A Model for Optimal Selection of Projects to Improve Running Time and Operating Cost Efficiency on Passenger Rail Corridors

TRB 16-1984

Submitted on November 15th, 2015

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5,660 words text (total) + 7 tables/figures x 250 words (each) = 7,410 words
Recent proposals for expanded intercity passenger rail service in the United States have included plans for incremental improvements to existing Amtrak service. Improvements to existing services aim to accommodate faster and more frequent passenger train operation, generally on trackage owned and operated by freight railways.

There are various projects and approaches to consider when decreasing the running time of passenger trains on a particular corridor. Raising the maximum operating speed can yield different benefits on different sections of the route and conditions on adjacent sections can interact with each other. For instance, the marginal travel time benefit of improving segments of a line from 79 to 110 mph maximum speed is less than the benefit of other improvements to eliminate segments currently restricted to lower speeds. Therefore, to maximize the potential of limited resources, project investments must be selected carefully to improve performance in a cost-effective manner.

This paper presents a methodology for optimally selecting projects or establishing program budgets to reduce running time on a passenger rail corridor with consideration of capital, maintenance and operating cost. The proposed project selection model is formulated with Genetic Algorithms (GAs). In the model, a route is divided into sections that can be independently upgraded and the objective function is formulated as minimization of running time along the route.

This model can aid in quickly and efficiently developing a strategic plan for improving running time on passenger rail corridors.

Keywords: Project Selection, Running Time, Operating Cost, Genetic Algorithms
INTRODUCTION
Recent proposals for expanded intercity passenger rail service in the United States have included plans for incremental improvements to existing short-haul regional intercity Amtrak service. Improvements to existing services aim to accommodate faster and more frequent passenger train operation, generally on track owned and operated by private heavy-axle-load freight railways. Since the track and signal infrastructure is privately owned and the passenger trains are typically supported by government agencies, investments to improve passenger service are made through public funds or, where there is mutual benefit to the freight railways, a public-private partnership. In either case, individual improvement projects must be justified based on their benefits and costs.

Running time is one of the major factors affecting the quality of passenger service (1). Although many upgrade project alternatives may be considered for individual route segments, they each may have different time reduction effects. Therefore, it is critical to make informed decisions on improvement project selection.

Several studies have investigated topics related to running time performance improvement of intercity passenger rail corridors. A Genetic Algorithm approach was developed to assign passenger train running time goals to different corridors while optimizing ridership and revenue of passenger service (2). A regional planning tool, CONNECTS, was developed for the Federal Railroad Administration to determine optimal service speeds and running time objectives on different passenger corridors (3). Neither of these high-level approaches selects the individual projects required to upgrade a corridor to the desired passenger train running time. Train performance calculators and other simulation tools can be used to assess the performance of different project alternatives through benefit-cost analysis (4). However, an optimal solution cannot be guaranteed and evaluating all possible combinations of upgrade alternatives may require substantial time and resources. A framework has been presented for using mathematical programming to identify an optimal strategy to reduce running time on a passenger rail corridor (5). This research did not consider the interaction between different route segments. Based on previous study, some scholars have incorporated the interaction between adjacent route segments as well as maintenance costs into the analysis of potential capital infrastructure and rolling stock improvements (6). However, the proposed model did not consider effects of train operating cost, a key consideration for upgrading route segments to higher operating speeds. This research proposes a model to select optimal upgrades while considering capital, maintenance and operating costs.

BACKGROUND
Principally, passenger train running time reduction is governed by maximum train operating speeds. In the United States, the Federal Railroad Administration (FRA) has identified nine track classes based on track quality and the ability to operate passenger and freight trains. In this classification system, the maximum possible running speed (and corresponding minimum time required to travel one mile) has been defined for each track class (Figure 1). The greatest benefits in running time reduction can be achieved from track class improvements on lower speed sections, rather than higher speed ones. For example, upgrading a route section from FRA track class one to two reduces running time by more than one minute per mile, whereas upgrading a segment from track class five to six saves only four seconds of running time per mile.
Figure 1: Passenger train speed and running time per mile by FRA Track Class

Running time reduction is also affected by the type of improvement projects and the condition of adjacent route segments. Upgrade alternatives include investments in track, signal, highway grade crossing, and rolling stock improvements. Each improvement approach has distinct benefits within different sections of the route and those improvement projects can interact with each other. For example, for section 2 with a current maximum speed A, consider two types of adjacent sections: adjacent sections 1 and 3 have higher maximum speeds (speed B) than speed A (Figure 2a); or adjacent sections have the same initial maximum speed as section 2 (Figure 2b). The project cost to upgrade section 2 from speed A to speed B remains the same for both cases. However, due to acceleration and deceleration effects, the incremental benefit of upgrading the intermediate segment will be greater for the former case. Thus, the benefit-to-cost ratio for the project to upgrade the intermediate segment varies greatly with the boundary conditions of adjacent sections.

The cost of running time reduction is also affected by fuel and energy consumption. This is critical when considering projects to upgrade routes to “higher-speed” operation above 90 mph. As average train speed increases, air resistance becomes the major component of the train resistive force. Since air resistance increases quadratically during train acceleration, energy and fuel consumption is disproportionately greater for higher operating speeds. This leads to an additional
operating cost penalty for selecting higher-speed versus lower-speed improvements, providing additional incentive to eliminate slower segments before raising the maximum speed on the corridor. Thus, by integrating operating cost into a project selection model, the optimal solution must balance decreases in running time with increases in energy for each incremental investment. Therefore, this paper develops a project selection model for selecting cost effective investments to improve performance on a passenger rail corridor with limited resources to fund capital, maintenance and operating expenses.

PROJECT ALTERNATIVES AND ANALYSIS
Three types of costs for various project alternatives are considered in this paper: capital cost, maintenance cost and operating cost.

Capital Cost and Project Alternatives
Capital cost refers to the fixed, one-time expenses for infrastructure improvement. To accommodate reduced running time through increased operating speeds, multiple components of the rail corridor infrastructure may need to be improved. The three main elements considered by this model when estimating the capital cost to upgrade each section of the route are: track structure/geometry, signal system, and number of highway grade crossings.

Track structure includes rails, crossties, fastening system, ballast, and subgrade. Common improvement practices include replacing one-third of ties with new ones, removing existing rail, spikes, plates, anchors and installing new 136-pound continuous welded rail (CWR). In addition to U.S. federal regulations (7), railway companies also apply stricter local standards and tolerances for higher operating speed.

In this research, track geometry is mainly concerned with curvature improvement due to its impact on maximum speed. Two upgrade methods are considered: increased super-elevation on curves and curvature reduction. In the first case, increasing the height of the outer rail on curves allows trains to operate at higher speeds. The cost of super-elevation adjustment consists of adjusting spirals and installing super-elevation for the new operating speed. Since maximum super-elevation is regulated, further speed improvements can only be achieved by reducing curvature. Curvature reduction consists of curve re-alignment through the curved section of the existing line within the given right-of-way. There is a limit to how much curve reduction can be achieved before construction extends beyond the right-of-way and costs quickly escalate. Although these larger curve reduction projects that go beyond a small curve shift are not included in the presented model, they can be included if specific project costs are provided as model inputs. More general upgrade costs for track structure and track geometry are estimated by U.S. dollars per mile.

The signal system is used to direct railway traffic safely and in the U.S., operations cannot exceed certain speed limits unless specific signal systems are in place. Upgrade alternatives include implementation of signalling systems like Centralized Traffic Control (CTC), Automatic Train Stop (ATS) and Automatic Train Control (ATC). In United States, CTC system provides centralized control of signals and switches within a pre-defined area. ATS and ATC systems provide automatic train stop and over-speed protection required to ensure train safety at higher operating speeds. If such a signal system is already installed on the existing line, then the corresponding upgrade cost is less expensive than if the line is not signalled. The cost to improve the signal system is estimated by U.S. dollars per mile.

Highway grade crossing protection is needed to alert motorists to approaching railway traffic
and the presence of a railway crossing. Warning facilities such as four quadrant gates, four quadrant gate crossings with intrusion detection, and fenced right-of-way (ROW) are implemented at different speed levels according to regulatory requirements and/or the engineering policies of the railway in charge of the rail infrastructure. The cost to upgrade each route segment depends on the number of crossings in the segment and speed levels.

To guide the project selection process, infrastructure improvement alternatives have been assigned to sections with different maximum speeds (track class) for the purpose of this research (Table 1). For example, to upgrade a given section from FRA track class 4 to class 5, the procedures include replacing one-third of timber crossties, installing 136-pound continuous welded rail, surfacing, adjusting curve super-elevation and/or curve alignment, installing ATS or ATC system and implementation of four quadrant gates at highway grade crossings. If any of these items were already present on the section, their cost would not be included in the capital cost of the project. This is only an illustrative example applied in this paper; a more comprehensive set of project alternatives may be applied in actual project situations.

### Table 1: Infrastructure improvement alternatives

<table>
<thead>
<tr>
<th>Track Class</th>
<th>Max. Speed (mph)</th>
<th>Track Structure / Geometry</th>
<th>Signal System</th>
<th>Grade Crossings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 3</td>
<td>60</td>
<td>Replace 1/3 Crossties (wood), 136RE CWR, Surfacing, Curve Shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 4</td>
<td>80</td>
<td>Replace 1/3 Crossties (wood), 136RE CWR, Surfacing, Curve Shift</td>
<td>CTC</td>
<td></td>
</tr>
<tr>
<td>Class 5</td>
<td>90</td>
<td>Replace 1/3 Crossties (wood), 136RE CWR, Surfacing, Curve Shift</td>
<td>CTC / ATS or ATC</td>
<td>Four quad gate crossings</td>
</tr>
<tr>
<td>Class 6</td>
<td>110</td>
<td>Replace 2/3 Crossties (wood), 136RE CWR, Surfacing, Curve Shift</td>
<td>CTC / ATS or ATC</td>
<td>four quad gate crossings with intrusion detection, fenced ROW</td>
</tr>
</tbody>
</table>

### Maintenance Cost

The maintenance cost, including regular service for track, signal system, etc., is important to keeping each track segment at a particular service level and track class (allowable operating speed) for a long period. If maintenance tasks are not carried out in a timely manner, track condition will deteriorate, affecting running time and the quality of rail service. As opposed to the one-time capital cost for infrastructure improvement, maintenance cost is an annual expenditure, and is therefore converted into net present value to be compatible with the capital cost analysis. Different physical characteristics of route sections and upgrade alternatives give rise to different maintenance costs in terms of a total cost per track mile.

### Operating Cost
For this research, operating cost is calculated by the fuel consumption of the passenger train. In practice, the operating cost of the corridor includes other factors such as crew cost and the costs of on-board amenities. However, these costs are not related to running time and would be constant for all scenarios considered by the project selection model. Thus they can be ignored by the project selection model developed through this research.

Fuel consumption for each train run is affected by two factors: the driving patterns and route characteristics. Driving patterns can be described as the series of throttles positions at particular moments along the route. Different combinations may have different energy performance. Higher throttle settings can generally provide higher acceleration, but consume more energy; while low throttle settings are more energy efficient. The characteristics of route such as speed limits, grades and curves also play an important role in the fuel consumption of a train. Frequent changes in speed restrictions may cause frequent cycles of acceleration and braking, consuming more time and energy.

**PROJECT SELECTION MODEL**

**Assumptions**

A few assumptions have been made to solve the project selection problem. The train is modelled as single-mass point, so train length is not considered when it enters and leaves each speed limit area. Since the passenger train is very short and has a relatively high power-to-weight ratio, the effects of grade are not included in this model. Thus all grades are assumed level along the route.

**Mathematical Model**

This paper proposes a project selection model to reduce minimum running time with respect to a net present value capital, maintenance and operating cost budget on a passenger rail corridor. Minimum running time includes scheduled passenger train stops (where applicable on the segment under study) but does not include unscheduled train meets and other delay resulting from the interaction between freight and passenger trains. Since previous research has shown that meet and pass events can control the performance of passenger trains on corridors dominated by freight operations (8, 9, 10), this model is best suited for passenger corridors where there are few freight trains and many passenger trains already achieve close to their minimum running time.

Model variables are defined as follows:

- \( s \) = Actual travel distance of train;
- \( S \) = Total length of the route;
- \( N \) = Total number of train trips;
- \( v_s \) = The train speed at distance \( s \);
- \( c_{\text{upgrade}}(v_1, v_2) \) = the per unit length capital and maintenance cost to upgrade from \( v_1 \) to \( v_2 \);
- \( c_{\text{oper}} \) = Unit diesel price;
- \( v' \) = Current speed limit;
- \( v'' \) = The upgraded speed limit;
- \( \delta_i \) = Train-specific time weighting coefficient for \( i \)th train trip;
- \( n_{T,s} \) = Applied tractive coefficient;
- \( n_{B,s} \) = Applied braking coefficient;
- \( F_T(v_s) \) = The tractive effort when train is at speed \( v_s \);
\( F_B(v_s) = \) The braking effort when train is at speed \( v_s \);
\( \lambda = \) Fuel efficiency;
\( \mu = \) Transmission efficiency;
\( m = \) Train weight;
\( R_m(v_s) = \) Basic resistance at the speed of \( v_s \);
\( R_G(s) = \) gradient resistance at position \( s \);
\( R_C(s) = \) curve resistance at position \( s \).

The mathematic model is presented in equations (1) to (8).

\[
\min \quad f = \delta_i \int_0^s \frac{1}{v_s} \, ds 
\]

\[
\int_0^s c_{\text{upgrade}}(v_s, v_s') \, ds + c_{\text{oper}} \sum_{i=0}^N \int_0^s n_{T,s} F_T(v_s) / \lambda_i ds_i \leq B
\]

\[
v_s = ds / dt.
\]

\[
m \cdot \ddot{v}_s = \begin{cases} 
  n_{T,s} F_T(v_s) - R_m(v_s) - R_G(s) - R_C(s) \\
  n_{B,s} F_B(v_s) - R_m(v_s) - R_G(s) - R_C(s)
\end{cases}
\]

\[
\begin{cases}
  n_{T,s} \in [0,1] \\
  n_{T,s} > 0: \text{Traction}; \quad n_{T,s} = 0: \text{Coasting} \\
  n_{B,s} \in [-1,0] \\
  \text{(Braking)}
\end{cases}
\]

\[
P_{v_s} = n_{T,s} F_T(v_s) \cdot v_s / \mu
\]

\[
v_0 = 0, \quad v_s = 0
\]

\[
0 \leq v_s \leq \bar{v}_s
\]

Equation (1) is the model objective function that minimizes the sum of the minimum running time over the route for each passenger train. It is described in the form of integration. A train-specific time weighting coefficient \( \delta_i \) is introduced so that the running time of certain trains may be more heavily weighted in the optimization process. Practitioners may adjust the value of \( \delta_i \) according to differences in ridership, revenue or priority of certain trains that influence their sensitivity to minimum running time.

Equation (2) constrains the net present value of capital, maintenance and operating costs along the route to not exceed a certain budget \( B \). The first term computes capital and maintenance cost. The second term computes operating cost summed over all passenger trains.

Motion equations (3) to (6) define train movement along the route. Equation (3) defines train acceleration. Equation (4) shows that a train is experiencing tractive effort, train resistance, grade resistance and curve resistance in tractive status; while braking effort will be applied instead of
tractive effort during braking process. Expression (5) gives the value range of tractive and braking coefficients. Equation (6) computes the power.

Expressions (7) and (8) constraints train speed during the trip. Equation (7) gives the boundary condition and (8) ensures speed will not exceed new speed limit.

APPLICATION OF GENETIC ALGORITHMS

Since the number of upgrade alternatives and possible combinations increasing exponentially for longer route network with many segments, the proposed project selection model is formulated as a Genetic Algorithm (GA). A global search algorithm technique based on the principle of natural selection, GA mimics the evolution of biological organisms to achieve optimal solutions with a given objective function in an artificial system. In GAs, a solution to the problem is encoded into strings of digital numbers. Each string (chromosome) represents one possible solution. The collective chromosomes form a set of possible solutions, called the population. GAs perform operations like selection, crossover and mutation on chromosomes in the population with a probability based on their corresponding fitness values. Optimal solutions, in the form of high fitness individuals will eventually appear after generations of evolution.

Compared with other optimization techniques, GAs have several advantages for a large scale optimization problem as demonstrated in their application to the problem of optimal train control to minimize energy consumption (11, 12). First, since a GA searches from a group of solutions instead of a single point, it avoids being trapped into a local stationary point. Second, a GA can be applied to various types of problems as the search is carried out based on the fitness function rather than derivatives. Third, probabilistic transition rules are used so that the optimum can be achieved faster with real-time adjustment.

However, traditional genetic algorithms will give rise to premature convergence if a dominant individual occurs in the population. Therefore, by introducing combinational selection method and adaptive probability, an enhanced genetic algorithm is proposed to solve the project selection model to ensure the effectiveness and efficiency of the solution.

Problem Coding and Fitness Function

In the project selection problem, a route is divided into \( N \) segments that can be independently upgraded. By discretization of the model, this problem can be solved by GAs. A chromosome has \( N \) genes and each one represents the project decision on a corresponding segment. The value of the gene indicates the target upgrade speed if the segment needs to be improved; otherwise it is the original speed limit.

As shown in (9), the fitness function is re-written from (1) and (2) as minimization of running time and net present value budget excess over all segments in the given route. In this function, \( M \) is the total number of segments along the route. \( V_j \) is the \( j \)-th gene that decides the target upgrade speed (or original speed limit if no upgrades are applied). \( T_{i,j} \) represents the travel time along the \( j \)-th segment for the \( i \)-th train trip. This value needs to be re-calculated if the maximum speed changes on a segment. \( C_{\text{upgrade}} \) is the capital and maintenance cost for the improvement project from the current maximum speed to \( V_j \) within the \( j \)-th segment. \( C_{\text{oper}} \) is the unit energy cost while \( E_{i,j} \) is the energy consumption of the train while it traverses the \( j \)-th segment for the \( i \)-th train trip. \( B_{\text{const}} \) is the given net present value budget for capital cost, maintenance cost and operating cost. To avoid solutions where the cost exceeds total budget, a large penalty \( \alpha \) is added to the over-budget term for the optimal solution.
Fitness Function \[ \begin{aligned} & = 1 / \left( \sum_{i=1}^{N} \sum_{j=1}^{M} T_{i,j} + \alpha \left( \sum_{j=1}^{M} C_{\text{upgrade}} (V_j, V_j) + C_{\text{oper}} \sum_{i=1}^{N} \sum_{j=1}^{M} E_{i,j} - B_{\text{const}} \right) \right) \end{aligned} \] (9)

**Combinational Selection**

Selection is the process used to identify a group of chromosomes from a population for later breeding based on their fitness values. Individuals with higher fitness values are more likely to be chosen to produce the next generation. Two main selection strategies are applied here: roulette wheel selection and rank selection.

Roulette wheel selection is a fitness-proportionate selection method and is commonly used due to its efficiency in best individual selection. The probability for a chromosome to be selected is proportional to its fitness. However, since this method can quickly eliminate the lower fitted individuals, the solution may inadvertently converge to a local optimum point.

To avoid this potential risk, rank selection is used for population selection in the early stages. Instead of using fitness value, rank selection assigns ranking numbers (from 1 to N) to each chromosome. The worst has 1 and the best has N. The selection probability is then established according to this ranking number. In this way, lower fitted chromosomes have more chances to survive.

The combination of these two methods ensures a variety of species in the early evolution stage and that multiple good solutions will emerge for breeding. As the evolution proceeds, by using roulette wheel selection, better-fitted individuals have a greater chances of selection. Therefore, the later evolution process will be accelerated.

**Adaptive Crossover**

Crossover is the process of taking more than one parent chromosomes and producing offspring by exchanging part of their gene information. Crossover has two key parameters: crossover probability and crossover operator. The former decides how likely an individual is to be chosen for crossover operation, while the latter decides how parents exchange information.

To ensure the efficiency of evolution, adaptive probability has been applied for crossover probability. According to adaptive probability, higher fitness individuals have lower probability for crossover. This means their good genetic information is preserved for the next generation. On the contrary, lower fitted solutions are have a higher crossover rate and are more likely to be recombined in an effort to improve them. Adaptive probability is defined in equation (10).

\[ P_c = \begin{cases} \frac{P_{c_{\text{max}}} - (f' - f_{\text{avg}})}{P_{c_{\text{max}}} - P_{c_{\text{min}}}} & f' > f_{\text{avg}} \\ \frac{P_{c_{\text{max}}} - f_{\text{avg}}}{P_{c_{\text{max}}}} & f' \leq f_{\text{avg}} \end{cases} \] (10)

For crossover operator, traditional two-point crossover is chosen. Everything between the two points is swapped between the parent chromosomes, rendering two child chromosomes.

**Adaptive Mutation**

Mutation prevents the search from being trapped into a local optimum point by introducing new genes to the selected chromosome. The adaptive method is again used here to decide the mutation probability for each chromosome. Similar to the crossover parameter, the actual mutation
probability varies according to the fitness of the chromosome.

**Proposed Algorithm Procedure**

In the proposed algorithm procedure, an initial reference value is calculated as the threshold for the two selection methods in the main search loop. The main GA search loop includes combinational selection, adaptive crossover and adaptive mutation. It tries to find the best-fitted individuals based on randomly initialized population. Two selection methods are used to ensure population diversity during the early stage and efficient convergence during the late period. If the best fitness value of the population is less than the reference value defined at the beginning, rank selection method is used as chromosome selection; otherwise roulette section will be applied. Final optimal solution will be achieved when the pre-defined generation value is reached.

**CASE STUDY**

To demonstrate the functionality of the passenger corridor project selection model, a case study was prepared on a hypothetical route. The route in the case study is a 48-mile segment based on a typical Midwest regional intercity passenger rail line. The route has 13 curves and 73 highway grade crossings. Due to the limitations of curvature or the signal system, the existing maximum passenger train operating speed limit varies for different portions of the route (Figure 3a). The maximum operating speed is currently 80mph.

For calculation purposes, the route is divided into 48 segments, each with constant infrastructure parameters (maximum speed, curvature etc.). Since the segments vary in length and the grade crossings are not evenly distributed over the length of the route, there are a different number of grade crossings in each segment (Figure 3b).

The train considered by the case study is a typical Amtrak regional intercity passenger train with one 4,250 horsepower four-axle diesel-electric locomotive, one locomotive without power (to serve as a lead control unit on the return trip) and six single-level passenger cars. With a maximum running speed of 110 mph, this type of train is frequently used for operations on regional intercity passenger rail corridors in the Midwest. The current running time of this train on the corridor is 48.75 minutes.

To reduce the running time along the example route, different improvement alternatives are considered for each route segment as described previously (Table 1). For each segment, the maximum speeds corresponding to FRA Track Classes 3-6 and the maximum speed dictated by curvature super-elevation and re-alignments are considered as possible target upgrade speeds. However, if a certain track class target speed exceeds the maximum speed allowable on a curve with added super-elevation and/or realignment, this speed cannot be supported by current route infrastructure and is excluded from consideration by the model.

The capital cost for infrastructure upgrade alternatives follows the guidelines proposed by Quandel Consultant for upgrades to several passenger rail corridors in the Midwest (13). Maintenance cost calculation is based on an official report which carried out a maintenance analysis under different service levels for a mixed freight and passenger corridor (14). The operating cost is derived from mechanical energy consumption for a single trip and the number of trips throughout a year. The total energy consumption is converted into dollars at the rate of $3.1 per gallon for diesel-electric propulsion (15). Since maintenance cost and operating cost are annual expenditures, they are converted into net present value over a 10-year planning period at a 5% discount rate.
To illustrate different applications of the project selection model to the case study route, two different scenarios are investigated: one with a fixed budget and varying numbers of passenger trains, and one with a fixed traffic level but varying budget.

RESULTS OF CASE STUDY SIMULATION
Genetic algorithm simulation of the case study route to optimally select projects for different budget constraints was executed via a Visual C++ platform installed on a laptop with 8 GB of RAM and a 2.4 GHz i7 processor. For each application of Genetic Algorithms (i.e. each different total budget scenario), 60 chromosomes with 48 genes are generated for genetic evolution. The optimization result can be achieved within 300 iterations, requiring less than 5 minutes for convergence.

**Fixed Budget with Varying Traffic**

Since operating cost is a function of traffic level, for a fixed budget, the amount of funds available for capital upgrade projects will decrease with increasing service frequency. To illustrate this effect, four scenarios from 10 trains per day to an extreme of 100 trains per day on the same case study route are optimized and compared. While 100 trains per day is unrealistic for a practical shared corridor, it is included here to show how the model makes different decisions based on relative magnitude of capital, maintenance and operating costs. Changing the number of trains effectively changes the weighting on the different cost parameters in the cost constraint, leading to different optimal running times and project selection decision. In practice, the model would typically be used to compare projects to support a smaller range of traffic when one or two round trips are added to a corridor or considered as future growth for long-term planning.

With a fixed budget of $60 million, different incremental infrastructure improvements are obtained for different traffic levels (Figure 4a-d). In the figures, the dash-dot line represents the original speed limit; the bold solid line represents the new speed limit after upgrade; the dash line represents the train speed profile under the new speed limit. In this case the trains are not making any stops along the route between the two end stations but the model does have the ability to consider intermediate station stops.

With the extreme traffic of 100 trains per day, operating cost becomes the dominant part of the $60M budget. To make effective infrastructure upgrades with the limited remaining budget, fuel consumption needs to be minimized. Considering the higher fuel consumption rates at higher operating speed, instead of selecting higher-speed segments, the upgrade priority in this case should be raising the maximum speed of slower-speed segments to match that of adjacent segments, such as the segment from mile 11 – 16.5 shown (Figure 4a). By eliminating these slow sections and saving operating energy cost, more investment can be made for infrastructure improvement and the segment with highest operating speed is extended for several miles (mile 20-24). The new minimum running time is 44 minutes.

For the case study scenarios with less daily traffic (Figure 4b and Figure 4c), the model can allocate more of the budget to projects that upgrade maximum speed. Therefore, more segments have been upgraded up to 80 mph (as opposed to introducing 110-mph segments) to balance running time reduction and fuel consumption. By selecting segments that are adjacent to existing 80-mph segments for upgrade implementation, running time reduction and fuel consumption are balanced. Additional throttle movements for transition between different speed levels are avoided, reducing time delay and additional fuel consumption due to acceleration and braking. By selecting 80 mph as the target upgrade speed instead of 110 mph, train operating energy and cost can be saved.
Figure 4: Improved speed profile for case study with (a) 100 trains per day (b) 70 trains per day and (c) 40 trains per day
Figure 4 (continued): Improved speed profile for case study with (d) 10 trains per day

For the route with 10 trains per day (Figure 4d), operating cost is only a minor part of the total budget. With ample capital and maintenance budget, more resources can be allocated to minimize running time. Finally, under this scenario, a portion of route between mile 34 – 42.9 is upgraded to 110mph because it offers the lowest construction cost compared to other segments. Even under this lower traffic level, to minimize operating energy costs, the entire route is upgraded to 80 mph maximum speed before 110-mph segments are introduced. The final minimum running time in this case is 35 minutes.

Figure 4 also illustrates how the model avoids upgrading the maximum speed of segments adjacent to the station stops at either end of the route segment. Since the passenger trains are always accelerating or braking on these segments due to the nearby station stop, no running time is saved by upgrading these particular segments to higher maximum speed.

Fixed Traffic with Varying Budget

Keeping the service level of 40 trains per day constant for this illustrative case study, optimal project plans for different budgets were determined to illustrate the impact on the final passenger train running time. Sixteen scenarios with different budgets amount are solved with the model for the service level of 40 trains per day. While the detailed improved speed profile for each simulated budget level between $25 million and $100 million are not presented here, the resulting running times are plotted to illustrate their relationship to available budget (Figure 5). With more budgets available, the operator is able to improve the infrastructure in order to accommodate higher operating speed and also cover any potential increases in fuel costs. Thus minimum running time decreases as the budget increases. However, running time does not decrease in a linear pattern; the relationship exhibits diminishing returns and implies different return on investment for each budget level.

To study the cost effectiveness of different budget investments, the running time reduction and time reduction per million dollars are calculated at each different budget level (Figure 6). Both the running time reduction and the amount of time reduction per million dollars of budget are important measures of the cost effectiveness of the upgrade program. By investing more money for infrastructure, maintenance and train operation, running time can be reduced, but cost
effectiveness decreases. Upgrade alternatives with higher benefit – cost ratio are selected by the model first when available budget is limited. With increasing budget, more improvements can be implemented, but those upgrades are either too expensive (more investment required for higher track class or fuel for higher operating speeds) or less effective in time reduction (poor acceleration characteristics at higher speed). The return on investment therefore decreases for higher budget scenarios.

If a practitioner can link running time reduction to a monetary benefit from increased ridership, then the reduction per million dollars can be translated into a rate of return. By setting a threshold rate of return, the corresponding budget in Figure 6 can give practitioners a guide for the level of investment in the corridor that reduces passenger train running time in an economical manner. The suite of projects identified by the model at this budget level can be used as an initial plan for more detailed engineering feasibility study. Using the project selection model as a screening tool in this manner can focus limited industry planning and engineering resources on a smaller number of project alternatives, leading to more efficient and effective passenger rail corridor planning.

![Figure 5: Running time for different budget scenarios (40 trains per day)](image1)

![Figure 6: Cost effectiveness of different total budgets](image2)
CONCLUSIONS

This paper presents a methodology for optimally selecting projects or establishing budgets to reduce passenger train running time with consideration of capital, maintenance and operating cost on a shared rail corridor. Genetic Algorithms have been implemented to solve this problem.

The case study simulation results indicate that solutions can be achieved by Genetic Algorithms within a short period of time. Under a fixed budget, this model can consider the performance of different upgrade options under the estimated daily traffic level to identify the most cost effective route segments for infrastructure improvements. For a fixed traffic level, the model can be used to determine the incremental time reduction and reduction per million dollars of budget at many different budget levels. This analysis can help practitioners estimate the appropriate budget to achieve a desired running time performance or return on investment.

With suitable infrastructure and cost data for a particular corridor of interest, this model can be incorporated into passenger rail corridor planning methodologies and used as a decision support tool for passenger rail service planners. Although the natural application of the model is to a single passenger rail corridor, through careful definition of segments within the Genetic Algorithms, the model can be used to select a suite of improvement projects on different routes to achieve an overall reduction in travel time across multiple train services operating on a network.

Future work to develop and increase the capability of this methodology could include examining the sensitivity of results to different grade profiles along the route since grades have important effects on running time and fuel consumption of heavier trains with less power. Also, this research only considers the free-flow minimum running time along a route. Expanding the model to include estimates of delay as a function of freight traffic volume and route infrastructure capacity would allow it to be applied to passenger corridors with higher numbers of freight trains. Last but not least, capital cost, maintenance cost and operating cost need to be analysed and compared separately in the future. Currently, the model incorporates them into a fixed budget. Since these costs usually come from different sources in public sector, separate analysis could help managers to make right decisions on investment. In this manner, the capabilities of the project selection model could be expanded to additional types of passenger and transit operations and even priority freight corridors.

ACKNOWLEDGEMENTS

The authors would like to thank Southwest Jiaotong University, Chengdu, China for train performance simulation software and simulation data. The primary author thanks the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) for advice and support as a visiting scholar and thanks the China Scholarship Council for financial support while at RailTEC. UIUC acknowledges the support of the Association of American Railroads and the National University Rail (NURail) Center, a Tier-1 University Transportation Center (UTC) under the United States Department of Transportation (USDOT) Office of the Assistant Secretary for Research and Technology (OST-R) program, in the conduct of this research.
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18