

# **A Quantitative Decision Support Framework for Optimal Railway Capacity Planning**

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## **Abstract**

Railways around the world are facing capacity constraints. In North America, railway freight traffic has increased nearly 30% over the past 10 years, and this demand is projected to increase 88% by 2035. It is clear that network capacity has to be increased by a combination of several engineering options, but the question is how railroads can allocate investment in infrastructure in the best possible way. In this paper, we demonstrate a new decision support framework to help capacity planners determine how to optimize the allocation of capital investment for capacity expansion projects. This framework has three stand-alone tools: (1) an "Alternatives Generator" that enumerates possible expansion options along with their cost and capacity effects; (2) an "Investment Selection Model" that determines which portions of the network (at the subdivision level) need to be upgraded with what kind of capacity improvement options; and (3) an "Impact Analysis Module" that evaluates the tradeoff between capital investment and delay cost. Based on the network characteristics, estimated future demand, and available budget, the proposed decision support framework can successfully determine the optimal solution regarding which subdivisions need to be upgraded and what kind of engineering options should be conducted. Such a tool will help railroads maximize their return from capacity expansion projects and thus be better able to provide reliable service to their customers, and return on shareholder investment.

## **Introduction**

Railways around the world are facing capacity constraints. In North America, railway freight traffic has increased nearly 30% over the past 10 years, and this demand is projected to increase 88% by 2035 [1]. This raises the question, how can railroads handle this additional traffic on a network that is already experiencing capacity constraints? It is clear that network capacity must be increased using engineering options, such as adding or lengthening sidings, modification of traffic control system, or doubling the track, etc.

To improve capacity using infrastructure upgrades, the North American railroad industry generally relies on experienced personnel and simulation software to identify bottlenecks and propose alternatives to reduce congestion [2,3,4]. Experienced railroaders often identify good solutions, but 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. Simulation can 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 based on corridor-based simulation analyses may move bottlenecks to other places in the network.

In this paper, we present a decision support framework to help capacity planners determine how to allocate money for capacity expansion in the best possible way. The objective of this research is to develop a network tool that can successfully identify the optimal investment plan regarding which subdivisions need to be upgraded and what kind of engineering options should be conducted based on the estimated future demands, available budget, and network properties. Such a decision support framework will help railroads maximize their return from capacity expansion projects and thus be better able to provide reliable service to their customers, and return on shareholder investment.

## **The Framework**

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

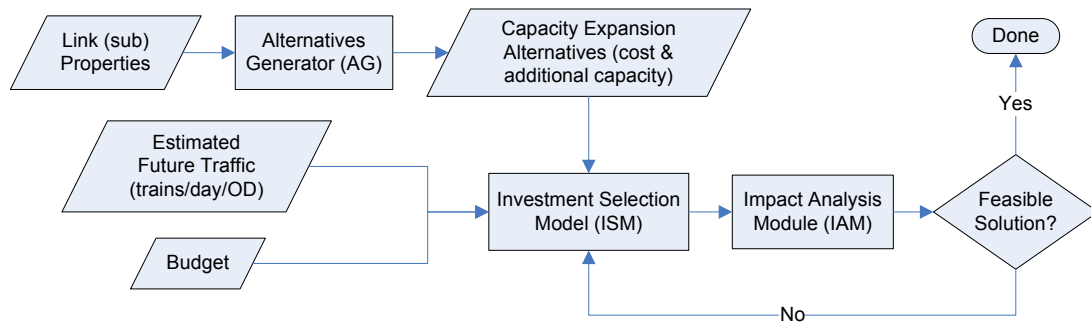


Figure 1: Decision support framework for railway capacity planning

Based on the link properties (plant, traffic, & operating parameters), the AG enumerates possible expansion alternatives for each link with the associated costs and capacity increases. 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 remains the same. Finally, the IAM evaluates the tradeoff between capital investment and delay cost to determine if the capital investment is cost-effective. The output will be a set of options that the capacity planner can use to guide decision making. Instead of solving capacity problems based solely on corridor analyses, this decision-support framework is able to conduct network-based analyses to ensure that the system fluidity and interaction between corridors are taken into account. In the following sections, we demonstrate these three modules in more detail.

### Alternatives Generator (AG)

The CN parametric line capacity model was chosen as the evaluation tool for rail traffic impact in the proposed decision support framework. In terms of its accuracy and ease of use, it falls between simple theoretical formulae, and detailed simulation, and incorporates the following key elements to determine line capacity [5]:

- Length of Subdivision
- Siding spacing and uniformity
- Intermediate signal spacing
- Percent of double track
- Peak train counts
- Average speed
- Traffic mix
- Dispatching priorities

The current CN model does not have the capability to enumerate possible alternatives and compute the associated construction costs; therefore, we created the AG by incorporating the enumeration function and cost data into the CN model. The purpose of the enumeration function is to automatically generate conventional capacity expansion alternatives for each subdivision in the network based on its current property. Three common types of capacity expansion alternatives are built in this module: adding (1) passing sidings, (2) intermediate signals, and (3) 2nd 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 demand averages 60 trains per day with a peak of 75, double-track must be added to single-track segments [4]. For each subdivision, the enumeration function will enumerate possible combinations of expansion alternatives until it reaches the limit of siding spacing or number of signals per spacing specified by the user (Figure 2).

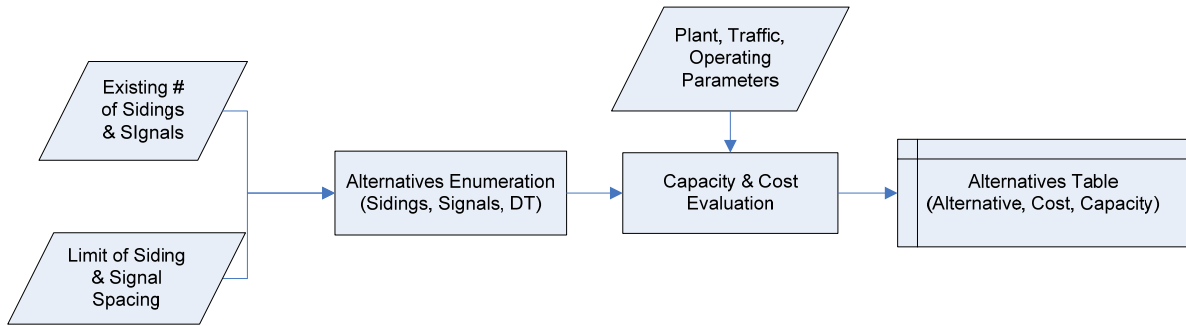


Figure 2: Flowchart of alternatives generator

After the enumeration, the next step is to evaluate the capacity increase and construction cost of each alternative (Figure 2). For each subdivision, AG will first evaluate the current line capacity based on the existing key parameters; this enables the AG to determine the current level of service by adjusting acceptable delay to match the capacity values from AG and from empirical experience if available [5]. After obtaining the base case (current condition), AG can then compute the capacity increase of each alternative by changing the plant parameters (e.g. siding spacing and signal spacing), assuming the traffic and operating parameters remain the same.

The unit construction cost of each type of expansion options is needed to compute the cost of expansion alternatives. Users can specify these values in advance or use the default cost estimates [6] built inside the AG.

Table 1 is an example of the possible alternatives for a 100-mile CTC subdivision with 9 existing sidings and no intermediate signals given that the smallest siding spacing is 8 miles and within each spacing there can be at most two signals. For the network analysis, there will be a table for each subdivision in the network, and they will be the input data for ISM. Ideally, capacity planners would review these alternatives before they are input into ISM. During this process, planners can remove inadequate alternatives or add additional alternatives based on their experience and judgment.

Table 1: Expansion alternatives with capacity increase and construction cost

Alternatives	Sidings	Signals/Spacing	Capacity (trains/day)	Cost
1	+ 0	+ 0	+ 0	\$0
2	+ 0	+ 1	+ 3	\$1,000,000
3	+ 0	+ 2	+ 4	\$2,000,000
4	+ 1	+ 0	+ 3	\$5,470,000
5	+ 1	+ 1	+ 6	\$6,570,000
6	+ 1	+ 2	+ 7	\$7,670,000
7	+ 2	+ 0	+ 6	\$10,940,000
8	+ 2	+ 1	+ 9	\$12,140,000
9	+ 2	+ 2	+ 10	\$13,340,000
10	Adding 2nd Main Track		+ 50	\$204,750,000

Although we chose the CN model for this study, it is not the only tool that can be used or enhanced as the AG. Railroads that have their own capacity analysis tools can substitute these for the CN parametric model as long as they possess similar functionality.

### Investment Selection Model (ISM)

The ISM is developed to identify which subdivisions need to be upgraded with what type of improvements in the network by using operations research (OR) and network techniques. Trains with different origins and destinations are similar to multiple commodities and they share common line capacity; therefore, we formulate this problem as a mixed integer network design model [7,8,9]. Based on the estimated future demands of all OD pairs and capacity expansion options, ISM determines an optimal investment plan for capacity expansion with the premise that “level of service (LOS)” remains the same as the current conditions. In other words, there is no difference between delay (hours/train) before expansion with existing traffic and delay after expansion with the future demand. The optimization model is as follows:

$$\text{Minimize } CI + FC - RV = NC + FC \quad (1)$$

Subject to:	
Budget Constraint	(2)
Capacity Constraint	(3)
Alternatives Constraint	(4)
Flow Conservation Constraint	(5)

Where:

- CI = Initial capital investment
- FC = Flow cost within horizon = transportation + maintenance of way (MOW) cost
- RV = Residual value at the end of decision horizon
- NC = Net cost = CI – RV

The objective function (1) takes into account capital investment, residual value, and flow cost; it aims to minimize the total cost that includes both the net cost of the new infrastructure and the total traffic flow cost over the planning horizon. “Net cost” is defined as the difference between capital investment and the residual value of new infrastructure. The residual value is usually a fraction of the initial capital investment, so it is embedded in the first part of the objective function, together with capital investment. Besides the necessary investment to accommodate future demand, additional capital investment might further reduce the total flow cost; the relative importance of these depends on the planning horizon. The longer the planning horizon, the more railroads should be willing to invest due to the larger reduction in flow cost over time.

Constraint (2) is the budget constraint, which can be removed if the task is to determine how much money, perhaps from both public and private parties, is required to meet the estimated future demand. Equation (3) is the line capacity constraint ensuring that the total flow on an arc must be less than or equal to its current capacity plus the increased capacity due to the upgraded infrastructure. For each arc, there can be at most one selected engineering option (constraint (4)). Finally, equation (5) is the network flow conservation constraint guaranteeing that the outflow is always equal to inflow for trans-shipment nodes; otherwise, the difference between them should be equal to the demand of that OD pair.

### Impact Analysis Module (IAM)

As mentioned above, ISM determines the best set of capacity improvement alternatives with the premise that “LOS remains the same”. For example, in Figure 3a, 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. With the same LOS, the upgraded infrastructure can provide more capacity than the existing track. However, it is also possible to gain additional capacity by reducing the LOS (increasing delay) as shown in Figure 3b. Line capacity is increased by increasing delay along the delay-volume curve of the existing infrastructure.

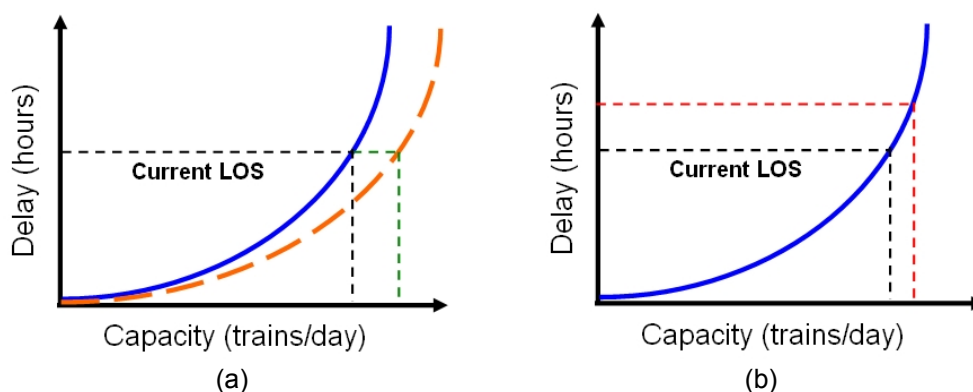


Figure 3: Line capacity is increased by (a) upgrading infrastructure, or (b) lowering LOS

The IAM evaluates if the capital investment is cost-effective by comparing the “required capital investment” to the “delay cost”. The “required capital investment” of each link is the output of ISM. The “delay cost” depends on the impact of adding additional demand to the existing track layout without upgrading the infrastructure. According to the new demand (of each link) obtained from ISM,

the increase in delay can be determined using the delay-volume curve (Figure 3b). We can then compute the delay cost as the product of total delay hours and unit delay cost per hour. From an operational point of view, the unit delay cost can be calculated by summing over unproductive locomotive cost; idling fuel cost; car/equipment cost; and crew cost.

After obtaining the delay cost, we can then rank the importance of each link based on benefit that is defined as the delay cost divided by net cost. A benefit value less than 1 means the investment is not cost effective because of negative return on investment. The output of IAM is a table with net cost, delay cost, and benefit of each link subject to capacity expansion. This expansion benefit table can be provided to the capacity planner for use in their decision-making.

### Case Study

To demonstrate the potential use of the decision support framework, a case study was selected, analyzed and is presented here. This case study has a network with 15 nodes, 22 links, and 14 train OD pairs. Among the 22 links, three of them are secondary lines currently serving limited traffic (close to zero). Converting a secondary line into a mainline is costly but, at the same time, it introduces additional routes in the network that may reduce the flow cost of certain trains. In this example, we are going to evaluate the tradeoff between capital investment and flow cost by comparing the results of including or ignoring secondary lines.

Figure 4 shows the selected network in which nodes represent cities or large yard locations, and arcs represent the existing rail lines. There are two types of links in this network, mainline (denoted by solid lines) and secondary line (dotted lines). In this application, I use both the AG and ISM to determine the optimal capital allocation plan and study the tradeoff between capital investment and flow cost.

To use AG to determine the current line capacity and expansion alternatives, we first need to compute the traffic, plant, and operating parameters. The AG then use these parameters to determine the current line capacity based on the link property (Figure 4).

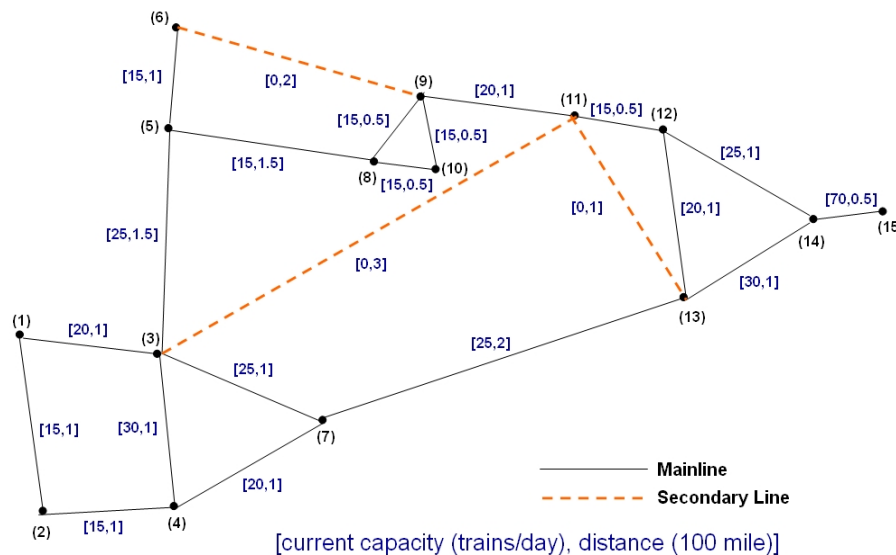


Figure 4: Current line capacity and distance of each subdivision in the case study

Two strategies are considered in this application to increase line capacity:

- Adding sidings: one, two, three, etc. (until the spacing is less than 8-mile).
- Adding intermediate signals: none, one per spacing, two per spacing (at most two per spacing).

Based on these options, Table 2 shows the possible capacity improvement options enumerated by AG for link (1, 3). Similarly, the rest of the single-track mainlines have the similar patterns. On the other hand, the cost of upgrading the secondary lines was assumed to be \$ 1 million per mile. Hence, it takes \$ 100, 200, and 300 million to upgrade link (11, 13), (6, 9), and (3, 11) to accommodate 15 more

trains per day, respectively.

Table 2: Capacity improvement options for link (1,3)

Sidings #	Signals #	Capacity Increase trains/day	Cost \$
6	0	0	0
6	7	2	700,000
6	14	3	1,400,000
7	0	2	5,470,000
7	8	5	6,270,000
7	16	6	7,070,000
8	0	5	10,940,000
8	9	7	11,840,000
8	18	8	12,740,000
9	0	7	16,410,000
9	10	9	17,410,000
9	20	11	18,410,000
10	0	9	21,880,000
10	11	12	22,980,000
10	22	13	24,080,000
11	0	12	27,350,000
11	12	15	28,550,000
11	24	16	29,750,000
12	0	16	32,820,000
12	13	18	34,120,000
12	26	20	35,420,000

Besides the expansion options, another set of inputs for ISM is the estimated future demand. The demand of the OD ( $i, j$ ) pairs represents the amount of trains running from origin  $i$  to destination  $j$  in one day. Table 3 demonstrates the estimated future demand being use in this study. It is assumed that there is only one type of traffic pattern so it is the same for every day within the study period.

Table 3: The estimated future demand of link ( $i, j$ )

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

Once the above inputs for ISM were defined the capacity expansion problem can be solved by ISM. Two scenarios are considered in this analysis, with or without considering secondary lines as improvement options. Both cases are coded in GAMS and solved by CPLEX. Figure 5 is the optimal solution for the scenario without secondary lines whereas Figure 6 is the scenario with secondary lines. In both figures, links with bold numbers beside them are links that require a capacity upgrade, and the number represents the amount of additional capacity needed. The net cost of scenario 1 is lower than in scenario 2; conversely, the flow cost over a 5-year span is higher in scenario 1 than that

in scenario 2. This is what we expected as the tradeoff between capital investment and flow cost. In this case, it is more beneficial to upgrade secondary lines because the total overall cost is lower than the scenario with only mainline upgrades.

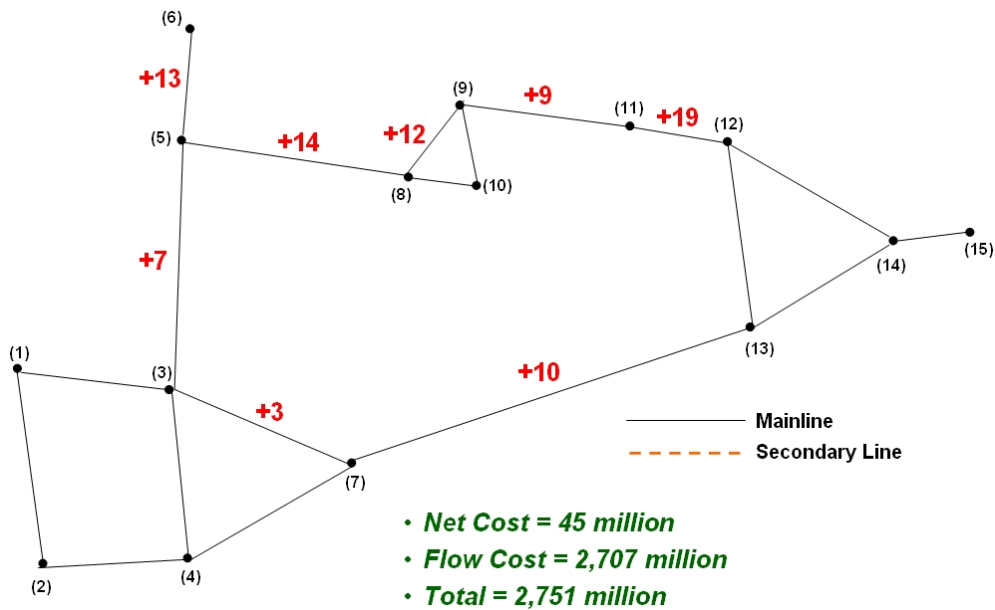


Figure 5: Optimal solution without with secondary lines

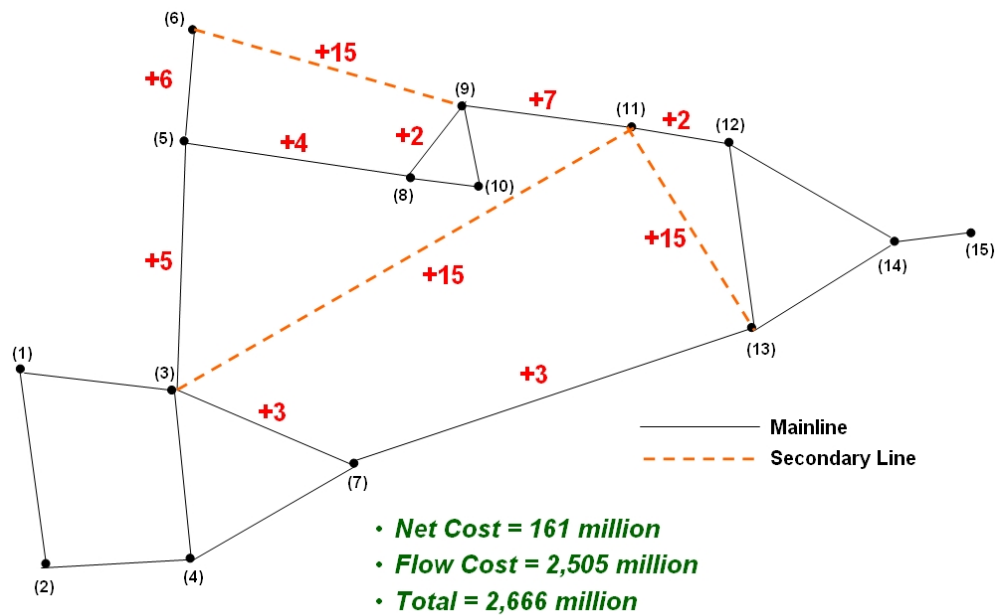


Figure 6: Optimal solution with secondary lines

Figure 7 shows the final capacity usage for each arc of the network. The red links are those links currently at capacity whereas the green links are not currently used. Hence, the ISM output helps to identify not only the important links but also unimportant links. Consequently, capacity planners could also use these results to consider downgrading unimportant links to reduce cost and shift resources to links with higher payoff.

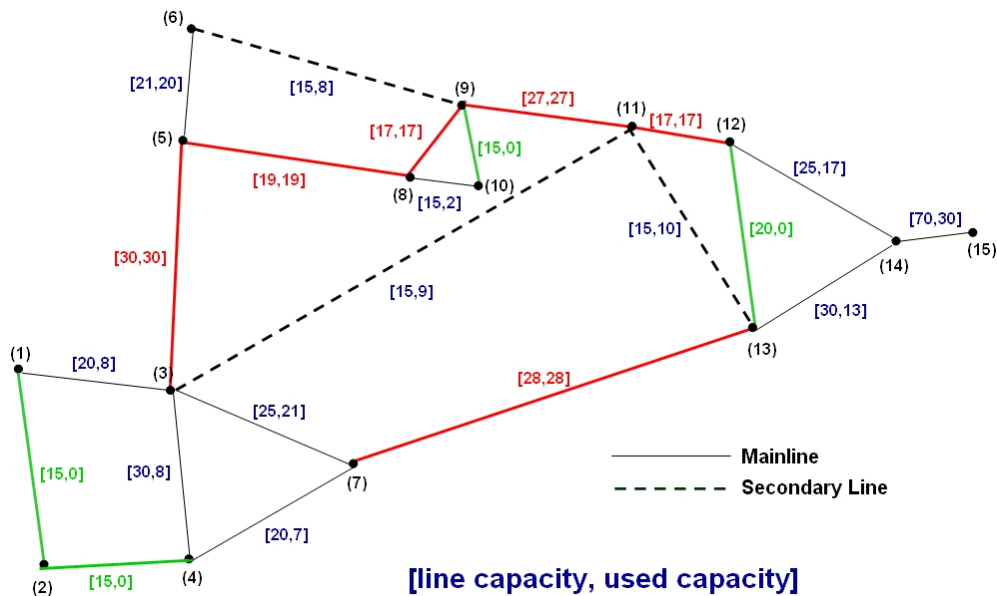


Figure 7: The capacity usage of each link

### Conclusion and Future Work

Many railroad lines are approaching the limits of practical capacity given their current infrastructure. We have developed a decision support framework to help capacity planners determine how to optimally allocate funds for railway capacity expansion projects. The framework is comprised of three components: (1) an “Alternatives Generator (AG)” that enumerates possible expansion options along with their cost and capacity effects; (2) an “Investment Selection Model (ISM)” that determines which portions of the network (at the subdivision level) need to be upgraded with what kind of capacity improvement alternatives; and (3) an “Impact Analysis Module (IAM)” that evaluates the tradeoff between capital investment and delay cost. These components can be used separately as stand-alone tools, or they can be combined as a consolidated decision-support framework.

Based on network characteristics, estimated future demand, and available budget, the proposed decision support framework can successfully determine the optimal solution regarding which subdivisions need to be upgraded and what kind of engineering options should be conducted. Such a tool will help railroads maximize their return from capacity expansion projects and thus be better able to provide reliable service to their customers, and return on shareholder investment.

The investment selection model we have developed here is a one-time investment deterministic model that does not account for stochastic future demand and multi-period decision making. The optimal investment plan may be different if we are constrained by limited funds per year within the planning horizon. Therefore, one extension may be using dynamic simulation to identify the optimal sequence of upgrades. Also, because the demands of all commodities are assumed to be fixed, an interesting extension would be to incorporate the seasonal demand pattern into the model, and again try to determine what the best set of investment options is. The multi-period stochastic investment selection model can help capacity planners determine how to optimally allocate the budget in different decision time(s) for capacity expansion projects.

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