USING A GRAVITY DISTRIBUTION MODEL AND DISCRETE EVENT SIMULATION TO ENHANCE FREIGHT PLANNING

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ABSTRACT. Freight analysis and planning has lagged behind traditional transportation planning and is often neglected in models following the four-step process. National projections are that freight shipments will double in the next decade. In Alabama, manufacturing growth and increasing heavy vehicle usage will continue to strain already limited infrastructure. Freight focused planning and analysis tools are greatly needed. This research used a gravity distribution model and discrete event simulation to analyze growth scenarios and quantify congestion. The gravity distribution model develops a trip exchange matrix for freight using Alabama industry sector data. The matrix passes to a discrete event simulation software package incorporating time-of-day statistics and providing a visual communication tool for educating governing officials not involved in the transportation industry. The results of the combined system are the identification of congestion chokepoints and a listing of high priority capacity improvements needed to ensure the continued mobility of the infrastructure system.

INTRODUCTION

The ability to make informed decisions on transportation issues, particularly those dealing with freight is limited by the quality and quantity of information available (Gorys et al., 1999). The ability to accurately model transportation infrastructure, identify congestion choke points, and define needed capacity shortfalls is vital to the planning decision-making needs on transportation systems for both people and goods (Rico et al., 1996). The timely and efficient movement of goods is quickly becoming one of the critical components of the world

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economy. Heavy vehicles, 18 wheel trucks, are the backbone of the logistics and economic success of industry in the United States. National projections are that freight shipments will double in the next ten years. This projected increase in freight will have a significant negative impact on the level of congestion along the national transportation infrastructure and will require innovative congestion mitigation solutions. A detailed understanding of the impact of the projected increase in truck traffic on the existing highway system is needed to examine the potential outcomes and develop a focused plan to accommodate the anticipated increase.

The ability to communicate with diverse audiences about transportation issues, particularly in goods movement, and the source of congestion is paramount to developing consensus on potential solutions and moving forward to creating a safe, effective and efficient transportation system. One successful method of communication is the use of models and simulations of the systems to visually portray the issues and the potential solutions. Visual representations allow for open discussion and debate on the underlying issues and the merits of the potential solutions. This was the purpose behind the development of the transportation system modeling capability at the University of Alabama in Huntsville. The statewide models developed using TRANPLAN® and ProModel® have proved to be a valuable communication and analysis tool for educating stakeholders.

A FREIGHT PLANNING FRAMEWORK

Transportation planning activities performed in essentially all metropolitan planning organizations (MPOs) in the U.S. Horowitz and Farmer (1999) found in a review of statewide planning models in 45 states that there was little consensus as to what should constitute a statewide model and that there was significant variety in the approaches taken. Those states with a comprehensive model generally followed the four-step urban planning framework. The four steps are:

- trip generation
- trip distribution
- modal split
- traffic assignment

Socio-economic characteristics of population and employment (aggregated to the traffic analysis zone level), and the available infrastructure (roadways with defined speeds and capacities) are the typical inputs to the sequential modeling process (Ortuzar and Willumsen, 1994). A trip generation methodology is applied to determine the quantity of trips that are expected to enter and exit each zone throughout the day. Trip exchanges between zones are developed through the application of a trip generation methodology. The exchange of trips is generally formulated on a gravity model that attempts to balance trips produced to locations. Once the trip exchange is complete, a mode split methodology is employed to determine which transportation mode will be utilized. This typically involves the examination of availability, costs and travel times to determine the number of trips made between origin and destination pairs. Finally, the trip exchange by mode is assigned to the available infrastructure network. For passenger car trips assignment is made to the roadway network through one of several methodologies intending to reduce the travel-time for all drivers (Ortuzar and Willumsen, 1994). Researchers have recently made attempts to optimize the transportation planning process and improve forecasting results. Major areas of study include the addition of feedback loops to incorporate congestion effects, and the detailed examination of each step to reduce potential error (Boyce, 2002). However, even as these improvements are shown to be successful, the underlying notion of the sequential, four-step model has remained.

The freight levels associated with the activity in the area is only applied as a function of total traffic (ALDOT, 2007). Additionally, NCHRP Report 365, which is used by many MPOs as the basis for transportation planning activities, does not incorporate freight into the modeling equations (Martin and McGuckin, 1998). Thus, traditional transportation planning activities often ignore freight transportation in the modeling process or add them as an afterthought to the model. Freight planning applications, if freight is included at all; often rely on projections that cannot account for major changes in the workforce or economy of the area. Therefore, an approach to freight modeling that accounts for economic activity and can be incorporated into the transportation planning process, or used on its own, is needed to better allocate resources to transportation infrastructure.

Zografos and Giannouli (2002), performing research into freight transportation systems in Europe, suggest that supply chain strategies have a significant impact on supply and distribution networks, which in turn influence the organizations, the utilization of the freight systems and performance of those same freight systems. They go on to state that the expected development of those supply chains drives the development of alternative policies for the development of future freight transportation systems through the use of simulation. These supply chain strategies are often particular to specific industries.

The idea of basing a freight planning methodology based upon industry sectors in Alabama was developed during the research into the relationship of transportation infrastructure and the economic growth in Alabama (Killingsworth et al., 2005). Using industry sectors for freight planning is relatively straightforward. By developing the understanding of how an industry sector creates freight and the need to access transportation resources, it is possible to develop the interrelationships that can then be used to predict freight requirements anywhere that industry sector is found. Aggregation of the known freight behaviors for the industry sectors in a region can produces a better prediction of the freight needs in the region than random sampling and roadside interviews. These concepts have resulted in the creation of a Freight Planning Framework, which provides an insightful new methodology for obtaining freight volumes. The methodology is built upon publicly available federal freight databases and is intended to be applied at the state, or regional level.

The Freight Planning Framework (FPF) builds upon the traditional four-step transportation planning process by establishing a forward looking approach to trip generation. Figure 1 provides a graphic depiction of the FPF. The following sections will present the approach and methodology proposed to overcome the problems with the traditional four-step process, and the interrelationships of the systems approach.

The FPF is a forward looking method and approach to freight planning. As such, the foundation of the framework is the use of industry sector analysis to establish the basic need for transportation infrastructure access. The planning factors used for the FPF approach are Value of Shipments, Personal Income, Population, and Employment. The reasoning for the inclusion of each factor is described below.

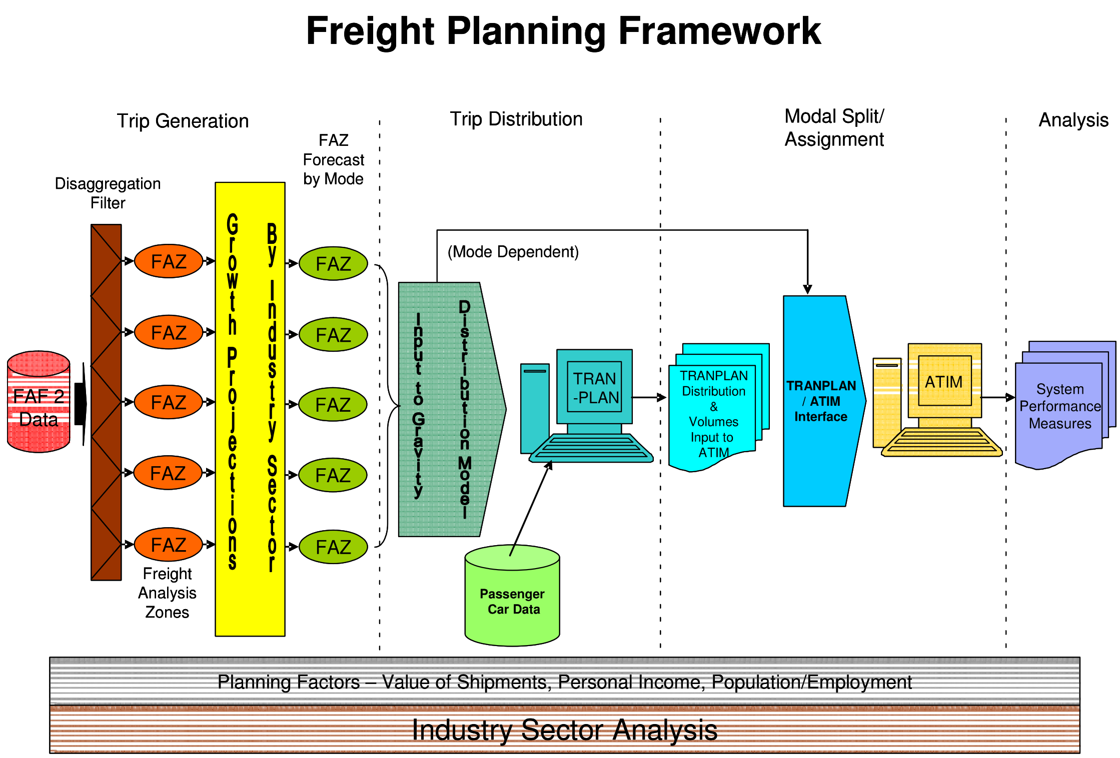

Figure 1. A Freight Planning Framework.

Value of Shipments

Employment as a freight planning factor does not take into account the productivity improvements by which U.S. companies compete in the world marketplace. If employment were the sole factor used in freight planning, the increase in production due to productivity improvement initiatives in a plant would be missed as the output per employee improves and the amount of freight increases. Even worse, if the same amount of production is achieved using fewer employees due to technology or productivity improvements, traditional freight planning methods would actually forecast a decrease in the demand for freight requirements.

Rico et al. (1996) suggested using economic freight flows for identifying and planning for project to be undertaken for the improvement of freight transportation networks in Mexico. The factor *Value of Shipments (VoS)* is included in this research to alleviate the issues with using employment and population exclusively. As productivity improvements increase the output of a plant, the VoS factor captures this information. With knowledge of the relationships between value and vehicle loads acquired on a particular industry sector, the freight system requirements can be calculated from the VoS. VoS provides a more consistent factor to use in the generation of freight from industries within the region.

Personal Income

Personal Income (PI) can be used as a proxy for the attraction of freight to a region. The perceived affluence of an area increases as PI increases. As the perceived affluence of a region increases, the willingness of the population to spend creates more demand for products, thus increasing the need for freight to the area to provide the desired consumer goods. As PI decreases in a region, the population perceives a loss of affluence and spending tends to slow. This reduced demand for products in the region causes a decrease in freight destined for the region.

Population/Employment

Population and employment are traditional factors used in transportation planning. The population of a region is a proxy for the volume of vehicles in the region, from which the number of trips and distances can be derived. Employment has traditionally been used as a proxy factor for freight. It is assumed that as employment increases, the amount of freight shipped into an area also increases and vise versa. However, these two factors alone do not provide an adequate predictor of freight activity, but combined with VoS and PI they can potentially improve the accuracy of the planning factors.

The Freight Planning Framework – Data and Models

The purpose for discussing the FPF in this paper is to develop the methodical process necessary to revolutionize transportation planning to include freight as an active component. The FPF employs both the gravity distribution model for the allocation and assignment of freight and passenger car traffic and a discrete event simulation to infuse variation into the model and planning process. The models employed, though, are only as good as the data provided to generate and operate the models. Because freight data is difficult to acquire, the authors approached the freight component of the model activity from the use of national, publicly available, databases (Horowitz and Farmer, 1999). The best currently available public freight data in the U.S. is provided by the second generation of the Federal Highway Administration's (FHWA) Freight Analysis Framework, known as FAF2. FAF2 provides commodity flow origin-destination (O-D) data and freight movement information on the FAF2 highway network. The O-D data includes the base year (2002) and future years between 2010 and 2035 in 5-year intervals, FAF2 (2007). Industry sector knowledge gathered through strategically performed surveys and interviews is used to supplement the information provided by the FAF2. The surveys provide a clearer understanding of the activity of particular industries in a region and the factors that affect freight generation and attraction. Gorys et al. (1999) employed a similar approach to the industry sector method developed in this research when investigating the development of strategic freight networks in the Greater Toronto Area. Ahanotu et al. (2003) developed a simila data analysis approach in developing a freight flow database from Transerach data and employing surveys of specific industries to enhance the available data. Conversion factors to determine the number of shipments by mode that the data represents are necessary to use the FAF2 and survey data successfully.

The data in the FAF2 database is presented in a format of 114 origins and destinations, graphically depicted in Figure 2 (FAF2, 2007). Alabama is included in the database as two zones, the Birmingham area, and the rest of Alabama. The highest number of FAF2 zones in a state is five, but 14 states have just one zone. The high level of aggregation limits the usefulness of the FAF2 data for local and sub-state planning. The FPF applies a disaggregation filtering technique to produce freight requirements at the county, or Freight Analysis Zone (FAZ) level.

The freight projections by county or FAZ are then distributed into origin/destination pairs for modeling purposes. Horowitz and Farmer (1999) found that those states with a comprehensive model for statewide planning tended to utilize software originally designed for urban planning. In the FPF the distribution of the freight volume across the network is accomplished through the use of an urban planning gravity model, such as TRANPLAN. A traditional gravity model distribution can be performed using the quantity of freight, segregated by commodity, produced and attracted for each county or FAZ along with friction factor values associated with the distance the specific commodity would likely be transported.

The result of the gravity model is then arranged into an Origin/Destination (O/D) matrix for the state.

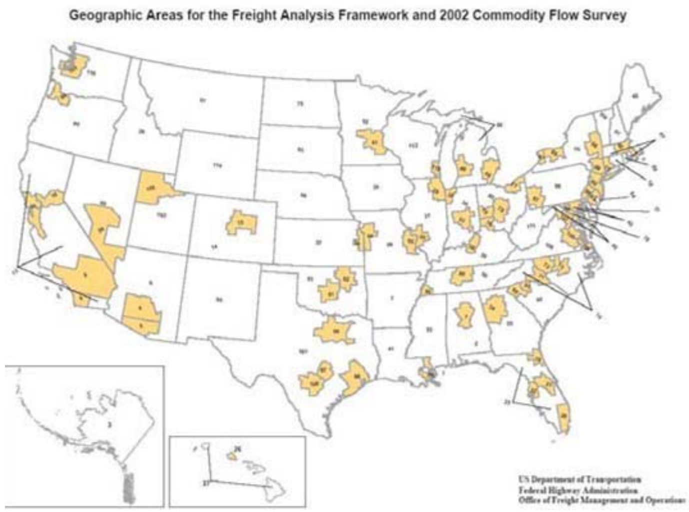

Figure 2. Geographic locations for FAF2 data.
(http://www.ops.fhwa.dot.gov/freight/freight_analysis/faf/cfs_faf_areas.htm)

The freight O/D matrix is assigned to the transportation infrastructure network developed to determine the travel paths for validation. In this fashion, it is possible to test the base year O/D patterns through a comparison of actual freight volumes on the existing infrastructure. Passenger car volume is introduced to the Interstate and highway network as a separate travel model and is produced using traditional transportation planning techniques. The freight forecast developed using projected industry clusters for the study area is routed through the gravity model to develop future year O/D patterns.

With freight volume distribution based upon the gravity distribution model, the next step is to understand how the freight distribution affects, and is affected by, the transportation network and the built in constraints of the system. This is accomplished by employing simulation resources. The tool used in the FPF is the Alabama Transportation Infrastructure Model (ATIM), developed by researchers at the University of Alabama in Huntsville. The ATIM is a discrete event simulation used to evaluate the impact of changing freight patterns in order to more accurately plan for future transportation infrastructure needs (Shar et al., 2005). The ATIM is a statewide multi-modal freight transportation model with the ability to quickly evaluate the impact of system decisions on the statewide freight transportation system including highway, rail, and water routes. The transportation network includes intermodal transfers between truck, rail, and water at the transfer points in Huntsville, Birmingham, Montgomery, and Mobile, Alabama.

The ATIM is based on the framework of the Virtual Intermodal Transportation System (VITS) model developed at the National Center for Intermodal Transportation at Mississippi State University (Tan and Bowden, 2004). The VITS was a first attempt to use discrete-event simulation to model multiple modes of transportation infrastructure in a single simulation. The ATIM expands and enhances the VITS in the manner and complexity in which it is employed to simulate the Alabama transportation network.

The result generated by the gravity distribution model is input to the ATIM through an interface designed to translate the data into the appropriate format for use in the simulation.

The coordination of gravity distribution modal networks and the modal networks within the statewide multi-modal simulation are critical for the load volumes to be accurately distributed.

The final piece of the FPF is the ability to measure the performance of the transportation system. The FPF is designed as a tool used for continuously improving the ability of the transportation system to efficiently, effectively, and safely move people and freight. Improvement cannot take place if a measurement system is not in place to quantify the performance.

There are many years of performance data that has been collected on the highway systems across the U.S. for multiple purposes. This data is point specific in nature and does not provide managers and planners of transportation systems with a measurement of how the system as a whole is performing. Metrics that accurately portray the performance of the system is a missing tool for transportation system planners and managers needed to optimize system performance.

Access to an efficient transportation system is a key element to economic growth and development within a region. It is essential that the performance measures used by Alabama be chosen with that goal in mind. It is also important to choose metrics appropriate to the needs of the intended audience: the state government, the state legislature, DOT management and staff, other agencies, elected officials, and the public at large. An optimal set of performance metrics will provide the ability to determine the impact of improvements to the transportation system performance over time, and compare the results to short-term and long-term goals and objectives.

The FPF methodology discussed here takes freight flow data at the national level and structures it in a format usable for freight planning purposes at a variety of levels. This methodology is expected to be a valuable piece of the overall transportation planning toolbox in the future. As with all new ideas, significant research is needed within each component of the FPF to ensure the final product provides value added information and data to transportation planners in Alabama and throughout the nation.

MODELS/PROGRAMS

This Framework utilizes two levels of transport models and an interface between them, written external to both programs. The integrated framework contains a combined micro- and macro-simulation, which employs the maximum abilities of both models. The macro-simulation model is used to distribute the freight trucks from origin to destination using a distance function to exchange trips and assigns the trips to the best possible roadway to minimize travel time. The micro-simulation model is used to convert the trips from daily totals into time-of-day dependent trips to allow for further analysis of queues and travel times.

TRANPLAN®/CUBE® MODEL

The travel demand model used in this work modeled freight production and attraction values at the county level and then distributed the values into origin/destination pairs for modeling purposes. A gravity model was then used to distribute the freight volumes across the transportation infrastructure network. The transportation infrastructure network follows the Interstate and primary U.S. and state highways in Alabama. In total, 5,000 miles of roadway are included in the model. There are 67 internal zones in the model, representing the each of the 67 counties in Alabama. In addition, there are 15 external locations to indicate the major freight corridors that connect Alabama with the rest of the nation. The results from the gravity model are an Origin/Destination (O/D) matrix for freight flows in Alabama. The freight O/D matrix is assigned to the transportation infrastructure network developed to determine the travel paths. An example is shown in Figure 3.

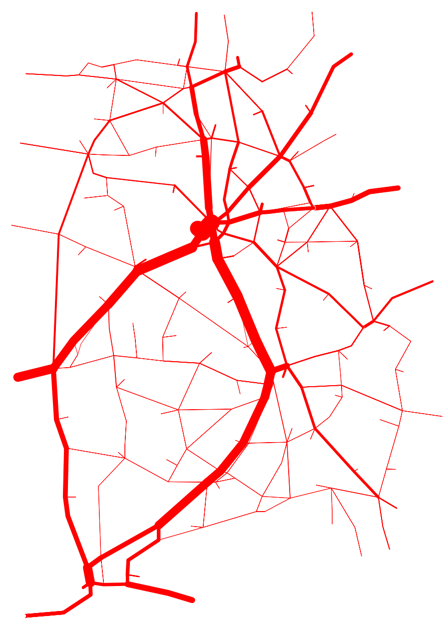

Figure 3. Output from TRANPLAN®/CUBE®, width proportional to volume

CONVERSION MODEL

The TRANPLAN®/CUBE® model output files cannot be read directly by the ATIM, which was built using ProModel® software. A data conversion model was developed using C Programming language to transfer the O/D matrix data obtained from the macro-simulation model into a format that could be used to perform the micro-simulation. The conversion program read the origin/destination values that could be obtained through the running of various utility functions provided in the TRANPLAN® software. The program then entered a value for freight traffic between each origin/destination into an EXCEL® spreadsheet formatted for input to the ATIM. Pointers in the ATIM then read the EXCEL® spreadsheet into the ATIM as an array when the program is initialized.

ALABAMA TRANSPORTATION INFRASTRUCTURE MODEL (ATIM)

The Alabama Transportation Infrastructure Model (ATIM) is a micro-simulation designed to work in conjunction with the TRANPLAN®/CUBE® model macro-simulation. The ATIM is a discrete event simulation that mirrors TRANPLAN®/CUBE® model and simulates traffic flows across Alabama's transportation infrastructure system over a twenty-four hour day. Passenger car traffic and freight truck traffic are independently calculated and used to simulate overall traffic flows. Alabama's rail and waterway infrastructure systems are also included, allowing the model to incorporate the dynamics between pair-wise modes of shipping, including truck-train, truck-barge, and barge-train. Air-to-truck transfers are not specifically modeled due to the low relative freight volumes carried by air. Instead, the truck movements initiated by airfreight are included in the truck-only movements. The ATIM is a stochastic program which incorporates the random variation inherent in transportation systems as well as the complex interactions of how freight moves over the transportation network and through intermodal connector points. Figure 4 presents a still shot of the screen display of the ATIM indicating roadways, railways and waterways in the Alabama transportation network.

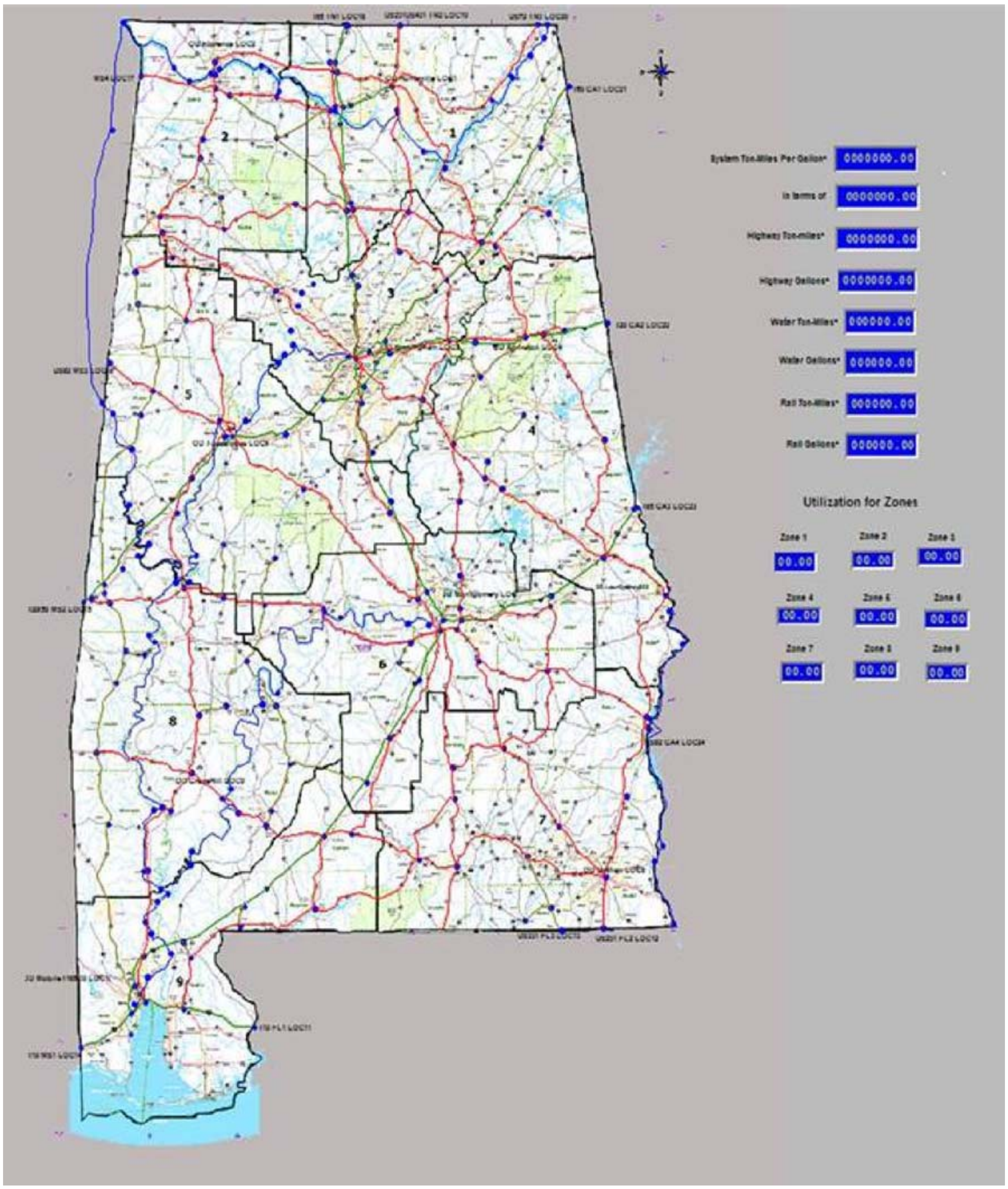

Figure 4. Screen Shot of the Alabama Transportation Infrastructure Model (ATIM)

The primary inputs to the ATIM are the truck volumes in the O/D matrix created by the TRANPLAN®/CUBE® model. These 24-hour average volumes are distributed throughout the model run according to an exponential distribution. A step function also modulates truck traffic to mirror the higher value of truck trips during the day. Truck trips are generated at each of the 82 O/D nodes (67 counties and 15 external points) and routed across Alabama infrastructure resources to their destination. For those trips originating or destined to a location outside of the state, the external border point serves as a proxy location. Passenger car traffic is loaded onto the network as a background data layer. Vehicle speeds during the model run are calculated using the BPR equation for each roadway section. To support the speed calculation, the number of passenger cars on a given section of roadway is determined by modulating the Alabama Department of Transportation traffic count data according to the time-of-day characteristics given in NCHRP 365 (Martin and McGuckin, 1998).

The ATIM provides estimates of how changes in the network or changes in utilization of network components will affect the performance of the overall transportation system. This enables effective communication of the expected performance of system investment alternatives through powerful visualization and animation presentations. Outputs of the ATIM model include travel time, truck flow volumes, congestion indicators, zone utilization, and fuel mileage (measured in system ton-miles), shown on the right side of the map in Figure 4. Additional metrics can be added based upon the specific goals of the alternative comparison under consideration.

The ATIM makes extensive use of the graphics and animation capabilities of the ProModel® software package. The simulation animation displays a background map of the state with the path networks representing interstates, US highways, state highways, rail lines, and navigable waterways overlaid onto the map (Figure 4). As the model executes, truck traffic, barge traffic, and rail traffic are shown moving between the origin and destination points throughout the state. The animation also shows counters which measure system ton-miles per gallon of fuel consumed, ton-miles and gallons of fuel consumed by each freight mode, and highway capacity utilization for each Alabama Department of Transportation planning district. Truck traffic has a secondary animation subroutine that changes the color of the truck graphic depending on the amount of congestion in the road link it is traveling on. When traffic is moving at free-flow speed, the truck graphics are green. When travel speed drops to between 60 and 80% of free-flow speed because of congestion, the truck graphic turns yellow. When travel speed drops below 60% of the free-flow speed, the truck graphic turns red. In this way, it is possible to see where congested roadways cause traffic flow to slow as the simulation progresses (Shar et al., 2005).

CONCLUSIONS

There are generally two types of models available as tools for assessing the benefits of providing transportation network and user information. The first, demand models, are regional in scope and optimize routing of trips based on destinations and network congestion. These demand models do not typically model the impacts of local network detail. Models of this type are developed as daily travel models that address system wide transportation investment or major land-use changes. The second, traffic micro-simulation models contain details over a smaller area. Traffic patterns are an input to the simulation. Combining the two types of models hold promise for evaluating systems with changing demand patterns over large areas and bring a focus to the local impact of system events (Anderson and Souleyrette, 2002).

The benefit of using both macro- and micro-simulation in the analysis of freight transportation systems is twofold: first, the macro-simulation can be employed to determine average volumes on roadway segments. This value is important for roadway planning and design to ensure that capacity is available for both current demand and future growth. The micro-simulation then brings the effects of variability of demand into the analysis. Traffic patterns are affected by driver decisions, manufacturing production and delivery times, route choices, and time of day. The combined variation created by the effect of multiple overlapping and interrelated travel distributions can cause peak traffic volumes to far exceed the calculated average demand. By providing better estimates of peak hour demand, the micro-simulation allows planners to refine their designs to make the most efficient use of limited construction budgets.

The second benefit of the combined simulation is the increased ability to effectively communicate the need for investment in transportation infrastructure to policy and lawmakers. Transportation infrastructure is a high-cost, long-term investment in the economic future of a region which may not show dramatic benefits for many years. However, without such an investment, the surrounding population will not have the ability to seek out and win projects needed to sustain continued growth and economic development. The animation and graphics capabilities provided by the micro-simulation provide a powerful tool to catch the attention of government officials and visually show the impact of their investment.

NEXT STEPS

This research is in the infancy of evolution and discovery. Freight has not been actively included as a major component of transportation planning but the time has come. Continuing to ignore freight as a major contributor to congestion and degradation of transportation infrastructure will reduce the viability of many regions to compete for new and expanding industry. It is imperative to continue to investigate, research, and develop the tools that are part of the Freight Planning Framework. Additional work in the collection and use of freight data is a key to successful planning. Continued development of the macro and micro simulation models will speed and enhance the ability to analyze options and communicate the benefits of potential solutions to stakeholders.

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