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Texas Urban Triangle: Pilot Study to Implement a Spatial Decision Support System (SDSS) for Sustainable Mobility

Final Report

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16. Abstract

This project addressed sustainable transportation in the Texas Urban Triangle (TUT) by conducting a pilot project at the county scale. The project tested and developed the multi-attribute Spatial Decision Support System (SDSS) developed in 2009 under a previous UTCM project (TRID Online Accession #01324956), in order to determine the most suitable locations for transportation infrastructure networks, including high-speed rail. The research team selected a key county in the Austin-San Antonio segment of the Interstate 35 corridor. The project mapped, using the eight different strategic economic, social, and environmental factors in the model, the most and least suitable locations for the new transportation infrastructure. It is expected that the outputs of the model be used by TUT metropolitan planning organization's (MPO's), Texas Department of Transportation (TXDOT), metropolitan visioning groups, high-speed rail providers, and similar entities.

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Texas Urban Triangle: Pilot Study to Implement a Spatial Decision Support System (SDSS) for Sustainable Mobility

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DISCLAIMER

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EXECUTIVE SUMMARY

The Texas Urban Triangle—comprised of the metropolises of Dallas-Fort Worth, Houston, San Antonio, and Austin—contains over 17 million people, almost 70 percent of the state's population. Projections indicate that over the next 20 years, population in the area will account for over 80 percent of the state's total. This makes Texas an urban state, despite its cowboys and open plains image. Moreover, the most rapid urban growth and land consumption in the state are in the Triangle cities' fringes. Not surprisingly then, most pollution and other environmental problems, along with unemployment and other social inequities, are generated in these metropolises and, therefore, in the Triangle itself.

The Texas Urban Triangle is a singular, new, complex, and important urban phenomenon. The Texas Urban Triangle, with official projections of more than 23 million people by 2030 (25 million by 2025, per the Governor's Business Council 2006 report, *Shaping Texas's Metropolitan Regions*) and covering more than 60,000 square mile, is the economic motor of Texas and hub of the national transportation network operating in a global economy. The Triangle accounts for 70 percent of the state's population, 80 percent of the state's employment, and 85 percent of its wages. The Triangle is emerging as a new urban mega-region in its own right, competing with Los Angeles and New York, by virtue of its extensive internal connections and activities.

The results of this project provide the most comprehensive data set available to form the basis for discussions and research about this phenomenon. The basic research questions researchers asked in this project are spatial in nature, so accordingly geographic information systems (GIS) will be the primary method of data analysis:

- Where should the growth go in the future?
- What are the impacts of this growth?
- Are these locations vulnerable to hazards, both natural and human?
- What scale/type/location of infrastructure is necessary to support it?

The Texas Urban Triangle has been the fastest-growing region of the state for decades, along with parts of the eastern Rio Grande Valley. How Texas handles this new growth will determine to a large degree whether Texas continues to prosper and enjoy a high quality of life.

The initial analysis revealed that two issues will dominate the Texan landscape and imagination over the next decades: water and energy. Data, analysis, findings, and policy and planning recommendations for water and energy are contained in the initial report, which can be found at http://texasurbantriangle.tamu.edu.

This project addresses sustainable transportation in the Texas Urban Triangle at the regional scale. Its aim was to determine the most suitable locations for new transport infrastructure by employing a spatial decision support system (SDSS) developed in this project. The SDSS differs from existing transportation decision systems in that it focuses on selected *strategic driving forces* of growth of the region *as a functional unit*—transport infrastructure, available land, economic activity, water, and energy—and then identifies corresponding measures of sustainability for key transportation systems and corridors within the Texas Urban Triangle. For example, development patterns driven by transportation infrastructure in turn create impacts on surface and groundwater resources in terms of water quantity and quality. Conversely, considerations about water availability and waste assimilative capacity can be used as a driver of infrastructure planning decisions to achieve greater long-term sustainability. The SDSS supports policy making for a comprehensive sustainable regionalism.

Another feature of the SDSS is that it considers explicitly the intermodal linkages that ensure greater intersystem operability, enhance travel connectivity, and therefore improve overall mobility. For example, for passengers, the decision model assesses and identifies suitable locations for linking intercity high-speed rail and metropolitan public transit (rail and buses of all speeds and gauges) with other surface transportation in key metropolitan nodes such as city centers and international airports. The SDSS assesses and identifies suitable locations for interconnections among freight modes, especially links among air, sea, and land in Houston, Dallas-Fort Worth, and San Antonio. Additionally, SDSS outputs suggest strategic sites for advanced logistics zones (ALZs) where both intermodal transshipment of goods and adding value to goods between modes (assembly, packaging, etc.) occur.

The SDSS developed in this project is being tested through its application to a prototype corridor parallel to Interstate 35 between San Antonio and Austin. The SDSS provides a composite foundation for enhanced regional mobility, and using it in policy analysis and investment decisions can strengthen the Texas Urban Triangle as a hub in national transportation networks that can be emulated in urban regions worldwide.

In addition to assessing and evaluating locations for transportation rights of way, the SDSS can be adapted to assess locations for other surface infrastructure networks that are configured by linear corridors in large networks, such as electric power and water supply. Decision criteria in the model identify opportunities for shared rights of way among infrastructure types, further saving capital and land acquisition costs, lessening environmental impacts and habitat fragmentation, etc. The SDSS model has been designed so that it accounts for parameters and factors that exist outside of Texas and the United States, thus broadening its applications geographically.

These research results can be used by state and federal transportation, utility, environmental, and urban/land development agencies; metropolitan planning organizations, councils of governments, and regional mobility authorities; counties and municipalities; industry; citizen groups; and professional and interest groups.

Project Plan

The project developed a GIS-based SDSS that is designed to help local, metropolitan, and state jurisdictions and authorities in Texas and elsewhere understand the implications of transportation planning and investment decisions, and plan appropriately for the future. Using the model, decision makers are able to assess multiple corridor location options and to determine, using a multi-attribute decision model, the suitability of locations for regional and metropolitan transportation corridors to the year 2030. It provides an easily accessible, graphically represented, interactive, multi-attribute database that considers the following factors: infrastructure, demographics, environment, agriculture, economics, hazard, and land use. These spatial factors are selected because of their strategic importance as drivers shaping growth and development, and corresponding transportation corridor and hub location decisions that reinforce both individual metro areas and the entire Texas Urban Triangle as a single functioning unit. One immediate application of the model is to locating possible high-speed rail corridors in the Texas Urban Triangle.

Strategic Drivers of the SDSS

Strategic drivers that have been incorporated into the SDSS include those factors that are foreseen to most likely shape growth patterns and resulting transportation demands/needs over the next 50 years: demographic and labor force changes; economic activity; land availability; environmental suitability; natural resources such as water, oil, and gas; utilities such as electric power and other infrastructures; accessibility and mobility of people and goods; producer services and secondary services availability; housing affordability; and the security and reliability of the transportation networks and other critical infrastructures. As strategic drivers, they are intimately connected to the surface transportation networks and therefore are accounted for in the SDSS.

SDSS Development Process

To develop the SDSS itself, researchers have taken the following steps:

1. Identify factors to be included in the SDSS analytical model.
2. Identify factor specialists across the Texas A&M University College Station campus and elsewhere to provide expert advice on the factors.
3. Select factors to be included in the SDSS model.
4. Identify data sources for the factors and collect data.
5. Determine rankings for each factor.
6. Determine weights for each factor.
7. Create a cost surface with the incorporated factors.
8. Find an optimized route based on the suitability score.
9. Confirm to horizontal radius allowance.

The factors in the SDSS refer to the individual criteria used in the model to assess the most suitable location for locating transportation corridors on the landscape. The research team initially selected 83 factors that could be included in the SDSS criteria, organized in seven categories: agriculture, demographics, engineering, environment, hazard, infrastructure, and land use. After research and deliberation, the team identified 42 factors appropriate in Texas.

Determination of Internal Classification for Each Factor

Factor weights refer to the value, on a scale of 1 to 5, assigned to each of the factors (decision criteria) in the SDSS. A value or weight of 5 is the highest weight for each factor and reflects a negative value for locating a transportation corridor in that place—the least suitable location. A value of 1 is the lowest weight for each factor and reflects a positive value for locating a transportation corridor—the most suitable location. For example, ES Table 1 shows the weights for population density in persons per square mile. Since there are 640 acres per square mile, a density of 2000 is less than four people per acre, or one to two households per acre, which is a low figure

ES Table 1. Weights for Population Density in Persons per Square Mile.

Population Density	Scale
0-999	1
1000-1999	3
2000 or more	5

Determination of Factor Weights

Factor weights refer to the relative value of factors compared to each other. Thus, for 42 factors, the most important factor to consider for locating high-speed rail in the Texas Urban Triangle is weighted most, the second most important factor is next, and so on. To determine appropriate factor weights, the research team used the analytic hierarchical process (AHP), a widely accepted decision-making strategy. For the pilot study, researchers tested the relationship between eight pre-selected factors: population density, property value, vertical slope, road types, hydrology, floodplain, geology, and soil types (ES Table 2). Researchers found that the relationships between the factors and factor weights are a crucial part of the entire SDSS process.

ES Table 2. Factor Weight Matrix Using AHP and Reliability Test.

	Density	Slope	Roads	Hydrology	Floodplain	Geology	Soils	Eigen Vector	%
Density	0.33	0.40	0.29	0.24	0.20	0.20	0.23	0.27	29.0%
Slope	0.22	0.27	0.43	0.24	0.16	0.23	0.23	0.26	27.0%
Roads	0.17	0.09	0.14	0.24	0.18	0.23	0.29	0.19	19.0%
Hydrology	0.07	0.05	0.03	0.05	0.08	0.02	0.02	0.04	5.0%
Floodplain	0.07	0.07	0.03	0.02	0.04	0.02	0.02	0.04	4.0%
Geology	0.11	0.08	0.04	0.17	0.16	0.07	0.09	0.10	9.0%
Soils	0.08	0.07	0.03	0.17	0.14	0.04	0.06	0.08	8.0%
SUM	1.04	1.02	0.99	1.15	0.96	0.80	0.94	1.00	100%

$\lambda_{max} = 7.7070$, Consistency Index (CI) = 0.1178, Random Index (RI) = 1.32 (n = 7)
Consistency Ratio (CR) = 0.0893 -> 8.93% < 10.0%
(CR less than 10% considered a consistent preference matrix)

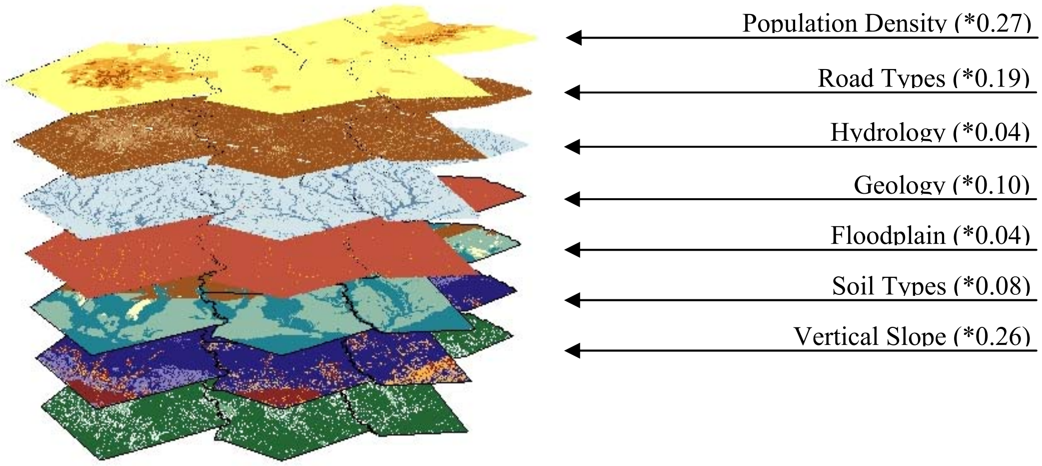
The map algebra can be written as follows:

$$Score_{total} = \Sigma\, a(S_{pop.density}) + b(S_{slope}) + c(S_{road\ type}) + d(S_{hydrology}) + e(S_{floodplain}) + f(S_{geology}) + g(S_{soil\ type})$$

(a ~ g = factor weight for each factor/S = internal classification of each factor)

Testing the SDSS

Researchers tested the GIS-based SDSS on a specific corridor segment between San Antonio and Austin. This pilot study/proof of concept in a focused geographic area selected a single county for ease of data gathering. Over time, researchers expect to apply the SDSS on an entire strategic transportation corridor that is now in play—the San Antonio–Austin–Dallas-Fort Worth corridor. The output of the model will be displayed using interactive, web-based GIS maps. ES Figure 1 represents the visual relationships of the selected factors with their weights, and shows how the cost surface is created.



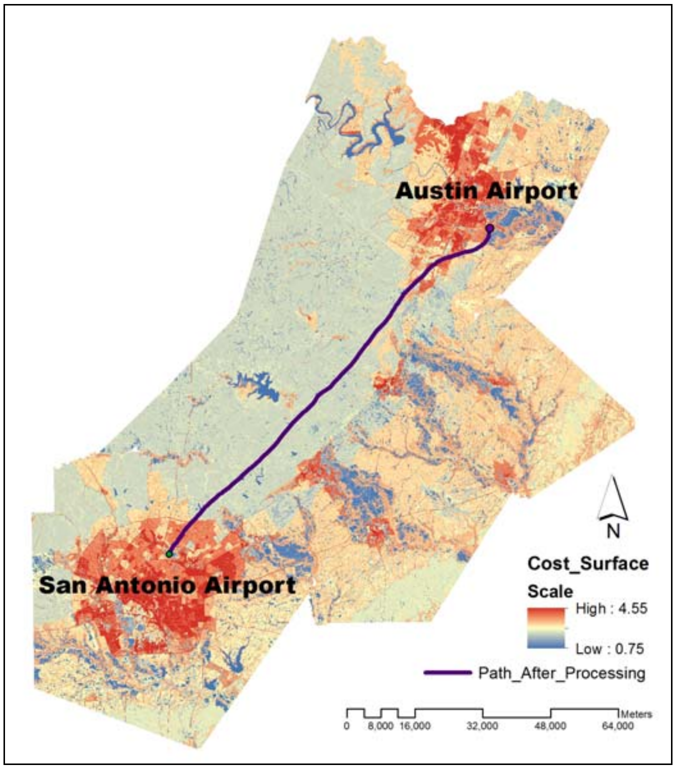
$$Cost\ Surface = \Sigma\,(0.27*Population\ Density) + (0.26*Vertical\ Slope) + (0.19*Road\ Type) + (0.04*Hydrology) + (0.04*Floodplain) + (0.10*Geology) + (0.08*Soil\ Type)$$

ES Figure 1. Cost Surface Maps for Eight Factors.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Conclusions

This SDSS is robust, meaning it is supported by valid theory, developed using a sound methodology, and based on reliable and accurate data. This robust quality, coupled with the wide range (42) of factors (variables) in the SDSS model, enables it to be adapted to a wide range of geographic and technological circumstances beyond Texas and its Urban Triangle, depending on the intended use. A wide range of geographic conditions means two things: places throughout the United States and the world, not just Texas; and a range of scales from the municipality to the multi-state region. The wide range of technological circumstances means any type of ground transportation technology or mode, whether rail, road, or multimodal.



ES Figure 2. Final Cost Surface with the Shortest Path after Post-process.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Furthermore, the adaptability/flexibility of the model is afforded by the ability of any user to tailor the 42 factors to suit the scale and territory to which the model is applied. Moreover, end users can adjust both the internal weights within each factor, and the external rankings among the factors as compared to the other factors selected.

The power of the SDSS thus resides in its wide-ranging capacity to incorporate a range of parameters (criteria/factors) related to transportation corridor decision making, its ability to display results graphically and geographically using GIS, and its ability to be adjusted and adapted to different places, circumstances, and infrastructure networks, merely by varying the factors/parameters chosen to be used in the model, and by varying the factor weights and factor rankings. ES Figure 2 shows the outcome derived from the entire research process with the given information and decision criteria.

PROBLEM AND BACKGROUND

The Texas Urban Triangle is a singular, new, complex, and important urban phenomenon, and is comprised of the metropolises of Dallas-Fort Worth, Houston, San Antonio, and Austin. Projections indicate that over the next 20 years, population in the area will account for over 80 percent of the state's total. Moreover, the most rapid urban growth and land consumption in the state are in the Triangle cities' fringes.

The Texas Urban Triangle is distinguished among megalopolises because it is not linear but rather triangular. Further, the urban development between its metropolises is not physically contiguous. The axis from San Antonio to Dallas is on its way to becoming fully urbanized due to the proximity of the string of cities along Interstate 35. In contrast, on Interstate 45 between Dallas and Houston, and on Interstate 10 between Houston and San Antonio, there are only small villages and towns along these arteries.

So on the one hand, the Texas Urban Triangle's characteristics corroborate findings of prior work on multiple-metropolis mega-cities in the United States: regional growth is polycentric, as it has been for individual metropolises. On the other hand, unlike megalopolises in the past, much of the Texas Urban Triangle's urban development is not continuous or contiguous, suggesting that connections among the metropolises that make it up take advantage of telecommunications and transportation infrastructure networks to make the links, indicating a new socio-spatial order, the networked region.

Texas is projected to continue to grow steadily, and population in the Triangle is projected to increase 57 percent between 2000 and 2030. The Texas Urban Triangle is projected to account for 8,407,000 of the state's 10,979,000 new inhabitants in that period, or 77 percent of all of Texas's growth. The attendant impacts of growth—new homes, new jobs and businesses, new transportation and infrastructure networks, less farm and ranch lands, and more pollution—are easy to predict based on past experience. How Texas handles this new growth will determine to a large degree whether the state continues to prosper and enjoy a high quality of life.

The initial analysis revealed that two issues will dominate the Texan landscape and imagination over the next decades: water and energy. Data, analysis, and findings, and policy and planning recommendations for water and energy are contained in the initial report, which can be found at http://texasurbantriangle.tamu.edu.

These initial, overall findings provide a baseline foundation for policy guidance to decision makers at all levels of government—especially state and federal—and the private sector. Unlike most sector-specific studies, the study took a broad and synthetic view of the key factors that drive regional growth so that in the future growth can be accommodated in a more sustainable regional design. The findings also inform and extend the debate about the future of the city region (Neuman and Hull, 2009). These findings provide a baseline for the current project, developing a spatial decision support system (SDSS) for mobility policy and investments that shape the sustainable growth of Texas. In the previous study, researchers developed an SDSS to find an optimized route for high-speed rail and conducted a pilot study. With help from factor specialists, relevant factors were extracted and articulated. Hays County was the initial geographic unit to test the SDSS developed in the study. Based on the outcome, researchers modified the methodology and approach. The expanded study boundary and factors are the main purpose and scope of this research. Finally, a realistic smoothened route will be drawn as the last part of the research.

The results of this longitudinal project provide the most comprehensive viewpoint to prolong and to sophisticate the basis of the SDSS. The basic research questions asked are spatial in nature, so accordingly geographic information systems (GIS) will be the primary method of data analysis:

- Where should the growth go in the future?
- What are the impacts of this growth?
- Are these locations vulnerable to hazards both natural and human?
- What scale/type/location of infrastructure is necessary to support it?

PROJECT SIGNIFICANCE

The Texas Urban Triangle, with its massive number of inhabitants and area of more than 60,000 square miles, is the economic motor of Texas and hub of the national transportation network operating in a global economy. The Triangle is emerging as a new urban mega-region in its own right, competing with Los Angeles and New York, by virtue of its extensive internal connections and activities. The volume of movements within the Triangle, especially among its metropolises, exceeds the volume of movements to places outside the Triangle, pointing to its increasing functionality as a single unit. Accordingly, freight and passenger mobility within and among the Triangle's metro areas, as well as outward across the continent, is critical to economic and social development, and to the preservation of its natural assets.

Given that transportation infrastructure shapes and supports growth, $58 billion of the $72 billion identified in Texas transportation infrastructure needs over the next 25 years is in the Texas Urban Triangle (Governor's Business Council, 2006)[1]. Transportation in all modes consumes over 28 percent of all U.S. energy (mostly oil based) (EIA, 2008); consequently, a new set of policy priorities for energy independence and renewable energy is emerging. Moreover, existing highway-dominated surface transport systems are exceeding design capacity and are increasingly costly to expand and maintain. Accordingly, there is an urgent need for policy and investment decisions that are based on a new and wider set of criteria that account for new conditions and considerations. A new form of decision making based on emerging realities could pave the way for a wider range of options for transportation that are *sustainable.*

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[1] Unofficial, unreleased, preliminary data as of late 2008 suggest that actual needs will be $120 billion through 2030 to keep congestion from getting worse and $150 billion to eliminate serious congestion in four Texas Urban Triangle metro areas: Dallas-Fort Worth, Houston, San Antonio, and Austin (Texas Transportation Institute [TTI] researcher personal communication). Regardless of the actual figures, transport infrastructure needs are extremely large, and sound decision methods are urgently critical.

This project addresses sustainable transportation in the Texas Urban Triangle at the regional scale. Its aim was to determine the most suitable locations for new transport infrastructure by employing an SDSS developed in this project. The SDSS differs from existing transportation decision systems in that it focuses on selected *strategic driving forces* of growth of the region *as a functional unit*—transport infrastructure, available land, economic activity, water, and energy—and then identifies corresponding measures of sustainability for key transportation systems and corridors within the Texas Urban Triangle. For example, development patterns driven by transportation infrastructure in turn create impacts on surface and groundwater resources in terms of water quantity and quality. Conversely, consideration about water availability and waste assimilative capacity can be used as a driver of infrastructure planning decisions to achieve greater long-term sustainability. The SDSS supports policy making for a comprehensive sustainable regionalism.

Another feature of the SDSS is that it considers explicitly the intermodal linkages that ensure greater intersystem operability, enhance travel connectivity, and therefore improve overall mobility. For example, for passengers, the decision model assesses and identifies suitable locations for linking intercity high-speed rail and metropolitan public transit (rail and buses of all speeds and gauges) with other surface transportation in key metropolitan nodes such as city centers and international airports. The SDSS assesses and identifies suitable locations for interconnections among freight modes, especially links among air, sea, and land in Houston, Dallas-Fort Worth, and San Antonio. Additionally, SDSS outputs suggest strategic sites for advanced logistics zones (ALZs) where both intermodal transshipment of goods and adding value to goods between modes (assembly, packaging, etc.) occur. ALZs are new strategic project areas in their metropolises, further enhancing economic growth and competitiveness.

The SDSS developed in this project is being tested through its application to a prototype corridor parallel to Interstate 35 between San Antonio and Austin. The SDSS provides a composite foundation for enhanced regional mobility, and using it in policy analysis and investment decisions can strengthen the Texas Urban Triangle as a hub in national transportation networks that can be emulated in urban regions worldwide.

In addition to assessing and evaluating locations for transportation rights of way, the SDSS can be adapted to assess locations for other surface infrastructure networks that are configured by linear corridors in large networks, such as electric power and water supply. Decision criteria in the model identify opportunities for shared rights of way among infrastructure types, further saving capital and land acquisition costs, lessening environmental impacts and habitat fragmentation, etc. The SDSS model has been designed so that it accounts for parameters and factors that exist outside of Texas and the United States, thus broadening its applications geographically.

These research results can be used by state and federal transportation, utility, environmental, and urban/land development agencies; metropolitan planning organizations, councils of governments, and regional mobility authorities; counties and municipalities; industry; citizen groups; and professional and interest groups. This project builds on the research project "Texas Urban Triangle: Framework for Future Growth" funded by the Southwest Region University Transportation Center. See http://sustainableurbanism.tamu.edu, and click on "Projects."

APPROACH

Project Plan

The project developed a GIS-based SDSS that is designed to help local, metropolitan, and state jurisdictions and authorities in Texas and elsewhere understand the implications of transportation planning and investment decisions, and plan appropriately for the future. Using the model, decision makers are able to assess multiple corridor location options and to determine, using a multi-attribute decision model, the suitability of locations for regional and metropolitan transportation corridors to the year 2030.

It provides an easily accessible, graphically represented, interactive, *multi-attribute* database that considers the following factors: infrastructure, demographics, environment, agriculture, economics, hazard, and land use. These spatial factors are selected because of their strategic importance as drivers shaping growth and development, and corresponding transportation corridor and hub location decisions that reinforce both individual metro areas and the entire Texas Urban Triangle as a single functioning unit. One immediate application of the model is to the location of possible high-speed rail corridors in the Texas Urban Triangle.

The SDSS can be modified by users to support location decisions regarding local and state transportation corridors, in addition to metropolitan- and regional-scale corridors. Moreover, it can be used to evaluate other types of infrastructure corridors that can be placed in shared rights of way within or alongside transportation corridors. In this sense the SDSS is *multi-scalar* in addition to multi-attribute, and should represent an advance in decision support system model development, building on existing transportation (TTI's TransDec 2.0) and planning decision support systems (Zhang & Wang, 1998).

Strategic Drivers of the SDSS

The vastly changed transportation investment decision panorama in Texas and the United States implies a new type of decision making that considers more than just capital costs and environmental constraints. It needs to consider the life cycle of the systems, and the economic, demographic, social, ecological, infrastructural, and fiscal parameters influencing decisions. Today, wildly erratic fuel prices, climate crises, CO_2 emissions, and met or exceeded highway and freight-rail capacities on several corridors—plus the spiraling costs of expanding highways in urbanized areas—seriously complicate decisions that in the past were conditioned by population, demographic, immigration, and economic development factors, along with U.S. Environmental Protection Agency (EPA) air and water pollution restrictions.

Strategic drivers that have been incorporated into the SDSS include those factors that are foreseen to most likely shape growth patterns and resulting transportation demands/needs over the next 50 years: demographic and labor force changes; economic activity; land availability; environmental suitability; natural resources such as water, oil, and gas; utilities such as electric power and other infrastructures; accessibility and mobility of people and goods; producer services and secondary services availability; housing affordability; and the security and reliability of the transportation networks and other critical infrastructures. As strategic drivers, they are intimately connected to the surface transportation networks and therefore are accounted for in the SDSS.

SDSS Development Process

To develop the SDSS itself, researchers have taken the following steps:

1. Identify factors to be included in the SDSS analytical model.
2. Identify factor specialists across the Texas A&M University College Station campus and elsewhere to provide expert advice on the factors.
3. Select factors to be included in the SDSS model.
4. Identify data sources for the factors and collect data.
5. Determine internal classification for each factor.
6. Determine weights for each factor.
7. Create a cost surface with the incorporated factors.
8. Find an optimized route based on the suitability score.
9. Confirm to horizontal radius allowance.

Steps 1 through 6 will be elaborated below since they are closer to pre-modeling process, and Steps 7 through 9 will be articulated in accordance with the SDSS testing process.

Identify Factors

"Factors" in the SDSS refers to the individual criteria used in the model to assess the most suitable location for locating transportation corridors on the landscape. The research team initially selected 83 factors that could be included in the SDSS criteria, organized in seven categories:

- Agriculture.
- Demographics.
- Engineering.
- Environment.
- Hazard.
- Infrastructure.
- Land use.

After research and deliberation, the team identified 42 factors appropriate for a transportation corridor location-determining SDSS in Texas. Eight were used in the previous study, and Hays County was the geographic unit. Researchers used the same number of factors but expanded the number of counties to six. This expanded geographic study boundary gives a much more comprehensive picture and suggests possible high-speed rail routes between Austin and San Antonio.

For each factor, researchers determined the criteria or indicators employed in the model. In some cases it is a simple binary, such as present or not present, which means high-speed rail right of way does or does not exist, or should or should not exist, within the transportation corridor. In other cases the factors are quantitative, and in still other cases the factors are qualitative. In some cases the factors mark a gradient or a range within which there are acceptable/suitable or non-acceptable/non-suitable values.

Identify Factor Specialists

For each of the SDSS factors, researchers identified factor specialists/experts, mostly located on the Texas A&M University campus, to assist in understanding the factor fully in relation to high-speed rail. The research team worked closely with these persons to determine the extent to which the factor is critical, what its dimensions are, and how it may be applied specifically in this SDSS in Texas. Researchers also asked the factor specialists if there were related factors not on the list that were pertinent to the SDSS. Researchers worked with the factor specialists to obtain data to test the SDSS model.

Select Factors for SDSS

The research team met numerous times throughout the year to review the factors and select which ones to use in the SDSS model. They started with over 80 factors and narrowed the number down to 42 by the end of the model development stage (see Appendix C, “SDSS Model Factors”). Finally, eight different factor categories were selected and implemented in the study.

Identify Data Sources

The research team identified and gathered databases and data sets for each factor. Many of the sources are online databases. In specific, population data sets were collected from the U.S. Census Bureau website in both TIGER shapefile and database file formats. The Texas Natural Resource Information System (TNRIS) website provides comprehensive data sets within Texas, and researchers obtained floodplain, hydrology, and transportation data from the site. The U.S. Geological Survey website has a massive amount of geological data sets, from which geology and soil data were downloaded. Some other governmental websites such as the Capital Area Council of Governments website were also helpful sources for collecting relevant data sets for each factor.

Determine Internal Classification for Each Factor

Factor weights refer to the value, on a scale of 1 to 5, assigned to each of the factors (decision criteria) in the SDSS. A value or weight of five is the highest weight for each factor and reflects a negative value for locating a transportation corridor in that place—the least suitable location. A value of 1 is the lowest weight for each factor and reflects a positive value for locating a transportation corridor—the most suitable location.

For example, population density is in the unit of persons per square mile. Since there are 640 acres per square mile, a density of 2000 is less than four people per acre, or one to two households per acre, which is a low figure. Improved property value units are in dollars per parcel. Some factors such as roads and hydrology were classified into a present or not present type. For example, researchers concluded that constructing high-speed rail over an interstate highway requires a complex decision-making process as well as high costs. Hence, having a rail route over an interstate highway receives a higher score than doing so over a local street. Similar logic is applied to the hydrology factor, and thus the major stream category receives a higher score than the others.

Table 1. Weights for Population Density.

Population Density	Scale
0-0.49	1
0.5-2.99	2
3.0-9.99	3
10.00-29.99	4
30.00 or more	5

Table 2. Weights for Roads.

Roads	Scale
Local streets	1
County roads	2
Farm-to-market roads	3
State highways	4
U.S. and interstate highways	5

Please refer to the “Findings” section for the complete reclassification for each factor.

This reclassification process involves many inputs from both professionals and literature. Based on relevant literature, each factor was scored. Some other factors that did not have strong theoretical backgrounds utilized experts’ and factor specialists’ opinions instead. In the GIS, these opinions were implemented with the reclassification tool, and the main categorization on a 1-to-5 scale was performed with standard deviation.

Determine Factor Weights

Factor weights refer to the relative value of factors compared to each other. Thus, for 42 factors, the most important factor to consider for locating high-speed rail (HSR) in the Texas Urban Triangle is weighted the most, the second most important factor is next, and so on, until the least important factor.

In order to determine appropriate factor weights, the research team implemented the analytic hierarchical process (AHP). The AHP is a widely accepted decision-making strategy, especially when dealing with various data sets with multiple criteria. The relationship between eight pre-selected factors was tested in this study: population density, property value, road types, vertical slope, floodplain, geology, soil types, and hydrology. Researchers found that the relationships between the factors and factor weights are a crucial part of the entire SDSS process. The way the factor weights are determined could give different result to the final routes. Table 3 illustrates the AHP result. Similar to the factor selection step, this process also encourages public participation. Participants can set up their own priorities and give different emphasis to each factor based on their own judgment. As will be described in the later section, Property Value factor has been dropped out because of data availability issue. Eigen vectors represent the factor weight for each factor and are standardized values.

Table 3. Factor Weight Matrix Using AHP and Reliability Test.

	Density	Slope	Roads	Hydrology	Floodplain	Geology	Soils	Eigen Vector	%
Density	0.33	0.40	0.29	0.24	0.20	0.20	0.23	0.27	29.0%
Slope	0.22	0.27	0.43	0.24	0.16	0.23	0.23	0.26	27.0%
Roads	0.17	0.09	0.14	0.24	0.18	0.23	0.29	0.19	19.0%
Hydrology	0.07	0.05	0.03	0.05	0.08	0.02	0.02	0.04	5.0%
Floodplain	0.07	0.07	0.03	0.02	0.04	0.02	0.02	0.04	4.0%
Geology	0.11	0.08	0.04	0.17	0.16	0.07	0.09	0.10	9.0%
Soils	0.08	0.07	0.03	0.17	0.14	0.04	0.06	0.08	8.0%
SUM	1.04	1.02	0.99	1.15	0.96	0.80	0.94	1.00	100%

λ_{max} = 7.7070, Consistency Index (CI) = 0.1178, Random Index (RI) = 1.32 (n = 7)
Consistency Ratio (CR) = 0.0893 -> 8.93% < 10.0%
(CR less than 10% considered a consistent preference matrix)

METHODOLOGY

The SDSS

The SDSS compiled these indicators/decision criteria into a land suitability analysis model (McHarg 1995), employing GIS to map strategic social, economic, and environmental characteristics, and overlay them to assess which locations are most and least suitable for regional transportation networks and urban-scale growth. This built on the preliminary suitability analysis for the non-urbanized areas of the Texas Urban Triangle conducted by co-principal investigator Professor Elise Bright and her Master of Urban Planning students in 2006. This SDSS, a composite of traditional decision support systems and multi-criteria land suitability analysis, differs markedly from standard environmental assessments employed in infrastructure network planning decisions in that it analyzes the finite and sustainable carrying capacity of the land in regard to existing and projected urban and infrastructural development (see the brief review of some decision support systems in Appendix A). The SDSS includes four general categories of decision attributes: infrastructural, environmental, social, and economic attributes. It evaluated these data and then mapped them to show suitable geographic locations.

Specific attributes include the capacities, locations, and other attributes of transportation corridors (e.g., grade and curvature requirements for rail) of transportation, water, wastewater, power, and telecommunications infrastructure networks and facilities, and utilities; the capacities and locations of hydrology, soil, climate, water, floodplains, aquifer recharge areas, slope, vegetation, species, elevation, natural hazards, ecosystems, and habitats; population, density, income, education, ethnicity, migration, and changes of these characteristics over time (e.g., growth rates and income inequalities); and job locations and density, available land, productive agricultural land, and housing availability/affordability. In the application of the model, researchers plan to work over the long term with the metropolitan-area councils of governments and metropolitan planning organizations to identify decision criteria and attributes. Their metropolitan analyses will inform the mega-regional analysis.

Testing the SDSS

Researchers tested the GIS-based SDSS on a specific corridor segment between San Antonio and Austin. Over time, they expect to apply the SDSS to an entire strategic transportation corridor that is now in play—the San Antonio–Austin–Dallas-Fort Worth corridor. The output of the model is displayed online using interactive, web-based GIS maps. Researchers Jeff Warner and Douglas Wunneburger, experts in GIS specializing in passenger systems and freight operations, and urban, regional, and environmental planning, respectively, have led and collaborated with a team of researchers to develop the web-based GIS component of the SDSS.

In order to use the SDSS in the GIS, the research team used a raster-based GIS model. Specifically, an ArcGIS (version 9.3.1)-based raster modeling process was adopted. Unlike vector-oriented methodologies, raster-based modeling converts all the necessary information into a raster format, meaning that all information is stored in a grid cell. Therefore, a map is not just a simple map representing the current situation, but contains relevant information in each pixel. Further, the pixels can be manipulated to create new information by using simple procedures such as map algebra. Merging eight factors with an appropriate weight differential provides suitability surfaces. These suitability surfaces are in a 30 m × 30 m grid format with the suitability scores in each cell. After that, by using shortest path analysis, the most suitable pixels are selected and connected to draw an optimal route.

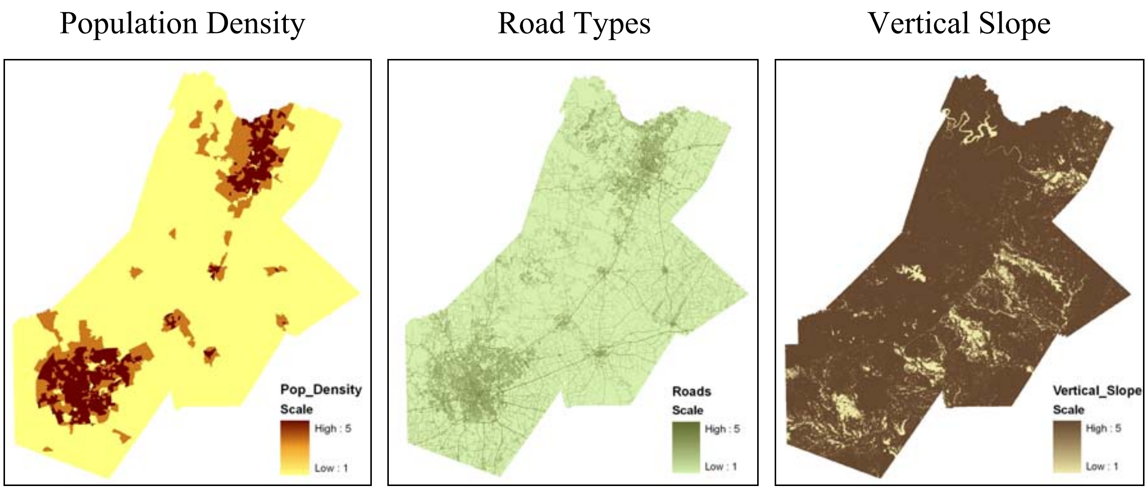
A raster-based modeling process is an especially powerful tool when new information is in heavy demand based on existing conditions. For example, by using the factors in geographical data formats and pre-established relationships among factors, a new suitability surface is created. This suitability surface indicates the most desirable locations of wanted facilities, a rail route in this case. By manipulating the factor weights and classifications, countless possible surfaces can be drawn. Therefore, this is a powerful tool to reflect diverse groups' opinions and provide different options for anticipated possibilities.

FINDINGS

First, the research team organized data sets into the proper format. Since collected data sets were mostly in a vector format, the team had to convert them into a raster format, using the “feature to raster” function in ArcGIS. Afterwards, each factor’s data set was ordered on a 1-to-5 scale. As discussed, this reclassification process was performed with the inputs from literature reviews and experts’ opinions. Further, each classification was performed using the standard deviation.

The population density data sets were obtained from the U.S. Census Bureau in spreadsheet and shapefile formats. As mentioned previously, road factors were ordered into types instead of their number of crossings. Based on the discussion with factor experts, high-speed rail (HSR) generally requires ground with less than 2 percent vertical slope. To calculate the slope in percentage, researchers used the Digital Elevation Model (DEM) from the U.S. Geological Survey (USGS) website and processed the percentages using the “spatial analyst” tool in ArcGIS. The floodplain factors were categorized into their definitions. This definition was acquired from the Federal Emergency Management Agency (FEMA) database. Hydrology data sets were downloadable from the Texas Natural Resources Information System (TNRIS) website. Both geology and soil data sets were acquired from the USGS website. Geology factors were classified into their degree of hardness, and soil factors were classified into their suitability to construct an underground structure. The Natural Resources Conservation Service (NRCS) in the U.S. Department of Agriculture provided helpful definitions and guidelines for such classifications. Finally, the parcel value factors were reclassified into their standard deviations. ArcGIS provided the standard deviations for the desired number of categories, in this case five. Because of data availability, however, the acquired data sets were all within the Capital Area Council of Governments (CAPCOG) area: Hays, Travis, and Caldwell Counties. The other counties do not provide a single, combined data set for their parcel information. This is the main reason for dropping the parcel value factor in creating the cost surface.

Figure 1 shows the results of the reclassification process. The maps are the visual outcomes, and the tables below the maps are the classification information for each factor.

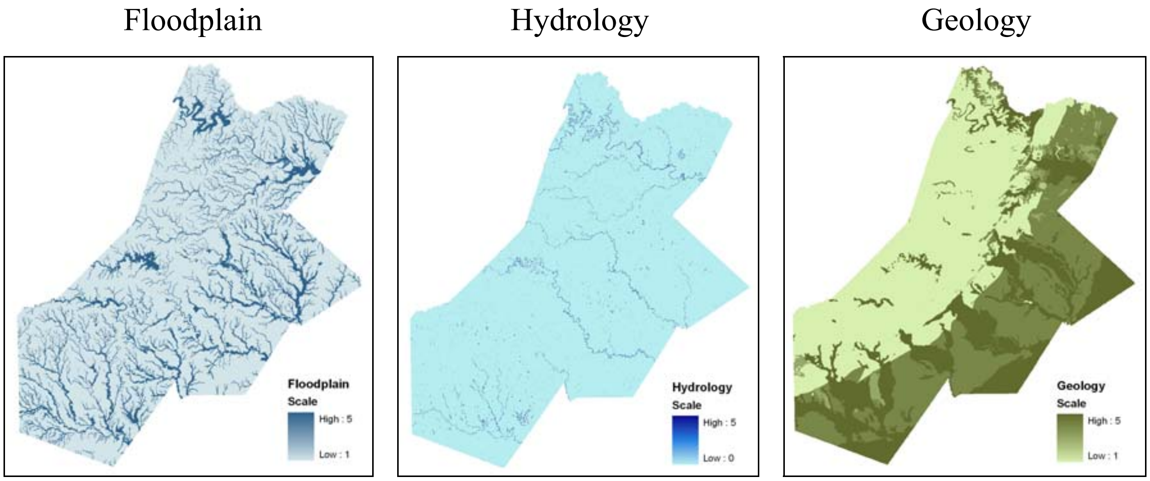


Pop. Density	Scale
0~0.49	1
0.5~2.99	2
3.0~9.99	3
10.0~29.9	4
30.0~	5

Roads	Scale
Local streets	1
County roads	2
FM roads	3
State hwy.	4
U.S. and interstate hwy.	5

Vertical Slope	Scale
0.0~0.9%	1
1.0~1.9%	2
2.0%~	5

Slope 2% is the max. value for HSR



Floodplain	Scale
500-year	1
100-year	2
1% annual –*	3
1% annual	4
1% annual +*	5

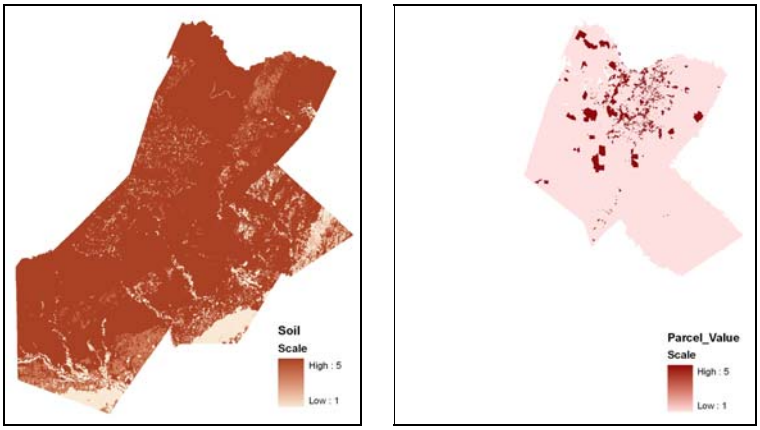
*1%+ requires most strict policy.
*1%– requires least strict policy.

Hydrology	Scale
Intermittent	1
Streams	2
Water body	3
Major streams	4
Dam	5

Geology	Scale
Limestone	1
Stone	2
Gravel	3
Clay	4
Sand	5

Figure 1. Factor Reclassification Maps and Tables.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).



Soil Types

Parcel Values

Soil*	Scale
Good	1
Moderate	2
Slight	3
Limited	4
Very limited	5

*Classified based on suitability to build underground structure.

Parcel Value*	Scale
\$0~\$299k	1
\$300k~\$1,499k	2
\$1,500k~\$4,999k	3
\$5,000k~\$11,999k	4
\$12,000k~	5

*Shows only available counties.

Figure 1. Factor Reclassification Maps and Tables (Continued).

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

After this reclassification process, the research team created a weight matrix to define the relationship between factors. As briefly mentioned, the analytic hierarchical process was adopted to determine the factor weights. As can be seen in Table 3, the CR came out to be less than 10 percent rate (8.93 percent), and this implies that the created weight matrix has an error variance less than 10 percent. In most AHP applied studies, a CR value less than 10 percent is considered a reliable measure.

Using these weights, an equation was created to create a cost surface. This process was done with the “raster calculator” function in ArcGIS. Figure 2 shows the visual relationship that was used to create the cost surface. By merging the factors with relevant weights, a single map representing suitability scores is created. This cost surface is in a grid format with a 30 m × 30 m pixel size. Each pixel contains suitability scores accrued by adding each factor’s reclassification scores. The map algebra can be written as follows:

$$Score_{total} = \Sigma\ a(S_{pop.density}) + b(S_{slope}) + c(S_{road\ type}) + d(S_{hydrology}) + e(S_{floodplain}) + f(S_{geology}) + g(S_{soil\ type})$$

(a ~ g = factor weight for each factor/S = internal classification of each factor)

$$\Downarrow$$

$$Cost\ Surface = \Sigma\ (0.27*Population\ Density) + (0.26*Vertical\ Slope) + (0.19*Road\ Type) + (0.04*Hydrology) + (0.04*Floodplain) + (0.10*Geology) + (0.08*Soil\ Type)$$

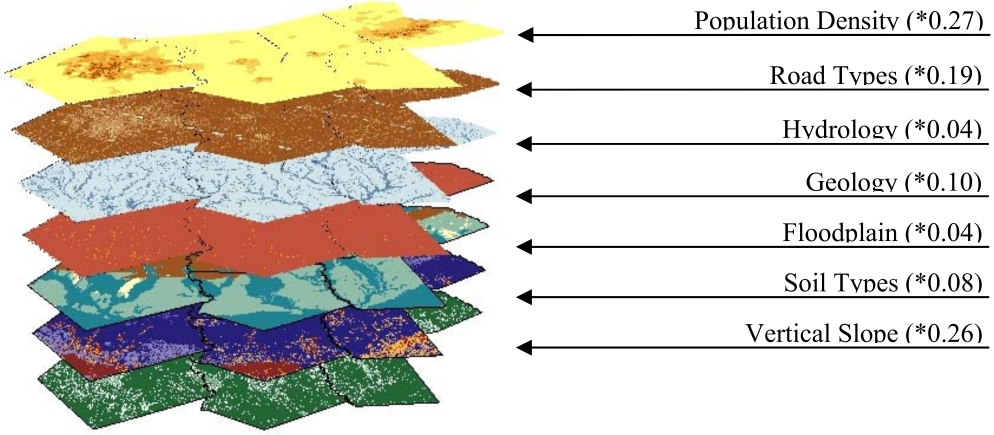


Figure 2. Visual Relationship between Factors and Their Weights.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Figure 3 represents the results using the equation. By allocating factor weights, all the scores are standardized and fit into a 1-to-5 scale, meaning that a pixel value closer to 5 indicates negative suitability for a high-speed rail route. Unlike the convention, this reversed scale is used because finding the shortest path in ArcGIS is based on the least possible scores of each pixel. Hence, the smaller the suitability scores, the better fit for the shortest path. As can be seen, the possible maximum value came out to be 4.55, and the minimum value is 0.75.

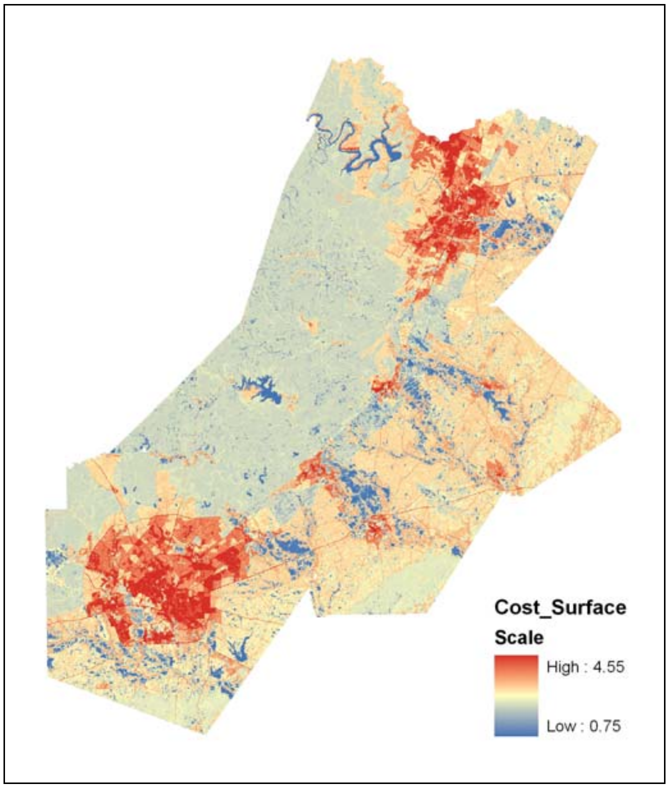


Figure 3. Created Cost Surface.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Figure 4 represents the suitability map with the shortest path. This path is drawn based on each pixel's suitability score. By setting up the departure and arrival points, ArcGIS calculates the least possible vector line connecting each pixel. Because this line is basically a vector line connected pixel by pixel, the shape is not a curve but rather a zigzag and thus requires a post-smoothing process.

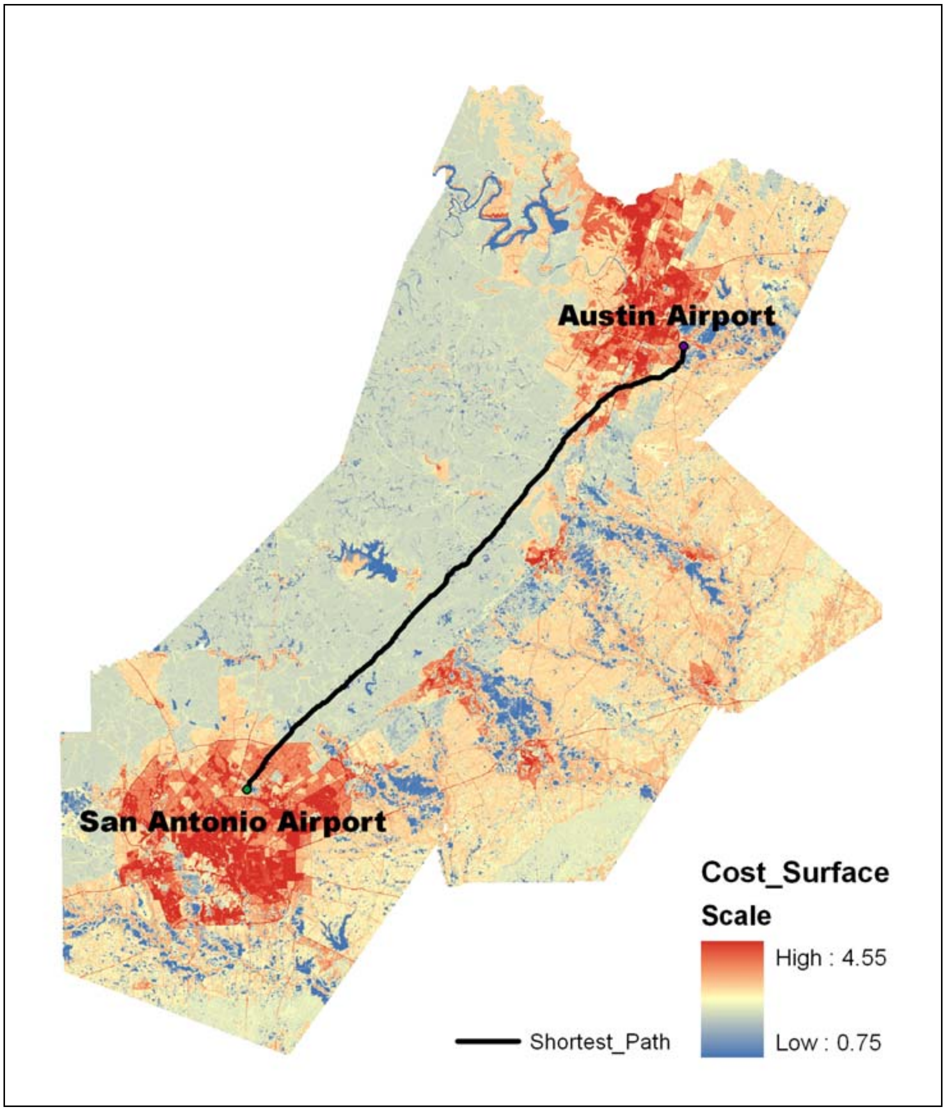
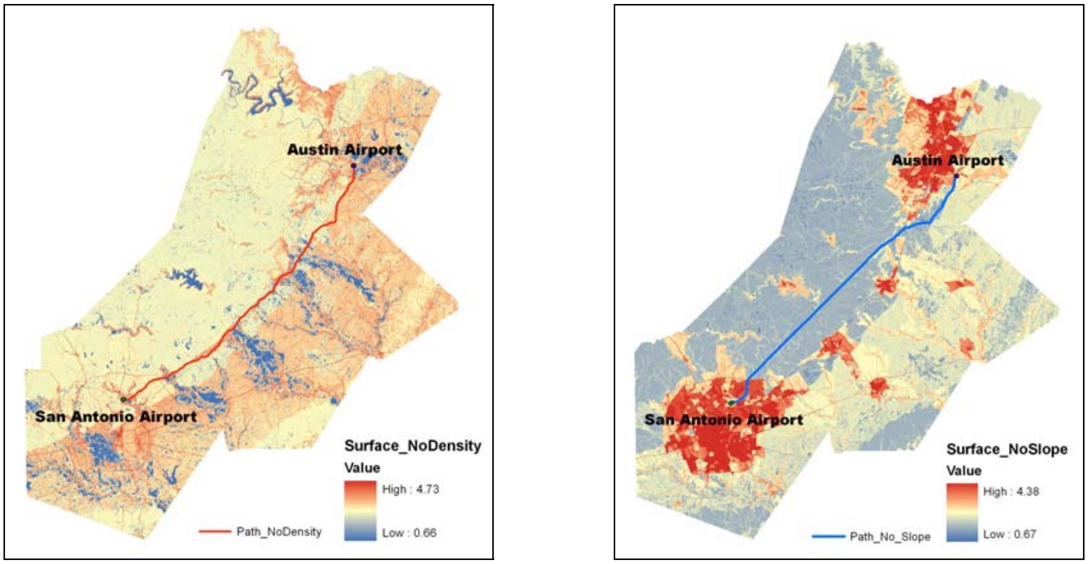


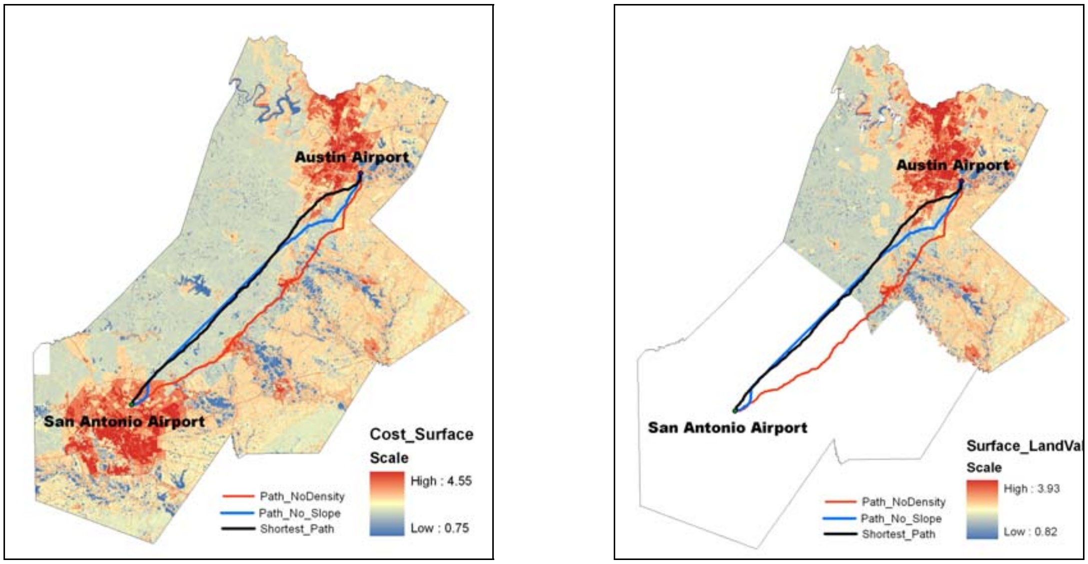
Figure 4. Shortest Path Based on Cost Surface with Factor Weights.
(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Then, the research team decided to explore how factors are related in terms of their impact on the cost surface and the route at large. Several different cost surfaces were created with different factor settings. For example, a cost surface without population density gave a route with very close proximity to cities' major population centers. Dropping the slope factor drew a straighter line than with the factor included. This exploration, represented in Figure 5, shows the visual relationship between the factors and the suitability surface.

Further, because of data availability issues, the parcel value factor was dropped to obtain a more balanced result. Although Hays, Travis, and Caldwell Counties have parcel value data sets that are completely open to the public, other counties, such as Bexar and Guadalupe Counties, do not provide land value information. This absence of a data set created a bias in the final suitability surface, and so the team decided to drop the factor and continue doing research with the available, unbiased seven factors.



Surface & Path without Population Density Surface & Path without Vertical Slope



All Surfaces & Paths Combined If Parcel Value Factor Is Included

Figure 5. Suitability Surfaces and Paths with Different Factor Settings.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Because this study does not include a decision regarding the location of any high-speed rail station, the airport in each city was chosen as the departure and arrival points. The Austin-Bergstrom Airport was set as the starting point, and the ending point was set to the San Antonio International Airport. Based on discussion, the location of a high-speed rail station involves a different set of indicators and requires important political inputs. Consequently, there should be a separate, more precise study.

The “shortest path” function finds the most suitable route by searching each pixel’s score in the cost surface. The result is in a vector line format connecting the most suitable 30 m × 30 m pixels; however, post-processing is required to smooth the line to the parameters required for construction. Construction parameters applied to high-speed rail require that turns must be limited to curves defined by a minimum 3-mile radius.

Figure 6 shows a representative portion of the path before and after smoothing. In this example, the post-processing step uses the “smooth” function provided in the ArcGIS Advanced Editing toolbox. The extent of smoothing is set by indicating the maximum allowable offset, limiting the maximum distance the output geometry (curves) can be from the input geometry (vertices). In order to determine the optimum offset to satisfy the engineering requirements of the minimum curvature radius for high-speed rail track (15,600 ft or 4754.88 m[1]), a step-wise evaluation employing three offset values was applied (14 m, 100 m, and 500 m). The curvature radius of each vertex on the polyline was calculated through coupling GIS with Mathematica[2] (a mathematical program). The mathematical calculation process and algorithm of curvature radius are included in Appendix D of this report.

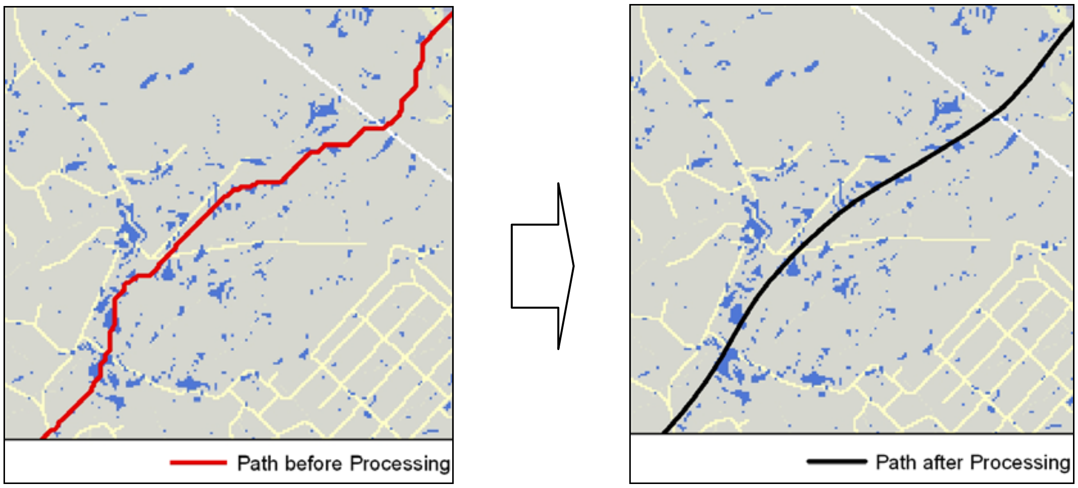


Figure 6. Path Before and After Post-Smoothing Process.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Figure 7 illustrates the smoothing result of the original polyline applying each offset value with highlighted vertices (in aqua) that satisfy the curvature radius requirement.

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[1] Texas TGV Consortium, *Franchise Application to Construct, Operate, Maintain, and Finance a High-Speed Rail Facility,* Austin, TX, 1991.

[2] http://www.wolfram.com/mathematica/.

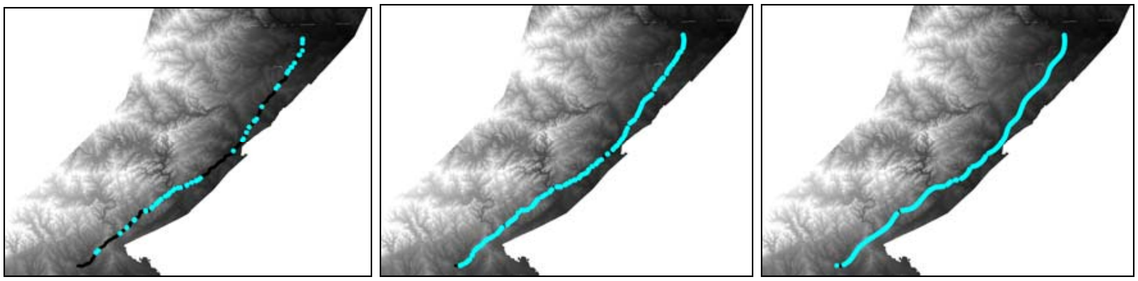

Figure 7. Smooth Lines with Offset of 14 m, 100 m, and 500 m.

(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

As shown in these graphs, the greater the offset value, the smoother the polyline becomes, and more vertices on the line satisfy the curvature radius requirement.

A GIS-based module can be developed to determine a route where every pixel satisfies the curvature radius requirement. At this time, the smoothing process has not been finalized. However, further research and development are encouraged to complete this process.

This step provides the final result, representing a possible high-speed rail route between Austin and San Antonio based upon high-speed rail selection factors and design limits.

CONCLUSIONS

For the effective application of the SDSS in the Texas Urban Triangle and beyond, the research team has determined two important criteria: the clarity of the methodology used to develop the SDSS model, and the rigor of the theory underlying it.

Researchers believe that this SDSS is robust, meaning that it is supported by valid theory, developed using a sound methodology, and based on reliable and accurate data. This robust quality, coupled with the wide range (42) of factors (variables) in the SDSS model, enables it to be adapted to a wide range of geographic and technological circumstances beyond Texas and its Urban Triangle, depending on the intended use. A wide range of geographic conditions means two things: places throughout the United States and the world, not just Texas; and a range of scales from the municipality to the multi-state region. The wide range of technological circumstances means any type of ground transportation technology or mode, whether rail, road, or multimodal.

Furthermore, the adaptability/flexibility of the model is afforded by the ability of any user to tailor the 42 factors to suit the scale and territory to which it is applied. For example, if a region is heavily forested and topographically rugged, those two environmental characteristics can be bolstered with additional factors, and those two factors themselves can be adjusted to suit the specific local conditions. Moreover, end users can adjust both the internal weights within each factor and the external rankings among the factors as compared to the other factors selected.

The power of the SDSS thus resides in its wide-ranging capacity to incorporate a range of parameters (criteria/factors) related to transportation corridor decision making, its ability to display results graphically and geographically using GIS, and its ability to be adjusted and adapted to different places, circumstances, and infrastructure networks, merely by varying the factors/parameters chosen to be used in the model, and by varying the factor weights and factor rankings.

Figure 8 represents the outcome of the SDSS process that this research has proposed. As mentioned earlier, the proposed SDSS in this research still requires more factors and consideration. Nevertheless, suggesting a decision support system that will house more people's interest makes this proposed SDSS one of a kind.

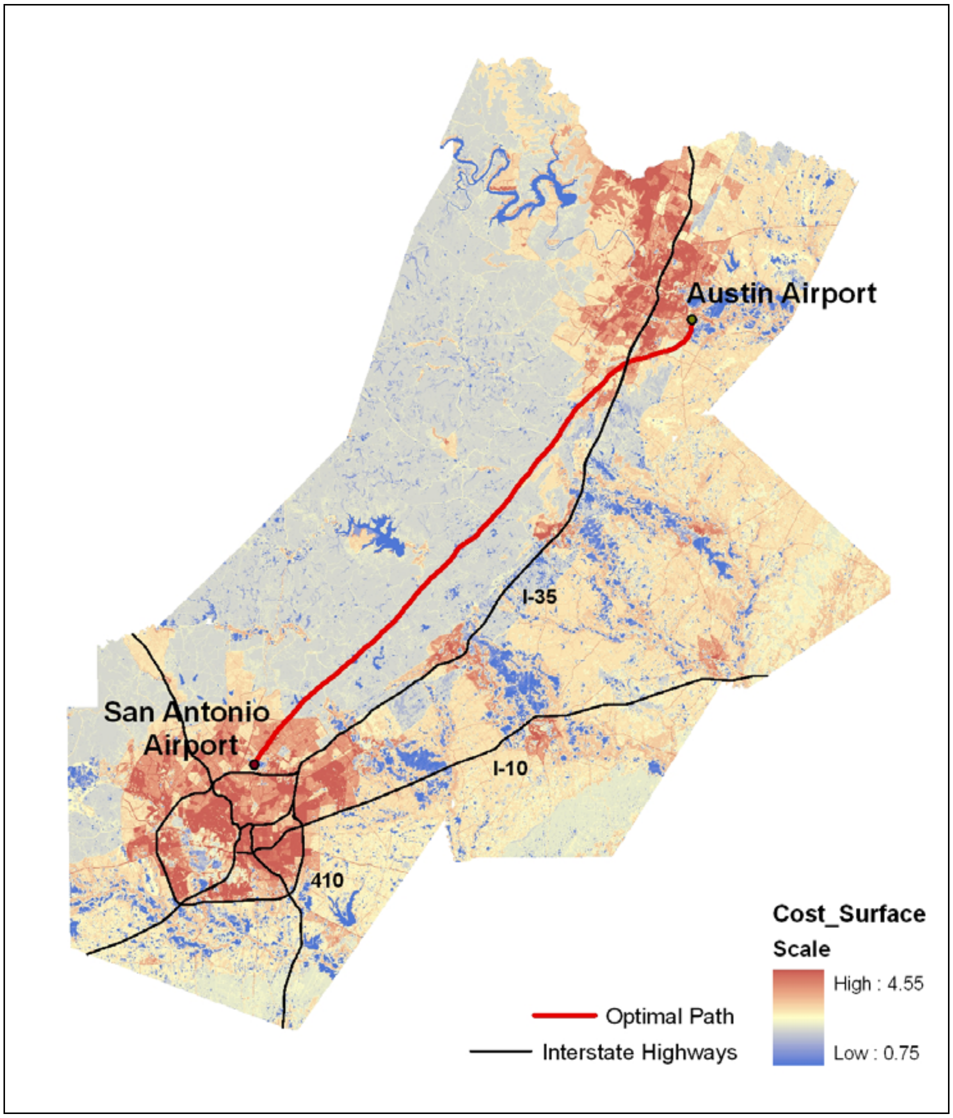

Figure 8. Final Cost Surface with the Shortest Path after Post-process.
(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

Based on two consecutive studies, the research team provided a prototype modeling process that enables a comprehensive and balanced view on a new infrastructure investment decision. Further, the capacity of this decision support system itself can be expanded to make more complex decisions by incorporating other, diverse characteristics (factors) and use them as additional inputs into the SDSS. By doing so, new transportation infrastructure does not only mean an opportunity for new economic possibilities and new urban development, but its right of way can also be located to support sustainable development for the future.

RECOMMENDATIONS

Based on the findings of this research, several avenues for future actions are suggested in no particular priority order:

- Continue developing and testing the SDSS in the Texas Urban Triangle.
- Apply the SDSS to actual decision making for transportation corridors in the Texas Urban Triangle in concert with key regional transportation entities, including but not limited to the four principal metropolitan planning organizations and councils of governments in the Triangle, as well as the Texas Department of Transportation (TxDOT).
- Apply and/or modify the SDSS to address perceptions held by stakeholders. For example, additional factors may be beneficial for analyzing and mitigating adverse impacts of large ownerships by fragmentation.
- Test the prototype modeling in the entire Texas Urban Triangle boundary area.

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APPENDIX A: LIST OF TRANSPORTATION DECISION SUPPORT SYSTEM MODELS REVIEWED IN SUPPORT OF THE DEVELOPMENT OF THE MODEL

TransDec 2.0 Transportation Decision-Making Software: Developed by TTI under National Cooperative Highway Research Program (NCHRP) 20-29 and 20-29 (2), TransDec is a multimodal investment model that takes into account many factors not easily measured in traditional benefit-cost assessments of project desirability, such as air quality considerations, gross mobility impacts, community livability factors, and aesthetic considerations. TransDec uses multi-criteria utility analysis methods to assess tradeoffs between transportation modes, planning methods, and priorities set by project evaluators. The TransDec software makes it possible to have a process that allows the decision maker(s) to rotate the emphasis from one category of measures to another to assess the resiliency of a given option across all of the selection criteria and choose those that perform well from all of the perspectives considered important.

"Low Cost" At-Grade Rail Crossing Warning Detection System Evaluation: NCHRP 3-76 (B) required TTI personnel to use TransDec 2.0 software to make a comparative evaluation of two proposed lower-cost at-grade rail crossing warning detection systems. An audible system and a radar-based system were compared against the performance of one another and against traditional track-based detection systems. Cost, functionality, placement ease, and maintainability were among the factors that were compared.

Development of Intercity Passenger Network in Texas, TxDOT Project 0-5930: This ongoing project has developed a state-wide network to move people between urban regions by either passenger rail or intercity bus services. For each intercity corridor, a set of criteria was developed to compare the suitability of each corridor against the others. Criteria utilized for this project include the population along each corridor, population density, projected population growth, total employees, number of public or private universities, air passenger travel between corridor airports, vehicular traffic, percent trucks, and average number of corridor flights per day. The outcome of this evaluation will be the recommendation of which corridors are most likely to support an intercity transit system and whether bus or rail is most suitable.

Evaluation of Locations for Idle-Reduction Technology (EPA): This project used GIS to identify the most appropriate location for truck stop locations with idling emissions-reduction technology. The research team developed a set of criteria to directly compare roadway segments throughout the entire United States that are best suited to accommodate a new truck stop containing the plug-in external power idle-reduction technology features. Criteria included roadway segment characteristics, such as truck volumes, criteria related to non-attainment areas, number of existing facilities, annual winter and summer temperatures, and proximity to major highway intersections.

MicroBENCOST Model: The MicroBENCOST software was developed by TTI researchers in the mid-1990s. It provides a planning-level economic analysis tool that can be used to analyze a variety of transportation projects.

Kendig Keast Collaborative: Kendig Keast Collaborative is a U.S. planning consulting firm that indicates an interest to "design with nature." According to their website (www.kendigkeast.com), they perform comprehensive plans, land use and design, and three-dimensional modeling. They appear to be very visual in their planning techniques. Two software offerings are identified on their website: ScenarioPlus and BufferBuilder. The software of interest for the University Transportation Center for Mobility (UTCM) Texas Urban Triangle project appears to be the ScenarioPlus package. They describe ScenarioPlus as "future land use modeling software that allows for the preparation of multiple development scenarios and an instantaneous quantification of their impacts." The stated focus of ScenarioPlus is the development impact analysis. Modeling in real time, it shows the "impacts that a proposed scenario would have on population, housing requirements, school enrollment, sewer and water demand, employment, trip generation, and established levels of service." Additionally, the website states that the fiscal consequences of alternative futures can be evaluated. They indicate that the software package "scans the alternatives and feeds the land use plan into a sophisticated spreadsheet, which calculates the acreage of each proposed land use and performs detailed environmental, community, and/or fiscal impact analyses." Although it does not appear to calculate the optimal alternative, it does calculate the impacts of all the alternatives based on the model inputs.

Feasibility Evaluation of Freight Pipeline System in Texas: Developed by TTI researchers, this project applied multi-attribute value/utility methodology to evaluate several alternatives of freight pipeline alignments in Texas. The criteria considered and the methods for weighting and ranking can be used in SDSSs.

UPlan: A Versatile Urban Growth Model for Transportation Planning: This is a GIS-based urban growth model that runs in the Windows version of ArcView on a personal computer. The model was designed by the research team to rely on a minimum amount of data, but it allocates urban growth in several land use types for small (parcel-sized) grid cells. It is a scenario-testing model and rule based; i.e., it is not strictly calibrated on historical data and uses no choice or other statistical models. The result, land use types can be applied to various urban impact models to forecast soil erosion, local service costs, and other impacts.

The "ALLOT" Model: A PC-Based Approach to Siting and Planning: This model is an early prototype of the SDSS developed in 1992 in an attempt to provide governmental jurisdictions and private landowners with more economically efficient and environmentally sound land use and development patterns than usually occur. It employed a GIS land suitability analysis model and multi-attribute value method that helped to determine the location of lands that are suitable for different land uses.

APPENDIX B: SUPPORTING LITERATURE

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APPENDIX C: SDSS MODEL FACTORS

Criteria	
Roadway right of way—existing private, state, county roads*	**Urban areas: present/not present**
Railroad right of way—existing active	**Superfund sites**
Bridges	**Location of hazardous material facilities**
Slope/maximum grade*	**Solid waste disposal site**
Width of right of way	**Subsidence**
Vertical clearances	**Coal deposits**
Horizontal alignment	**Forestland & forestland patches**
Option to enter and leave highway right of way	**Riparian areas**
Air quality	**Threatened & endangered species**
Control speeds on turns (turning radius < 2 miles)	**Farmland**
Inactive railroad stations	**Floodplain***
Turnouts	**Aquifers**
Location of power generators	**Geology/faults***
Station locations	**Surface waters***
Historic areas	**Soil types***
Historic sites	**Wetlands**
Historic markers	**Property line divisions**
Cemeteries: existing/not existing	**Oil & gas pipelines**
Archeological/paleontological resources	**Population density***
Parks & wildlife areas	**Structure value/improvements (parcel value)***
American Indian sites: present/not present	

* Factors applied in the model.

APPENDIX D: RADIUS OF CURVATURE CALCULATION

Definition: The radius of curvature is the radius of the circle that best fits the curve at that given point.

Corollary: At the intersection point, the curve and turning circle have the same tangent.

How to calculate the radius of curvature from a set of points from a path:

The analytical expression for the radius of curvature, TR, for a curve f(x) is

$$\mathrm{TR} = \frac{(1 + d_x f^2)^{3/2}}{| d_{x,x} f |}$$

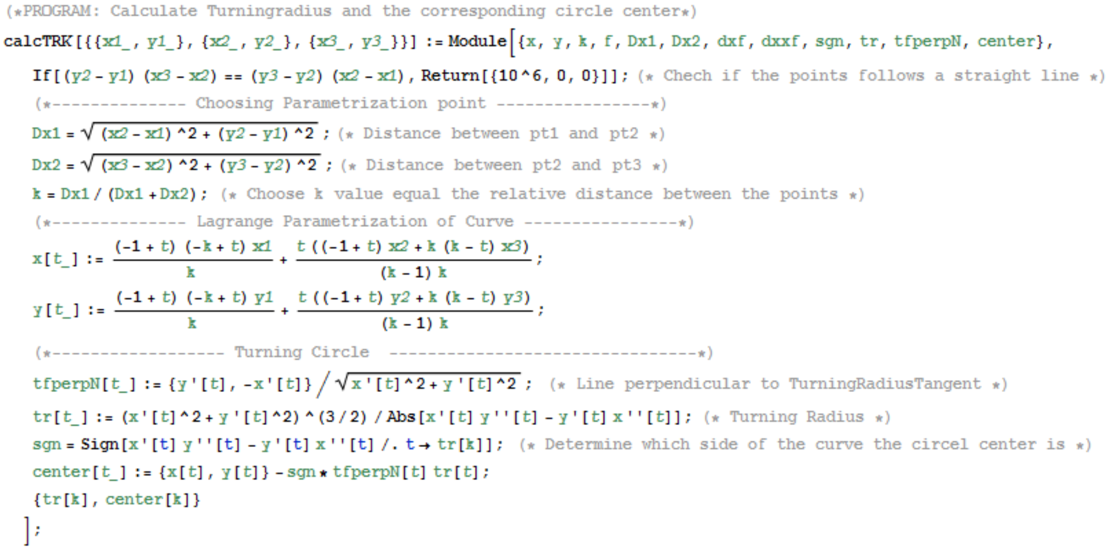
In order to interpolate a general sequence of location points in two dimensions, a parameter representation is required: f[t] = (x[t], y[t]). Here f[t] represents a curve that passes through all the points. The points are independent of each other, so only three points will be considered at a time.

To interpolate a curve that passes through three arbitrarily points, the Lagrange polynomial is used:

$P[x] = f_0\ L_{3,0}+f_1\ L_{3,1}+f_2\ L_{3,2}$ will be used for x[t] and y[t].

Given the curve C={x[t],x[t]}, then the radius of curvature is $r = \frac{1}{|\kappa[t]|} = \frac{\left(x'^2+y'^2\right)^{3/2}}{|x'\,y''-y'\,x''|}$ and the center of the circle is $\{x_c, y_c\} = \{x, y\} + r\{y', -x'\} \Big/ \sqrt{x'^2 + y'^2}$.

The calculation is coded and implemented in Mathematica:



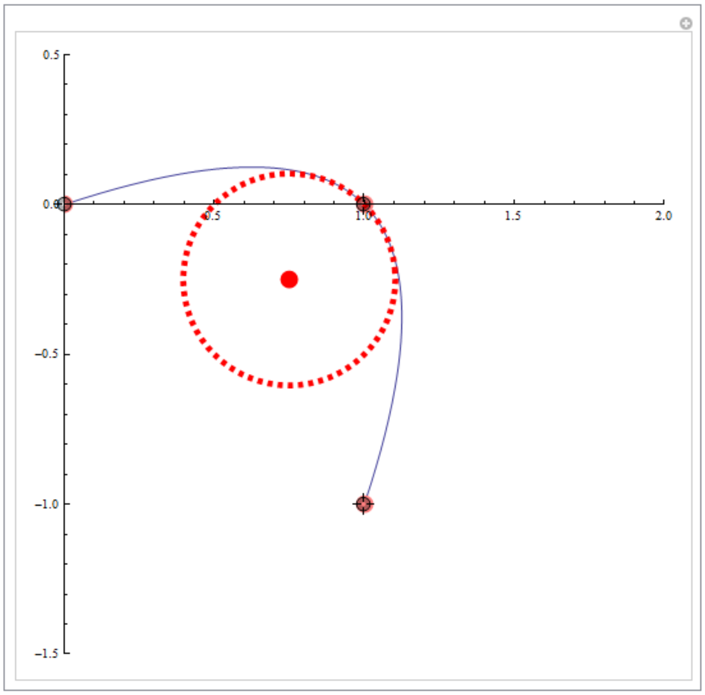
```
(*PROGRAM: Calculate Turningradius and the corresponding circle center*)
calcTRK[{{x1_, y1_}, {x2_, y2_}, {x3_, y3_}}] := Module[{x, y, k, f, Dx1, Dx2, dxf, dxxf, sgn, tr, tfperpN, center},
  If[(y2 - y1) (x3 - x2) == (y3 - y2) (x2 - x1), Return[{10^6, 0, 0}]]; (* Chech if the points follows a straight line *)
  (*-------------- Choosing Parametrization point ----------------*)
  Dx1 = √((x2 - x1)^2 + (y2 - y1)^2); (* Distance between pt1 and pt2 *)
  Dx2 = √((x3 - x2)^2 + (y3 - y2)^2); (* Distance between pt2 and pt3 *)
  k = Dx1 / (Dx1 + Dx2); (* Choose k value equal the relative distance between the points *)
  (*-------------- Lagrange Parametrization of Curve ----------------*)
  x[t_] := ((-1 + t) (-k + t) x1)/k + (t ((-1 + t) x2 + k (k - t) x3))/((k - 1) k);
  y[t_] := ((-1 + t) (-k + t) y1)/k + (t ((-1 + t) y2 + k (k - t) y3))/((k - 1) k);
  (*------------------ Turning Circle  --------------------------------*)
  tfperpN[t_] := {y'[t], -x'[t]} / √(x'[t]^2 + y'[t]^2);  (* Line perpendicular to TurningRadiusTangent *)
  tr[t_] := (x'[t]^2 + y'[t]^2)^(3/2) / Abs[x'[t] y''[t] - y'[t] x''[t]]; (* Turning Radius *)
  sgn = Sign[x'[t] y''[t] - y'[t] x''[t] /. t → tr[k]];  (* Determine which side of the curve the circel center is *)
  center[t_] := {x[t], y[t]} - sgn * tfperpN[t] tr[t];
  {tr[k], center[k]}
 ];
```

Verifying/testing solution:

```
(* Plotting the calculated turingradius and corresponding circle *)
plotK[{{x1_, y1_}, {x2_, y2_}, {x3_, y3_}}] :=
  Module[{x, y, k, f, Dx1, Dx2, dxf, dxxf, sgn, tr, tfperpN, center, plotCurve, plotPts, plotBox, r, xc, yc, plotCPt, plotCirc},
   (*-------------- Lagrange Parametrization of Curve ----------------*)
   Dx1 = √((x2 - x1) ^2 + (y2 - y1) ^2) ; (* Distence between pt1 and pt2 *)
   Dx2 = √((x3 - x2) ^2 + (y3 - y2) ^2) ; (* Distence between pt2 and pt3 *)
   k = Dx1 / (Dx1 + Dx2); (* Choose k value equal the relative distance between the points *)
           (-1 + t) (-k + t) x1   t ((-1 + t) x2 + k (k - t) x3)
   x[t_] := -------------------- + ------------------------------ ;
                    k                        (k - 1) k
           (-1 + t) (-k + t) y1   t ((-1 + t) y2 + k (k - t) y3)
   y[t_] := -------------------- + ------------------------------ ;
                    k                        (k - 1) k
   (*------------------ Turning Circle  --------------------------------*)
   {r, {xc, yc}} = calcTRK[{{x1, y1}, {x2, y2}, {x3, y3}}];
   (*--------------------------- Plotting------------------------------*)
   plotBox = Plot[, {x, 0, 1}, PlotRange → {{0, 2}, {-1.5, .5}}, ImageSize → 500, AspectRatio → 1 ];
   plotCirc = {Red, Dashed, Thickness[.01], Circle[{xc, yc}, r]};
   plotCPt = {PointSize[.03], Red, Point[{xc, yc}]};
   plotCurve = ParametricPlot[{x[t], y[t]}, {t, 0, 1}];
   plotPts = {PointSize[.03], Pink, Point[{{x1, y1}, {x2, y2}, {x3, y3}}]};
   Show[plotBox, plotCurve, Graphics[{plotPts, plotCPt, plotCirc}]]
  ];
```

```
In[23]:= Manipulate[plotK[pts], {{pts, {{0, 0}, {1, 0}, {1, -1}}}, Locator}]
```

Out[23]=



(Color figure may be viewed at http://utcm.tamu.edu/publications/final_reports.stm#neum57).

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