High-Speed Rail Network Design and Station Location

Model and Sensitivity Analysis

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To improve the personal mobility, safety, and environmental impact of passenger travel and to strengthen regional and national economies, planners, governments, and transportation companies throughout the world have been building high-speed rail (HSR) systems for more than half a century. Although many early systems were principally government projects, public–private partnerships are increasingly being used to design, build, operate, and maintain these HSR networks. However, engaging the private sector requires a clear understanding of the potential profitability of such a system. A key question affecting this understanding is the configuration of the line in terms of its length, number and location of stations, and ultimate alignment. A computer model was developed; it used station, route, and system data to determine the most profitable routes based on the proposed stations. In addition, a sensitivity analysis was conducted to determine which variables had the greatest impact on the costs and returns of an HSR route. The sensitivity analysis led to the division of the design variables into three categories based on their impact on profitability. Variables that were found to have a major influence were project concession period, ridership, fare, annual fare increase, train set availability, cost of building on a viaduct, and land value increase. Categorizing the design variables allows the model to be used more efficiently in a multiphase approach that reduces the time and resources required to assess potential HSR lines.

To achieve improved personal mobility, safety, and environmental impact of passenger travel and to strengthen regional and national economies, planners, governments, and transportation companies throughout the world have been planning and building high-speed rail (HSR) systems for over half a century (*1–7*). Although many early systems were principally government projects, public–private partnerships are increasingly being used to design, build, operate, and maintain HSR networks. However, engaging the private sector requires a clear understanding of the potential profitability of such a system. A key question affecting this understanding is the configuration of the line in terms of its length, number and location of stations, and ultimate alignment (*8, 9*).

Although HSR network analysis has been approached from different perspectives, a rigorous, quantitative method for determining the optimal network routing or station placement does not appear to have been developed (*10–12*). A quantitative method would help developers, planners, and investors quickly and reliably evaluate the relative merits of different station locations, characteristics, and routes. To fill this gap, a computer model was developed that quantitatively determines the optimal HSR route for a region.

Given the interrelated nature of the many inputs considered for an HSR route and the inherent uncertainty that comes with a project of this type, the top-performing routes generated by the model were used to conduct a sensitivity analysis on the design variables of the model. Currently, the model considers 27 design variables; the result is a fairly complex model requiring extensive time and computer power to run. Furthermore, finding accurate values for such a large number of variables is time-consuming and potentially very expensive. Conducting a sensitivity analysis of the model's variables allows developers, planners, and investors to have an understanding of which variables will have the greatest influence on the project costs and potential returns (*13*). Knowing the relative influence of the design variables facilitates the use of the model by giving developers a better understanding of how to allocate their resources as they begin planning an HSR network (*14–16*).

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MODEL

The model described here represents a quantitative method for optimizing HSR routes. The model uses station, route, and system data to determine the most profitable routes by maximizing a profit objective function. Initially an enumeration model was developed that permuted every possible combination of stations and evaluated each combination's costs and revenues. However, after evaluation of the limitations of the enumeration model, including computational and time constraints, it became evident that the model was insufficient for larger problems. To overcome the computational limitations of the enumeration model, a genetic algorithm (GA) model was developed that allows for a guided search through the possible routes rather than a look at each individual alternative. Neither model is currently capable of evaluating hub-and-spoke–type networks; this capability would allow for more network possibilities to be considered. In order for the model to be readily available with a convenient user interface for developers, planners, and investors, it was built in Microsoft Excel 2010 and coded by using Visual Basic for Applications.

Enumeration Model

The initial model used an enumeration process to find the optimal route: the model calculated the profit for every combination of the proposed stations. For example, given Stations A, B, and C, the possible route options are A-B, B-C, A-C, A-B-C, C-A-B, and B-C-A. The model then computes several intermediate values, including environmental impacts, projected ridership, fare box returns, land development revenue, the distance and travel time from one end of the route to the other, the initial ridership and passenger miles traveled, and the land development, capital, and operating costs. The model uses these values to compute the total profit that the developer can expect to earn over the time it operates and maintains the route.

One major disadvantage of using Excel for the enumeration process is that the program limits the alignment alternatives to just over 1 million; this limitation in turn constrains the number of station alternatives to nine. A second disadvantage of the enumeration model is the time required to process the data and produce results. The model was run on a computer with 16 GB of RAM, a 3.8-GHz 8-core central processing unit, 64-bit Windows 7, and 64-bit Excel. This computer required only seconds to run the model for two-, three-, four-, and five-station alternatives; approximately 5 min for six- and seven-station alternatives; approximately 15 min for eight-station alternatives; and approximately 5 h for nine-station alternatives. Given that the model permutes the alignment alternatives on the basis of the number of proposed stations, the trend of increased computation time is on the order of an *n*-factorial. Therefore, every station added to the model for consideration in an HSR network will require many more hours of computational time.

GA Model

To resolve the computational limitations of the enumeration model, a GA model was developed to allow for a faster search of the solution space. A GA is a search heuristic that mimics the process of natural evolution to generate and identify useful solutions to optimization and search problems (*17*). The GA model follows the same evaluation procedure as the enumeration model by computing the intermediate values and calculating the profit that the developer can earn. However, the GA model uses a guided approach to finding the optimal solution. Rather than permuting every combination, the model randomly generates a user-defined number of route alternatives for evaluation. The second generation is produced by selecting two parent routes with preference given to those from the first generation with the highest profit and randomly selecting a portion of each. These portions are then combined to create a new route. After a new route is created, there is the possibility of a mutation that allows for additional route combinations. The mutations consist of adding, removing, or replacing a station. This process is repeated until the new generation is populated. New generations are created until one of the following three criteria is met: 10 generations all result in the same optimal route, a user-defined generational limit is met, or a user-defined time limit is exceeded.

The GA model overcomes the nine-station limitation of the enumeration model because each generation will be less than the 1 million rows to which Excel is limited. In addition, the time factor can be mitigated by reduction of either the generation limit or the time limit. If a user wants a higher probability of finding the global optimum route, more time, generations, or both, will be required.

DESIGN VARIABLES

In part, the model was developed to identify the design variables that have the greatest impact on the costs and potential returns of an HSR route. Identifying these variables allows for a standardized, quantifiable analysis of HSR routes that can be universally employed. Over 100 variables were initially identified for use in the model, but because not all of these can be conveniently quantified, only 27 were selected for use in this model. The design variables currently in use by the model are divided into three categories: station variables, route variables, and system variables.

Station Variables

Station variables describe the proposed station alternatives along the corridor:

- Population within a 30-min driving distance from the station; this alternative is based on the procedure used for planning the Taiwanese HSR system (*18*);
- Land value for and around the station ($/acre);
- Quantity of land purchased for the station and surrounding development (acres);
- Rental value of the station and the surrounding area ($/acre/year);
- Other revenue associated with development of the station ($/year);
- Planned dwell time at the station (s);
- Annual increase in land value around the station (%);
- Environmental impact cost ($), which is based on current wetland mitigation rates, environmental justification rates, and so forth; and
- A grouping number, which is used to prevent stations with overlapping ridership catch basins from being selected.

Route Variables

Route variables are used to describe the HSR origin–destination segments that connect the proposed stations within the network. All of the following will be either entered or computed for the route between each of the proposed stations:

- Minimum distance between stations (mi);
- Estimated ridership between any two proposed stations;
- Maximum speed between any two proposed stations (mph);
- Land value along the route ($/acre);
- Infrastructure type, either at grade or on a viaduct;
- Special infrastructure costs [e.g., long-span bridges or tunnels ($)];
- Environmental impact costs ($); and
- Other route revenue associated with the construction of the line ($/year).

System Variables

System variables are those that are applied to the entire HSR network regardless of which stations are selected:

- Number of hours the route will be operated each day;
- Peak headway, that is, minutes of headway between trains during peak travel hours;
- Off-peak headway, that is, minutes of headway between trains during off-peak hours;
- Train set cost [($) it is assumed that the trains have sufficient capacity for all levels of ridership];
- Turnaround time, that is, the number of minutes required to clean a train and prepare it for the next run;

- Train set availability, that is, percentage of the train set fleet that will be ready for use at any point in time;
- Capital interest rate (%);
- Project concession, that is, the number of years the HSR line will be operated and maintained by the developer before it is returned to governmental control;
- Capital payback period (years);
- Cost of building at grade ($/mi);
- Cost of building on a viaduct ($/mi);
- Fare ($/mi); and
- Expected annual fare increase (%).

SENSITIVITY ANALYSIS

Because some of the input variables required by the model can be costly and time consuming to gather (e.g., ridership and environmental impacts) a sensitivity analysis was performed to determine which design variables have the greatest impact on the profitability of an HSR network. With the enumeration model, eight sample routes were selected as base scenarios and their total profit was calculated by using representative data for a region in the United States that is considering development of an HSR system. The eight routes selected were the best-performing routes with two, three, four, five, six, seven, eight, and nine stations. This selection allows for control of the variation due to route length. In addition, using sample routes rather than running the complete enumeration of the GA model allows for control of variability between stations; for example, a changing land value may result in selection of a different route, which would not allow for comparison between different iterations of the sensitivity analysis. The sensitivity analysis could have been performed with longer alignments, but it was determined that nine stations would be an appropriate limit since that is the longest alignment in which the global optimum was known from the enumeration model that considered all the route options. A summary of the sample alignments and the profit the developer would earn for the base case is shown in Table 1 and a map of the relative locations is shown in Figure 1.

TABLE 1 Selected Alignments for Use in Sensitivity Analysis

Number of Stations	Proposed Stations in the Alignment	Total Base Profit ($ millions)
2	C-D	–725
3	B-C-D	–1,222
4	B-C-D-E	–1,687
5	A-B-C-D-E	–640
6	A-B-F-G-H-I	9,648
7	C-B-A-F-G-I-H	19,430
8	D-C-B-A-F-G-I-H	24,931
9	D-C-B-A-E-F-G-I-H	29,073

The sensitivity analysis involved adjusting one input variable while holding all others constant. When a sensitivity analysis is performed, it is important to ensure that the range of each input variable is reasonable. Some inputs have a wide range of reasonable possibilities, such as interest rates, land values, and environmental costs. For these inputs, values ranging from 10% to 200% of the base scenario values were used. Although this range may be extreme for some cases, it provides interesting insight into their impact. Other inputs are limited by either the model or practicality.

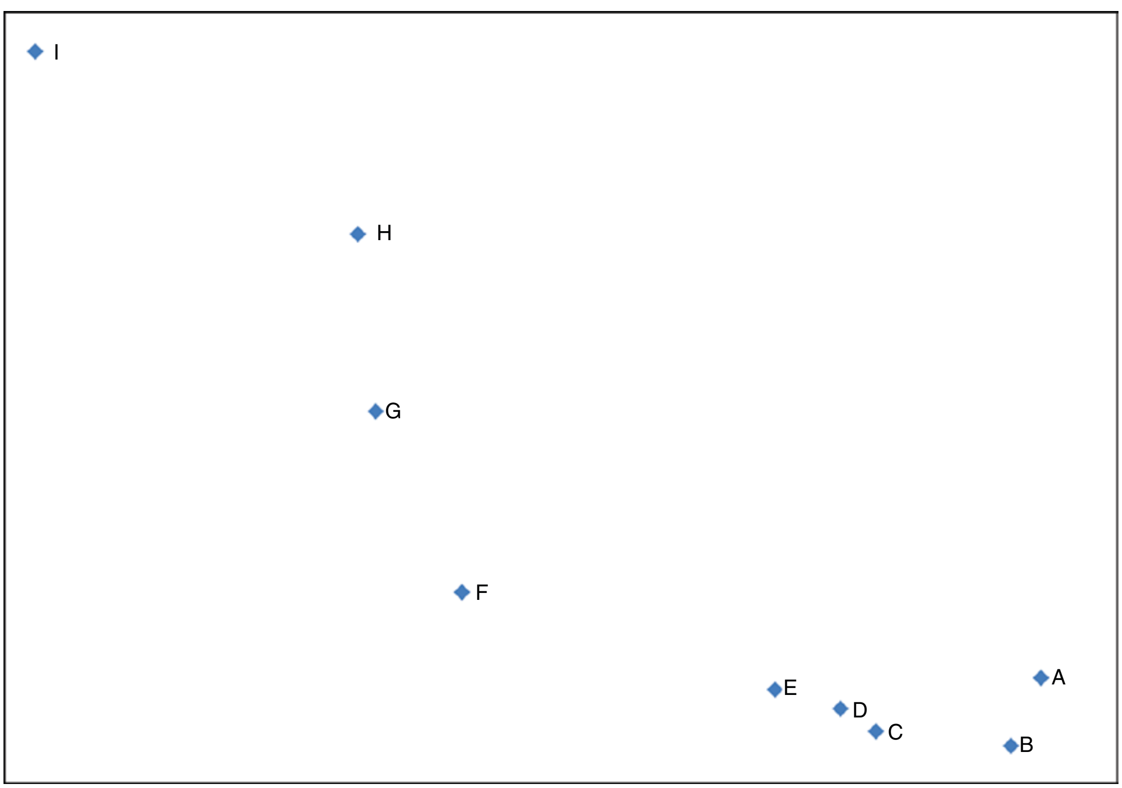

FIGURE 1 Hypothetical map of relative locations of proposed stations.

Inputs with limited ranges include maximum speed, infrastructure type, mileage between stations, availability, and hours of operation. The maximum speed was varied from 10% to 100% of the base value with a maximum speed of 220 mph. The upper speed was constrained by the capability of the train performance calculator used in this study to accurately simulate acceleration and deceleration. If a different train performance calculator were used, this constraint could be removed. Since the routes in the base case are partly at grade and partly on a viaduct, the infrastructure type was varied by having all of the route segments built either on a viaduct or at grade and then varying the cost per mile. The cost to build on a viaduct and at grade was varied from 10% to 200% for the respective infrastructure variation. The mileage was varied from 100% to 200% because the base mileage between two stations was taken as the straight-line distance; thus all shorter lengths were infeasible. Train availability and hours of operation have upper bounds of 100% and 24 h, respectively. These inputs were varied from 10% of their base value to their respective maxima. Specifying the range of these design variables helps avoid the possible error of using unreasonable values, which could result in the sensitivity analysis's indicating that the variable is more sensitive than it actually is (*13*).

DISCUSSION OF RESULTS

For each route alternative, the model provided the solution to the profit objective function with the 27 design variables at 10% intervals between the defined limits. The maximum and minimum profits obtained for all of the design variables were plotted on a tornado diagram for each alignment alternative. Sample tornado diagrams are shown for the two-, four-, and nine-station routes (Figures 2, 3, and 4, respectively). A tornado diagram consists of plotting a bar chart with the maximum and minimum values as the ends with the baseline in between. The variables are sorted in descending order and those with the largest spread are placed at the top; this procedure results in the tornado shape that provides the diagram's name (*13, 16*). The baseline of each tornado diagram was placed at the base scenario profit. The tornado diagram provides a graphical representation of the sensitivity analysis; it allows one to discern divisions between the sensitivity of different variables (*19*). In the case of the sensitivity analysis of this model, it is helpful to show how the model inputs are grouped for the different alignment lengths. One quality that becomes evident in the tornado diagrams is the difference of each input's sensitivity depending on the number of stations in the network. The diagrams shown in Figures 2, 3, and 4 were selected because they demonstrate this variability.

Important relationships are revealed when the ordering of the variables in the tornado diagrams is examined. The tornado diagram for the two-station route differs the most from the others and is skewed in the opposite direction. Project concession is not the most sensitive variable, and the profitability for the two-station route is heavily affected by availability and peak headway. A higher value for either of these variables would mean that fewer train sets need to be purchased. Viaduct costs are next, followed by train set cost and capital interest rate, all of which are directly related to capital expense. However, variables that affect revenue (i.e., ridership, fare, fare increase, land value, land value increase, and other revenue) are not particularly important. Ridership and the quantity of land purchased have

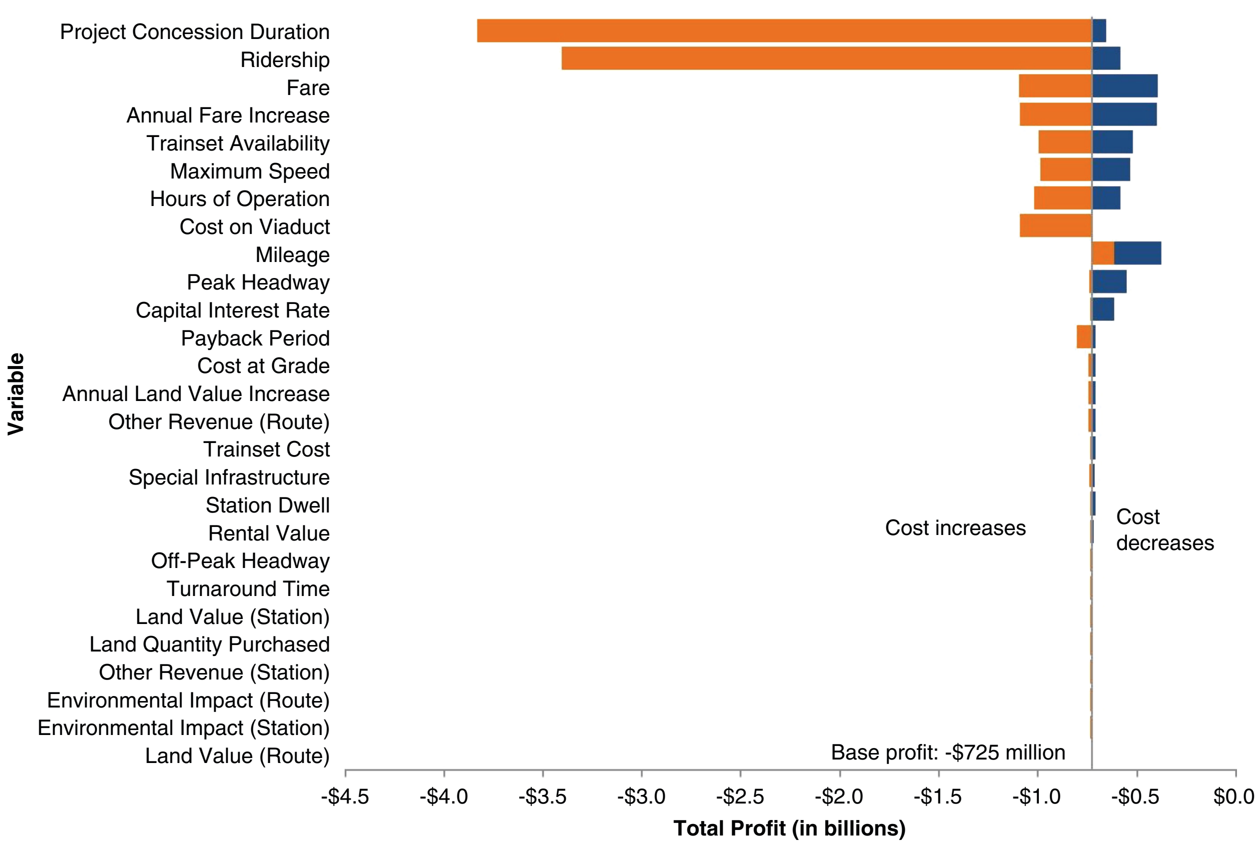

FIGURE 2 Tornado diagram for two-station route.

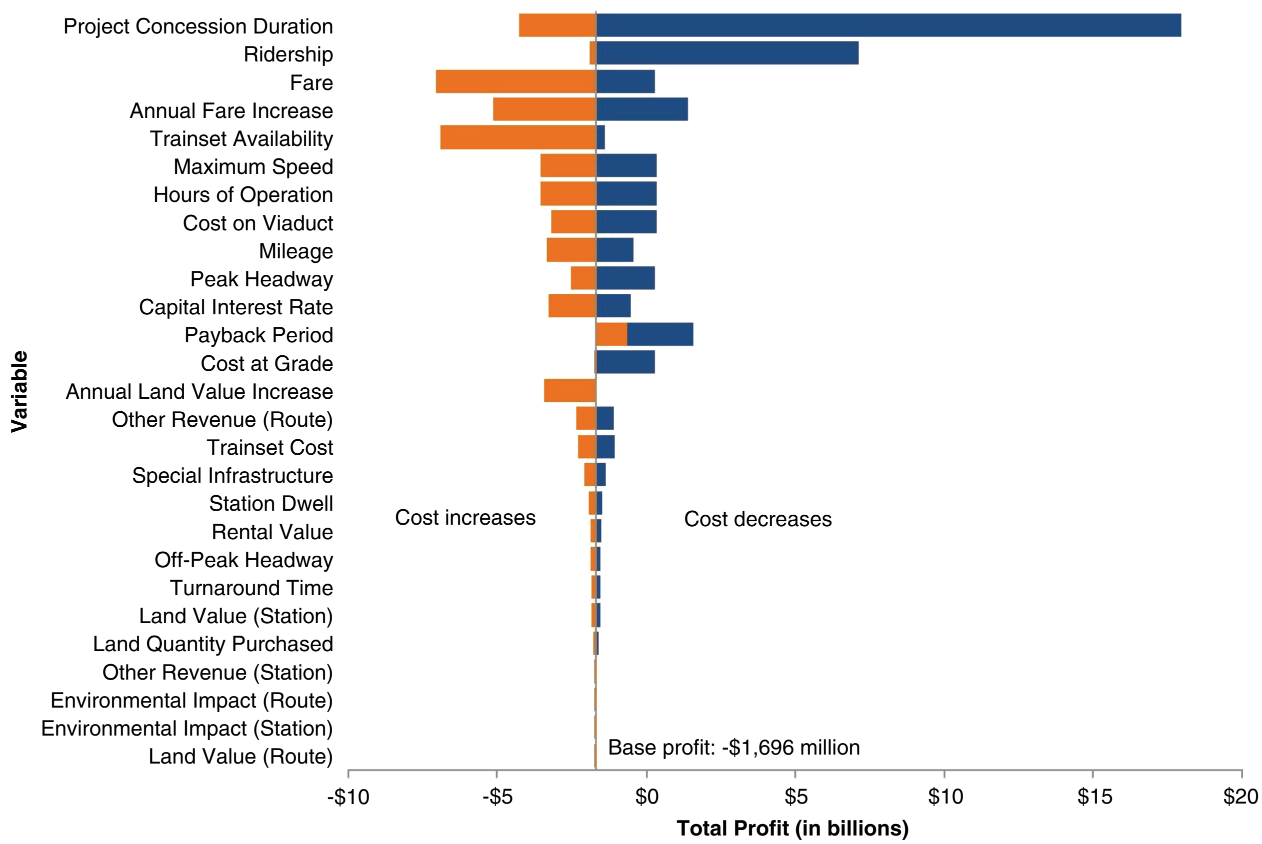

FIGURE 3 Tornado diagram for four-station route.

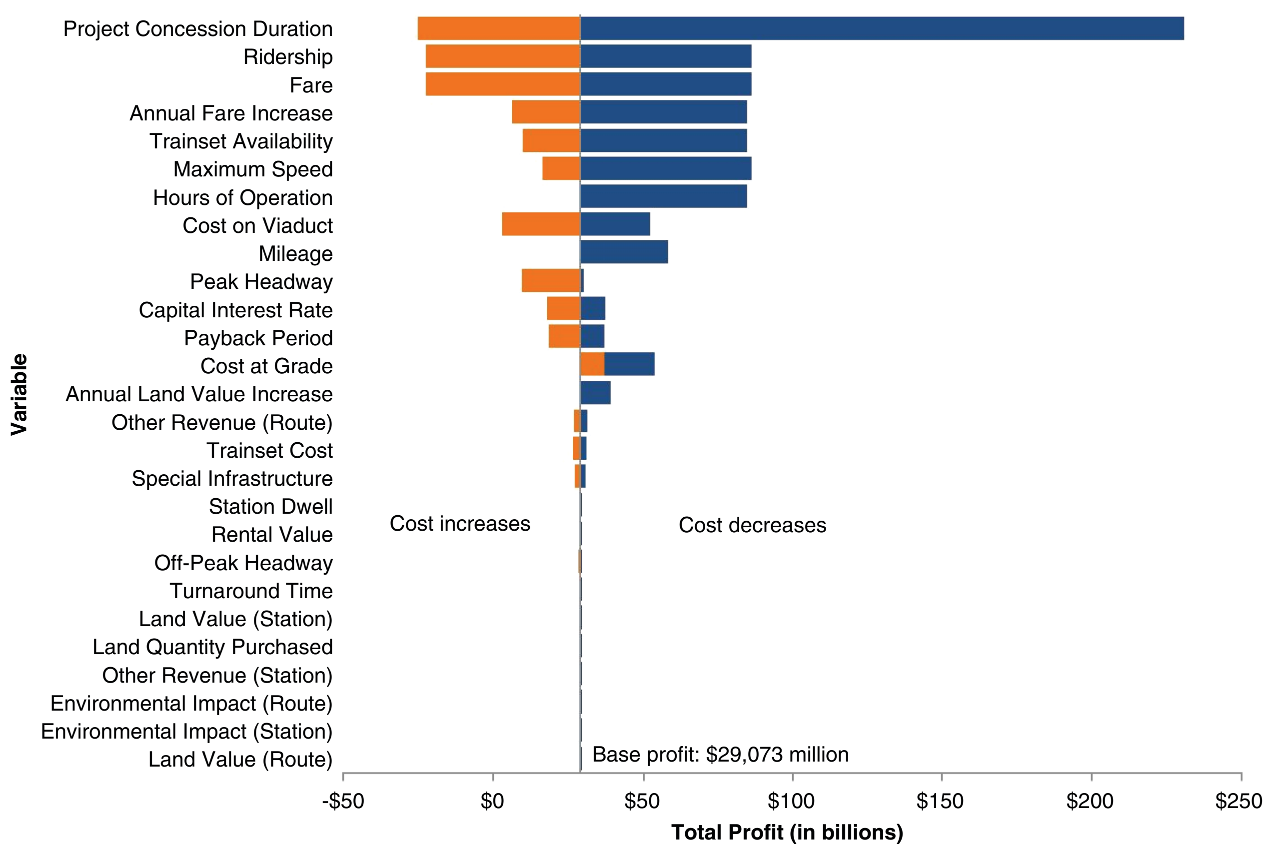

FIGURE 4 Tornado diagram for nine-station route.

relatively little impact; this finding accounts for the lack of impact that revenue variables have on profitability. No reasonable value of these revenue variables was large enough to affect the profitability substantially given the enormous costs that are associated with building even a short HSR route. Another interesting effect is that when all of the route segments were built at grade, the route was always more profitable than in the base case (as seen in Figures 2, 3, and 4). This finding was because the routes were initially partly at grade and partly on a viaduct, so changing the entire route to at grade would always be less expensive than in the base case.

The three- and four-station route tornado diagrams are similar in their order but not their shape. One difference is that the four-station route is more sensitive to the cost of building on a viaduct; this finding is likely due to the addition of the fourth station since the other three stations are the same as in the three-station route. An important point is that the three- and four-station routes can be profitable. Although ridership is still relatively low, enough land has been purchased for the stations and development that the increase in property value, and the associated rental values, can overcome the capital costs. However, the land value increase must maintain its initial rate throughout the concession period in order for these alternatives to be profitable, and such a rate of increase may not be sustainable. Starting with the three-station alternative, project concession duration becomes the most influential factor for all remaining alternatives. Once the capital is repaid, the concession period determines the length of time the developer has to make positive returns on the investment.

The five-station route tornado diagram is different from either the four- or the six-station scenarios, and this is the first diagram in which the ridership and fare are in the top five most sensitive variables. This finding is likely due to the increase in ridership associated with the additional station. In addition, revenues can be high enough over the concession period for the developer to cover the capital costs. The majority of the revenues for the five-station alternative still come from the land value increase, but ridership has become sufficiently large to contribute to profitability.

The six- and seven-station route diagrams have the same top nine variables in the tornado diagram with the exception of fare increase and availability. In the seven-station route diagram, these two have the same spread, so the actual ordering is irrelevant. Any variability between the two diagrams would have been caused by the addition of the seventh station because the other six stations in the seven-station route are the same as in the six-station route. The six-station route is the first route in which the route segment mileage begins to be more important. The eight- and nine-station routes are also similar. The first 21 most sensitive variables are the same, and the profit is not very sensitive to the remaining variables. Starting with the six-station alternative, ridership, fare, and annual fare increase surpass the land value increase to become the most important revenue factors after project concession. For these alternatives, the ridership is finally sufficient to produce enough revenues to offset the costs, despite the fact that infrastructure costs remain an important factor.

Variables move to different influence levels in the diagrams because as the total profit increases, the contribution of a particular variable to the total profit may become more or less important in comparison with other variables. For example, the sample three-station route has total revenues of $5 billion and the land value increase accounts for 80% of that amount. For the sample nine-station route, total revenue is $100 billion and the land value increase accounts for $11 billion of the revenue. However, that increase is only 11% of the total profit in the nine-station case, while the land value increase accounts for 80% of the total revenue in the three-station case. This finding means that the relative importance of the land value increase declines for nine stations compared with three stations even though the profit contributed by the variable has increased.

In addition to the impact of the major decision variables, the tornado diagrams reveal which design variables have relatively little effect on the profitability of the station alternatives, even when extreme values are used for those variables. The costs associated with the environmental impacts of the stations and routes were found to be not influential because they are typically on the order of millions or tens of millions of dollars whereas the cost of the entire project is on the order of tens of billions of dollars. However, there are other factors that need to be addressed, such as delay caused by public opposition, which could potentially be factored in by evaluating the costs that such delays would have on the construction. Land value and rental value did not have a significant impact because they too are small. However, the increase in land value that occurs after HSR construction accounts for the majority of the profit generated in alternatives with only a few stations. Land cost is not very important because the cost of buying land is much less than the cost of the infrastructure itself. Even when land is expensive, as in urban areas, the quantity of land purchased may be small.

Dwell time at stations and turnaround time at terminals, though related to availability, remain unimportant even when availability is a major factor. This finding may be because they are short periods of time compared with total trip time. Also tied to availability are peak headway and cost of train sets. These variables are important when availability is a major factor in alternatives with five or fewer stations; however, their impact declines as availability drops in importance. This result may be due to the fact that even with large headways, long routes will likely need more train sets to serve the desired schedule.

The cost of special infrastructure is not very influential because of its relatively small value compared with that of the whole project, even when varied by 200% from its initial value. However, some alignments may require advanced forms of special infrastructure, such as deep tunnels under skyscrapers, the cost of which could have a greater impact on profitability. To use the model effectively, designers and planners should anticipate the need for these advanced forms of special infrastructure.

Mileage, a variable of minor importance, is less influential than expected despite being related to construction and operating costs. Reliable data for other revenue generated from the route and stations were not available, and therefore modest estimates were used. These variables may become more important in cases with low ridership if their initial values greatly exceed these low estimates. In addition, some variables that interact in practice are not mathematically linked in the model. This feature is the case with ridership, in which the impact of hours of operation, total travel time, and fare are either not well understood or have relationships that should be addressed in future work. However, other variables such as delay are included in the ridership estimation.

Although the cost of infrastructure is important, the capital interest rate and payback period did not appear to be particularly influential. Nevertheless, these variables will always remain significant to some extent because of their relation to the cost of infrastructure. Further, the capital interest rate should not exceed the estimated range because of the large amount of money being borrowed. If the rate exceeded the estimated range, its influence would increase.

The value of the land purchased for stations consistently had a low influence on profitability. This finding would indicate that purchasing more expensive land in a city center may be a better option than buying cheaper land on the outskirts because it will allow access to a higher population density. Also, public transportation will be more likely to already have service to an area in the city than one on the periphery. However, the possibility of development must also be considered because even though the revenue from the land in and around the station does not have much variability, it still has the potential to contribute greatly to enterprise profitability, as is seen in the Hong Kong rail system (*20*).

CONCLUSIONS

The results of the sensitivity analysis allow some conclusions to be drawn about the relative influence of the model's design variables and can facilitate the use of the GA model. Although each route alternative has some difference in its sensitivity to the variables, there are enough similarities for a list of variables most likely to be generally influential to be established. Accurate design and planning require the use of a list common to all route lengths because the optimal number of segments on the route cannot necessarily be anticipated. If a planner only inputs accurate data for the variables that are influential to an alternative with a specific number of stations, the route generated by the model may not be the same as what would have been generated when all influential factors are considered.

The variables that this sensitivity analysis found to be most influential in all cases include

- Project concession duration,
- Ridership,
- Fare,
- Annual fare increase,
- Train set availability,
- Cost of building on a viaduct, and
- Annual land value increase.

These seven variables appeared near the top of the tornado diagrams for all station alternatives. The analysis further reveals that the following eight variables have minor importance and should be considered when a more detailed analysis of an HSR route is done:

- Peak headway,
- Hours of operation,
- Maximum speed,
- Mileage,
- Cost to build at grade,
- Train set cost,
- Capital interest rate, and
- Payback period.

These variables are important because of their relationships with the seven major variables. Peak headway and hours of operations relate to availability, and maximum speed and mileage relate to ridership because ridership is directly related to the duration of a particular trip compared with other modes and capital interest rate and payback period affect the total cost of infrastructure. In general, these minor variables affect the projected values of the major variables.

Analysis of the results reveals that the remaining 12 variables are relatively unimportant in determining the profitability of an HSR system: turnaround time, station dwell time, off-peak headway, land value, rental value, cost of land, quantity of land purchased, other station revenues, other route revenues, special infrastructure, environmental impacts at stations, and environmental impacts along the route.

TABLE 2 Sample Multiphase Approach to Using HSR Model

Phase	Description
1	The number of stations being considered can be reduced by running the model with appropriate values for the major variables. Reasonable assumptions and easily accessible information can be used for the minor and uninfluential variables.
2	More detailed values for major variables will be used and appropriate values will replace the assumptions made for the minor variables; this will further reduce the number of stations being considered.
3	With many superfluous station alternatives eliminated by Phases 1 and 2, the model can be run with the most detailed information available for all variables to produce the final route.

Categorizing the design variables allows the model to be used more efficiently in a multiphase approach for proposing and analyzing large networks. A sample multiphase approach is shown in Table 2.

Use of the results from the sensitivity analysis to optimize the GA model and its application through a multiphase approach has the potential to facilitate objective planning for HSR systems. The model can enable more informed decisions about where to develop HSR systems and the basic design of the network.

FUTURE WORK

The findings of the sensitivity analysis bring to light several areas for future work. First, additional research into relationships between variables can provide a more accurate understanding of their impact on profitability. As mentioned earlier, the relationships among ridership and fare, hours of operation, and total travel time are not represented mathematically in the model. However, ridership may be affected since values for these other variables fluctuate. In addition, results of the analysis have shown a need for further analysis into the interactions between variables. Once a better understanding of these relationships has been represented mathematically, a multivariable sensitivity analysis could be conducted to better establish how these variables interact to determine the overall profitability of a route.

Other topics that could improve the quantitative modeling of HSR networks are consideration of the impact of express service, hub-and-spoke networks, and access. Express service would have the benefit of reducing travel time for some passengers since they could take trains that will skip some intermediate stations; however, some analysis would need to go into this aspect because the schedules would need to be constructed so as to provide the optimal service (*21*). Also, there are some areas in which a single, semilinear passenger corridor is insufficient, for instance, in the Midwest of the United States where there are metropolitan areas that could not easily, or effectively, be connected in one line (*22*). These cases require a hub-and-spoke arrangement to effectively connect major cities in the region. On a local level, it is necessary for passengers to be able to access the station on either end of their trip. In Europe and Asia, this access is usually provided by mass transit, but the impacts of mass transit will be different in the United States where private automobile use is more prevalent. Therefore, the costs of building a station near a belt route or other location easily accessible by automobile would need to be considered to provide access for passengers in areas where public transportation is not sufficient.

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