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DEVELOPMENT OF A MULTI-CRITERIA DECISION METHOD FOR HIGH-SPEED RAIL CORRIDOR EVALUATION

by

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ABSTRACT

High-speed intercity passenger rail projects are very complex and require many years of planning and environmental activities before construction can begin. Given the complexity of planning and environmental reviews associated with high-speed intercity passenger rail corridor planning, a systematic approach for high-level screening of various alternative routings for proposed high-speed rail corridors is desired. In this context, this paper proposes a multi-criteria decision-making framework to assist high-speed rail planners with the preliminary screening and ranking of potential high-speed rail corridors. The proposed framework is applied to the question of ranking 13 alternative routings for connecting the South Central and Gulf Coast federally-designated high-speed rail corridors located in Texas. Attributes that are incorporated in the decision framework include population, travel demand, capital costs, land use and environmental impacts, and engineering suitability. While the multi-criteria decision-making framework developed in this paper cannot be used to completely replace the environmental review process and formal alternatives analysis, it can be used by planners as a tool for preliminary screening or ranking of proposed high-speed rail corridors for detailed analysis.

INTRODUCTION

In April 2009, the U.S. DOT released the *Vision for High-Speed Rail in America* plan, which outlined an agenda to significantly enhance the nation's intercity passenger rail network (*1*). The renewed efforts for improved intercity passenger rail are focused in 11 federally-designated high-speed rail corridors, which, by many accounts, represent the future of passenger rail in the U.S.

While initial investments in the U.S. intercity passenger rail network have focused on the 11 existing federally-designated high-speed rail corridors, there are noticeable gaps across the proposed network. Most notably, in places such as Ohio-New York-Pennsylvania, Florida, Texas, Kansas-Oklahoma, and the Southwest, additional links between existing corridors may be desired to provide greater connectivity across a nationwide high-speed rail network. Furthermore, within several corridors, such as the Northeast, Florida, Chicago Hub, and the South Central corridors, there are many different alternative routings that can be selected for a high-speed rail line to connect major endpoint cities. Issues related to high-level screening of various alternative routings for a proposed high-speed rail line within a corridor are typically addressed in the "alternatives analysis" project phase, generally as part of a broader environmental analysis. Alternatives analyses are typically quite complex and consider a number of different metrics to evaluate potential routings for proposed high-speed rail lines within a corridor. This complexity is multiplied when political issues of selecting corridors that, for example, serve one community over another are taken into account.

Given the complexity of planning activities associated with high-speed rail corridor planning, as well as the high levels of initial investment cost and risk inherent in high-speed passenger rail projects, coupled with the political liabilities associated with major policy decisions, a rational and systematic approach for high-level screening of various alternative routings for proposed high-speed rail corridors is desired. Further, given the limited public resources available for detailed route scoping and planning activities, a method for prioritizing alternative routings to identify a handful of routes for more detailed study, utilizing readily-accessible data sources, is also desired. In this context, this paper proposes a multi-criteria decision-making (MCDM) framework to assist high-speed rail planners with the preliminary screening and ranking of potential corridors for an alternatives analysis or related activities. The framework is applied to the question of ranking alternatives for connecting the South Central and Gulf Coast federally-designated high-speed rail corridors.

LITERATURE REVIEW

Multi-Criteria Decision-Making Background

Decision making can be defined as "the process of selecting a possible course of action from all the available alternatives" (*2*). For most situations, decisions must be made in a context where many objectives or constraints (often conflicting) contribute to the overall decision process. Multi-criteria decision making (MCDM, sometimes referred to as multi-objective decision-making, or MODM) is a branch of decision-making theory that attempts to resolve conflicts among the many criteria (objectives or goals) that are taken into account for a decision. While there are many MCDM methods that can be applied to a decision-making problem, all approaches share the following three characteristics (*2*):

1. A set of criteria of judgment;

2. A set of decision variables; and
3. A process of comparing the alternatives.

An excellent overview and taxonomy of the methods and applications of multi-criteria decision making can be found in (*2*). Triantaphyllou (*3*) outlines three basic steps used in any decision-making technique, including MCDM, involving the numerical analysis of alternatives:

1. Determine the relevant criteria and alternatives.
2. Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
3. Process the numerical values to determine a ranking of each alternative.

MCDM in Transportation Planning

One of the primary tasks of transportation planning is to consider alternative treatments or courses of action for a particular transportation problem and provide information to policymakers to support investment decisions or other policy approaches towards a solution to the problem at hand. Given the complexity of decision-making that is inherent in transportation planning activities, it is not surprising that MCDM methods can be applied in the field. Giuliano (*4*) notes that MCDM has been particularly applicable in transportation planning, given the following changes in the planning environment starting in the early 1970s:

- Expanded Emphasis: Shift from a focus on economic efficiency to increased emphasis on the environmental and social impacts of infrastructure projects, resulting in a more complex decision-making environment where MCDM methods are useful.
- Increasing Number of Alternatives: Modern-day transportation planning and decision-making generally involves a greater number of alternatives. In addition to a larger range of modes and technologies being considered, the size, scope, and complexity of alternatives has also increased. As a result, the use of MCDM methods to rank or eliminate alternatives from consideration is of increasing value.
- Increasing Number of Stakeholders: Current planning processes have a larger number of participants than the past. This increase is due to policy requirements to include a greater number of stakeholders (e.g., through the NEPA process). One could also argue that the proliferation of technology has allowed for the swift organization of stakeholder groups on both sides of an issue. Increasing number of participants results in a greater variety of objectives being considered, which further expands complexity. Hwang and Masud (*2*) note that one feature of MCDM is the ability to treat these objectives independently.

The application of MCDM methods to transportation planning have been demonstrated in the literature. Cheslow (*5*) and Hill (*6*) report on the use of multi-criteria methods in the consideration of transportation alternatives with a regional-level scope. The NCHRP published a report on effective-decision making, including the use of MCDM methods, for transportation corridor planning studies; however, this report did not specifically reference any rail studies (*7*).

MCDM Application to High-Speed Rail Corridor Problem

The application of rational decision-making methods has also been applied to the consideration of high-speed intercity passenger rail. Like other decision contexts in transportation systems, the decision environment for high-speed rail is complex. Additionally, the large capital investment required to develop a high-speed rail line and the potential to interact with privately-owned railroad companies provide additional layers of complexity in the decision-making process. Because of the high investment cost, most of the literature applying a formal decision-making structure to high-speed rail is of a single-objective nature, with a focus on the economic impacts (either as a benefit-cost ratio or a net present value). For single-objective methods such as the benefit-cost ratio, the externalities (that is, user benefits or costs not directly applied to the project) are tied to a dollar amount and included in the final calculations. Applications of the benefit-cost analysis method for high-speed rail service are described in Brand et al. (*8*) for proposed high-speed rail in California and by de Rus and Inglada (*9*) for existing service in Spain, among others. A specific single-objective (benefit-cost) application within the context of high-speed passenger rail includes the selection of the appropriate high-speed train technology for a given corridor by Allen (*10*). It is not surprising that the literature on this topic is primarily focused on cost-effectiveness on high-speed service. Given the high costs necessary to establish high-speed rail service, it is likely that policymakers would wish to have assurance that the investment will be cost-effective before other factors are considered.

Formal multi-criteria decision making methods, on the other hand, appear to be rare in the literature on decision-making for high-speed rail. One application by Chang et al. (*11*) describes the use of a fuzzy MCDM method to develop a service plan (station stops and service frequency) for a high-speed rail line in Taiwan. Research on the selection of a route for a high-speed passenger rail link between Madrid and Valencia (Spain) by Anton and Grau applied two MCDM methods, the ELECTRE-I and analytic hierarchy process (AHP) methods, to identify a preferred route (*12*). A "compromise programming" method was also analyzed. Four criteria (cost, trip duration, potential users, and environmental impact) were considered for the selection of a preferred route from among three potential routes. It is noted that this research bears much resemblance to the question being considered in this paper. One key difference between the two is that Anton and Grau had the benefit of a full route scoping study from which to draw attribute levels for each alternative, while this study is specifically considering only sketch-level data.

The rarity of formal MCDM applications on the subject of high-speed rail corridor selection is not surprising, given the cost considerations discussed above. However, MCDM can be useful for high-speed rail planning because of its flexible nature and specifically, its capability to incorporate values on different measurement scale types (as opposed to a benefit-cost analysis where all the external factors are monetized). Another benefit of MCDM analysis for high-speed rail planning is its ability to consider input and criteria from many stakeholders with possibly conflicting goals and objectives, rather than using a single measure of assessment.

NOMENCLATURE

The formulation of the MCDM method in this paper follows the general steps of a multi-criteria decision-making problem outlined by (*3*). The first step in the process is the identification of the relevant criteria and alternatives for the problem. The basic structure of an MCDM problem is shown below. This structure, referred to as a decision matrix, consists of alternatives $A_i = \{1,2,\ldots,m\}$ and evaluation criteria $C_j = \{1,2,\ldots,n\}$. The importance of each criteria C_i is given by the criteria weights w_j. The performance of alternative A_i with respect to criterion C_j is denoted by a_{ij}.

$$
\begin{array}{c|ccccc}
 & C_1 & C_2 & C_3 & \ldots & C_n \\
 & w_1 & w_2 & w_3 & \ldots & w_n \\
\hline
\boldsymbol{A_1} & a_{11} & a_{12} & a_{13} & \ldots & a_{1n} \\
\boldsymbol{A_2} & a_{21} & a_{22} & a_{23} & \ldots & a_{2n} \\
. & . & . & . & . & . \\
. & . & . & . & . & . \\
. & . & . & . & . & . \\
\boldsymbol{A_m} & a_{m1} & a_{m2} & a_{m3} & \ldots & a_{mn}
\end{array}
\qquad (1)
$$

This structure and nomenclature will be used throughout the duration of this paper.

SETTING & ALTERNATIVES

Case Study Setting

In Texas, two high-speed rail corridors have been designated: the South Central high-speed rail corridor and the Gulf Coast high-speed rail corridor. Designated in 2000, the South Central high-speed rail corridor consists of a hub in Dallas-Fort Worth, with spokes extending north towards Oklahoma City and Tulsa, east towards Texarkana and Little Rock, and south towards Austin and San Antonio. The Gulf Coast high-speed rail corridor includes a hub in New Orleans with spokes extending west to Houston, north towards Birmingham and Atlanta, and east towards Mobile. The Gulf Coast corridor was designated in 1998 with the extension to Atlanta approved in 2000 (*13*).

Examining the federally-designated high-speed rail corridors in Texas in greater detail, noticeably absent is a link between the western termini of the Gulf Coast high-speed rail corridor in Houston and any portion of or city along the South Central high-speed rail corridor. Given the extensive urban area populations in both Houston and cities along the South Central corridor including Dallas-Fort Worth, Austin, and San Antonio, a connection between the two corridors would appear to be a logical course of action. A connection between the South Central and the Gulf Coast high-speed rail corridors would be beneficial to statewide mobility in Texas as well as the nation’s intercity passenger rail goals by facilitating more efficient mobility and alternatives for intercity travel in the region as well as providing additional connectivity towards a nationwide passenger rail network.

Definition of Alternatives

A total of 13 alternative routes to connect the South Central and Gulf Coast high-speed rail corridors were developed for this paper. Figure 1 shows a map of the two existing high-speed rail corridors and the 13 proposed alternative routings. The development of alternative routes for connecting the two high-speed rail corridors was guided by several assumptions, as follows:

- All connections to the Gulf Coast corridor would be in Houston and that the connection to the South Central corridor would be in San Antonio, Austin, Temple, Waco, or Dallas.

- Alternative corridors are defined within existing railroad rights-of-way wherever possible, based on the assumption that the owner of the right-of-way is willing to allow higher-speed passenger operations along the corridor. Experiences with high-speed rail development in the U.S. in locations such as California suggest that this assumption may be too presumptive; however, for the purposes of this hypothetical exercise, constraining the alternative routes to existing freight railroad right-of-way is necessary.
- Alternative corridors were defined to end in close proximity to the urban area boundary of the major urban areas (Houston, Dallas, Austin, and San Antonio). It was assumed that the connection between the endpoints of each alternative corridor at the urban area boundary and the central city would be completed, as the development of high-speed passenger rail within the urban boundary is outside of the scope of this paper.

Table 1 provides a general description of the 13 alternative routes, including the endpoint city, length, and other notes. For 10 of the 13 alternatives, 100 percent of the route-miles incorporated freight railroad right-of-way. Two routes, routes A_2 and A_5, incorporate an 18.6-mile section of abandoned freight railroad right-of-way between Houston and Austin. Another alternative route, route A_{10}, utilizes a 105-mile "greenfield" right-of-way approximately parallel to Interstate 45 between Houston and Dallas. This alternative route was developed specifically for this paper and has not been examined by any official feasibility study, past or present. The locations of the abandoned right-of-way and the proposed "greenfield" right-of-way parallel to Interstate 45 are noted in Figure 1. Certain alternatives considered in this paper resemble those that have been considered in the past for high-speed intercity passenger rail service in Texas; however, this analysis is performed independently of any previous or on-going high-speed intercity passenger rail planning activities.

EVALUATION CRITERIA

The development of evaluation criteria for any MCDM problem is guided by the overall goals and objectives for the problem outcomes. From these objectives, specific criteria or attributes can be defined to measure progress towards these goals. Keeney and Raiffa (*14*) report that approaches to developing objectives include "examination of the relevant literature, analytical study, and casual empiricism." In a more detailed methodology, meetings with policymakers and other stakeholders would reveal additional objectives for the proposed link between the two high-speed rail corridors. However, at this level of detail, no such information is provided. This analysis considers four objectives, reported in the left-hand column of Table 2. Within each stated objective, several measures can be used to evaluate the performance of each alternative towards meeting a specified objective. The right-hand column of Table 2 reports the proposed evaluation criteria.

Maximize Travel Demand

Criteria C_1, Travel Demand Index, is a proxy variable for total system travel demand. For this paper, the "system" is the total demand for travel between Houston and the five key cities along the South Central High-Speed Rail Corridor: Dallas-Fort Worth, Waco, Temple, Austin, and San Antonio. Travel demand was estimated using a simple gravity model given by (2) below:

$$T_{1-2} = k \frac{P_1 P_2}{\left(d_{1-2}^{\,2}\right)} \tag{2}$$

The numerator of the gravity model (P_n) is the product of the urban area populations of the two endpoint cities n = 1, 2. Population data were obtained from the U.S. Census (*15*). Populations were compiled by county, including Harris (Houston), Bexar (San Antonio), Travis (Austin), Bell (Temple), and McLennan (Waco). The population for the Dallas-Fort Worth area was computed as the sum of Dallas, Tarrant, and Collin Counties. The denominator of the gravity model (d_n) is the square of the distance between the two urban areas between which the demand is being estimated (distance approximated from distances reported in Table 1). For each alternative, the distance between Houston and each corridor endpoint and the corresponding travel demand was calculated separately. In some cases, additional mileage along the South Central High-Speed Rail Corridor was added to account for additional travel time between Houston and San Antonio, Austin, and Dallas.

The use of the gravity model to estimate travel demand assumed that only endpoint population and travel distance impact the demand for travel. It is noted that the estimated travel demand is for all travel in the system. One key assumption for this approach, lacking specific demand elasticity with respect to travel time, is that the high-speed rail service would capture the same proportion of intercity travelers across each alternative. It is also noted that the constant of proportionality k is not needed here as it is constant across all alternatives. The total travel demand for each city pair was summed across all five sets of city pairs to compute the total travel demand for each alternative. For this analysis, a larger travel demand is better.

Maximize Service Area Population

Criteria C_2, Corridor Population, is a measure of the total population that could be affected by high-speed rail development along each alternative route. This measure was computed for each alternative by summing the 2010 population of all Census blocks within a 10-mile buffer around each alternative. It should be noted that the task of this analysis was not to identify the station stops for a proposed high-speed passenger rail service. Therefore, while it is conceivable that none of the populations included in this calculation would actually be served by the high-speed service, other benefits may accrue, such as regional or local rail service to complement the high-speed service. For this analysis, a higher corridor population is better.

Minimize Total Cost

Minimize Track Upgrade Costs

The first cost criterion (C_3) was the total costs to upgrade existing or construct new track for high-speed rail service. For this criterion it was assumed that the cost per mile of laying track and related structures was approximately equal across the alternatives. The difference in cost resulted from the varying amount of space available to build new infrastructure for high-speed passenger rail parallel to existing right-of-way. It was assumed that the highest per-mile cost would be for the acquisition of new right-of-way where no railroad lines exist. This process would likely require a full environmental study and property purchase. For route segments where right-of-way has been abandoned, the cost for developing high-speed rail will be much less, as only activation of the line would be necessary. Along routes where active railroad operations are taking place, the property acquisition needs are much less and are likely to be approximately proportional to the maximum allowable speeds associated with the adjacent track. The mileage of track along each route (or necessary right-of-way in some cases) was divided into eight categories: new right-of-way, abandoned, and class one through six and higher (based on FRA track classification). Allowable speeds for existing track were identified from highway-rail grade crossing inventory data supplied by the FRA Office of Safety. A value measurement for each of the eight classifications was estimated using a direct rating technique described by von Winterfeldt and Edwards (*16*). The value measurement technique allows for the estimation of the relative difference between different classifications (in this case, FRA track class) without having to know actual values. Figure 2 shows the value curve for the total cost per-mile of route at each classification, estimated by the authors with input from various high-speed rail feasibility studies. Using each alternative route's total mileage of each track classification and the value curve shown in Figure 2, a weighted average score for each alternative was computed. Using this value-rating system in lieu of actual project costs fulfills the objective of utilizing easy-to-obtain, sketch-level data to support the analysis. For sketch-level purposes, the exact cost estimates for high-speed rail may not be known; the utility curve shown in Figure 2 offers an alternative to this data requirement.

Number of Crossings along Route

The second cost criterion (C_4) was the total number of highway-railroad grade crossings that exist along each alternative as identified by the grade crossing inventory data or manual inventory from satellite imagery in the case of abandoned/new routes. This criterion was included because it is likely that high-speed train operations would require significant grade separations and/or closures. At a minimum, additional grade crossings increase complexity and cost regardless of if they are physically separated. The more crossings along a route, the higher the cost to implement high-speed passenger rail along the route. Therefore, a smaller total number of crossings are desired.

Percentage of High-Grade Right-of-Way

The third cost criterion (C_5) was the percentage of each alternative's total route-miles that was identified with high vertical grades. Slope is highly important to rail line development because the low coefficient of friction of steel wheels on steel rail limit the grade that trains can operate on. While high-speed rail in France operates at grades of up to 5 percent, modern train manufacturers typically design for grades of 2.5 percent or less. For this analysis, areas with slopes above 3 percent were considered in need of remediation to allow train operation. A 300-foot right-of-way buffer was considered for each alternative. Steep grades were identified from a Digital Elevation Model (DEM) obtained from the 1/3 Arc Second (approximately 10 meter spatial resolution) National Elevation Dataset (NED) on the National Map Viewer of the United States Geological Survey (USGS) website. The DEM was imported into ArcGIS and the "Slope" function in the Toolbox was used to calculate the slope percentage.

Percentage of Developed Area Right-of-Way

The fourth cost criterion (C_6) was the percentage of each alternative's total route-miles that was identified as passing through a developed area. For this analysis, developed area right-of-way is considered with the assumption that constructing high-speed rail may be more difficult as development in the area around the right-of-way increases. For this criterion, a "less is better" measure is used since construction costs would increase as the difficulty of construction increases, indicating a more favorable evaluation of open and undeveloped areas. This criteria identifies developed areas within a 300-foot buffer where rail alignments operate and the percentage of each alignment in a developed area was determined using data from the 2006 National Land Cover Data (NLCD) obtained from the USGS.

Environmental Impacts

Increase in Trains per Day

The first environmental impacts criterion (C_7) was a measure relating to the increase in the number of trains per day along a section of proposed high-speed rail route. While it was not the task of this analysis to identify a suitable frequency of passenger service, it was assumed that adding new service to a section of track with little activity would have a greater impact on the surrounding community (including noise and safety) than adding new service to a track with relatively high current traffic levels. The total number of current trains per day was identified from the grade crossing inventory data. A range of hypothetical passenger train frequencies was considered for each level of train activity observed, and the resulting percent increase in train activity on a section of track was calculated. The percent increase for each level of train activity was scaled from zero to 100, with zero representing a section of track where no trains per day currently exist (highest impact of new service) and 100 being the sections of track with the most train activity (lowest impact). Figure 3 shows the resulting value curve. For each alternative, an average value, weighted by the number of route-miles of each train activity level, was computed.

Percentage of Existing Right-of-Way Used

The second environmental impacts criterion (C_8) was the percentage of each alternative's route-miles that were within existing railroad rights-of-way. This was included as an environmental impacts measure as the taking of new right-of-way will likely alter the natural landscape and have impacts on wildlife habitat, agricultural lands, and other impacts. As discussed previously, 10 of the 13 alternatives were 100 percent within existing right-of-way.

Percentage of Right-of-Way through Environmentally-Sensitive Areas

The third environmental impacts criterion (C_9) was the percentage of each alternative's route-miles that was identified as passing through an area considered environmentally-sensitive. Environmentally-sensitive areas included areas that are wetlands, open water, and forests. These areas can increase costs for rail projects by requiring extra mitigation efforts to limit impacts from rail operation and construction. Data was obtained from the 2006 USGS National Land Cover Data (NLCD) with a spatial resolution of approximately 33 meters and a 300-foot buffer around each alternative considered. The percentage of each alternative in an environmentally-sensitive area was determined with a lower percentage desired to limit impacts.

MCDM EVALUATION

Identification of Inferior Alternatives

Table 3 shows the completed decision matrix and the dominated status of each alternative. Dominance is a strategy used to eliminate alternatives for which at least one other alternative is "better" for some criteria and at least as good for all criteria (*14*). If x` and x`` are defined as the set of attribute levels $a_{ij}$ for two alternatives, x` dominates x`` when:

$$x` \geq x`` \text{ for all criteria } j \quad (3)$$

and

$$x` > x`` \text{ for some criteria } j \quad (4)$$

If x` dominates x``, then x`` is considered an inferior alternative and removed from further consideration. A review of the decision matrix reveals that there were no inferior alternatives among the 13 alternative routes examined in this analysis. Therefore, no alternatives were eliminated and all 13 were forwarded to the numerical analysis.

Criteria Weighting

The next step in the MCDM process is the identification of the relative importance of each of the evaluation criteria. The result of this process is the individual criteria weights, which are then used in the final step of the analysis, processing of the numerical data and ranking of alternatives. In a formal MCDM evaluation, criteria weights would be identified through interaction with relevant stakeholders. For the ranking of potential high-speed rail corridors, stakeholders might include state and federal representatives, key political and other policy figures, local elected officials, the general public through public meetings, and others. From this process, the analyst can identify the relative importance of each criterion for the final analysis. The weighting of each criterion affects the final analysis and a thorough stakeholder evaluation should be performed to minimize the bias introduced in the weighting. As an alternative to stakeholder interaction, this analysis utilized a simulation approach to assigning criteria weights. Five weighting schemes were considered, one where equal weights are assigned to each objective group and one each with a slightly greater emphasis on each of the four objectives. Table 4 describes the criteria weighting scenarios and individual criteria weights for each scenario.

The rules of criteria weighting in MCDM require that the sum of the criterion weights over all criteria must be equal to one. It is noted from Table 4 that the criteria corresponding to the cost and impacts objectives are equally distributed such that the total weight of the criteria within each objective is equal to the target value.

NUMERICAL ANALYSIS

The MCDM analysis culminates in the processing of the values from the completed decision matrix for non-inferior alternatives, including the attribute weights developed in the previous section. Before the numerical processing, one final manipulation of the attribute levels was necessary to place all attributes on equivalent scales. For seven criteria (C_1, C_2, C_4, C_5, C_6, C_8, and C_9), the attribute levels a_{ij} were re-scaled with zero being assigned to the "worst" alternative and the 100 being assigned to the "best" alternative for each criteria. A linear relationship between the two was assumed and linear interpolation used to compute the remaining values. For criteria C_3 (cost) and C_5 (trains per day), this scaling was already built-in to the value curve development, so no scaling was necessary. To rank the alternatives, a simple weighted sum model (WSM) was employed (*3*). The structure of the WSM is given by (5).

$$A_{WSM-score} = \max_i \sum_{j=1}^{n} a_{ij} w_j \tag{5}$$

One of the assumptions of the WSM is the additive utility assumption, which requires that each attribute level is directly comparable across all criteria for a single alternative (*3*). By scaling the criteria as discussed above, this assumption was satisfied. For each weighting scheme, the WSM score was computed and ranked. Table 5 reports the overall scores and ranks for each alternative by scenario, listed in order of composite rank from the highest to lowest. The composite rank for each alternative was computed by taking a simple average of the ranks for each of the five weighting scenarios. Based on this analysis, the highest-ranked alternative was A_2, which was the highest-ranked alternative in each of the five criteria weighting scenarios. The second-ranked alternative was A_9, which was ranked second in three of the five scenarios.

The highest-ranked alternative route, alternative A_2, connects the Gulf Coast and South Central high-speed rail corridors with a 139-mile route between Houston and Austin. The second highest-ranked route, alternative A_9, connects to the South Central high-speed rail corridor in Waco via Bryan/College Station for a distance of 161 miles, all existing right-of-way.

DISCUSSION & CONCLUSIONS

This paper encompassed two objectives. The first objective was to develop a simple multi-criteria decision making model for the selection of a high-speed rail corridor route, using readily-accessible data elements and simple analysis methods. The MCDM framework developed included nine criteria related to four objectives. The four objectives were to maximize travel demand, maximize potential service area, minimize total cost, and minimize environmental impacts. The methodology, including the value curves, can be transferred to other high-speed rail corridor problems in other regions.

The second objective of the paper was to use the MCDM methodology developed in this paper to rank alternative routings to connect the South Central and Gulf Coast high-speed rail corridors. A total of 13 alternatives were identified, primarily following existing railroad alignments. The alternatives were ranked on each of the nine criteria using a simple weighted sum model. Five weighting schemes were considered, one with each objective equally-weighted and one each with a higher weighting on each of the four objectives. While the multi-criteria decision-making framework developed in this paper cannot replace the required environmental review process and formal alternatives analysis, it can be used by planners as a tool for preliminary screening or ranking of proposed high-speed rail corridors for detailed analysis. Policymakers planning expansion of the country's high-speed rail corridors program are encouraged to consider the findings of this work in pursuit of efforts towards an interconnected national system of high-speed intercity passenger rail corridors.

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The views expressed in this paper are solely the opinions of the authors. The analysis presented in this paper was performed independent of any previously completed or on-going high-speed

intercity passenger rail activities in Texas and do not represent the official views of the Texas A&M Transportation Institute, Oregon State University, or the Texas Department of Transportation. Any errors, inaccuracies, or omissions are the responsibility of the authors.

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LIST OF TABLES & FIGURES

TABLE 1 General Description of Alternative Routes Considered in MCDM Problem

(A_i)	Endpoint (From Houston)	Length (Miles)	Notes
A_1	San Antonio	151.03	Includes existing Amtrak *Sunset Limited* service
A_2	Austin	139.08	Includes 18.6 miles of abandoned RoW.
A_3	Austin	147.60	
A_4	Austin	145.84	
A_5	Temple	139.45	Includes 18.6 miles of abandoned RoW.
A_6	Temple	156.69	
A_7	Temple	154.77	
A_8	Waco	162.78	
A_9	Waco	160.86	
A_{10}	Dallas	238.61	
A_{11}	Dallas	236.68	
A_{12}	Dallas	192.35	
A_{13}	Dallas	198.40	Includes 105 miles of “greenfield” alignment approximately parallel to I-45

TABLE 2 Objectives and Corresponding Criteria for MCDM Problem

Objective	**Criteria (C_j)**
Maximize Travel Demand	C_1: Travel Demand Index (*More is Better*)
Maximize Potential Service Area	C_2: Total Population within 10 Miles of Route (*More is Better*)
Minimize Total Cost	C_3: Track Upgrade Costs (*Less is Better*)
	C_4: Number of Crossings Along Route (*Less is Better*)
	C_5: Percentage of "High Grade" Right-of-Way (*Less is Better*)
	C_6: Percentage of Developed Area Right-of-Way (*Less is Better*)
Minimize Environmental Impacts	C_7: Increase in Trains per Day (*Less is Better*)
	C_8: Percentage of Existing Right-of-Way Used (*More is Better*)
	C_9: Percentage of Right-of-Way Passing Through Areas Considered Environmentally-Sensitive (*Less is Better*)

TABLE 3 Decision Matrix and Dominated Status of Alternative Routes

(A_i)	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	**Dominated?**
A_1	493.52	636,229	95.0	114	16.3%	43.3%	99.3	100.0%	18.9%	**Non-Inferior**
A_2	592.23	1,665,709	67.3	123	21.3%	43.3%	53.9	86.6%	13.4%	**Non-Inferior**
A_3	501.88	1,049,802	90.0	130	16.1%	47.8%	98.2	100.0%	11.3%	**Non-Inferior**
A_4	509.22	1,071,064	90.0	141	19.3%	40.5%	98.9	100.0%	15.7%	**Non-Inferior**
A_5	558.03	956,712	74.2	108	28.0%	36.6%	84.0	86.7%	21.0%	**Non-Inferior**
A_6	484.18	1,127,465	88.7	140	17.5%	45.5%	98.5	100.0%	11.8%	**Non-Inferior**
A_7	491.61	1,145,782	90.0	151	20.6%	38.4%	99.2	100.0%	16.0%	**Non-Inferior**
A_8	503.02	1,196,222	90.0	135	12.1%	41.6%	97.8	100.0%	8.4%	**Non-Inferior**
A_9	510.74	1,214,539	90.0	146	15.0%	34.6%	98.5	100.0%	12.4%	**Non-Inferior**
A_{10}	439.52	2,194,257	90.0	195	18.6%	42.5%	97.5	100.0%	17.7%	**Non-Inferior**
A_{11}	446.21	2,212,574	90.0	206	20.6%	37.7%	97.9	100.0%	20.5%	**Non-Inferior**
A_{12}	520.38	1,073,220	85.0	139	24.7%	25.1%	95.8	100.0%	15.1%	**Non-Inferior**
A_{13}	494.82	954,998	41.2	159	30.3%	24.0%	46.1	47.1%	26.3%	**Non-Inferior**
OBJ.	MAX	MAX	MAX	MIN	MIN	MIN	MIN	MAX	MIN	

TABLE 4 Criteria Weighting Scenarios and Individual Criteria Weights

Objective	**(C_j)**	**I: Equal Weights**	**II: Demand Emphasis**	**III: Population Emphasis**	**IV: Cost Emphasis**	**V: Impacts Emphasis**
Demand	C_1	0.25	0.4	0.2	0.2	0.2
Service Area	C_2	0.25	0.2	0.4	0.2	0.2
Cost	C_3	0.0625	0.05	0.05	0.1	0.05
	C_4	0.0625	0.05	0.05	0.1	0.05
	C_5	0.0625	0.05	0.05	0.1	0.05
	C_6	0.0625	0.05	0.05	0.1	0.05
Impacts	C_7	0.0833	0.067	0.067	0.067	0.133
	C_8	0.0833	0.067	0.067	0.067	0.133
	C_9	0.0833	0.067	0.067	0.067	0.133
Sum of Weights		1.0000	1.0000	1.0000	1.0000	1.0000

TABLE 5 Alternative Evaluation Scores and Ranks by Weighting Scheme

(A_i)	**I: Equal Weights**	**II: Demand Emphasis**	**III: Population Emphasis**	**IV: Cost Emphasis**	**V: Impacts Emphasis**	**Composite Rank**
A_2	80.5 (1)	84.4 (1)	84.4 (1)	75.4 (1)	77.8 (1)	1.0 (1)
A_9	63.6 (2)	60.2 (3)	59.4 (2)	65.4 (2)	69.3 (3)	2.4 (2)
A_8	63.4 (3)	59.0 (4)	58.8 (3)	65.1 (3)	70.5 (2)	3.0 (3)
A_4	58.5 (4)	55.9 (6)	54.8 (4)	59.1 (5)	64.0 (5)	4.8 (4)
A_3	58.4 (5)	54.9 (7)	54.2 (5)	59.0 (6)	65.5 (4)	5.4 (5)
A_5	58.3 (6)	62.1 (2)	53.4 (6)	58.3 (7)	59.2 (9)	6.0 (6)
A_{12}	56.6 (7)	55.9 (5)	48.8 (11)	59.3 (4)	62.5 (7)	6.8 (7)
A_7	55.1 (8)	50.9 (8)	52.3 (7)	56.0 (8)	61.2 (8)	7.8 (8)
A_6	54.9 (9)	49.8 (9)	51.6 (9)	55.7 (9)	62.6 (6)	8.4 (9)
A_{11}	48.4 (10)	39.6 (11)	51.9 (8)	48.0 (11)	54.1 (11)	10.2 (10)
A_{10}	48.2 (11)	38.6 (12)	51.4 (10)	48.0 (12)	55.0 (10)	11.0 (11)
A_1	46.7 (12)	44.4 (10)	37.3 (12)	51.6 (10)	53.4 (12)	11.2 (12)
A_{13}	26.7 (13)	28.6 (13)	22.9 (13)	30.8 (13)	24.4 (13)	13.0 (13)

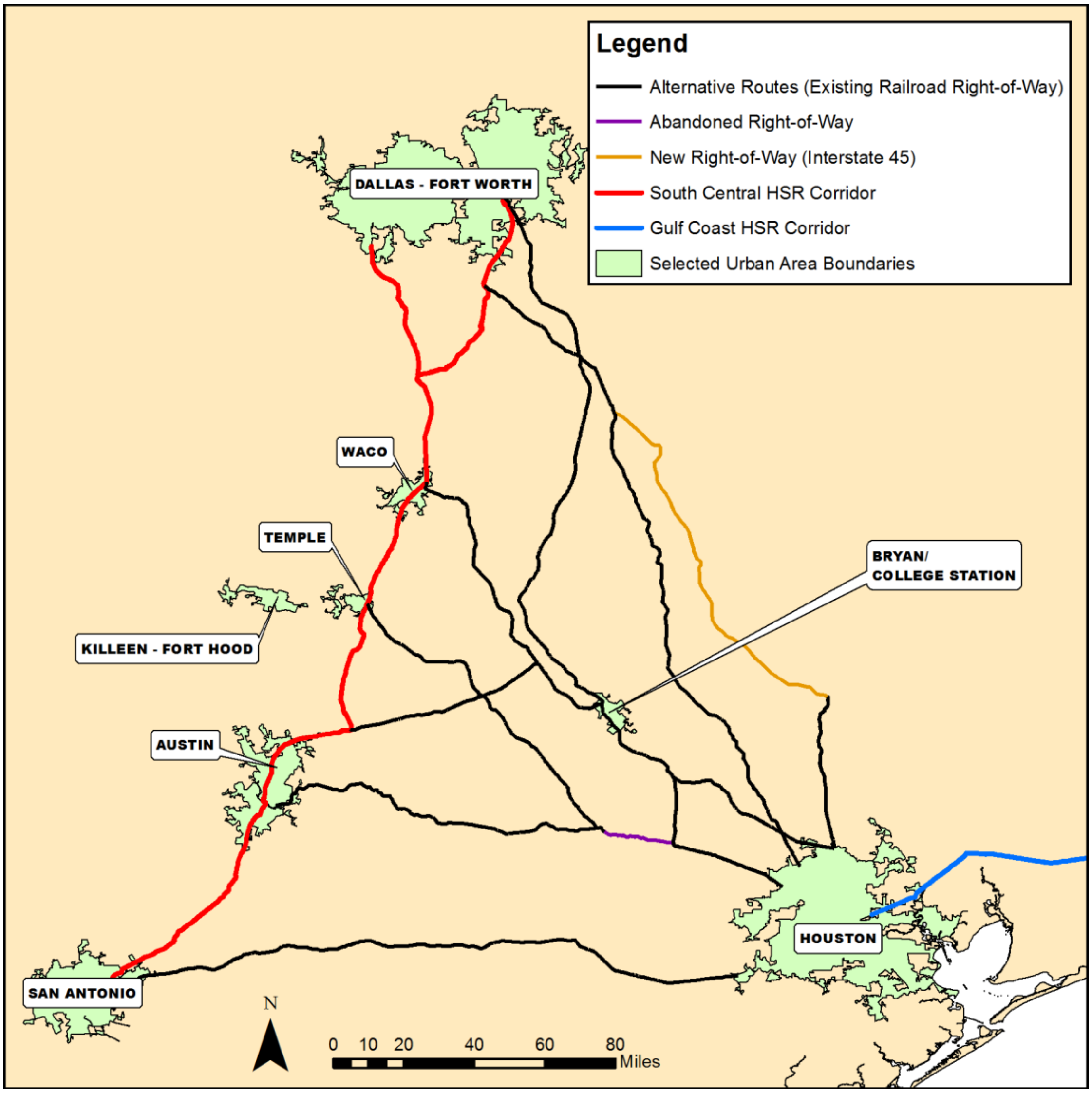

FIGURE 1 Alternative Routes Considered for MCDM Problem

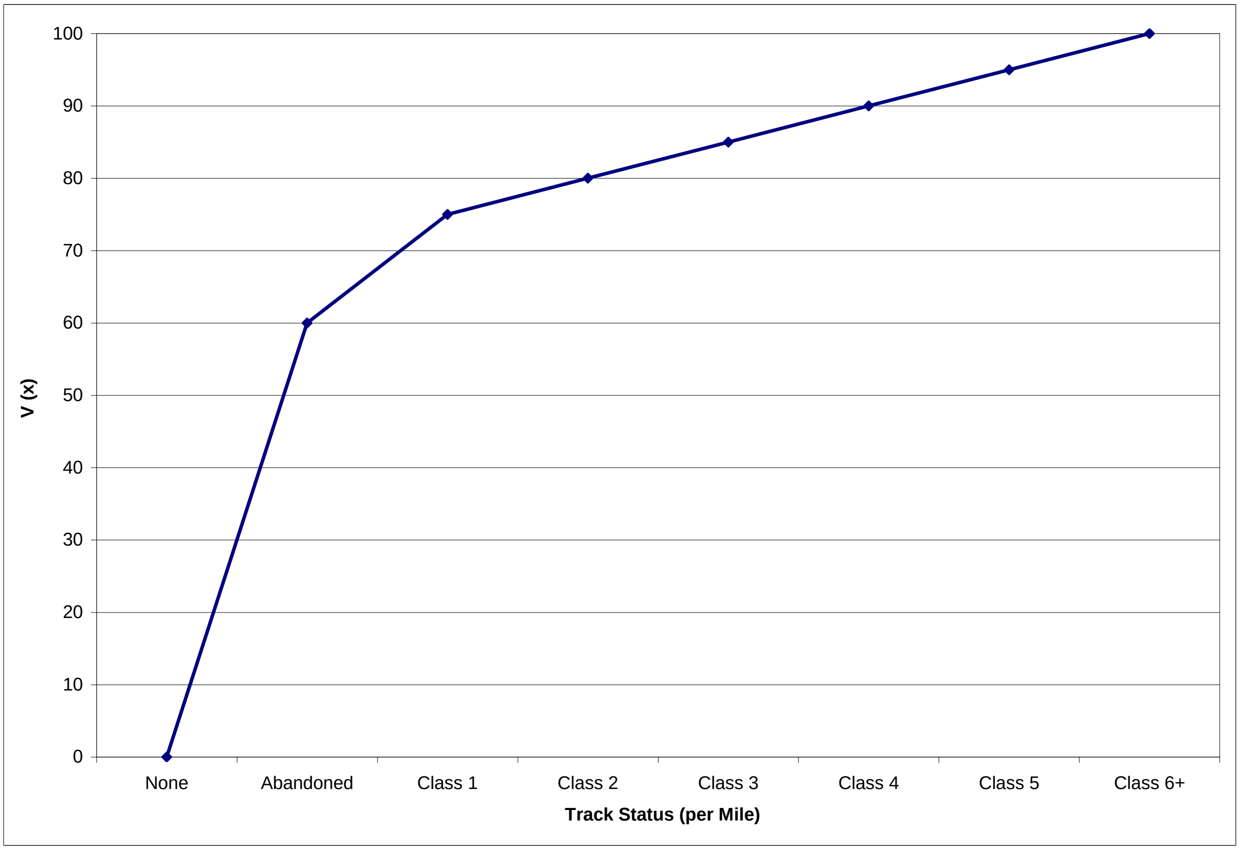

FIGURE 2 Value Curve for Total Cost per Mile of Track Classification

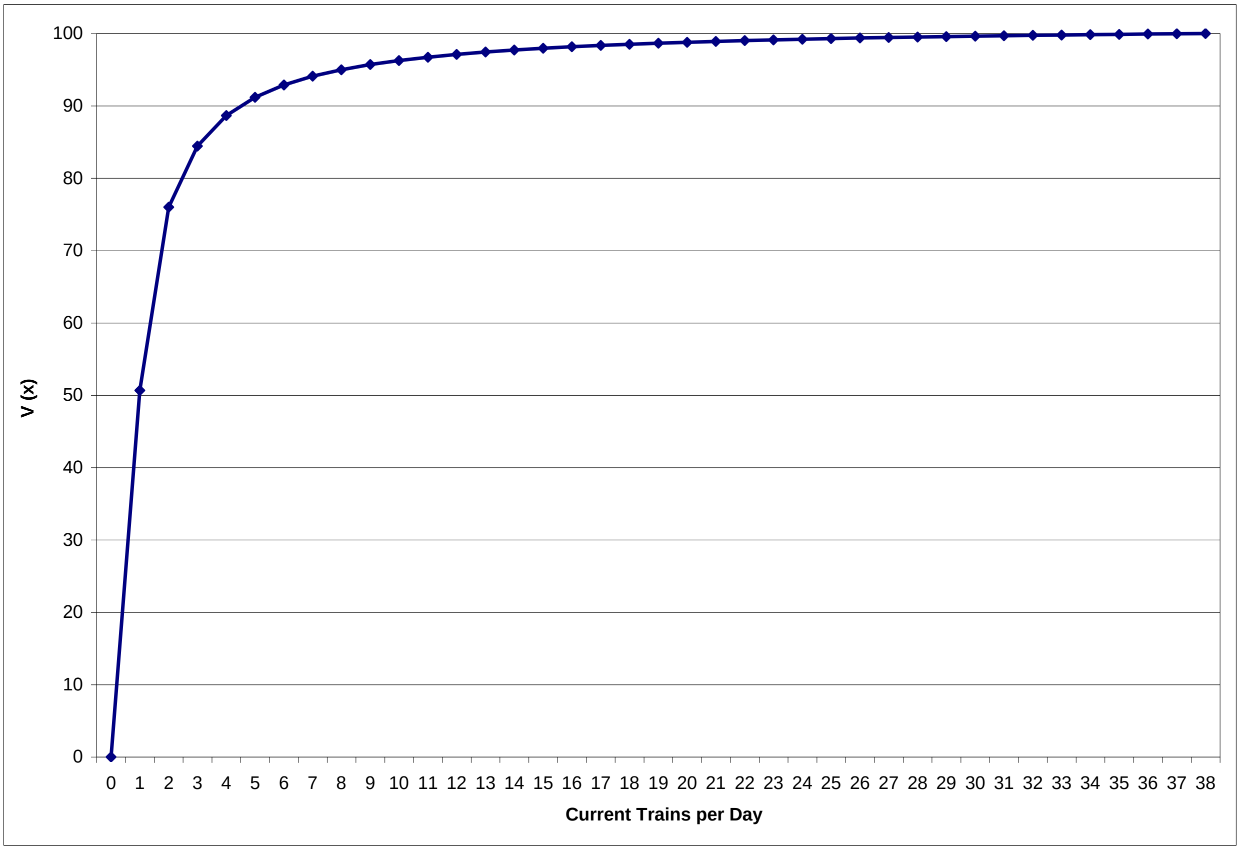

FIGURE 3 Value Curve for Increase in Total Trains per Day