Comprehensive Decision Support Framework for Strategic Railway Capacity Planning

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Abstract: The potential growth of railway traffic is expected to be substantial worldwide; hence, railway companies and agencies are looking for better tools to allocate their capital investments to capacity planning in the best possible way. This paper presents a comprehensive decision support framework with three stand-alone tools for strategic railway capacity planning: (1) "Alternatives Generator," which enumerates the possible expansion options along with their cost and capacity effects; (2) "Investment Selection Model," which determines the portions of the network that need to be upgraded with certain capacity improvement alternatives; and (3) "Impact Analysis Module," which evaluates the trade-off between capital investment and delay cost. This research also developed and implemented a specific decision support framework for North American class 1 railroads. On the basis of the network characteristics, estimated future demand, and available budget, this decision support framework can successfully determine the optimal investment plan. This tool can significantly help railroads maximize the return on investment from capacity expansion projects, thus enhancing their ability to provide reliable service to customers.
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Introduction

Railways all over the world are increasingly experiencing capacity constraints. In North America, railway freight traffic has increased nearly 30% over the past 10 years and is projected to reach 84% by 2035 (AASHTO 2007). Adding to the importance of rail transportation, alternative modes are increasingly unable to handle the traffic. For example, highway construction is unable to keep up with the growth in demand. Even if the capacity is available, much rail traffic is not economically transported by truck. Rail is also generally recognized as safer and better in terms of land use and energy efficiency. Therefore, public officials increasingly view rail as a more sustainable transport mode for handling the increasing freight traffic that will accompany continued economic growth [Leilich 2006; Transportation Research Board (TRB) 2007; AASHTO 2007; Bing et al. 2010]. These circumstances raise a key question on how railroads can handle additional traffic on a network that is already experiencing constrained capacity in many locations [Association of American Railroads (AAR) 2007].

North American class 1 railroad networks are typically divided into divisions assigned to different superintendents for operating purposes. These divisions are further divided into subdivisions or "subs" representing a portion of the railroad designated by timetable. At the subdivision level, railway line capacity can be improved using operations and/or engineering options. Operational options should be considered first because they are generally less expensive and more quickly implemented than building new infrastructure. However, the projected increase in demand is unlikely to be satisfied by changing operating strategies alone; hence, clearly, network capacity must be increased using engineering options, such as adding or lengthening sidings, modifying the traffic control system, or doubling the track.

To improve capacity using infrastructure upgrades, the North American railroad industry generally relies on experienced personnel (also known as capacity planners) and simulation software to identify bottlenecks and plan upgrades through strategic capacity planning projects [Ramsey et al. 1986; Uzarski and McNeil 1994; HDR 2003; Canadian National Railway (CN) 2005; Vantuono 2005]. Experienced railroaders often identify good solutions; however, this does not guarantee that all good alternatives have been evaluated or that the best one has been found. Furthermore, the aging demographics of the railroad industry means that many experienced capacity analysts will soon retire (Lautala 2007; Barkan 2008). Regarding the simulation software, this type of tool can be used to model a section of the network in great detail, but it is not suitable for network capacity planning. Instead of solving the real problem, solutions developed for corridor-based simulation analyses may move bottlenecks to other places in the network.

A good decision support tool for railway capacity expansion projects should have the ability to generate and evaluate possible expansion alternatives and suggest an optimal network capacity expansion plan that minimizes the cost of increasing capacity. Several authors have proposed methods to compare different investment alternatives in rail transportation systems. Felipe et al. (1996) developed a multicommodity, multimodal network design model to determine investment priorities for a freight intercity network. Jelaska (1998) proposed a capacity planning support model to evaluate the investment impact for a range of options. Fransoo and Bertrand (2000) developed an aggregate capacity estimation model

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to compare alternatives for investment in passing sidings that can identify the most promising infrastructure alternatives without the time-consuming simulation process. Petersen and Taylor (2001) presented a nested dynamic programming model to determine the optimal timing and economic feasibility of a new rail line in Brazil. Delorme et al. (2001) created a constraint programming model and a unicost set packing model to evaluate railway infrastructure capacity. Putallaz and Rivier (2004) presented a methodology and the basis for the development of an effective decision support system. The methodology also deals with planning investment in capacity and considers the effect of timetables on maintenance and renewal policies. Wahlborg (2004) calculated capacity consumption on the basis of the International Union of Railways (UIC) Capacity Leaflet for current and future traffic.

Although these methodologies enable the comparison of various proposed alternatives, they cannot automatically create alternative options. Lai and Barkan (2009) devised an enhanced parametric railway capacity evaluation tool (RCET) to enumerate possible capacity expansion alternatives and evaluate their effect. However, RCET does not contain a network optimization model to identify the location and method required for upgrade. Lai et al. (2010) proposed a capacity planning process specifically for the passenger railway system in Taiwan, which is not applicable for North American class 1 railroads and cannot evaluate the trade-off between capital investment and train delay. This is the incentive for the development of the new decision support tool described in this paper.

In this paper, a comprehensive decision support framework to help capacity planners determine how to allocate funds for capacity expansion in the best possible way is presented. This framework is also adopted and implemented for North American class 1 railroads in the case studies. Such decision support framework can help railroads maximize their return on investment from capacity expansion projects, thus enhancing their ability to provide reliable service to customers.

Comprehensive Decision Support Framework for Strategic Railway Capacity Planning

Strategic capacity planning is a type of long-term planning process that aims to optimize allocation of capital for capacity expansion projects in a rail network. This research seeks to develop a comprehensive framework to generate and evaluate possible capacity expansion alternatives and consider capacity planning problems at the network level. Therefore, the developed framework in this study is a new process to determine the best strategy for network capacity planning and to ensure that the system fluidity and interaction among corridors are considered (Lai 2008; Lai and Barkan 2008).

The developed framework comprises three modules: (1) “Alternatives Generator” (AG), which enumerates the possible expansion options along with their cost and capacity effects; (2) “Investment Selection Model” (ISM), which determines the portions of the network (at the subdivision level) that need to be upgraded with certain capacity improvement alternatives; and (3) “Impact Analysis Module” (IAM), which evaluates the trade-off between capital investment and delay cost (Fig. 1). These three components can be used either separately as stand-alone tools or combined into an integrated decision support framework.

On the basis of the properties of the links (i.e., subdivisions), the AG enumerates the possible expansion alternatives for each link along with the associated costs and capacity effects. The ISM then combines this information with the estimated future demand and available budget to determine the best set of investment options for the network, assuming the level of service (LOS) remains the same. Finally, the IAM evaluates the trade-off between capital investment and delay cost to determine whether the investment is cost effective. The output is a set of options that the capacity planner can use to guide the decision making on the optimal investment plan. This comprehensive framework can be adopted and adapted for different railway systems with appropriate capacity evaluation and enumeration tools. This paper further develops a specific decision support framework for North American class 1 railroads and implements it in the case studies. In the following sections, these three modules are described in detail.

Alternatives Generator

Railway capacity is a measure of the ability to move a specific amount of traffic (e.g., trains per day) over a defined rail line with a given set of resources under a specific service plan, known as level of service (e.g., delay). To consider possible capacity expansion options, a tool is required to evaluate the current state of each subdivision in the network and then generate the possible expansion alternatives along with the associated capacity increases and construction costs. Lai and Barkan (2009) developed the RCET by incorporating alternative enumeration and cost estimation processes into the CN parametric capacity evaluation model (Krueger 1999). The RCET automatically generates the possible expansion alternatives and computes line capacity and investment costs according to the network properties, including the following key elements for each subdivision (Krueger 1999; Vantuono 2005):

- Length of subdivision,
- Siding spacing and uniformity,
- Intermediate signal spacing,
- Percentage of double track,
- Peak train counts,
- Average speed,
- Traffic mix, and
- Dispatching priorities.

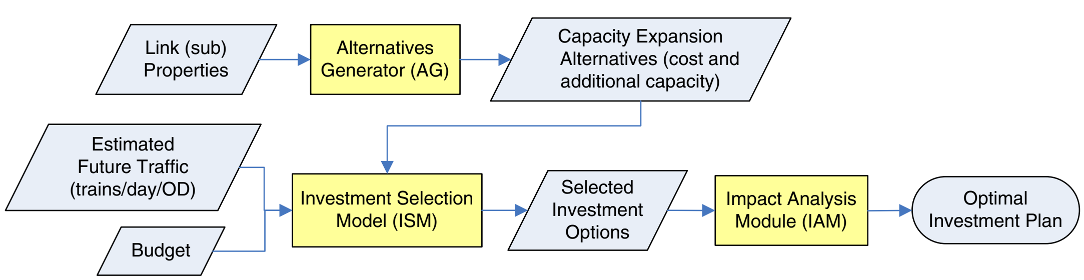

Fig. 1. Decision support framework for strategic railway capacity planning

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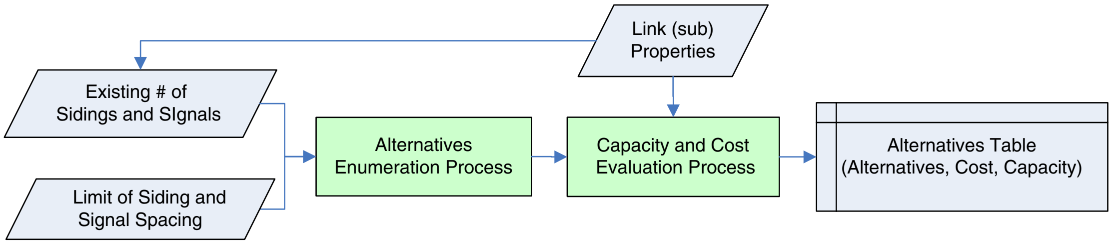

Fig. 2. Flowchart of the AG

In this research, RCET was adopted as the basis of the AG. Three common types of capacity expansion alternatives are built in the enumeration process: adding (1) passing sidings, (2) intermediate signals, and (3) a second main track. For the single-track scenario, increasing the number of sidings can reduce meet and pass delay, and increasing the number of signals and shortening block length can reduce the headway between trains, thereby increasing line capacity. Beyond that, if the demand averages more than 60 trains per day with a peak of 75, a double track must be added to single-track segments (Vantuono 2005). For each subdivision, the enumeration process enumerates the possible combinations of expansion alternatives until it reaches the limit of siding spacing or number of signals per spacing specified by the user (Fig. 2).

After the enumeration, the next process is to evaluate the capacity increase and construction cost of each alternative (Fig. 2). For each subdivision, the AG first evaluates the current line capacity on the basis of the existing key parameters; this enables the AG to determine the current LOS by adjusting the acceptable delay to match the capacity values from AG and from empirical experience if available (Krueger 1999). After obtaining the base case (current condition), AG can then compute the capacity increase of each alternative by changing the network properties (e.g., siding spacing and signal spacing) related to capacity upgrade. The unit construction cost of each type of expansion option is needed to compute the cost of expansion alternatives. Users can specify these values in advance or use the default cost estimates obtained from the North American Railroad Industry (Lai 2008) built inside the AG.

Table 1 is an example of the possible alternatives for a 161-km (100-mi) Centralized Traffic Control subdivision with 8 existing sidings and no intermediate signals, given that the smallest siding spacing is 12.88 km (8 mi) and that there can be two signals, at most, in each spacing. For the network analysis, a table for each subdivision in the network is available; these tables become the input data for the ISM. Ideally, capacity planners review these alternatives before they are fed into the ISM. During this process, planners can remove inadequate alternatives or add additional alternatives on the basis of their experience and judgment.

Investment Selection Model

The ISM was developed to identify the subdivisions that need to be upgraded with a certain type of improvement in the network using optimization and network analysis techniques. Trains with different origins and destinations can be considered in a manner similar to multiple commodities sharing a common line; therefore, this problem was formulated as a mixed-integer, network design model (Magnanti and Wong 1984; Minoux 1989; Ahuja et al. 1993). This formulation also considers the possibility of adding or upgrading the infrastructure as a general location model (Bigotte and Antunes 2007; Marin and Garcia-Rodenas 2009; Mathew and Sharma 2009). On the basis of the estimated future demands of all origin-destination (OD) pairs and capacity expansion options, the ISM determines the best set of investment options for capacity expansion with the premise that LOS remains the same as the current conditions. In other words, there is no difference between delay (hours per train) before expansion with existing traffic and delay after expansion with the future demand.

Table 1. Expansion Alternatives with Capacity Increase and Construction Cost

Alternatives	Sidings (#)	Signals/ spacing (#)	Capacity (trains/day)	Total cost ($)	Cost per extra train ($)
1	+0	+0	+0	0	0
2	+0	+1	+3	900,000	300,000
3	+0	+2	+4	1,800,000	450,000
4	+1	+0	+3	5,470,000	1,823,333
5	+1	+1	+6	6,470,000	1,078,333
6	+1	+2	+8	7,470,000	933,750
7	+2	+0	+6	10,940,000	1,823,333
8	+2	+1	+9	12,040,000	1,337,778
9	+2	+2	+11	13,140,000	1,194,545
10	+3	+0	+10	16,410,000	1,641,000
11	+3	+1	+13	17,610,000	1,354,615
12	+3	+2	+15	18,810,000	1,254,000
13	Adding 2nd main track		+55	204,750,000	3,722,727

General ISM Formulation

The following notation is used in the investment selection model. Let $G = (N, A)$ be the network, where N = set of all nodes denoting the stations or terminals where trains originate, terminate, or pass through; and A = set of links in the network, that is, $(i, j) \in A$ if there is a physical arc from node i to node j. The variable K = set of the OD pair, where $k \in K$ corresponds to the kth OD pair from origin node $o(k)$ to destination node $d(k)$; Q = set of engineering alternatives indexed by q. The set of arcs in A entering and emanating from node i is given by $I(i)$ and $O(i)$, respectively; B = available budget for capital investment; α and γ = weights that account for the planning horizon; c_{ij} = flow cost of running on arc (i, j); v^k = demand of kth origin-destination pair; h_{ij}^q represents the cost of the qth engineering option on arc (i, j); U_{ij} = current capacity of arc (i, j); and u_{ij}^q = increase in capacity of arc (i, j) by selecting the qth engineering option.

There are two sets of decision variables in the ISM. The first variable is denoted by x_{ij}^k, which is the number of trains running on arc (i, j) from the kth OD pair. The second variable is a binary variable denoted by y_{ij}^q, which determines whether the qth engineering option is used for arc (i, j), namely:

$$y_{ij}^q = \begin{cases} 1, & \text{if the } q^{th} \text{ engineering option is used for arc } (i, j) \\ 0, & \text{otherwise} \end{cases}$$

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The general ISM is formulated as follows:

$$\min \alpha \sum_{(i,j)\in A} \sum_{q\in Q} h_{ij}^{q} y_{ij}^{q} + \gamma \sum_{(i,j)\in A} \sum_{k\in K} c_{ij} x_{ij}^{k} \tag{1}$$

subject to:

$$\sum_{(i,j)\in A} \sum_{q\in Q} h_{ij}^{q} y_{ij}^{q} \leq B \tag{2}$$

$$\sum_{k\in K} x_{ij}^{k} + x_{ji}^{k} \leq U_{ij} + \sum_{q\in Q} u_{ij}^{q} y_{ij}^{q}, \quad \forall\ (i,j) \in A \tag{3}$$

$$\sum_{q\in Q} y_{ij}^{q} \leq 1, \quad \forall\ (i,j) \in A \tag{4}$$

$$\sum_{(i,j)\in O(i)} x_{ij}^{k} - \sum_{(i,j)\in I(i)} x_{ij}^{k} = \begin{cases} v^{k} & \text{if } i \in o(k) \\ -v^{k} & \text{if } i \in d(k) \\ 0 & \text{otherwise} \end{cases}, \quad \forall\ k \in K \tag{5}$$

and

$$x_{ij}^{k} \geq 0, \qquad x_{ij}^{k} \in \text{integer}, \qquad y_{ij}^{q} \in \{0,1\}, \quad \forall\ (i,j) \in A \tag{6}$$

The objective function aims to minimize the total cost, which is composed of the net cost from the infrastructure upgrade and flow cost associated with running trains. The net cost is the difference between the capital investment and the residual value of new infrastructure at the end of the planning horizon. The residual value is usually a fraction of the initial capital investment, and thus it is embedded in the first part of the objective function together with the capital investment using α. The total flow cost is the summation of the transportation cost and the maintenance of way (MOW) cost. Aside from the necessary investment to accommodate future demand, additional capital investment may further reduce the total flow cost. The relative importance of these factors depends on the planning horizon. The longer the planning horizon is, the more that railroads should be willing to invest because of larger reductions in flow cost over time. Therefore, the appropriate weights (α and γ) should be determined using a life cycle cost analysis method (Zoeteman and Esveld 1999; Lee 2002; Ozbay et al. 2004) according to the implementation circumstances. The following section uses an example of a North American class 1 railroad to demonstrate a way to determine the appropriate weights.

The first constraint (Eq. (2)) is the budget constraint, which can be removed if the task is to determine the funding required to meet the estimated future demand. Eq. (3) is the line capacity restriction, which ensures that the total flow on arc (i,j) is less than or equal to the current capacity, plus the increased capacity attributable to upgraded infrastructure. For each arc (i,j), there can be one selected engineering option (Eq. (4)) at most. Finally, Eq. (5) is the network flow conservation constraint guaranteeing that the outflow is always equal to the inflow for transshipment nodes; otherwise, the difference between them should be equal to the demand of that OD pair.

ISM for a Class 1 Railroad

In this section, the network for a North American class 1 railroad is used as an example to discuss how to determine α, γ, and the flow cost in the ISM. For a multiyear capacity planning project, the increase in flow cost over time and the discount factor to compute the net present value are considered; therefore, c_{ij} in this general formulation is a set of discounted flow costs by year within the planning horizon (Acharya et al. 1991; Lee 2002; Ling et al. 2006).

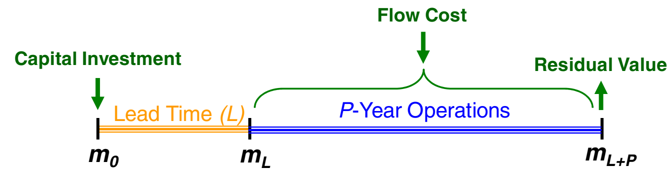

Fig. 3. Time frame of multiyear capacity expansion projects

Fig. 3 is a general time frame for multiyear capacity expansion projects. At year zero (m_0), the decision maker must make the capital investment decision; the new infrastructure will be completed after the construction lead time (L years); and the effect on the operational cost will last for P years on the basis of the planning horizon. At the end of the horizon, the residual value of the new infrastructure must be accounted for.

The first part of the objective function accounts for both capital investment and residual value. Residual value is usually computed as follows:

$$\frac{\text{Remaining Service Life}}{\text{Total Service Life}} \times \text{Initial Capital Investment} \tag{7}$$

As net cost is defined as the difference between capital investment and the residual value, it can be computed as

$$\text{Net Cost} = \left(1 - \frac{\text{Remaining Service Life}}{\text{Total Service Life}}\right) \times \text{Initial Capital Investment} \tag{8}$$

As a result, α in Eq. (1) is

$$\alpha = 1 - \frac{\text{Remaining Service Life}}{\text{Total Service Life}} \tag{9}$$

The unit flow cost is the operational cost per train-mile incurred by railway traffic flow; the total flow cost is the summation of transportation cost and MOW cost over the planning horizon. The MOW cost should include both ordinary maintenance expense and renewal expenditures (Grimes and Barkan 2006). The transportation cost is the train-operation transportation cost. As a result, the unit flow cost can be computed as follows:

$$c_{mij}^{e} = \frac{\text{Annual}(\text{MOW Cost} + \text{Transportation Cost})}{\text{Total Train Kilometers or Total Train Miles}} \tag{10}$$

where c_{mij}^{e} = estimated unit flow cost of running on arc (i,j) at year m.

Table 2 shows the unit flow cost from 1998 to 2007. The annual unit flow cost was sharply higher from 2003 to 2006, with an 11% average yearly increase; it dropped in 2007. In a multiyear planning project, the unit flow cost in the future should be estimated on the basis of the projected MOW cost, transportation cost, and total train kilometers (or train miles). These important input values, along with the estimated future demand and budget, are usually provided by the marketing department to the capacity planners before the capacity planning process.

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Table 2. Unit Flow Cost from 1998 to 2007

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Unit flow cost ($/train-km)	18.44	18.43	19.43	19.53	19.76	20.41	22.43	24.28	27.77	26.13

With the estimated unit flow cost (c^e_{mij}), discounting is another essential element of the overall cost benefit analysis (Ozbay et al. 2004), especially for strategic planning projects. For each year of a P-year operation (Fig. 3), a specific discounted flow cost is computed on the basis of the estimated unit flow cost and the real discount rate. If c^e_{mij} is the estimated unit flow cost in year $m \in M$, and f is the real discount rate, the discounted flow cost in the base year would be

$$c_{mij} = c^e_{mij}\left(\frac{1}{(1+f)^m}\right) \tag{11}$$

North American class 1 railroads generally operate freight trains according to a base train schedule, which is a guideline of which trains should run on what day (or days) of the week. This schedule can be preprocessed to seven daily traffic flow patterns depicting each day of the week. Consequently, the decision variable of the traffic flow in the ISM should be denoted as x^k_{tij}, which depicts the number of trains running on arc (i,j) from the kth OD pair on day $t \in T$, where t = index that represents each day of the week (Monday–Sunday).

Eq. (12) is the ISM for a large North American railroad's strategic capacity planning project. The life of a railroad infrastructure is assumed to be approximately 20 years in this example. Hence, if a 5-year operation is considered in this project, $\alpha = 0.25$; γ is determined on the basis of the number of weeks in a year; thus, $\gamma = 52$ because the traffic flow pattern is fixed for every week of the year:

$$\min 0.25 \times \sum_{(i,j)\in A}\sum_{q\in Q} h^q_{ij} y^q_{ij} + 52 \times \sum_{m\in M}\sum_{t\in T}\sum_{(i,j)\in A}\sum_{k\in K} c_{mij} x^k_{tij} \tag{12}$$

subject to Eqs. (2)–(6).

Impact Analysis Module

The ISM determines the investment options with the premise that "LOS remains the same." In Fig. 4, the solid exponential curve represents the delay-volume relationship of the existing infrastructure, whereas the dashed curve depicts another delay-volume relationship of the upgraded infrastructure (Krueger 1999). With the same LOS, the upgraded infrastructure can provide more capacity (C_3) than the existing track (C_1). However, gaining additional capacity by reducing the LOS (increasing delay) is also possible. Line capacity (C_2) is increased by increasing delay along the delay-volume curve of the existing infrastructure. Therefore, a tool is needed to evaluate whether the investment option is cost effective by comparing the "required capital investment" with the "delay cost."

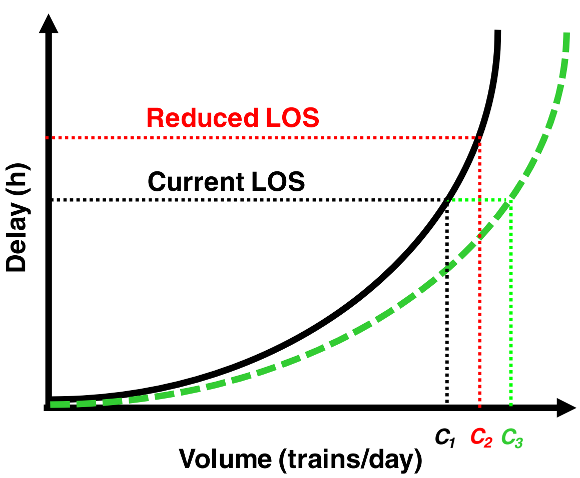

Fig. 4. Delay-volume curves of existing infrastructure (solid line) and upgraded infrastructure (dashed line)

In this study, the IAM process developed by Lai and Barkan (2009) was adapted and improved with an optimization model to determine the optimal investment plan. The IAM process can be summarized as follows:

Step 1 For each link included in the selected investment options from ISM:
- Step 1a Obtain its "net cost" from ISM.
- Step 1b Compute its "delay cost" without upgrading the infrastructure.
- Step 1c Compute its "benefit" defined by dividing delay cost by the net cost.

Step 2 Incorporate all data for all links in the network into the "impact and benefit table" and then rank them by "benefit."

The "net cost" of each link is the output of the ISM. The "delay cost" is the product of total delay hours and unit delay cost per hour. The former can be obtained from the delay-volume curve (Fig. 4), whereas the latter can be estimated by the summation of (1) unproductive locomotive cost, (2) idling fuel cost, (3) car/equipment cost, and (4) crew cost. The typical average delay cost for major North American railroads ranged between $200 and $300 per train-hour in 2007 (Schafer and Barkan 2008). In the calculations for this study, a figure from one of the class 1 railroads of $261 per train-hour was used (Lai 2008).

The "benefit" described in the process is the ratio between delay cost and net cost. A benefit value < 1 means that the investment is not cost effective (benefit $<$ cost). The output of the IAM is a table showing net cost, delay cost, and benefit for each link subject to capacity expansion. This effect and benefit table can be provided to the capacity planners for use in their decision making on the optimal investment plan.

To determine the final investment plan, this problem can also be formulated as a "knapsack" model if the investment set obtained from the ISM is determined without budget constraint [Eq. (2)]. The objective of this model is to minimize the delay cost. With a specific budget level (B), the final investment plan can be determined by solving the following optimization model:

$$\min \sum_{(i,j)\in A} w_{ij}(1 - z_{ij}) \tag{13}$$

subject to:

$$\sum_{(i,j)\in A} h_{ij} z_{ij} \le B \tag{14}$$

and

$$z_{ij} \in \{0,1\}, \quad \forall\ (i,j) \in A \tag{15}$$

where z_{ij} = binary decision variable determining whether arc (i,j) is upgraded ($z_{ij} = 1$) or not ($z_{ij} = 0$); w_{ij} = delay cost attributable to

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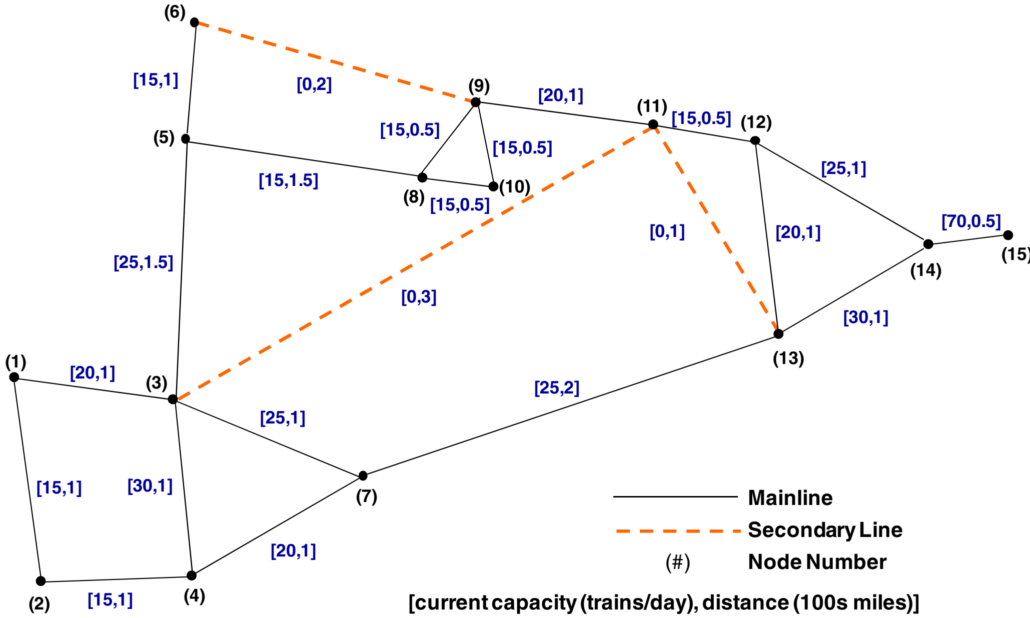

Fig. 5. Case study I network with current line capacity and distance of each subdivision

the increase in future demand on arc (i,j) without upgrading the subdivision; and h_{ij} represents the cost of upgrading link (i,j).

Case Studies

Two case studies were analyzed to demonstrate the use of the proposed decision support framework. Case study I is a railroad network with 15 nodes, 22 links, and 14 train OD pairs. Among the 22 links, three are secondary lines with very limited traffic (close to zero trains per day). Converting a secondary line into a mainline is costly, but by introducing additional routes into the network, the flow cost of certain trains may be reduced substantially. In this example, the trade-off between capital investment and flow cost was evaluated by comparing the results of including or ignoring the secondary lines.

Case study II is based on a major North American railroad network and its traffic data, including 39 nodes, 42 links, and more than 1,000 train OD pairs. This example was considered to investigate the computational efficiency of the decision support framework for a large-scale network problem. The IAM was used to evaluate the trade-off between capital investment and delay cost, assuming a 50% increase in traffic demand. Both case studies assumed that the operational horizon was five years, and the inflation in flow cost was assumed to be the same as the discount rate. This simplified the calculation by making the real unit flow cost constant irrespective of year.

Table 3. Capacity Improvement Options for Link (1,3)

Sidings (#)	Signals (#)	Capacity increase (trains/day)	Cost ($)	Cost per extra train ($)
6	0	0	0	0
6	7	2	700,000	350,000
6	14	3	1,400,000	466,667
7	0	2	5,470,000	2,735,000
7	8	5	6,270,000	1,254,000
7	16	6	7,070,000	1,178,333
8	0	5	10,940,000	2,188,000
8	9	7	11,840,000	1,691,429
8	18	8	12,740,000	1,592,500
9	0	7	16,410,000	2,344,286
9	10	9	17,410,000	1,934,444
9	20	11	18,410,000	1,673,636
10	0	9	21,880,000	2,431,111
10	11	12	22,980,000	1,915,000
10	22	13	24,080,000	1,852,308
11	0	12	27,350,000	2,279,167
11	12	15	28,550,000	1,903,333
11	24	16	29,750,000	1,859,375
12	0	16	32,820,000	2,051,250
12	13	18	34,120,000	1,895,556
12	26	20	35,420,000	$1,771,000

Table 4. Estimated Future Demand of Link (i,j)

i	j	Demand (trains/day)
1	9	8
3	6	6
3	11	9
3	15	8
4	6	8
4	13	7
5	15	9
6	3	6
9	13	5
10	3	2
13	3	8
13	9	5
15	6	8
15	3	5

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Case Study I

In the selected network, nodes represent junctions, whereas arcs represent the connecting rail lines (Fig. 5). There are two types of links in this network: mainline and secondary lines (solid and dotted lines, respectively). As mentioned previously, upgrading secondary lines is costly in terms of capital investment, but it may reduce the total flow cost. In this application, it was assumed that the decision maker would like to keep the LOS the same, so the AG and the ISM were used to determine the best set of investment options and study the trade-off between capital investment and flow cost.

Alternatives Generation Process

To use the AG to determine the current line capacity and expansion alternatives, the characteristics of each subdivision in the network were processed (Lai and Barkan 2009). The AG then used these data to determine the current line capacity (Fig. 5).

Similar to the process demonstrated in the AG, two strategies in this application to increase line capacity were considered:

- Add sidings: one, two, three, and so on [until the distance between adjacent sidings is reduced to 12.88 km (8 mi)];
- Add intermediate signals (signals between adjacent sidings): none, one, and two (maximum of two signals on average between sidings).

On the basis of these options, the possible capacity improvement options were enumerated by the AG for link (1, 3) (Table 3). The remaining of the single-track mainlines each had similar patterns. The cost of upgrading the secondary lines to 15 trains per day capacity was assumed to be $1 million per mile. Since a secondary line is usually not a centralized traffic control (CTC) territory, the

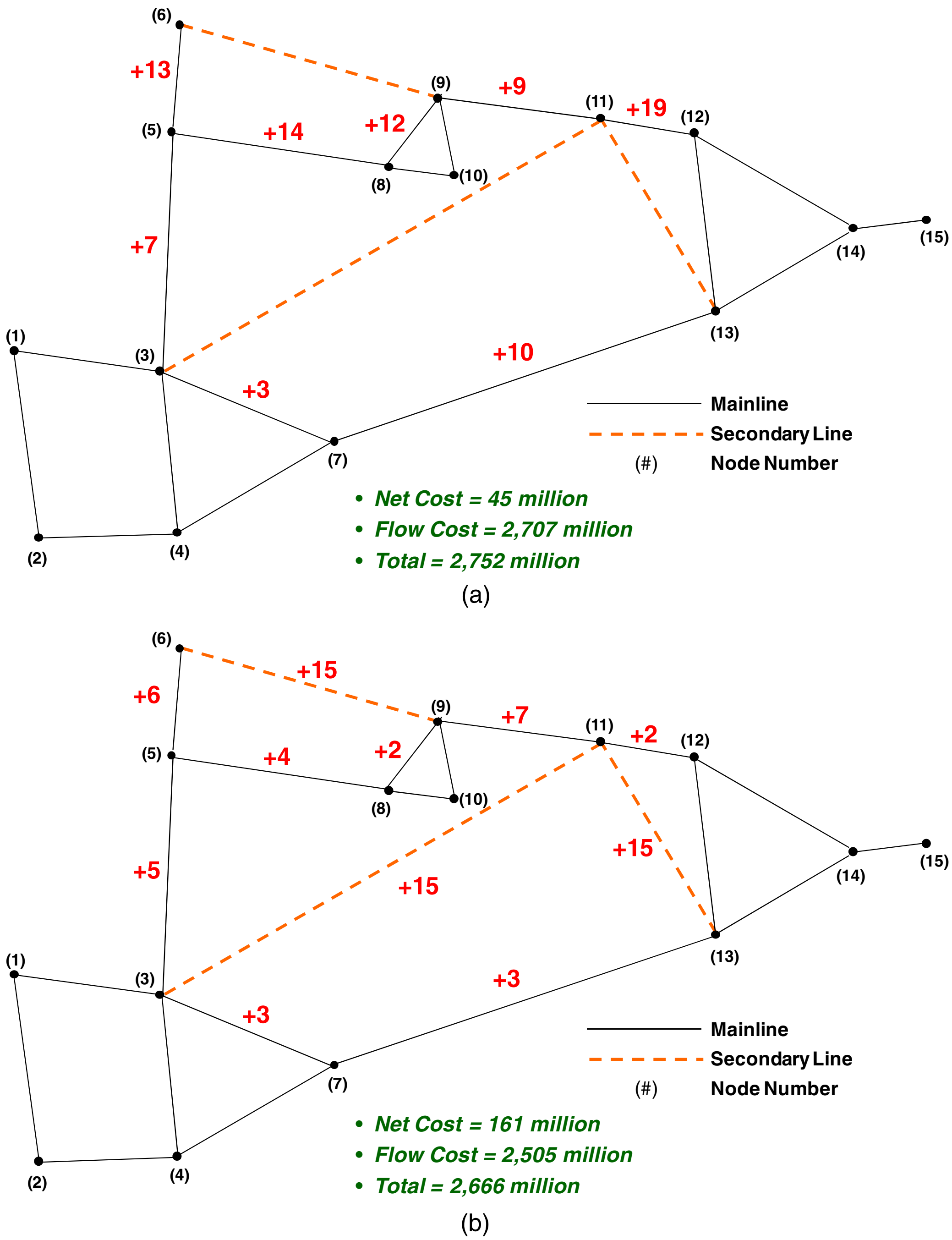

Fig. 6. Optimal solution of case study I: (a) without secondary lines; (b) with secondary lines

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Table 5. Selected Investment Option for Each Link (i, j) without (Top) and with (Bottom) Secondary Lines

i	j	Alternatives	Cost ($ millions)
3	7	Add signals (2)	1.60
3	5	Add 2 sidings and signals (2)	13.74
8	9	Add 3 sidings	16.41
9	11	Add 3 sidings and signals (1)	17.41
11	12	Add 3 sidings and signals (1)	17.01
5	6	Add 5 sidings and signals (2)	29.35
7	13	Add 5 sidings and signals (2)	32.35
5	8	Add 8 sidings and signals (1)	45.26
i	j	Alternatives	Cost ($ millions)
3	11	Upgrade secondary line	300.00
6	9	Upgrade secondary line	200.00
11	13	Upgrade secondary line	100.00
8	9	Add signals (1)	0.30
11	12	Add signals (1)	0.30
7	13	Add signals (2)	4.00
3	5	Add 1 siding and signal (2)	8.07
5	8	Add 1 siding and signal (2)	7.07
5	6	Add 2 sidings and signals (1)	11.64
9	11	Add 2 sidings and signals (1)	11.84

Note: Numbers in parentheses = # of signals per spacing.

authors only considered upgrading the track structure in this case (excluding the possibility of upgrading signaling and traffic control systems). Hence, it requires \$100, \$200, and \$300 million to improve links (11, 13), (6, 9), and (3, 11), respectively.

Investment Selection Process

Aside from the expansion options, another set of inputs for the ISM is the estimated future demand. The demand for each OD pair is expressed as the number of daily trains projected to be required from origin i to destination j (Table 4). This example assumes that there is only one type of daily traffic pattern, and thus all days are the same in the study period.

Once the inputs are defined, the capacity expansion problem can be solved by the ISM. Two sets of optimal solutions were developed in this analysis. In scenario 1, secondary line improvement options were not considered [Fig. 6(a)], whereas in scenario 2, they were [Fig. 6(b)]. Both cases were coded in GAMS and were solved by CPLEX (GAMS 2008). Links with bold numbers represent those that require capacity upgrade, whereas the number represents the amount of additional capacity needed. Table 5 shows the selected expansion option for each link requiring an upgrade. The net cost of scenario 1 is lower than that of scenario 2; conversely, the flow cost over a 5-year span is lower in scenario 2 than that in scenario 1 (Fig. 6). This is what was expected as the trade-off between capital investment and flow cost. In this case, upgrading the secondary lines is more beneficial because the total overall cost is lower than that in the scenario with only mainline upgrades.

Capacity Usage Evaluation

Fig. 7 shows the final capacity usage for each arc of the network. The dashed lines represent the links currently at capacity (important links), whereas the dotted lines depict unused links (unimportant links). Hence, the output of ISM helps identify not only the important links but also the unimportant ones. Consequently, capacity planners can also use these results to consider downgrading unimportant links to reduce cost and shift resources to links that provide higher benefit.

Case Study II

The decision support framework was implemented in case study II to establish the multiyear capacity expansion plan on the basis of a large North American railroad network and its base train schedule (Fig. 8).

Alternatives Generation Process

According to the "base train schedule" obtained from the railroad, trains are scheduled to run on a certain day (or days) each week. Therefore, the base train schedule can be converted into a weekly traffic flow pattern with seven individual daily demand patterns (one for each day of the week), resulting in more than 1,000 train OD pairs each week.

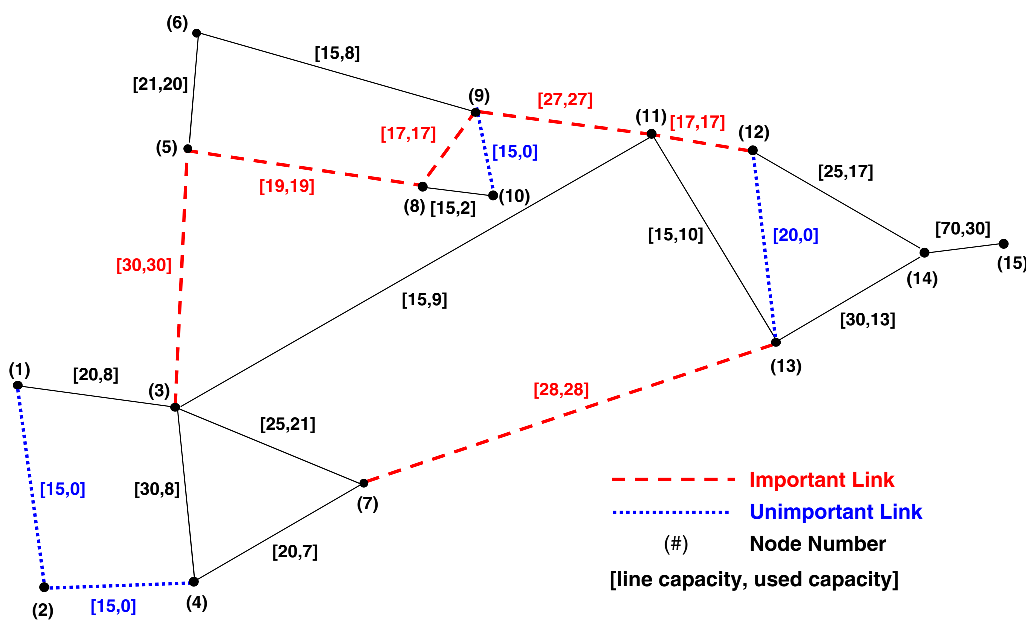

Fig. 7. Capacity usage of each link

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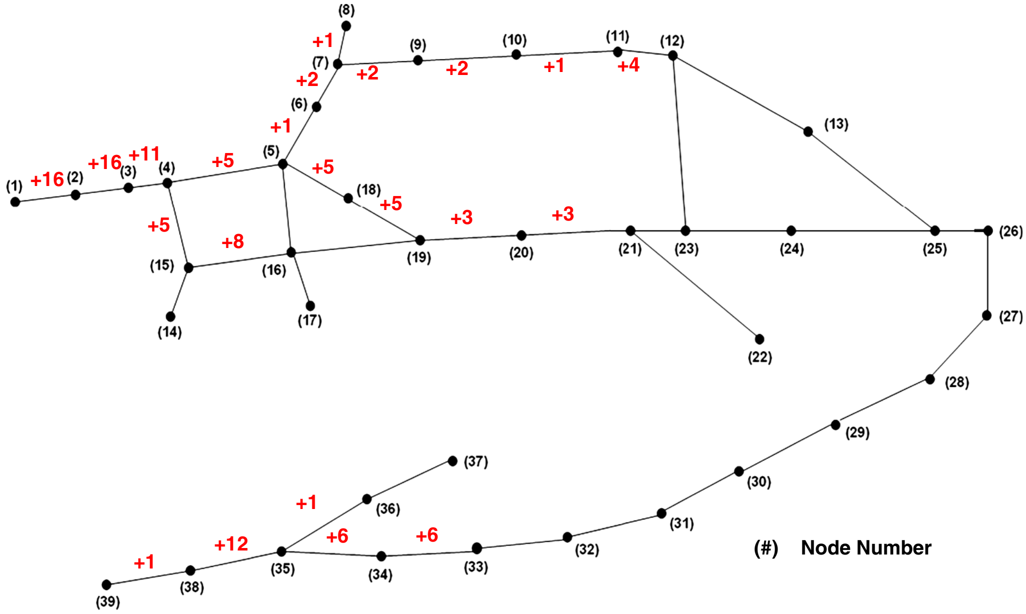

Fig. 8. Case study II network and the optimal solution

The estimated future demand in this case study was assumed to be 50% greater than the current traffic flow. This arbitrary rate of increase was selected to test the efficiency of the solution time of ISM. This application considered three types of expansion strategies:

- Add sidings: one, two, three, and so on [until the spacing is reduced to 12.88 km (8 mi)];
- Add intermediate signals: none, one, two, and three per spacing (at most, three signals per spacing on average);
- Add a second main track.

As in case study I, the AG was used to evaluate the current line capacity on the basis of the current network characteristics and to generate the possible capacity expansion options from the preceding strategies.

Investment Selection Process

On the basis of the available options and future demand, the ISM gives the best set of investment options (represented by links with bold numbers in Fig. 8). In this problem, the model included 89,712 variables and 41,015 equations; the solution time was only 3.5 s. Although more empirical evidence can help generalize this finding, it shows the feasibility and computational convenience of using the decision support framework to solve large-scale network problems of this type.

Table 6. Required Additional Capacity for Each Link and Day of the Week

i	j	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2	16	15	16	16	16	16	16
2	3	14	15	15	16	15	16	13
3	4	9	10	10	11	10	11	8
4	5	4	4	5	4	5	4	5
5	6	1	0	0	0	0	0	1
6	7	1	2	2	1	2	0	2
7	8	1	0	1	1	1	0	0
7	9	1	2	0	1	0	1	1
9	10	1	2	0	1	0	1	1
10	11	0	1	0	1	0	1	1
11	12	2	0	4	0	4	0	3
4	15	3	5	5	5	5	5	4
15	16	7	7	6	7	6	7	8
5	18	4	5	5	5	5	5	5
18	19	4	5	5	5	5	5	5
19	20	1	3	3	3	3	3	3
20	21	1	3	3	3	3	3	3
33	34	6	4	5	5	6	5	6
34	35	5	4	2	6	5	6	6
35	36	0	0	1	0	1	0	0
35	38	2	7	9	11	12	12	10
38	39	0	0	0	1	0	1	0

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Table 7. Additional Delay Attributable to the Increase in Future Traffic Demand without Upgrades

Link		Delay (train-hours/day)						
i	j	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2	280.50	250.00	280.50	280.50	280.50	280.50	280.50
2	3	235.20	290.00	290.00	321.30	290.00	321.30	206.40
3	4	245.00	300.00	300.00	331.50	300.00	331.50	192.00
4	5	15.50	15.50	19.20	15.50	19.20	15.50	19.20
5	6	1.60	0.00	0.00	0.00	0.00	0.00	1.60
6	7	1.60	2.55	2.55	1.60	2.55	0.00	1.70
7	8	0.80	0.00	0.80	0.80	0.80	0.00	0.00
7	9	0.30	1.05	0.00	0.30	0.00	0.30	0.30
9	10	0.60	1.40	0.00	0.60	0.00	0.60	0.60
10	11	0.00	0.35	0.00	0.35	0.00	0.35	0.35
11	12	0.80	0.00	3.00	0.00	3.00	0.00	1.80
4	15	4.75	9.45	9.45	9.45	9.45	9.45	7.00
15	16	16.80	16.80	14.00	16.80	14.00	16.80	22.00
5	18	34.20	39.00	39.00	39.00	39.00	39.00	39.00
18	19	22.80	27.30	27.30	27.30	27.30	27.30	27.30
19	20	3.70	11.70	11.70	11.70	11.70	11.70	11.70
20	21	3.70	11.70	11.70	11.70	11.70	11.70	11.70
33	34	15.60	9.60	12.50	12.50	15.60	12.50	15.60
34	35	12.50	9.60	4.40	15.60	12.50	15.60	15.60
35	36	0.00	0.00	1.65	0.00	1.65	0.00	0.00
35	38	5.20	40.30	59.40	80.50	100.80	100.80	71.40
38	39	0.00	0.00	0.00	2.40	0.00	2.40	0.00

Table 8. Benefit of Upgrading Track

Link		Capacity		Cost ($\$, k$)		Difference ($\$, k$)		
i	j	Current	Maximum	Train delay	Net cost	(delay − netcost)	Benefit	Cumulative benefit
35	38	24	36	31,107	2,289	28,818	13.59	13.59
5	18	34	39	18,200	1,643	16,558	11.08	24.67
3	4	40	51	135,720	13,169	122,551	10.31	34.98
18	19	34	39	12,663	2,735	9,928	4.63	39.61
20	21	36	39	5,015	1,393	3,622	3.60	43.21
15	16	14	22	7,953	2,435	5,518	3.27	46.48
2	3	35	51	132,612	42,188	90,425	3.14	49.62
19	20	36	39	5,015	1,693	3,322	2.96	52.58
4	5	27	32	8,116	4,278	3,839	1.90	54.48
1	2	35	51	131,173	84,813	46,361	1.55	56.03
33	34	20	26	6,372	4,870	1,502	1.31	57.34
34	35	20	26	5,822	4,870	952	1.20	58.53
4	15	16	21	4,004	4,870	−866	0.82	59.35
6	7	15	17	852	1,218	−366	0.70	60.05
38	39	23	24	326	1,218	−892	0.27	60.32
11	12	6	10	584	2,435	−1,851	0.24	60.56
35	36	32	33	224	1,218	−994	0.18	60.74
5	6	15	16	217	1,218	−1,000	0.18	60.92
7	8	15	16	217	1,218	−1,000	0.18	61.10
9	10	5	7	258	2,435	−2,177	0.11	61.21
10	11	6	7	95	1,218	−1,122	0.08	61.28
7	9	5	7	153	2,435	−2,282	0.06	61.35
Sum				506,697	185,852	320,845		

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As previously mentioned, the ISM determines the required upgrade with the premise that "LOS is unchanged," but gaining capacity by increasing the delay (reduce LOS) of the subdivision is possible. This is particularly important for routes that require only a small amount of additional capacity. For example, from Table 6, link (35, 36) requires additional capacity of only one train per day for Tuesdays and Thursdays. Instead of investing millions of dollars to upgrade the infrastructure, reducing the LOS on this link may be more beneficial than incorporating additional trains on those two days. By contrast, link (1, 2) requires additional capacity of at least 15 trains per day; therefore, the return from investment in infrastructure of this link is more likely to be cost justified. Consequently, the trade-off between capital investment and delay cost should be considered in the final decision.

Impact Analysis Process

The IAM determines the cost effectiveness of the capital investment by comparing the investment with delay cost. According to the additional capacity required for each link (output of ISM), the delay-volume relationship for the current link properties can be used to compute the increase in delay for each link attributable to additional traffic if there are no upgrades (Table 7).

The total delay cost of a subdivision is then computed as the product of total delay hours and unit delay cost per train-hour ($261 per train-hour). Table 8, which is the effect and benefit table, shows both the train delay cost and net cost for each link. The links were ranked according to their benefit, which is the ratio between delay cost and the net cost. The rank obtained from using this ratio is similar to the rank computed from return on investment. The first 12 links had benefit value greater than 1, which means the return is greater than the investment; however, the other 10 links had a negative return from investment. This table is provided to the capacity planner as an aid to their final decision making on the basis of the available budget.

With limited budget (B), the final investment plan can be determined by solving the knapsack formulation presented in the IAM:

$$\min \sum_i \sum_j w_{ij}(1 - z_{ij}) = 506,697 - \sum_i \sum_j w_{ij} z_{ij} \qquad (16)$$

subject to Eqs. (14) and (15).

For example, if the available budget is $70 million, the optimal investment plan will be to upgrade links (35, 38), (5, 18), and (3, 4), because they can provide the most reduction in total delay within the budget constraint.

Conclusion

Many railroad lines are approaching the limits of practical capacity given their current infrastructure. A comprehensive decision support framework was developed to help capacity planners determine how to allocate funds optimally for railway capacity expansion projects at the network level. The framework has three components: (1) AG, which enumerates the possible expansion options along with their cost and capacity effects; (2) ISM, which determines the portions of the network that need to be upgraded with certain capacity improvement alternatives; and (3) IAM, which evaluates the trade-offs between capital investment and delay cost. These components can be used either separately as stand-alone tools or combined as an integrated decision support tool.

This research also developed and implemented a decision support framework for North American class 1 railroads. On the basis of network characteristics, estimated future demand, and available budget, the proposed decision support framework can successfully determine the optimal investment plan. This tool can help railroads maximize the return on investment from capacity expansion projects, thus enhancing their ability to provide reliable service to customers.

The ISM developed in this study is a deterministic, one-time investment model that does not account for stochastic future demand or multiperiod decision making. The optimal investment plan may be different if funding is constrained for each railroad considered in each year of the planning horizon. Therefore, an interesting extension may be to use a multiperiod optimization model to identify the optimal sequence of upgrades for all the railroads considered in the capacity expansion projects. Moreover, because the demands of all commodities are assumed to be fixed, another interesting extension is to incorporate the uncertainty in future demand into the model and again try to determine the best set of investment options. A multiperiod stochastic investment selection model such as this can help capacity planners determine how to allocate optimally the budget in different decision time(s) for capacity expansion.

Notation

The following symbols are used in this paper:

- A = set of arcs in the network, $(i, j) \in A$ if there is a physical arc from node i to node j;
- B = available budget for capital investment;
- c_{ij} = unit flow cost of running on arc (i, j);
- c_{mij} = discounted unit flow cost of running on arc (i, j) at year m;
- c^e_{mij} = estimated unit flow cost of running on arc (i, j) at year m;
- $d(k)$ = set of destination node of OD pair k;
- f = discount rate;
- G = rail network;
- h_{ij} = cost of upgrading arc (i, j);
- h^q_{ij} = cost of upgrading arc (i, j) using the qth engineering option;
- $I(i)$ = set of arcs in A entering from node i;
- K = set of OD pair;
- k = $1, 2, \ldots, K$, the subscript for OD pair, corresponding to the kth OD pair from origin node $o(k)$ to destination node $d(k)$;
- L = construction lead time;
- M = total number of years;
- m = $1, 2, \ldots, M$, the subscript for year;
- N = set of all nodes denoting the stations or terminals where trains originate, terminate, or pass through;
- $O(i)$ = set of arcs in A emanating from node i;
- $o(k)$ = set of node of OD pair k;
- P = year of operations with upgraded infrastructure in the planning horizon;
- Q = set of engineering alternatives;
- q = $1, 2, \ldots, Q$, the subscript for engineering alternatives;
- T = set of days in the week;
- t = Monday, Tuesday,…, Sunday, the subscript for day of the week;
- U_{ij} = current capacity on arc (i, j);
- u^q_{ij} = increase in capacity on arc (i, j) by selecting the qth engineering option;
- v^k = demand of kth OD pair;
- w_{ij} = delay cost attributable to the increase in future demand on arc (i, j) without upgrade;
- x^k_{ij} = number of trains running on arc (i, j) from the kth OD pair;

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x_{tij}^{k} = number of trains running on arc (i,j) from the kth OD pair on day t;
y_{ij}^{q} = whether or not the qth engineering option is selected for arc (i,j);
z_{ij} = whether or not arc (i,j) is upgraded;
α = weight for capital investment; and
γ = weight for flow cost.

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