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

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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 track owned and operated by freight railways. Various projects and approaches can be considered when the running time of passenger trains is being decreased 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. For instance, the marginal travel time benefit of improving segments of a line from a maximum speed of 79 to 110 mph 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 costs. The proposed project selection model is formulated with genetic algorithms. 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.

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 freight railways carrying heavy-axle loads. Because 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—when freight railways see a mutual benefit—a public–private partnership. In either case, individual improvement projects must be justified on the basis of 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, each may have a different effect on time reduction. Therefore, making informed decisions on improvement project selection is critical.

Several studies have investigated topics related to performance improvement of running times on intercity passenger rail corridors. A genetic algorithm (GA) approach was developed to assign running time goals for passenger trains to different corridors while optimizing ridership and revenue of passenger service (*2*). A regional planning tool, CONNECTS, was developed for FRA 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 running time of the passenger train. Train performance calculators and other simulation tools can be used to assess the performance of 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. On the basis of the previous study, some scholars have incorporated the interaction between adjacent route segments as well as maintenance costs into the analysis of potential capital improvements in infrastructure and rolling stock (*6*). However, the proposed model did not consider effects of train operating cost, a key consideration for upgrading route segments to higher operating speeds. The current research proposes a model to select optimal upgrades while considering capital, maintenance, and operating costs.

BACKGROUND

Principally, a reduction in the running time of a passenger train is governed by maximum train operating speeds. In the United States, FRA has identified nine track classes on the basis of 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 1 mi) has been defined for each track class (Figure 1). The greatest benefits to reducing

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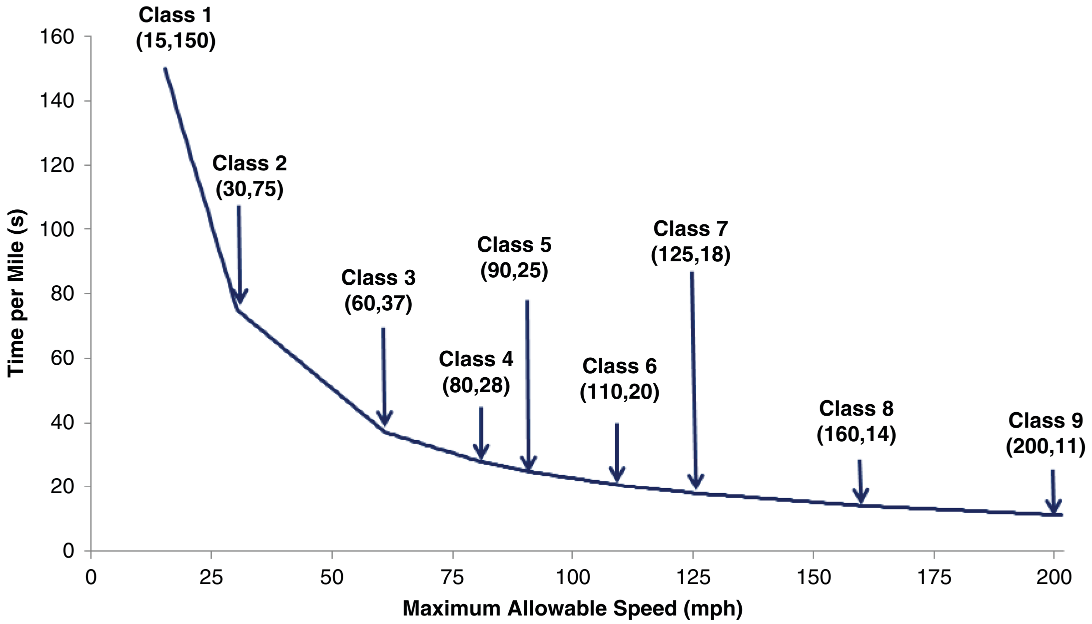


FIGURE 1 Passenger train speed and running time per mile by FRA track class.

running time can be achieved from track class improvements on lower-speed sections rather than on higher-speed ones. For example, upgrading a route section from FRA Track Class 1 to 2 reduces running time by more than 1 min/mi, whereas upgrading a segment from Track Class 5 to 6 saves only 4 s/mi in running time.

Reduction in running time is also affected by the type of improvement projects and the condition of adjacent route segments. Upgrade alternatives include investments in improvements in track, signals, highway grade crossings, and rolling stock. Each improvement approach has distinct benefits on different sections of the route, and those improvement projects can interact. For example, for Section 2 in Figure 2, with a current maximum Speed A, consider two types of adjacent sections: (a) Sections 1 and 3 have higher maximum speeds (Speed B) than Speed A (Figure 2*a*), and (*b*) Sections 1 and 3 have the same initial maximum speed as Section 2 (Figure 2*b*). The project cost to upgrade Section 2 from Speed A to Speed B remains the same in both cases. However, because of 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 reducing running time is also affected by fuel and energy consumption. This factor is critical when projects to upgrade routes to higher-speed operation above 90 mph are being considered. As average train speed increases, air resistance becomes the major component of the train's resistive force. Because air resistance increases quadratically during train acceleration, energy and fuel consumption is disproportionately greater for higher operating speeds. This situation leads to an additional operating cost penalty for selecting higher-speed versus lower-speed improvements and provides 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 model for selecting cost-effective project investments to improve performance on a passenger rail corridor with limited resources to fund capital, maintenance, and operating expenses.

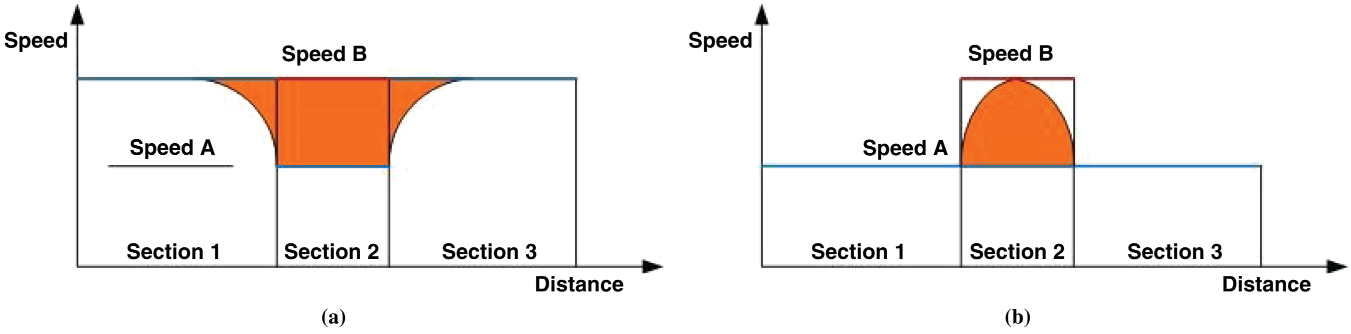


FIGURE 2 Running time benefit for speed upgrade on Section 2 when (*a*) adjacent segments have higher maximum Speed B and (*b*) adjacent segments have the same maximum Speed A as Section 2 initially.

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 the capital cost to upgrade each section of the route are being estimated are track structure–geometry, signal system, and number of highway grade crossings.

Track structure includes rails, cross ties, 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-lb continuous welded rail. In addition to applying U.S. federal regulations, railway companies also apply stricter local standards and tolerances for higher operating speed (*7*).

In this research, track geometry is mainly concerned with curvature improvement caused by its impact on maximum speed. Two upgrade methods are considered: increased superelevation 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 superelevation adjustment consists of adjusting spirals and installing superelevation for the new operating speed. Because maximum superelevation is regulated, further speed improvements can be achieved only by reducing curvature. Curvature reduction consists of curve realignment through the curved section of the existing line within the given right-of-way. A limit exists in the amount of curve reduction that 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 in dollars per mile.

The signal system is used to direct railway traffic safely and in the United States, operations cannot exceed certain speed limits unless specific signal systems are in place. Upgrade alternatives include implementation of signaling systems like centralized traffic control, automatic train stop and automatic train control. In the United States, a centralized traffic control system controls signals and switches within a defined area. Automatic train stop and automatic train control systems, respectively, automatically stop trains and provide overspeed 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 than if the line is not signaled. The cost to improve the signal system is estimated in 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 are implemented at different speed levels in accordance with regulatory requirements, the engineering policies of the railway in charge of the rail infrastructure, or both. The cost to upgrade each route segment depends on both the number of crossings in the segment and speed levels.

To guide the project selection process, alternatives for infrastructure improvement 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 5, the procedures include replacing one-third of timber cross ties; installing 136-lb continuous welded rail; surfacing; adjusting curve superelevation, curve alignment, or both; installing an automatic train stop or automatic train control system; and implementation of four-quadrant gates at highway grade crossings. If any of these items was already present on the section, their cost would not be included in the capital cost of the project. This illustrative example applies only for the paper; a more comprehensive set of alternatives may be applied in project situations.

Maintenance Cost

The maintenance cost, including regular service for track, signal system, and the like, 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 performed in a timely manner, track condition will deteriorate, and running time and the quality of rail service will be affected. In contrast 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

TABLE 1 Alternatives for Infrastructure Improvement

Track Class	Maximum Speed (mph)	Track Structure or Geometry	Signal System	Grade Crossings
3	60	Replace 1/3 cross ties (wood), 136RE CWR, surfacing, curve shift	na	na
4	80	Replace 1/3 cross ties (wood), 136RE CWR, surfacing, curve shift	CTC	na
5	90	Replace 1/3 cross ties (wood), 136RE CWR, surfacing, curve shift	CTC-ATS or ATC	Four quad gate crossings
6	110	Replace 2/3 cross ties (wood), 136RE CWR, surfacing, curve shift	CTC-ATS or ATC	Four quad gate crossings with intrusion detection, fenced ROW

NOTE: 136RE CWR = 136-lb continuously welded rail; na = not applicable; CTC = centralized train control; ATS = automatic train stop; ATC = automatic train control; ROW = right-of-way.

give rise to different maintenance costs in relation to 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 onboard amenities. However, these costs are not related to running time and would be constant for all scenarios considered by the project selection model. Thus, the costs can be ignored by the project selection model developed through this research.

Fuel consumption for each train run is affected by two factors: driving patterns and route characteristics. Driving patterns can be described as the series of throttle 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 the 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 and the subsequent consumption of more time and energy.

PROJECT SELECTION MODEL

Assumptions

A few assumptions have been made to solve the project selection problem. The train is modeled as a single-mass point, so train length is not considered when it enters and leaves each speed limit area. Because the passenger train is very short and has a relatively high power-to-weight ratio, the effects of grade are not included in the 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 capital, maintenance, and operating cost budget at net present value 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 delays resulting from the interaction between freight and passenger trains. Because previous research has shown that meet and pass events can control the performance of passenger trains on corridors dominated by freight operations, 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 (*8–10*).

Model variables are defined as follows:

s = travel distance of train,
S = length of route,
N = number of train trips,
v_s = train speed at distance s,
$c_{\text{upgrade}}(v_1, v_2)$ = per unit length capital and maintenance costs to upgrade from v_1 to v_2,
c_{oper} = unit diesel price,
$\bar{v}_s$ = current speed limit,
$\bar{v}'_s$ = upgraded speed limit,
δ_i = train-specific time-weighting coefficient for ith train trip,
$n_{T,s}$ = applied tractive coefficient,
$n_{B,s}$ = applied braking coefficient,
$F_T(v_s)$ = tractive effort when train is at speed v_s,
$F_B(v_s)$ = braking effort when train is at speed v_s,
λ = fuel efficiency,
μ = transmission efficiency,
m = train weight,
$R_m(v_s)$ = basic resistance at speed v_s,
$R_G(s)$ = gradient resistance at position s, and
$R_C(s)$ = curve resistance at position s.

The mathematic model is presented in Equations 1 through 8.

$$\min f = \sum_{i=1}^{N} \delta_i \int_0^S \frac{1}{v_s} ds \tag{1}$$

$$\int_0^S c_{\text{upgrade}}\left(\bar{v}_s, \bar{v}'_s\right) ds + c_{\text{oper}} \cdot \sum_{i=1}^{N} \int_0^S \frac{n_{T,s,i} F_T\left(v_{s,i}\right)}{\lambda_i ds_i \leq B} \tag{2}$$

$$v_s = \frac{ds}{dt} \tag{3}$$

$$m \cdot \dot{v}_s = \begin{cases} n_{T,s} F_T(v_s) - R_m(v_s) - R_G(s) - R_C(s) \\ n_{B,s} F_B(v_s) - R_m(v_s) - R_G(s) - R_C(s) \end{cases} \tag{4}$$

$$\begin{cases} n_{T,s} \in [0, 1] & \left(n_{T,s} > 0\text{: traction; } n_{T,s} = 0\text{: coasting}\right) \\ n_{B,s} \in [-1, 0] & (\text{braking}) \end{cases} \tag{5}$$

$$P_{v_s} = n_{T,s} \cdot F_T(v_s) \cdot \frac{v_s}{\mu} \tag{6}$$

$$v_0 = 0, \quad v_S = 0 \tag{7}$$

$$0 \leq v_s \leq \bar{v}'_s \tag{8}$$

Equation 1 is the model objective function that minimizes the sum of the minimum running times over the route for each passenger train. It is described in the form of integration. A train-specific time-weighting coefficient δ_i is introduced so that the running times of certain trains may be more heavily weighted in the optimization process. Practitioners may adjust the value of δ_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 costs. The second term computes operating cost summed over all passenger trains.

Motion Equations 3 through 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 the braking process. Expression 5 gives the value range of tractive and braking coefficients. Equation 6 computes the power.

Equations 7 and 8 constrain train speed during the trip. Equation 7 gives the boundary condition, and Equation 8 ensures that speed will not exceed the new speed limit.

APPLICATION OF GAs

Because the number of upgrade alternatives and possible combinations increase exponentially for longer route networks with many segments, the proposed project selection model was formulated as a GA. An algorithm technique for global searches that is 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 a GA, 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 such as selection, crossover, and mutation on chromosomes in the population with a probability that is based on their corresponding fitness values. Optimal solutions in the form of high-fitness individuals will eventually appear after generations of evolution (*11*).

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 (*12, 13*). First, because a GA searches within 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 performed on the basis of 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 GAs will give rise to premature convergence if a dominant individual occurs in the population. Therefore, by introducing a combinational selection method and adaptive probability, an enhanced GA 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 remains the original speed limit.

As Equation 9 (below) shows, the fitness function is rewritten from Equations 1 and 2 as minimization of both running time and budget excess at the net present value over all segments in the given route. In this function, M is the number of segments along the route, V_j is the jth gene that decides the target upgrade speed (or original speed limit if no upgrades are applied), and $T_{i,j}$ represents the travel time along the jth segment for the ith train trip. $T_{i,j}$ needs to be recalculated if the maximum speed changes on a segment. C_{upgrade} is the capital and maintenance costs for the improvement project from the current maximum speed to V_j within the jth segment. C_{oper} is the unit energy cost, while $E_{i,j}$ is the energy consumption of the train while it traverses the jth segment for the ith train trip. B_{const} is the given net present value budget for capital cost, maintenance cost, and operating cost. To avoid solutions in which the cost exceeds total budget, a large penalty α is added to the overbudget term for the optimal solution.

$$\text{fitness function} = \frac{1}{\left(\sum_{i=1}^{N}\sum_{j=1}^{M} T_{i,j} + \alpha\left(\begin{array}{c}\sum_{j=1}^{M} C_{\text{upgrade}}\left(\bar{v}_j, V_j\right) \\ + C_{\text{oper}}\sum_{i=1}^{N}\sum_{j=1}^{M} E_{i,j} - B_{\text{const}}\end{array}\right)\right)} \tag{9}$$

Combinational Selection

Selection is the process used to identify a group of chromosomes from a population for later breeding on the basis of 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 for its efficiency in best individual selection. The probability for a chromosome to be selected is proportional to its fitness. However, because 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 is ranked 1 and the best 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 the emergence of multiple good solutions for breeding. As the evolution proceeds, by using roulette wheel selection, better-fitted individuals have a greater chance of selection. Therefore, the later evolution process will be accelerated.

Adaptive Crossover

Crossover is the process of taking more than one parent chromosome 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 a lower probability of crossover. This inverse relationship means that their good genetic information is preserved for the next generation. However, lower-fitted solutions 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.

$$P_c = \begin{cases} P_{c\_\max} - \left(f' - f_{\text{avg}}\right) \cdot \dfrac{\left(P_{c\_\max} - P_{c\_\min}\right)}{\left(f_{\max} - f_{\text{avg}}\right)} & f' > f_{\text{avg}} \\ P_{c\_\max} & f' \le f_{\text{avg}} \end{cases} \tag{10}$$

For crossover operator, traditional two-point crossover is chosen. Everything between the two points is swapped between the parent chromosomes, an action that renders 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.

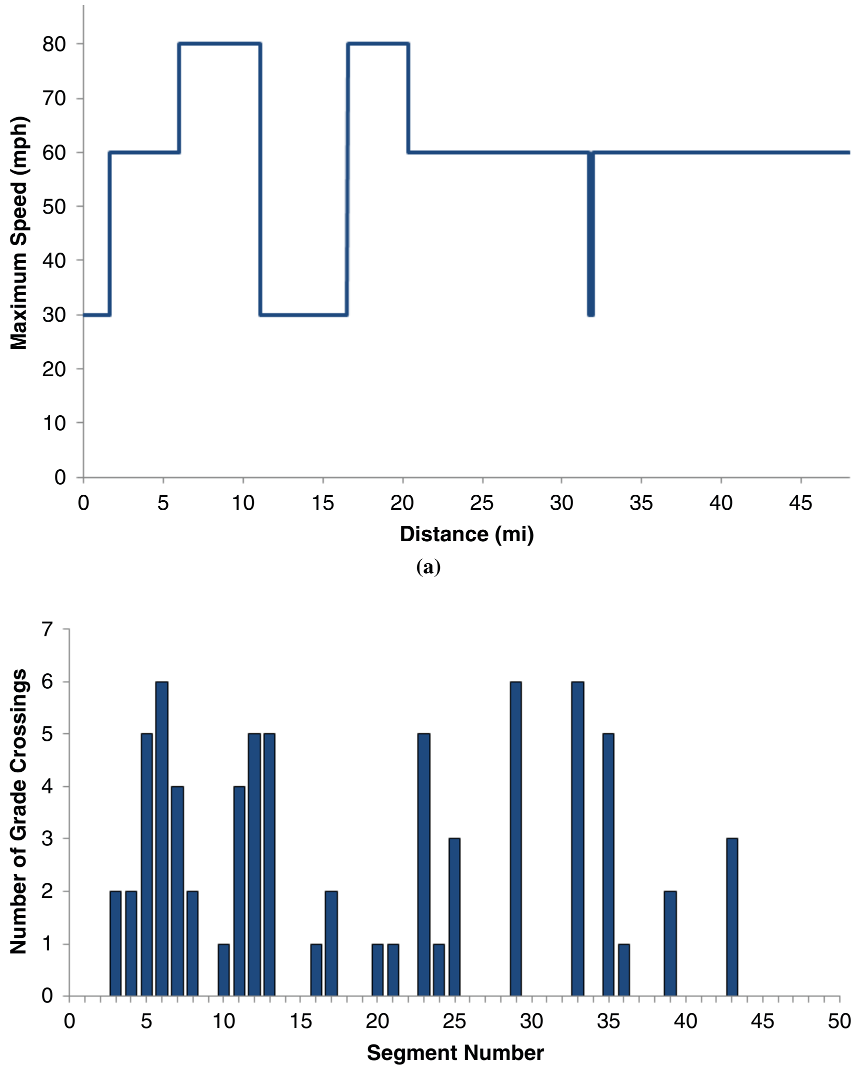
Proposed Algorithm Procedure

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. This loop tries to find the best-fitted individuals on the basis of 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, the rank selection method is used for chromosome selection; otherwise, roulette selection will be applied. The final optimal solution will be achieved when the defined generation value is reached.

CASE STUDY

To demonstrate the functionality of the model for selecting the passenger corridor project, a case study was prepared on a hypothetical route. That route is a 48-mi segment that is based on a typical intercity passenger rail line in the Midwest. The route has 13 curves and 73 highway grade crossings. Because of the limitations of curvature or the signal system, the maximum speed limit for passenger trains varies along the route (Figure 3*a*). The maximum operating speed is 80 mph.

For calculation purposes, the route is divided into 48 segments, each with constant infrastructure parameters (maximum speed, curvature,



(a)

(b)

FIGURE 3 Route parameters for case study: (*a*) existing maximum speed profile and (*b*) number of highway grade crossings in each segment.

etc.). Because the segments vary in length and the grade crossings are not evenly distributed over the length of the route, each segment has a different number of grade crossings (Figure 3*b*).

This case study considers a typical Amtrak regional intercity passenger train with one 4,250-hp, four-axle, diesel–electric locomotive, one locomotive without power (to serve as the 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 corridors for intercity passenger rail in the Midwest. The running time of this train on the corridor is 48.75 min.

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

The capital cost for infrastructure upgrade alternatives follows the guidelines proposed by Quandel Consultants for upgrades to several passenger rail corridors in the Midwest (*14*). Calculation of maintenance costs is based on an official report that performed a maintenance analysis under different service levels for a mixed freight and passenger corridor (*15*). 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/gal for diesel–electric propulsion (*16*). Because maintenance cost and operating cost are annual expenditures, they are converted to 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 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

GA simulation of the case study route to select projects optimally 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 GAs (i.e., each total budget scenario), 60 chromosomes with 48 genes were generated for genetic evolution. The optimization result can be achieved within 300 iterations, requiring less than 5 min for convergence.

Fixed Budget with Varying Traffic

Because operating cost is a function of traffic level, for a fixed budget, the 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 were optimized and compared. While 100 trains per day is unrealistic for a practical shared corridor, that scenario is included here to show how the model makes different decisions on the basis of the 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 and leads to different optimal running times and project selection decisions. 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 4, *a* through *d*). In the figures, the dashed–dotted line represents the original speed limit; the bold solid line represents the new speed limit after upgrade; the dashed line represents the train speed profile under the new speed limit. In this case, the trains do not make any stops along the route between the two end stations, but the model has the ability to consider intermediate station stops.

With the extreme traffic of 100 trains per day, operating cost becomes the dominant part of the \$60 million budget. To make effective infrastructure upgrades with the limited remaining budget, fuel consumption needs to be minimized. By 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 to Mile 16.5 (Figure 4*a*). 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 will be extended for several miles (Miles 20 to 24). The new minimum running time is 44 min.

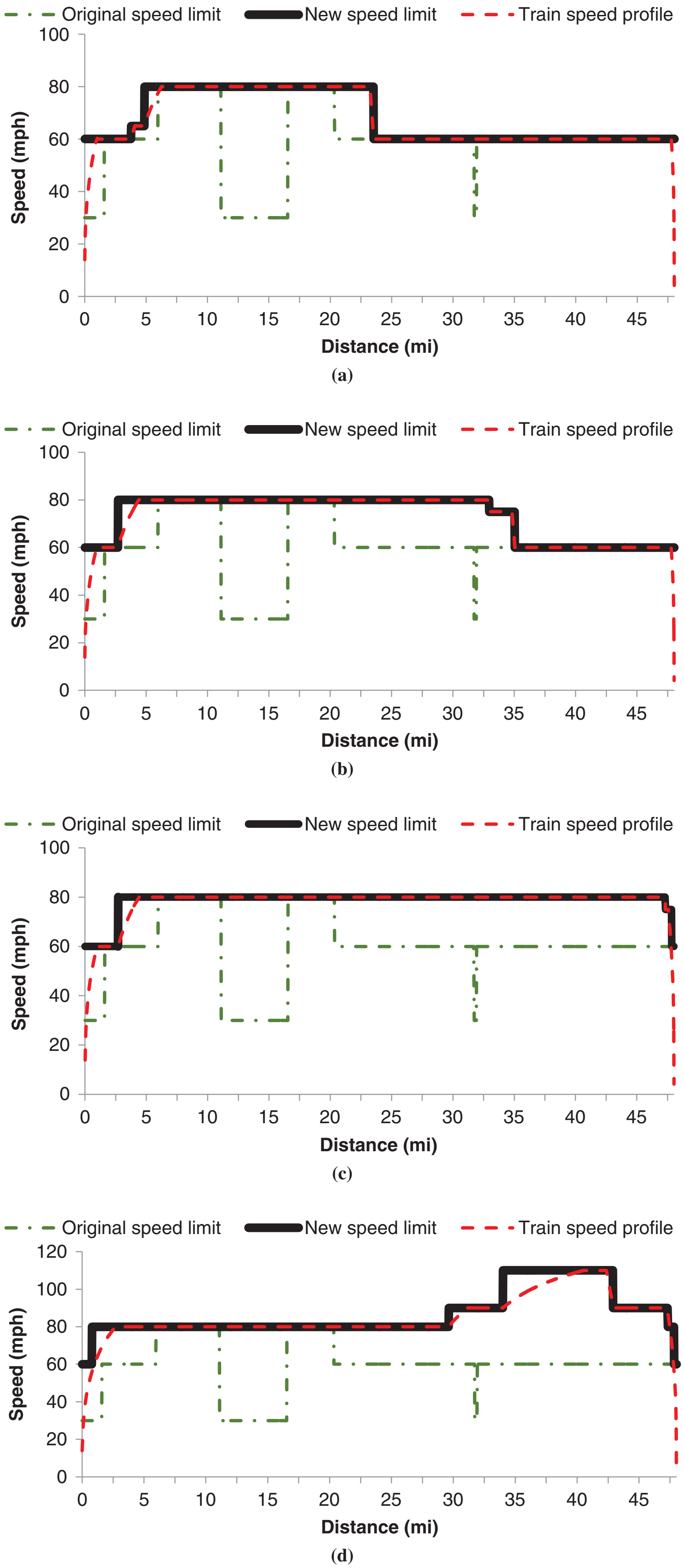
For the case study scenarios with less daily traffic (Figure 4, *b* and *c*), the model can allocate more of the budget to projects that upgrade maximum speed. Therefore, more segments have been upgraded to 80 mph (as opposed to introducing 110-mph segments) to balance running time reduction and fuel 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 from acceleration and braking. By selecting 80 mph instead of 110 mph as the target upgrade speed, train operating energy and costs can be saved.

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

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. As the passenger trains are always accelerating or braking on these segments because of the nearby station stops, no running time is saved by upgrading these segments to higher maximum speed.

Fixed Traffic with Varying Budget

By 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



(a)

(b)

(c)

(d)

FIGURE 4 Improved speed profile for case study by number of trains per day: (*a*) 100 trains (running time = 44 min), (*b*) 70 trains (running time = 40.8 min), (*c*) 40 trains (running time = 37.6 min), and (*d*) 10 trains (running time = 34.95 min).

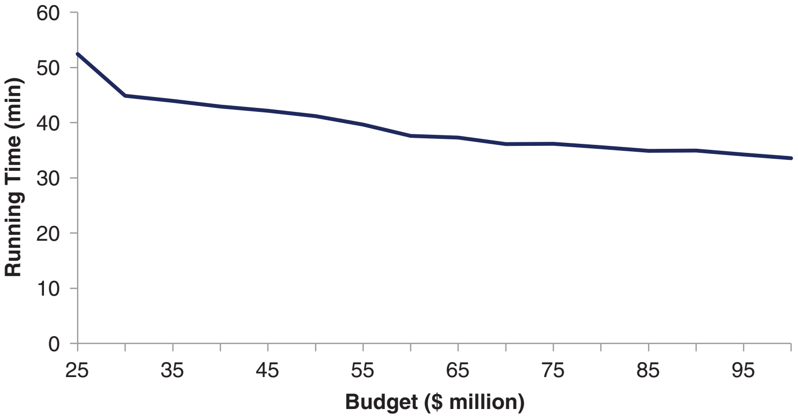


FIGURE 5 Running time by budget scenario (for 40 trains per day).

running time. Sixteen scenarios with different budget amounts were solved with the model. 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 the available budget (Figure 5). With more budgets available, the operator is able to improve the infrastructure to accommodate higher operating speed and 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 returns 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 were 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 ratios are selected by the model first when the available budget is limited. With an 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 to 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 economically. The suite of projects identified by the model at this budget level can be used as an initial plan for a 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 and lead to more efficient and effective passenger rail corridor planning.

CONCLUSIONS

This paper presented a methodology for optimally selecting projects or establishing budgets to reduce running times for passenger trains with consideration of capital, maintenance, and operating costs on

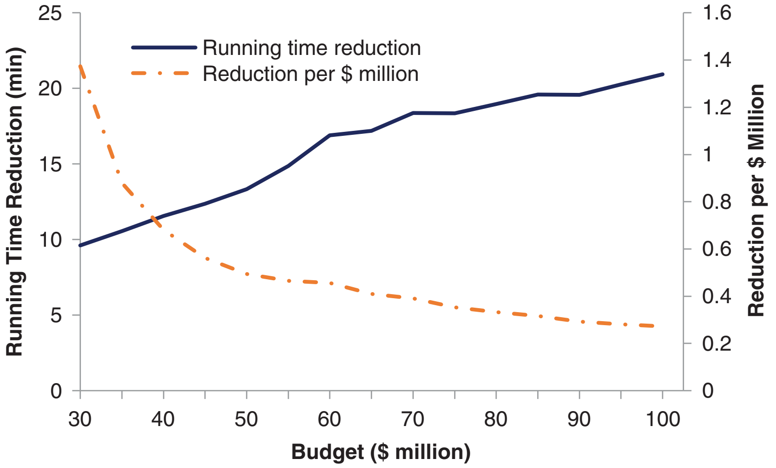


FIGURE 6 Cost-effectiveness by total budget.

a shared rail corridor. GAs have been implemented to solve this problem.

The case study simulation results indicate that solutions can be achieved by GAs in a short 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 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 planning methodologies for passenger rail corridors and used as a decision support tool for planners of passenger rail service. Although the natural application of the model is to a single passenger rail corridor, through careful definition of segments within the GAs, 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 because grades have important effects on running time and fuel consumption of heavier trains with less power. In addition, this research considers only 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. Finally, capital cost, maintenance cost, and operating cost need to be analyzed and compared separately; the model incorporates them into a fixed budget. Because these costs usually come from different sources in the 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.

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