman Publishing Corporation, New York, 2013.
6. Vantuono, W. C. Capacity Is Where You Find It: How BNSF Balances Infrastructure and Operations. *Railway Age,* Vol. 206, No. 6, 2005, pp. 17–24.
7. Section 16.1.2. Railway Location, Design Considerations. In *AREMA Manual for Railway Engineering,* American Railway Engineering and Maintenance-of-Way Association, Lanham, Md., 2013.
8. *Railway.* BNSF Railway, Fort Worth, Tex., 2012.
9. Abril, M., F. Barber, L. Ingolotti, M. A. Salido, P. Tormos, and A. Lova. An Assessment of Railway Capacity. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 44, No. 5, 2008, pp. 774–806.
10. Lai, Y.-C., M.-C. Shih, and J.-C. Jong. Railway Capacity Model and Decision Support Process for Strategic Capacity Planning. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2197,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 19–28.
11. Petersen, E., and A. Taylor. Design of Single-Track Rail Line for High-Speed Trains. *Transportation Research Part A: General,* Vol. 21, No. 1, 1987, pp. 47–57.

12. Pawar, S. P. S. *An Analysis of Single Track High Speed Rail Operation.* University of Birmingham, United Kingdom, 2011.
13. Higgins, A., E. Kozan, and L. Ferreira. Modeling the Number and Location of Sidings on a Single Line Railway. *Computers and Operations Research,* Vol. 24, No. 3, 1997, pp. 209–220.
14. Ahuja, R. K., T. L. Magnanti., and J. B. Orlin. *Network Flows: Theory, Algorithms, and Applications.* Prentice Hall, Englewood Cliffs, N.J., 1993.
15. Harrod, S. Capacity Factors of a Mixed Speed Railway Network. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 45, No. 5, 2009, pp. 830–841.
16. Lamorgese, L., and C. Mannino. The Track Formulation for the Train Dispatching Problem. *Electronic Notes in Discrete Mathematics,* Vol. 41, 2013, pp. 559–566.
17. Qiang, L. S., and E. Kozan. Scheduling Trains as a Blocking Parallel-Machine Job Shop Scheduling Problem. *Computers and Operations Research,* Vol. 36, No. 10, 2009, pp. 2840–2852.
18. Jaumard, B., T. H. Le, H. Tian, A. Akgunduz, and P. Finnie. An Enhanced Optimization Model for Scheduling Freight Trains. *Proc., Joint Rail Conference,* Knoxville, Tenn., American Society of Mechanical Engineers, 2013.
19. Landex, A., A. H. Kaas, E. M. Jacobsen, and J. Schneider-Tilli. The UIC 406 Capacity Method Used on Single Track Sections. *Proc., International Association of Railway Operations Research 2nd International Seminar on Railway Operations Modelling and Analysis,* Hannover, Germany, 2007.
20. Lai, Y.-C., M. H. Dingler, C.-E. Hsu, and P.-C. Chiang. Optimizing Train Network Routing with Heterogeneous Traffic. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2159,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 69–76.
21. Dingler, M. H. *The Impact of Operational Strategies and New Technologies on Railroad Capacity.* University of Illinois at Urbana–Champaign, 2010.
22. Dingler, M. H., Y.-C. Lai, and C. P. L. Barkan. Mitigating Train-Type Heterogeneity on a Single-Track Line. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* Vol. 227, No. 2, 2013, pp. 140–147.
23. Dingler, M. H., Y.-C. Lai, and C. P. L. Barkan. Effect of Train Type Heterogeneity on Single-Track Heavy Haul Railway Line Capacity. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* 2013 (published online before print).
24. Lai, Y.-C., and C. P. L. Barkan. Comprehensive Decision Support Framework for Strategic Railway Capacity Planning. *Journal of Transportation Engineering,* ASCE, Vol. 137, No. 10, 2011, pp. 738–749.
25. Krueger, H. Parametric Modeling in Rail Capacity Planning. In *1999 Winter Simulation Conference Proceedings: Simulation—A Bridge to the Future,* Phoenix, Ariz., 1999, Vol. 2, pp. 1194–1200.
26. *AIMMS User's Guide.* Paragon Decision Technology, Haarlem, Netherlands, 2006.

The Freight Rail Transportation Committee peer-reviewed this paper.