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An Integrated Model to Study Environmental, Economic, and Energy Trade-offs in Intermodal Freight Transportation

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Abstract: The Geospatial Intermodal Freight Transportation (GIFT) system is an integrated model and tools to aid policy analysts and decision makers to understand the environmental, economic, and energy impacts of options for intermodal freight transportation. GIFT integrates multiple geospatial transportation networks (highway, railway, waterway) connected by intermodal transfer facilities (ports, railyards, truck terminals). Added to this network are models of the environmental, energy, and economic impacts of different types of vehicles (trucks, locomotives, vessels) traversing the network. GIFT also models the volumes of freight flowing between originations and destinations. This paper describes the architecture and use of the current GIFT system, new GIFT needs as policy analysts begin to study regional and corridor impacts of freight flow volumes, and GIFT system improvements to better meet those needs. These system improvements incorporate computer-aided scenario generation and tools for the policy analyst to select and analyze scenarios using advanced visualization and analysis techniques.

Keywords*:* Freight transportation; transportation models; environmental impacts.

1. INTRODUCTION

The United States Bureau of Transportation Statistics [2009] reports that the United States (U.S.) spends 6-7% of its gross domestic product on freight transportation. The U.S. Energy Information Administration [2009] reports that freight transportation emits about 7.8% of total U.S. CO_2 emissions. The U.S. Environmental Protection Agency [2006] reports that trucking consumes more energy and emits more greenhouse gasses and other pollutants than rail and water-based transportation. From these reports, we expect that policies that favor intermodal freight transportation, shifting freight movement from trucks to rail and ships, promise to reduce the environmental and energy impact of freight transportation. However, the economic impact of these mode shifts need to be understood along side the energy and environmental impacts of policies such as carbon taxes, alternate fuels and vehicles, and investment in transportation infrastructure. Further, there are broad environmental, economic, and social impacts of mode shifts that need to be understood, such as changing land use resulting from infrastructure development or abandonment, changing employment and economic profiles, and the long-term impact of using and maintaining the freight transportation system. Policy makers, transportation planners, and shippers need decision support tools to help them evaluate the impact of transportation mode selection decisions and transportation policies and investments.

We have developed the Geospatial Intermodal Freight Transportation (GIFT) model to aid policy makers and transportation planners to understand the environmental, economic, and

energy impacts of intermodal freight transportations. GIFT does not address some of the broad impacts such as changing land use, but it does provide insight on the impacts of many of the operational and investment decisions around freight transportation

GIFT integrates three types of models to characterize freight transportation so that decision makers and policy analysts can understand this complicated transportation system and assess the possible impact of their operational and policy decisions. Figure 1 illustrates the three model types and their flow in a typical case study analysis. The three model types are:

1. A geospatial-referenced network model integrating three distinct modes of transportation networks (road, rail, and waterway) integrated by intermodal transfer facilities (ports, railyards, truck terminals) where freight can be transferred from one transportation mode to another,
2. Models of the environmental impact (emissions of carbon, particulate matter, etc.), energy consumption, and economic impact (operational cost and benefit) of freight transportation for each mode of operation and for intermodal transfer facilities,
3. Models of the current and possible future demand on the transportation networks, characterizing the originations, destinations, and flow volumes and values of goods movement across the transportation network.

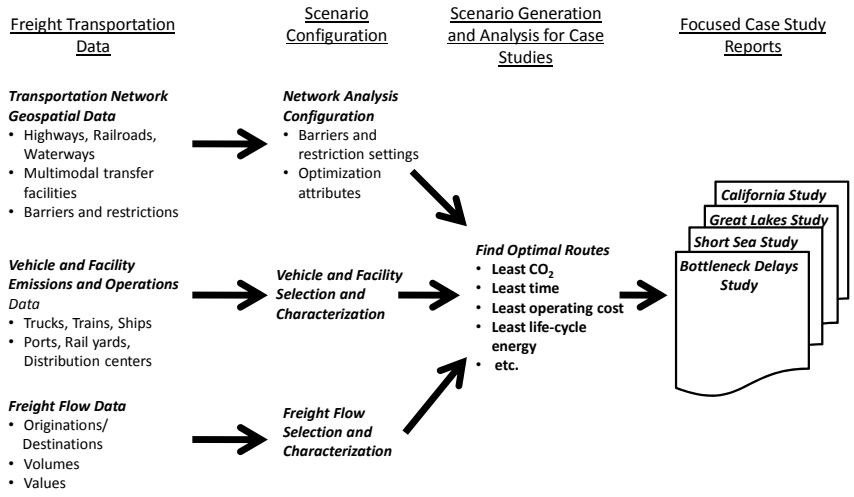

Figure 1. Data flow for GIFT case study analysis

For a given transportation origin and destination, an analyst can use GIFT to identify the transportation modes and routes that minimize a given attribute (such as CO_2 emissions, time, or operating cost) and understand the impacts of alternate mode selections or alternate types of vehicles (different sized ships, for example) or different fuel types. By varying the model's emissions, cost, and time impacts, the analysts can explore the impacts and trade-offs of alternative policies.

Policy analysis case studies using the current GIFT system, such as Winebrake et al. [2008] and Comer et al. [2010], have analyzed impacts and trade-offs for a single transportation origin/destination (O/D) pair or a small set of O/D pairs. They are now beginning to perform more comprehensive analyses of regional impacts with multiple O/D pairs and corridor bottleneck delay case studies. These case studies will require stronger computational support for configuring and managing hundreds or thousands of scenarios and for providing visualization and decision support aids so the analyst truly understands the behavior of the freight transportation system and the possible impacts and trade-offs among policy decisions.

The following sections first describe the kinds of policy case studies that GIFT enables and the kinds of results found. This illustrates the functional features of the GIFT software

system. We then describe the GIFT data and computation models. Following that, we describe new, more comprehensive policy case studies and the features and software architecture changes we are adding to GIFT to enable these new studies. We conclude with a summary of the current GIFT model and its evolution.

2 USING GIFT FOR CASE STUDIES

Early uses of GIFT, such as Winebrake et al. [2008], focused on analyzing impacts and options for single O/D pairs in regions where intermodal transportation may have significant value, such as on the eastern U.S. seaboard. In that study, nominal values of emissions, energy, operating cost, and speeds were provided for each transportation mode and intermodal transfer facility type. With these values and a given O/D pair, GIFT found the least "cost" path between the origin and the destination, where "least cost" is one of minimum time, minimum operating cost (monetary), minimum CO_2, minimum energy, etc. Figure 2 illustrates some results of such a case study. GIFT is usually used to create a landscape of possible scenarios to compare the boundaries of policy impacts, such as minimizing transport time compared with minimizing CO_2 emissions. GIFT also has a weighted cost optimization capability (minimizing a weighted combined cost across multiple attributes) to enable sensitivity analysis.

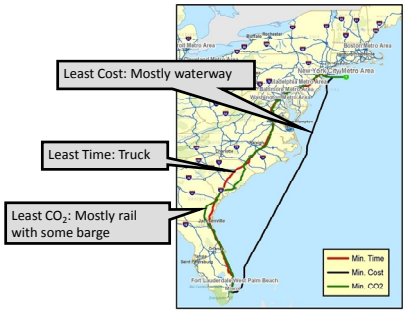

Figure 2. Example case study for transportation modes that minimize various "costs"

Comer et al. [2010] provides another case study using GIFT, looking at opportunities for intermodal shipping using shipping containers in the Great Lakes region of Canada and the U.S. In that region, there is a wide variety of ship types that can be used, and different ship types have different emissions factors, operating costs, and other characteristics. Different locomotives and different trucks using different fuels also have different operating characteristics. We added to GIFT an emissions calculator (described in more detail in the following section) and performed analysis of trade-offs between different ships, trucks, and locomotives. Figure 3 shows that when one ship type is used, then the least CO_2 route uses rail, but when a second ship type is used, the least CO_2 route uses that ship. However, as Figure 4 shows, that second choice results in increased delivery time. This is another example of the use of GIFT to consider the trade-offs of different decision options.

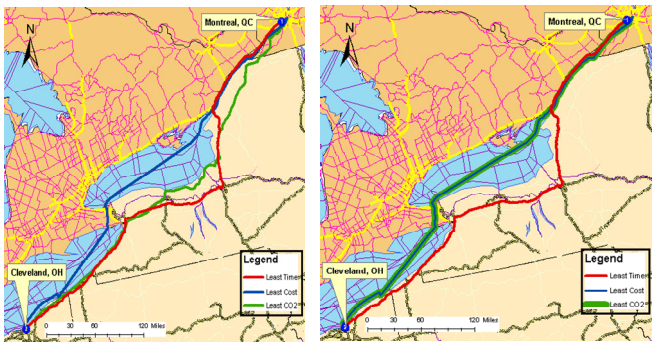

Figure 3. Mode shift occurs when a different ship type is used (Comer et al. [2010])

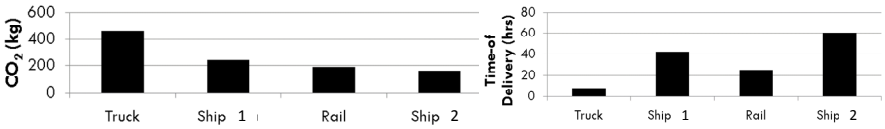

Figure 4. CO_2 and time-of-delivery trade-offs for different ship types for Montreal to Cleveland (Comer et al. [2010])

3. CURRENT GIFT SYSTEM

GIFT incorporates three basic data and computational models: a geospatial transportation network model, a vehicle operations and emissions model, and a freight flow model. The current overall system is shown in Figure 5. Figure 5 is a conceptual diagram illustrating the data flow of model building and model use in case study analysis, plus the identification of user roles and the tools that they use. Toward the bottom of the diagram are the model-building tasks (the downward-flowing arrows), toward the top are case study definition and model use (upward flowing arrows), and the case study results are then saved as files. The following sections describe the integrated model building and use in more detail.

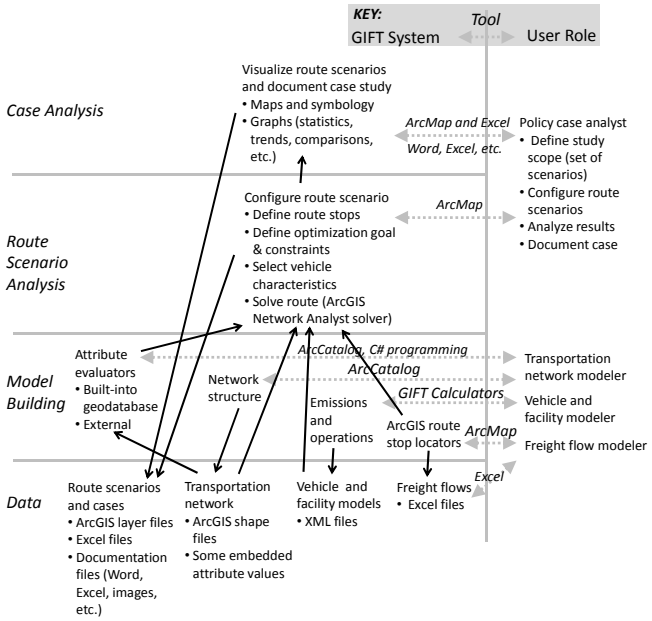

Figure 5. Overall GIFT conceptual architecture

3.1 Transportation Network Model

The GIFT geospatial model uses ESRI ArcGIS products (ArcCatalog and ArcMap) to build an intermodal transportation network, and it uses the ArcGIS Network Analyst extension to find least-cost routes between specific O/D pairs. Each transportation mode is modeled by a separate portion of the geodatabase (separate shapefiles, in ArcGIS terminology). The three transportation modes are integrated through intermodal transfer facilities. So, freight can only transfer from one mode to another by going through a transfer facility. This is illustrated in Figure 6. The intermodal transfer facility is modeled as a point (a "hub") and a geoprocessing script is run to generate "spokes" from that hub to the nearest transportation network elements for those modes that the hub serves (for example, a railyard would connect the railroad network with the highway network).

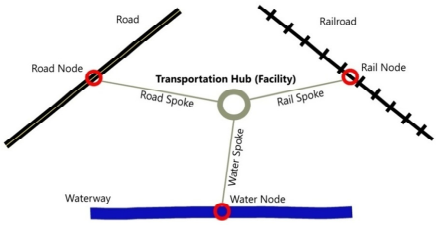

Figure 6. Three transportation networks integrated through intermodal transfer facilities

3.2 Transportation "Cost" Models

Since the primary purpose of GIFT is to understand and trade-off the environmental, energy, and economic impacts, we developed multiple ways to define, manage, and use impact "costs." The main concept is to associate costs with traversing each segment of the transportation network, and to provide multiple ways to make the specific cost depend on the vehicle type, fuel choice, operational and governmental policy in force, and other scenario attributes.

As Figure 7 illustrates, we associate with each segment in the network various costs of traversing that segment. In ArcGIS, these costs are defined as network attributes in the network geodatabase. Some of the attributes are predefined in the network datasets and have fixed values (such as the distance attribute), some are predefined attributes whose values we can change (such as using posted highway speed limits or observed truck speeds for a speed attribute), and some are attributes we have added specifically to support GIFT (emissions, energy, operating cost). The impacts of transportation through intermodal facilities are similarly captured as attribute values on the "spokes" we created to model intermodal transfers, where the attribute values model the impact of freight handling equipment, facility energy use, delays loading and unloading ships, etc.

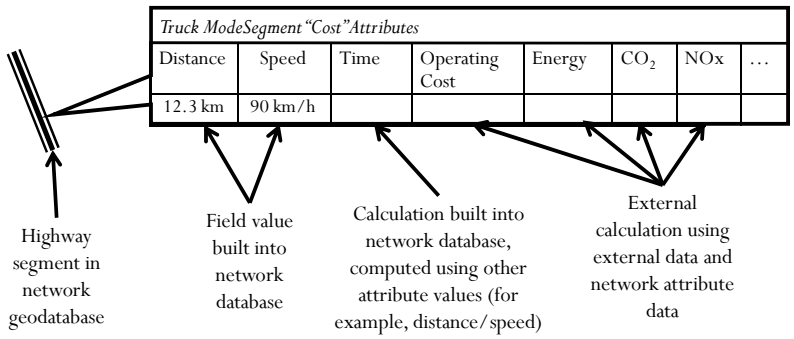

Figure 7. "Cost" attributes associated with transportation network segments

The values for network attributes can be accessed during network analysis run-time (that is, during least-cost optimization or during computations of route data for determined routes) in multiple ways, depending on the data used and their source. Some data are stored statically in the network geodatabase (such as segment distance or posted speed limit), some are computed using VisualBasic scripts embedded into and stored with the database (using ArcCatalog and Network Analyst utilities), and some values are computed using external computations ("custom evaluators" in Network Analyst terminology) that we implemented as C# program components registered in the ArcGIS run-time framework. The embedded computation evaluators can use any data defined as attributes in the network model, whereas the custom evaluators can also access external data and computations. Hawker et al. [2007] provides details on implementing these various attribute value computation mechanisms. Assigning attribute values or associating evaluators with attributes is performed using ArcCatalog while building the transportation network geodatabase.

Since a key use of GIFT is to study trade-offs of energy, emissions, and operating costs, most of these attributes are computed using custom evaluators that access data that the policy analyst can modify to reflect differing operational scenarios. We developed a user interaction and data management tool, illustrated in Figure 8, to define and manage cost factors used by the external evaluators. In addition, we provided a tool to define the emissions for specific types of trucks, locomotives, and ships, and to manage libraries of these vehicles that the policy analyst can select when defining a case study scenario. This tool uses first principle models of energy efficiency, fuel content, and other equations to compute energy and emissions. We have this tool for trucks, locomotives, and ships, and we are developing similar bottom-up, first-principles tools to model freight handling equipment and its operational use for transfer facilities.

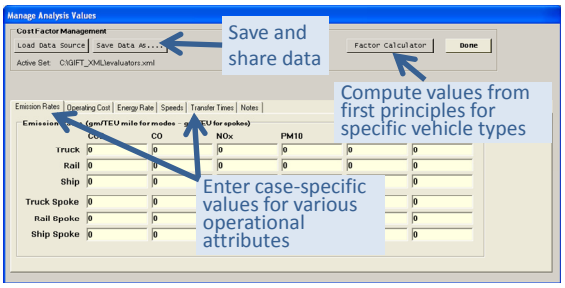

Figure 8. GIFT tool to define and manage case study analysis values

3.3 Freight Flow Models—Needs for Advanced Policy Analysis Tools in GIFT

Most of our uses of GIFT, to date, have involved a policy analyst selecting a few origin/destination pairs and studying the impact on a per-unit of freight basis (per ton of freight or per container of freight). As we begin to study the regional and transportation corridor impact of freight transportation, we are developing models of freight flows. These, plus advanced GIFT tools in development (see the next section) will enable more advanced freight transportation policy decision support.

Our freight flow models identify the origin, destination, volume, commodity type, and value of almost all freight transportation in the U.S., using the Commodity Flow Survey from the U.S. Bureau of Transportation Statistics (http://www.bts.gov/). Figure 9 illustrates the results of an initial analysis of the flow-weighted CO_2 impact of freight originating near the Ports of Los Angeles/Long Beach, California, USA.

Figure 9. An example study of flow-weighted CO_2 impact (cumulative impact of routes originating at port of Los Angeles/LongBeach, California, USA)

To perform flow analysis requires the analyst to interact with GIFT at a level beyond the current single O/D trade-off studies. Defining and managing hundreds of O/D pairs plus volumes, values, and other data items is difficult, at best. Expecting the analyst to understand the interactions and implications of these multiple O/D routes using different vehicle types and route optimization choices is impossible without significant visualization and computing support. That is the subject of the next section.

3.4 Computer-Aided Scenario Generation, Management, and Analysis

We are extending the GIFT system to help policy analysts manage and understand flow-oriented freight transportation analysis. It is increasingly common to use computers to automatically generate large numbers of scenarios and manage them so that analysts can understand the behavior of large-scale systems. Lempert et al. [2003] and Ritchey [2006] discuss common approaches, and these and similar approaches are commonly used in transportation system simulation, modeling, and decision support, such as in Ritchie-

Dunham et al. [2000], Xu et al. [2004], and Li et al. [2007]. Li et al. [2007] specifically discusses software architecture approaches as does Lepreux et al. [2004] and many others.

Figure 10 illustrates the GIFT Scenario Management and Analysis system currently under development. Where-as much of the analyst's interaction with the current GIFT system was through the ArcMap-based Network Analyst user interface, we have automated much of that route definition and generation functionality (the Route Scenario Analysis layer of Figure 5, above). The automation uses the ArcGIS programming interfaces (ArcObjects) and Microsoft C# programs to generate objects that organize and store pre-computed routes. We have pre-generated route results for hundreds of route scenarios—multiple O/D pairs with multiple vehicle types and multiple optimization settings. This provides a repository of pre-defined scenarios for analyst selection and comparison. On top of this scenario repository we are developing what are, in effect, query processing and reporting tools (analogous to relational database query and reporting tools in business intelligence systems). We are providing ways for the analyst to define a case study, select scenarios associated with that case, and select ways to visualize and analyze the related scenarios.

3.5 Model Validation

Sanchez-Marre et al [2006] and Sojda [2007] emphasize that validating a model of environmental, economic and other impacts is difficult, but necessary. As an overall validation of freight movement, we use the annual average daily truck trip data and rail movement data provided by U.S. state and federal departments of transportation, combined with the Commodity Flow Survey from the U.S. Bureau of Transportation Statistics (http://www.bts.gov/) and its derived data. This data helps ensure that GIFT's least-time, least-cost, and least CO_2 values are within bounds. We also compare our results with those from other researchers, such as Lutsey's assessments of truck activity [2009].

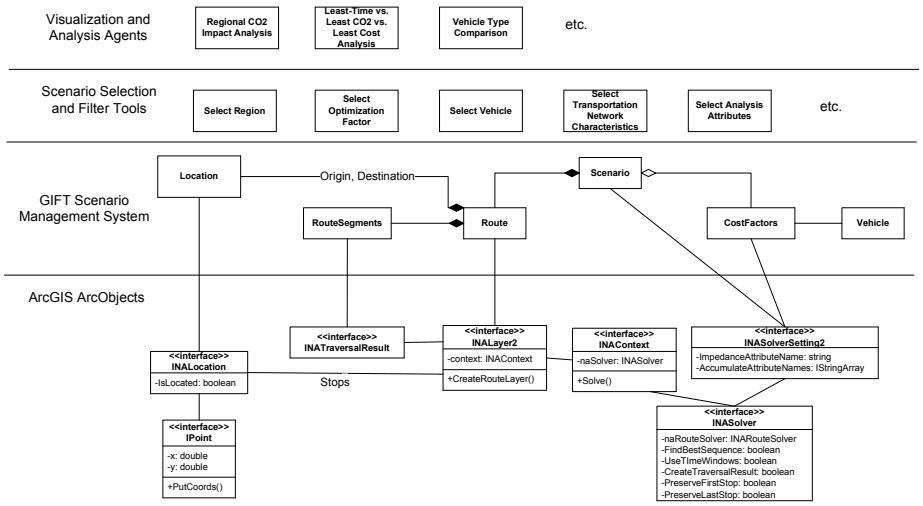

Figure 10. GIFT Scenario Management and Analysis architecture concept

To validate the intermodal transfer facilities of our transportation network, we use mapping and visualization resources available on the internet (such as Google Maps) to visually confirm the existence and location of a facility and the transportation modes that it supports; we modify the model based on these validation results.

We need to improve our model validation methods. We are currently validating our model for specific regions, and we seek better data and methods to validate our model results.

4 CONCLUSION

GIFT is an integrated model of the freight transportation system that has proven very useful in understanding the possible impacts of transportation policy decisions, including the environmental, energy, and economic impact of different vehicles, target reductions in environmental emissions, and the impact of infrastructure and capital investments. This paper describes how the GIFT model integrates multiple transportation networks (highway, railway, waterway) at intermodal transfer facilities, associates the network with models of the environmental, energy, and economic impacts of different types of trucks, trains, and vessels, then adds models of the flow volumes and originations/destinations of freight. We described GIFT model building and described how policy analysts use GIFT to build policy analysis scenarios that use the integrated GIFT models in focused policy case studies.

New uses of GIFT to study regional and corridor impacts of freight transportation are faced with limitations in GIFT's current support for only a few O/D pairs in a given study. Analysts need to model and understand trade-offs among hundreds of O/Ds and the comparisons of dozens of vehicle choices and optimization selections. To enable this, we have automated the generation of route scenarios, providing a repository of pre-computed route scenarios with various vehicle and optimization selections. We are now working to provide tools for policy analysts to select route scenarios relevant to a given case study and to provide ways to visualize and analyze the impacts and trade-offs across these scenarios. We seek ways to enable policy analysts to understand the environmental, energy, and economic impacts of policy decisions affecting complicated intermodal freight transportation systems.

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REFERENCES

Bureau of Transportation Statistics. National Transportation Statistics 2009, Washington, DC, U.S. Department of Transportation, Research and Innovation Technology Administration, 2009.

Comer, B., J.J. Corbett, J.S. Hawker, K. Korfmacher, E.E. Lee, C. Prokop, J.J. Winebrake, Marine vessels as substitutes for heavy-duty trucks in Great Lakes freight transportation, accepted for *Journal of the Air & Waste Management Association*, March 2010.

Hawker, J.S.., A.M. Falzarano, S. Ketha, K. Korfmacher, J.J. Winebrake, S. Zilora, Intermodal Transportation Network Custom Evaluators for Environmental Policy Analysis, *Proceedings 2007 ESRI International User Conference*. San Diego, CA, 2007.

Lempert, R.T., S.W. Popper, S.C. Bankes, *Shaping the Next One Hundred Years - New Methods for Quantitative, Long-Term Policy Analysis*. Santa Monica : RAND Corporation, 2003.

Lepreux, S., C. Kolski, M. Abed, Decision support systems design as knowledge-based tool integration, *Proceedings of the 2004 IEEE International Conference on Information Reuse and Integration*, pp. 516- 521, 2004

Li, J.; T. Shuming, W. Xiqin, W. Fei-Yue, A software architecture for artificial transportation systems - principles and framework, *Proceedings of the 2007 IEEE Intelligent Transportation Systems Conference*, 2007, pp.229-234, 2007

Lutsey, N. Assessment of out-of-state truck activity in California, *Transportation Policy*, vol. 16, 2009, pp. 12-18.

Ritchie-Dunham, J., D.J. Morrice, J. Scott, E.G. Anderson, A strategic supply chain simulation model, *Simulation Conference Proceedings*, 2000 Winter , vol.2, pp.1260-1264, 2000

Ritchey, T. Problem structuring using computer-aided morphological analysis, *Journal of the Operational Research Society*, pp. 792-80, 2006.

Sanchez-Marre, M., K. Gibert, R. Sojda, et al, Uncertainty management, spatial and temporal reasoning, and validation of intelligent environmental decision support systems, *Proceedings of the iEMSs Third Biennial Meeting*, International Environmental Modelling and Software Society, Burlington, Vermont, USA, http://www.iemss.org/iemss2006, 2006

Sojda, R.S. Empirical evaluation of decision support systems: Needs, definitions, potential methods, and an example pertaining to waterfowl management, *Environmental Modelling & Software*, Volume 22, Issue 2, Environmental Decision Support Systems, pp. 269-277, February 2007

U.S. Energy Information Administration, Annual Energy Outlook 2009 with Projections to 2030, Washington, DC, U.S. Department of Energy, 2009.

U.S. Environmental Protection Agency, U.S. Greenhouse Gas Inventory Report, Annex 2. Washington, D.C., 2006.

Winebrake, JJ., J.J. Corbett, A. Falzarano, J. S. Hawker, K. Korfmacher, S. Ketha, and S. Zilora, Energy, environmental, and economic tradeoffs in freight transportation decision-making, *Journal of the Air & Waste Management Association*, Volume 58, Number 8, August 2008.

Xu, J., K.L. Hancock, Enterprise-wide freight simulation in an integrated logistics and transportation system, *IEEE Transactions on Intelligent Transportation Systems*, vol.5, no.4, pp. 342- 346, 2004