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IMPACTS-Hamilton: A GIS-Based Decision-Support Tool for Evaluating the Transportation-Related Impacts of an Aging Population

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**A GIS-Based Decision Support Tool to Study the Impact of Elderly
Population on the Transportation System in Hamilton Census
Metropolitan Area (CMA)**

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ABSTRACT

Recent advancements in computing and Geographic Information Systems (GIS) have revolutionized the development of decision support tools to study and simulate urban transportation systems. Alarmed by the increasing number of older drivers in Canadian cities, a modeling exercise was undertaken to study the impact of this population group on the transportation system in Hamilton Census Metropolitan Area (CMA). A number of demographic and travel demand models for different periods of the day were calibrated using census and traffic survey data obtained from Statistics Canada and the Joint Program In Transportation at the University of Toronto, respectively. The models were incorporated in a GIS-based decision support tool that is based on the MapObjects spatial software components. Unlike most of the existing four-stage travel demand modeling systems, the benchmark of our system is a population demographic model that predicts the spatial distribution of population by age classes. Population for the 1996 base-year is being evolved in five-year increments to evaluate the contribution of older-population to travel demand, traffic congestion and transport related pollution levels in Hamilton CMA. The developed system enables the specification of demographic and travel demand scenarios interactively via the maps and spreadsheets of its scenario dialogue boxes. It is also capable of producing both statistics and maps of population demography, travel demand, traffic congestion and automobile emissions. This paper reports on the effort to develop this stand-alone GIS-based Urban Transport Modeling System (UTMS) for Hamilton CMA.

Keywords: Elderly population, Hamilton CMA, Travel demand, Demography, Decision support tools, UTMS, GIS, MapObjects, Traffic Congestion, emissions

1. INTRODUCTION

Over the past five decades, most North American cities became progressively more dependent on the automobile. As a result, road traffic and the associated levels of tail pipe emissions and energy consumption have grown to alerting rates. This was accompanied with massive capital investments in road infrastructure, which is still a common practice in the planning of cities. Urban transport planners and practitioners sought tools to conduct cost-benefit analysis of such infrastructure investment projects. Consequently, the trip-based Urban Transportation Modeling System (UTMS) was adopted by most metropolitan planning organizations (Meyer and Miller, 2001). To date, UTMS is used, as the state of practice tool, to project future traffic and evaluate the need for new road capacity. It also plays a major role in assessing changes in transit service and land use patterns in cities around the globe. It has done so by focusing on peak-period, work related travel.

UTMS has normally ignored the contribution of older retired drivers on the urban transportation system. However, population in most developed countries is aging, which means that in coming decades there will be a significant increase in both the number and percentage of older drivers in urban areas. Statistics Canada (2002) estimates that by 2021 one in five Canadians will be at least 65 years old. Recent research for the United States, Australia and some European countries provides evidence suggesting that as people age they become more dependent on the automobile (Rosenbloom, 2001). Despite these observations, very little has been done to address the issue in the Canadian context in general and to assess scenarios on how population aging will impact the urban transportation system in particular.

This paper addresses these issues and reports the work we undertook to develop a GIS-based decision support tool, to study the impact of older population on the urban transportation system. While the approach we describe has general applicability, we focus our attention to an application for the Hamilton Census Metropolitan Area (CMA) in Canada (Figure 1). The significance of our work is threefold. First, unlike most of the existing four-stage travel demand UTMS; the foundation of the devised system is a multiregional demographic (MRD) model that is integrated with the UTMS. The MRD model ages the population over time based on vital statistics (fertility, mortality and migration trends) that are available by age and sex (Rogers, 1995). The devised MRD model is extended by a Spatial Aggregate Multinomial Logit Model (SAMNL) to perform small area projections. That is, the model will be able to update the spatial distribution of population by sex and age in the traffic analysis zones of the CMA. Second, the system is developed to predict the travel pattern by purpose (work and non-work) and for all periods of the day (morning, day, afternoon and night). Finally, the system is developed as a stand-alone GIS-based decision support tool that is based on the MapObjects spatial software components to enable interactive specification of demographic and travel demand scenarios via map and spreadsheet scenario dialogue boxes.

The model is made operational based on demographic and travel data that were obtained from Statistics Canada and the Joint Program in Transportation at the University of Toronto (JPINT), respectively. Here is a summary of the remainder of the paper. Section two starts with a background to provide an overview of the basic elements

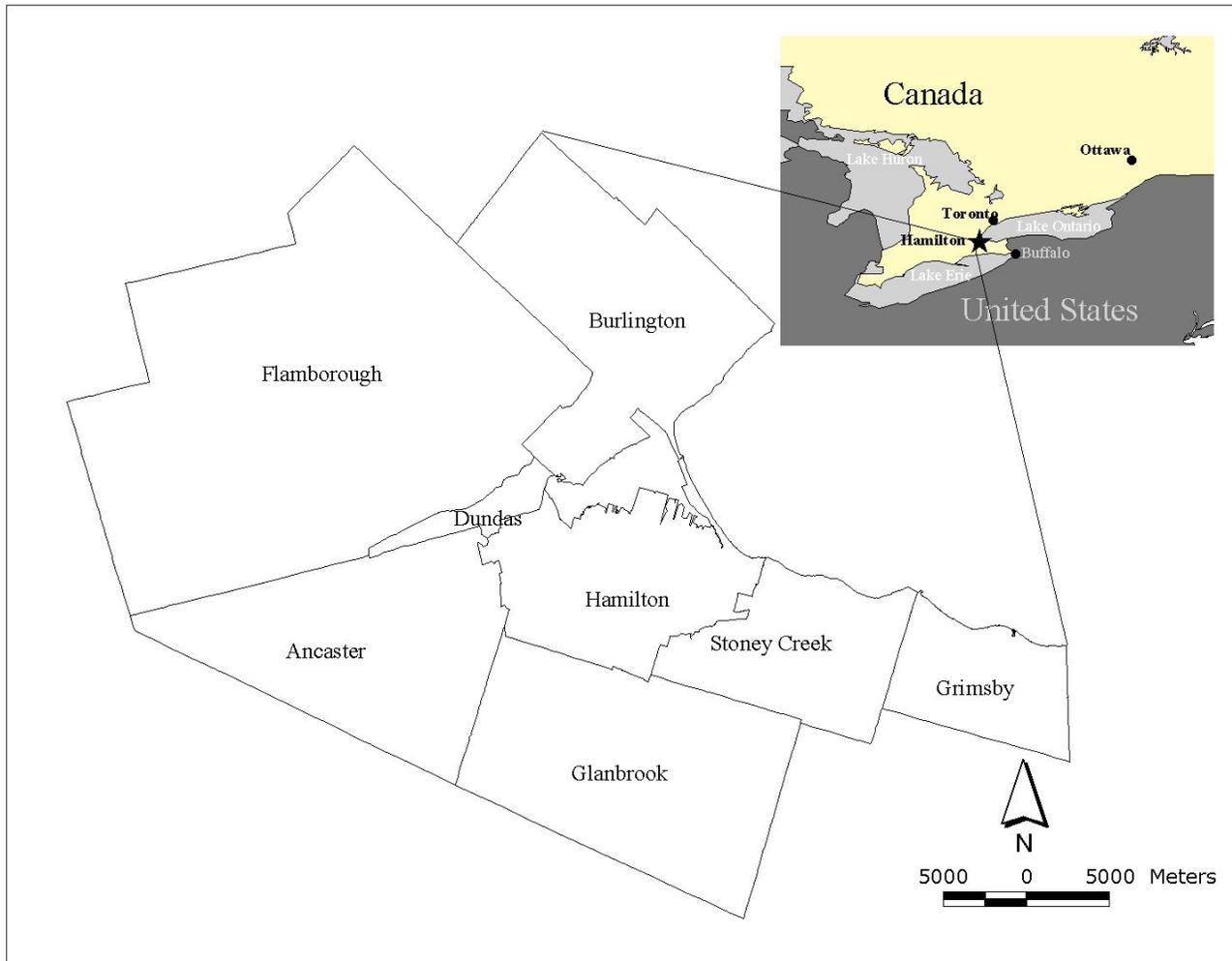


Figure 1: The Hamilton Census Metropolitan Area (CMA) in the regional context

comprising a travel demand UTMS. It also sheds light on the significant role that Geographic Information System (GIS) can offer to enhance the performance of these urban transportation-planning tools. Section three describes the general structure of the devised decision support tool and discusses in some detail the different components used in its development. Section four discusses the development environment of the system while section five provides some output results that were obtained from running simulations until the year 2051. Finally, the last section provides a conclusion of the paper.

2. BACKGROUND

Travel demand modeling continues to be one of the most important aspects of the urban transport planning process. The common practice for travel demand modeling is to use an Urban Transport Modeling System to simulate travel behavior in the city's transport network. UTMS are conceived as predictive models since their purpose is to predict the possible outcomes of alternative policies. Early versions of such models appeared in the mid- 1950s and their use became commonplace by many metropolitan areas around the world by the 1960s (Southworth, 1995). Typically, the UTMS, known also as the four-stage model, consists of four sub-models that are executed sequentially. These are: trip generation, trip distribution, modal split and traffic assignment. The model starts with an exogenous distribution of land uses, population, employment and other economic activities for a particular base year. Therefore, the UTMS makes the assumption that land use planning provides the impetus for transportation infrastructure development. This one-way relationship assumption between the land use and transportation systems is one of the main drawbacks in most of the existing UTMS. There is sufficient evidence in the literature on the two-way relationship between land use and transportation (Wegener, 2004; Kanaroglou and Scott, 2001). Despite this limitation, UTMS remains the most widely used travel demand-modeling tool.

Within an UTMS, the metropolitan area is represented with two layers of exogenous information: (1) a set of mutually exclusive zones known as Traffic Analysis Zones (TAZs), and (2) a set of connected links to represent the city's transportation network. The trip generation submodel utilize the exogenous land use information to determine the number of trips originating from each TAZ as well as the numbers of specific purpose of trips destined to each TAZ. Trip generation models are typically based on either regression models or categorical data analysis (Kanaroglou and Scott, 2001). More recently, more elaborate methods such as the ordered logit and probit models were also used to enhance the predictive ability of the trip generation models (Páez et al. 2006). The trip distribution submodel uses the information produced by the trip generation submodel to generate a set of origin-destination trip matrices by trip purpose and time of day. Gravity based spatial interaction models and multinomial logit models are usually used to formulate trip distribution models. Once the trip distribution submodel is executed, the modal split submodel accepts the purpose specific origin-destination matrices and split them by travel mode (motorized, passenger, transit, walking, etc.). The most popular econometric models used to achieve a modal split are the multinomial logit and nest logit models.

Once the modal split submodel is executed, all the motorized origin-destination trip matrices that relate to the same time of day are added up. The resulting matrix serves as input to the traffic assignment sub-model. The objective at this stage is to generate an origin-destination travel-times matrix in a congested situation on the network. Several algorithms have been developed for this purpose, including the all-or-nothing, user equilibrium and stochastic user equilibrium algorithms (Sheffi, 1985). The whole process starts with an initial origin-destination travel-times matrix that corresponds to a free flow situation. After the first pass through all the sub-models, a new set of inter-zonal travel times is estimated. Then, the trip distribution, modal split and traffic assignment sub-models are run again with this new set of inter-zonal travel time values. The iterations are repeated until the travel costs stabilize. The outcome is the number of total motorized trips on the links of the city's transport network. These trips can then be translated into a system performance indicator to reflect the congestion level on the road network. This could be achieved by comparing the assigned motorized trips on a particular link to that link's design capacity.

While the UTMS is based on the TAZ and network layers that are spatial in nature, early development in UTMS was based on non-spatial computer programs. However, recent advancements during the 1990s in computing and Geographic Information Systems (GIS) have revolutionized the development of decision support tools to study and simulate urban transportation systems. Processing speed and storage capabilities has increased at an exponential rate in the past decade. At the same time, new ideas in software engineering, such as object-oriented languages, have facilitated the maintenance and incremental development of simulation programs. The widespread use of GIS made it easier to organize and display large volumes of spatial data. GIS has also provided an excellent interface to planners to experiment and simulate scenarios without the need to be trained in modeling and programming.

Despite the advances made in GIS during the past decade and a half, a limited number of applications have emerged, which demonstrate the potential of GIS as part of the urban modeling framework. The majority of these applications adopted an encompassing framework as oppose to a modular one. The encompassing framework is based on extending the functionality of the core GIS via scripting or macro languages that are native to the GIS software. This, however, requires the UTMS to be dependent on an existing large GIS-T platform (e.g: TRANSCAD or EMME/2) even if it is only using some of the functionalities of that GIS-T. On the other hand, a modular framework leads to a stand-alone product since within this framework a set of systems are linked together to fulfill the objective of utilizing specific functions such as mapping to visualize spatial information and graphical user interface to define input to the system and summarize output after the simulations.

An example of the later is the utilization of the MapObjects spatial software components (ESRI, 1996) within the Visual C++ programming language to develop the IMULATE integrated urban land use and transportation model (Buliung et al, 2005). IMULATE has been developed since 1994 to study urban problems that relate to land use and transportation in the Hamilton CMA (Anderson et al., 1996; Scott et al., 1997; Kanaroglou and South, 1999). While each of the two frameworks has its own advantages and disadvantages, a major benefit of adopting an encompassing framework is to avoid carrying around the overhead of a large GIS-T (Buliung et al., 2005). Consequently, the

development of our UTMS model will be based on a modular framework similar to the one used to develop IMULATE. Such initiative is deemed innovative and cost-effective, since it will re-use many of the GIS-T functionalities already developed and built in IMULATE. These include mapping functionalities, interactive scenario dialogue boxes, shortest path and traffic assignment routines and graphical output summaries.

3. MODEL ARCHITECTURE

The developed decision support tool aims at quantifying over time the likely impacts of an expanding older population coupled with its increased automobility on the Hamilton's CMA urban environment. At the heart of the devised tool is an UTMS that will allow us to analyze and model the travel behavior of older Canadians residing in the Hamilton CMA. Unlike most of the existing UTMS, the foundation of our system is a demographic model that predicts the spatial distribution of population by age and sex in the TAZ of the study area. Population for the 1996 base-year is being evolved in five-year increments to evaluate the contribution of the elderly cohort to travel demand, traffic congestion and transport related pollution levels in the Hamilton CMA.

Figure 2 presents the architecture of the model, which consists of the following three interlinked modules: (1) demographic, (2) transportation and (3) environmental. The two layers representing the CMA consist of a TAZ layer that is based on the 1996 census tract divisions and road network layer. The devised system has 163 TAZ, 1542 links and 1183 nodes.

The demographic module consists of two sub-modules: (1) Rogers' Multi-regional Demographic (MRD) Model (Rogers, 1995) and (2) Spatial Aggregate Multinomial Logit Model (SAMNL) (Kanaroglou and Ferguson, 1996; Ferguson and Kanaroglou, 1997). The sequence of operation starts by executing MRD model to simulate the change in the age pyramid of the CMA's municipal population. This change is modeled as a function of the inter-municipal migration and death rates by age and sex as well as the fertility rates of Canadian females. Next, SAMNL model is executed to allocate the predicted municipal population to the census tracts in the CMA. The allocation procedure makes use of a logit-based formula, which predicts the probability of choosing zone i from the set of zones of a given municipality M , by migrant n who moved to M . The utility of the logit model reflects individual characteristics, such as age and gender, and zone attributes, like the level of accessibility in the zone, the number of new dwellings, rent value and the distribution of land uses in the zone.

The transportation module is based on the four-stage model discussed in the previous section. However, to achieve our objective, we model work and non-work trips that are made by two cohorts: (1) all driving population (age > 15) and (2) the adult driving population (age between 15 and 64) during a typical day. The difference in the output from the two cohorts will provide the contribution of the elderly population (age 65+). Therefore, a number of trip generation, distribution and modal split models by purpose for the two cohorts were estimated for the morning (6am – 9am), day (9am – 4pm), afternoon (4pm – 7pm) and night (7pm – 6 am) periods.

Generated trips are predicted with ordered probit models, which appeared to be more theoretically consistent and provide more robust outcomes when compared to

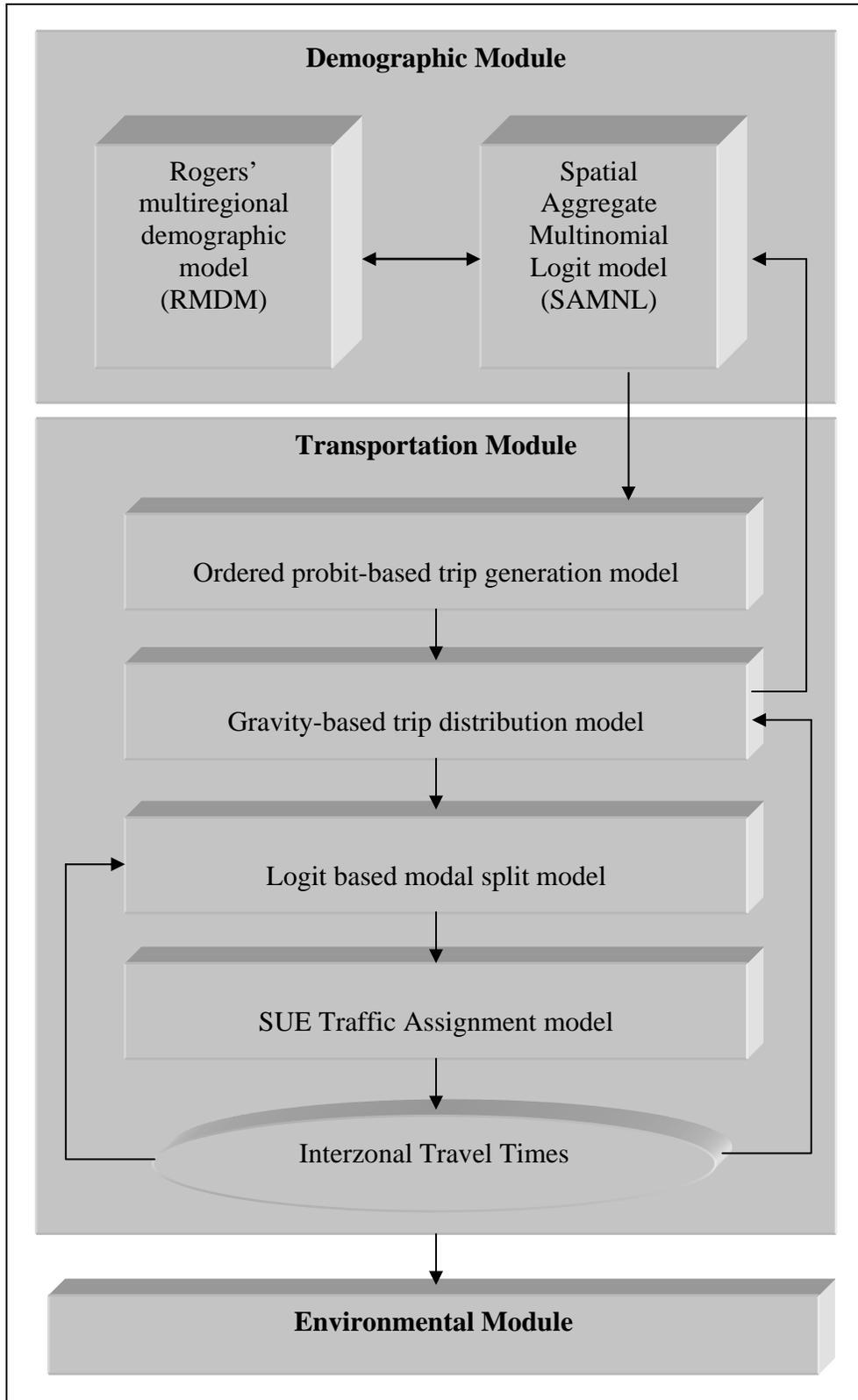


Figure 2: Model General Structure

multivariate regression-based models. The generation submodule accepts the information produced by the demographic module and employs it to predict the generated trips. The trip distribution submodule is based on production constraint gravity models, which predict work and non-work origin-destination (OD) trip matrices for the modeled cohorts in the four time periods. Trips that originate in a certain census tract, as provided by the trip generation models, are allocated to other census tracts in proportion to the inverse of a function of impedance cost that separates the origin from its destinations. In our setting, we use interzonal congested travel time to reflect the separation cost between the different census tract pairs.

Initially, the model starts with a free flow interzonal travel times matrix to generate OD trip matrices. The modal split submodule accepts the trip distribution information and splits it by mode to identify motorized work and non-work trips in a given period of the day. Those are then added to generate the total motorized trips that are then assigned to the network via the traffic assignment routine. The assignment is performed using a free flow travel times matrix to estimate a new set of travel times in a congested situation. Then, the trip distribution, modal split and traffic assignment sub-modules are run again with this new set of inter-zonal travel time values. The iterations are repeated until the travel costs stabilize. The result is link flows for all the population as well as the adult drivers. The difference between those two measures is the contribution of elderly drivers to the total flow on the network.

The environmental module uses link flows and average speeds from the traffic assignment to provide estimates for CO, HC and NO_x pollutants on each link. It also generates the total energy consumed per link. Average link speed is calculated from the link congested travel time that the traffic assignment produces. Link emissions are estimated after matching the MOBILE5.C emission factors to estimates of link average speed and adjusting by link volumes. Energy consumption, on the other hand, is calculated with a formula that relates the amount of fuel consumption (in liters) to the total flow and average congested speed on the link. The parameters of the fuel consumption model are the same as those employed in a study of transportation emissions and energy by the City of Toronto Planning and Development Department (Cheng and Stewart, 1992).

4. DEVELOPMENT ENVIRONMENT

The development of the devised system follows a modular approach that integrates components from different technologies as shown in Figure 3. The demographic modules are programmed in the GAUSS language. The choice of this computing technology facilitates the programming of the system since most of the mathematical operations in the demographic submodule involve matrix algebra. On the other hand, the components of the UTMS submodule were programmed in C++. This includes the traffic assignment and shortest path submodules. As a result, the develop system is a stand-alone GIS-T package and does not rely on EMME/2 or TransCad to perform the traffic assignment. Currently, the Stochastic User Equilibrium (SUE) traffic assignment routine converges after 11 iterations in approximately 77 seconds when

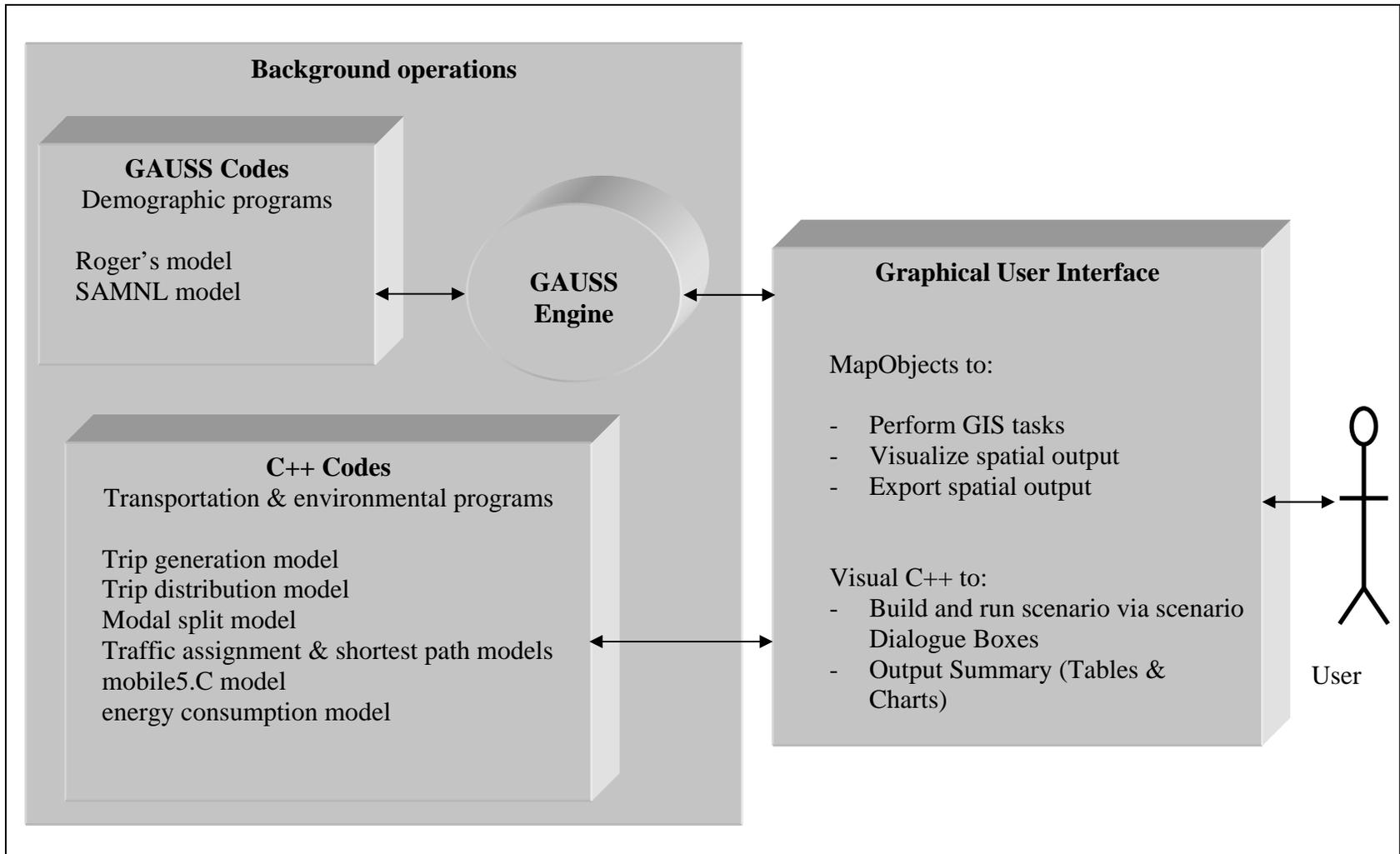


Figure 3: Modular Framework

applied to the Hamilton transportation network. This level of performance can be achieved on a workstation with a Xeon 2.0GHz processor.

The developed platform is supported with windows Graphical User Interface (GUI) that is based on the MapObjects spatial software components and Visual C++. MapObjects are software components that enable developers to incorporate mapping or spatial data handling capabilities into applications (ESRI, 1996). Therefore, the user can manipulate, manage and analyze spatial and non-spatial information using familiar GIS and windows controls through the application. Visual C++ provides a set of GUI dialogue boxes and enables the user to devise a certain scenario interactively via maps and spreadsheets. The program creates a set of internal rules to reflect the components of the defined scenario. Once a scenario is devised, the Visual C++ program applies the rules to the systems' database and stores the information in a format acceptable by the GAUSS and C++ routines. When the user executes a scenario, Visual C++ communicates with the GAUSS code through the GAUSS engine (see Figure 3). The GAUSS Engine is a dynamic library that enables the Visual C++ application to communicate with the GAUSS codes of the different submodules. On the other hand, the transportation component is executed directly depending on the sequence of operation described in Figure 2. When the system converges, all the output information is updated in the system's database.

The output from simulating a scenario is accessible through an intuitive GIS-based or map-driven GUI. The interface consists of a number of standard windows and additional controls that are commonly found in desktop GIS software like ArcView3.3 or ArcGIS 9.0. Users are able to view, query and manipulate spatial and attribute data interactively via an onscreen map. The system provides summary statistics in charts and tables for the most critical indicators by cohort. The next section provides an illustration of the output from the developed system.

5. SIMULATION OUTPUTS

The developed system is called IMPACT-Hamilton, where IMPACT stands for "Integrated Model for Population Aging Consequences on Transportation". It is capable of simulating demographic and transportation related scenarios between 1996 and 2051, in five-year increments. IMPACT allows the user to retrieve two types of outputs once a simulation is completed: (1) spatial output that reflect link and census tract based outputs, as shown in Figures 4, 5 and 6, and (2) system wide aggregates that can be provided by cohort, period of the day and simulation period. The system provides an array of output figures that could be used in the analysis of the simulated scenario. Figure 7 provides a good illustration of those system wide outputs. Further more, the model provides system wide demographic projections that describe how the population ages and evolves over time, as shown in Figure 8. Finally, IMPACT produces trends over time charts to allow the user to view the emergences of demographics, travel patterns, emissions and energy consumption over time. Figures 9 and 10 illustrate the change in population size for adults and elderly as well as the amount of Vehicle Kilometers Traveled by the elderly in the Hamilton CMA between 1996 and 2051.

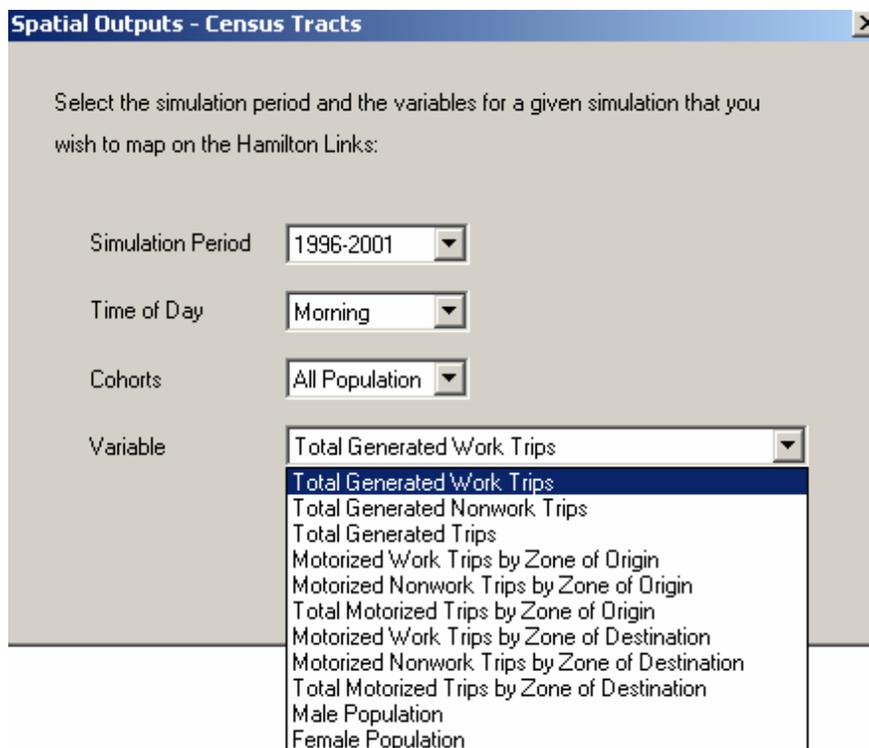
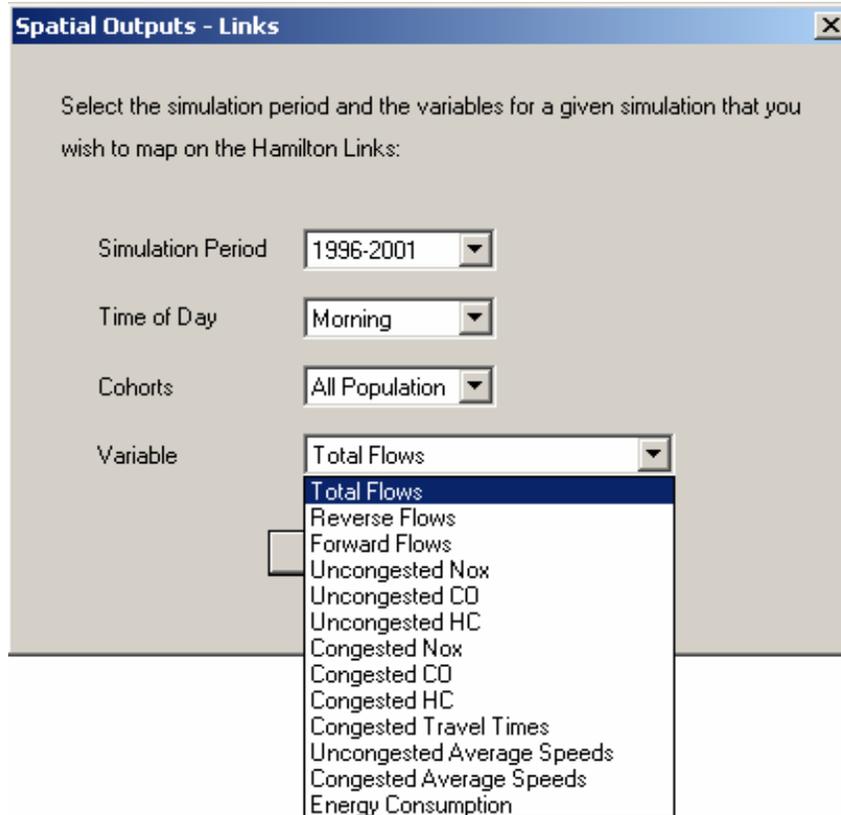


Figure 4: List of link and census tract spatial outputs

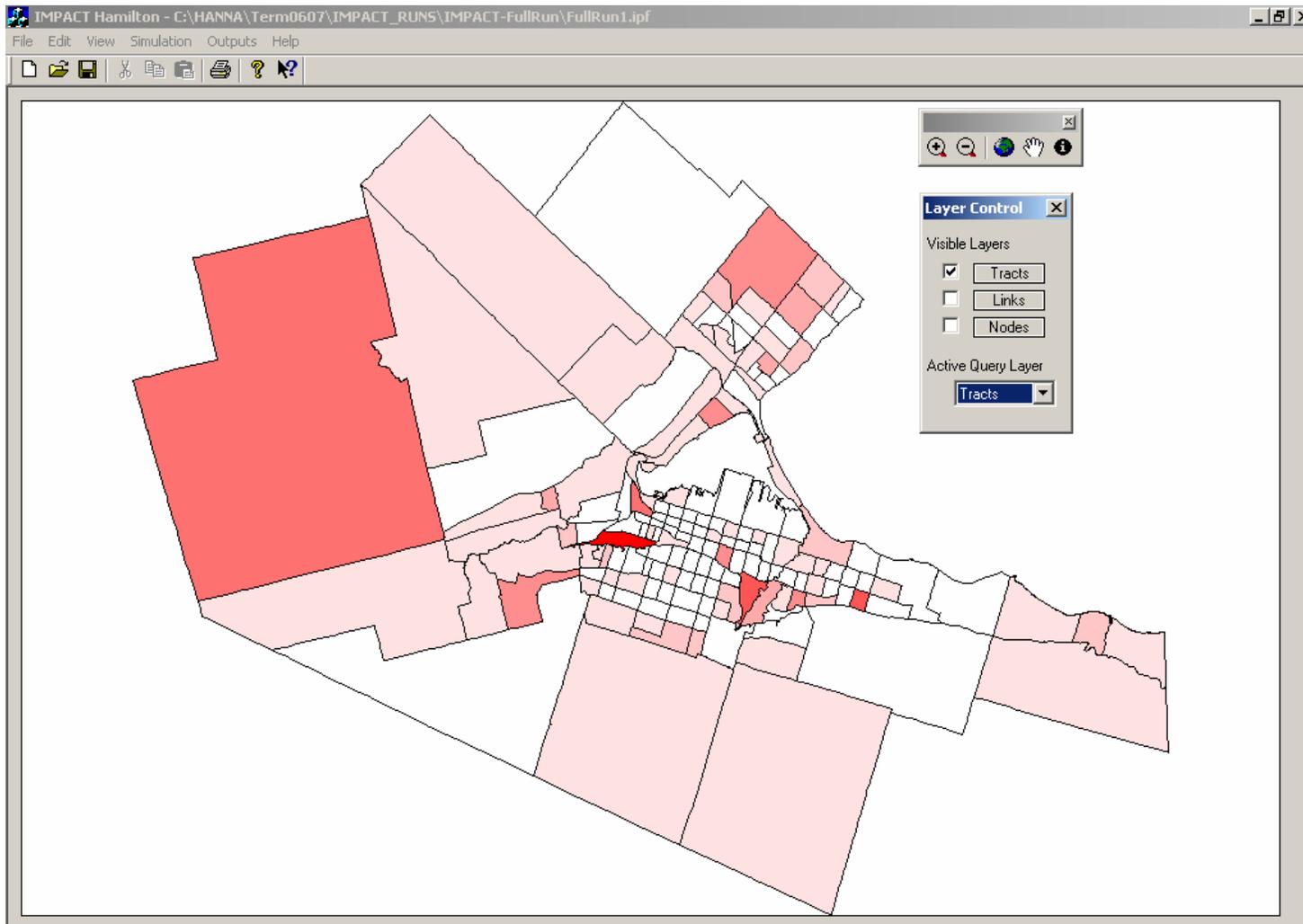


Figure 5: Spatial output by census tract (e.g. total generated trips by elderly in the morning, 2031– 2036)

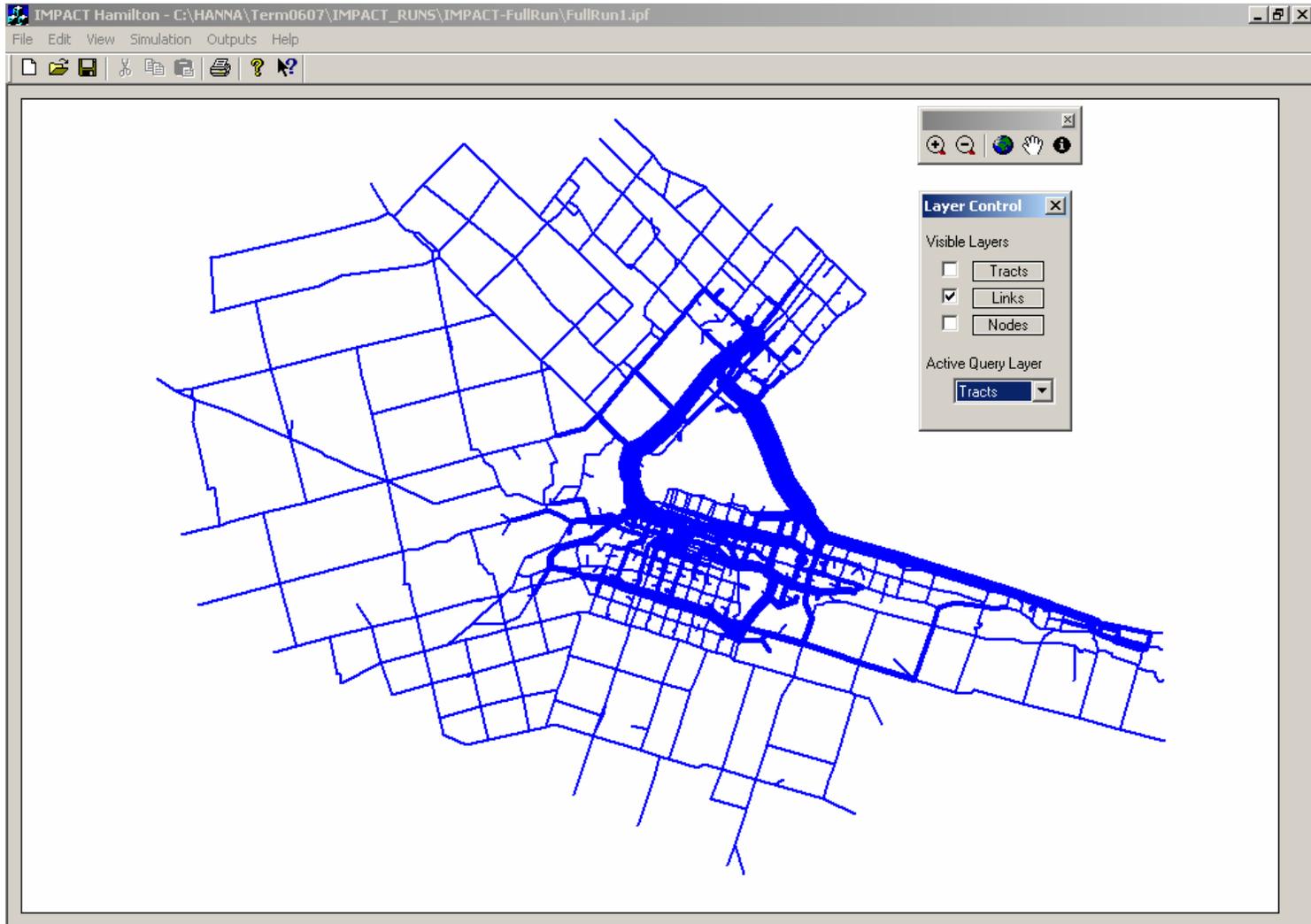


Figure 6: Spatial output by link (e.g: total flow by all population, 2046 – 2051)

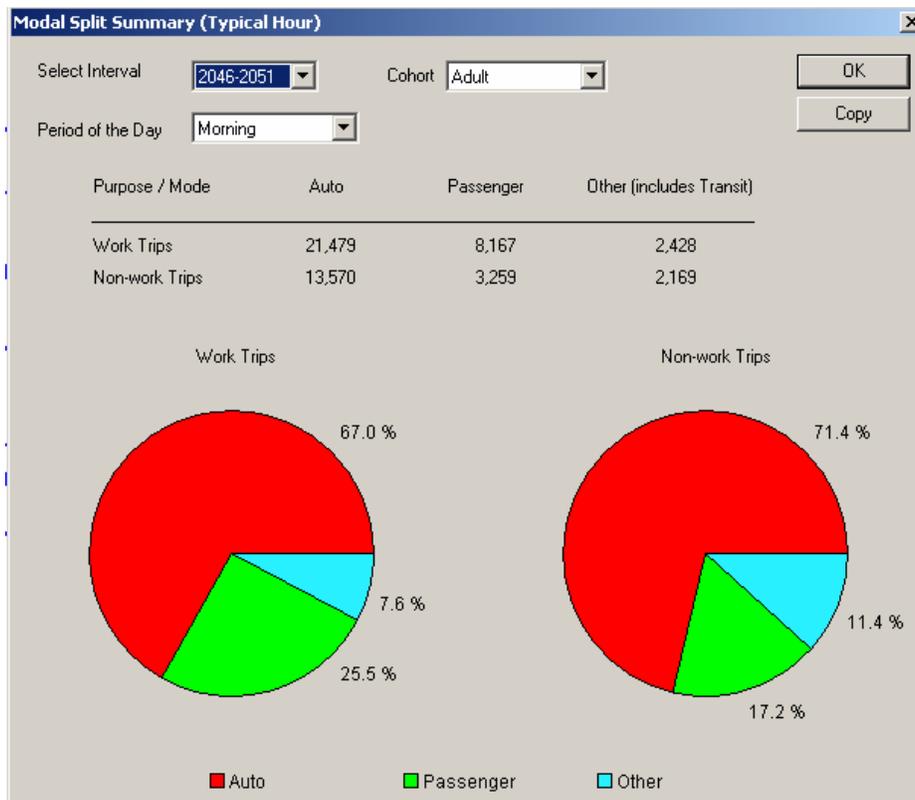
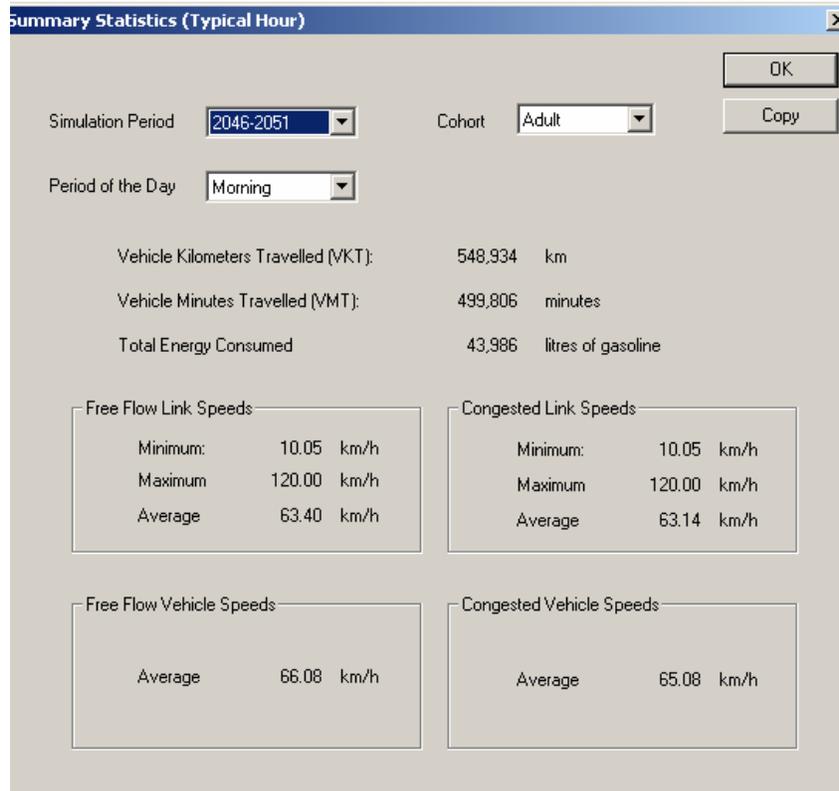


Figure 7: System Wide Summary Statistics

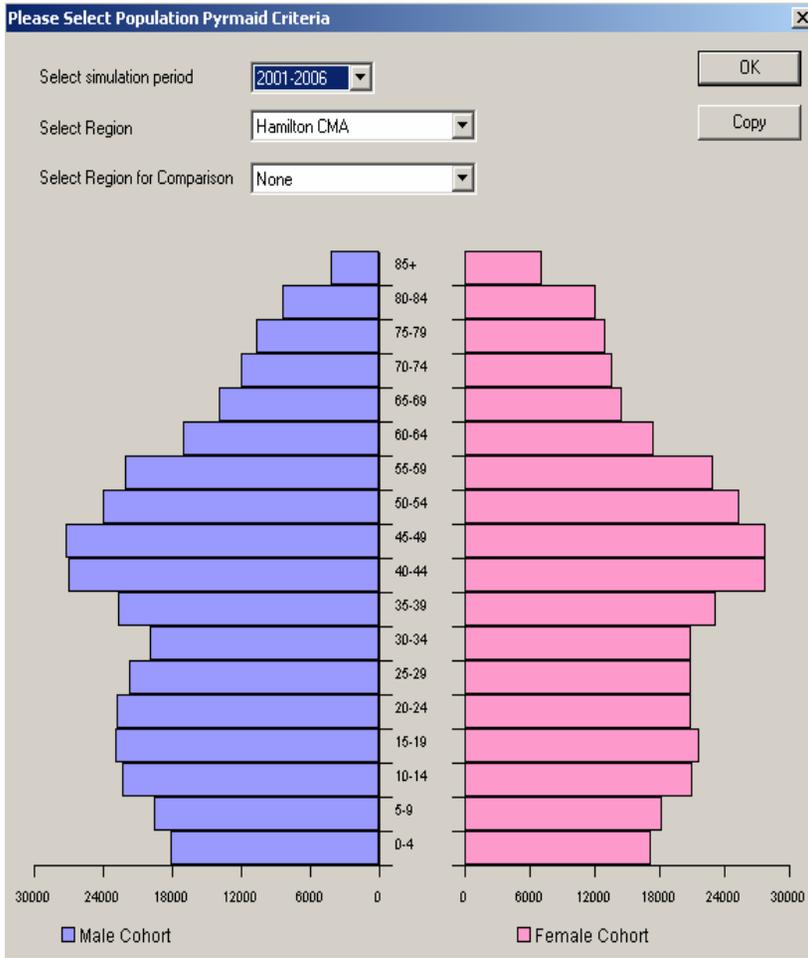


Figure 8: Population Pyramids, 2001 – 2006 and 2031 – 2036

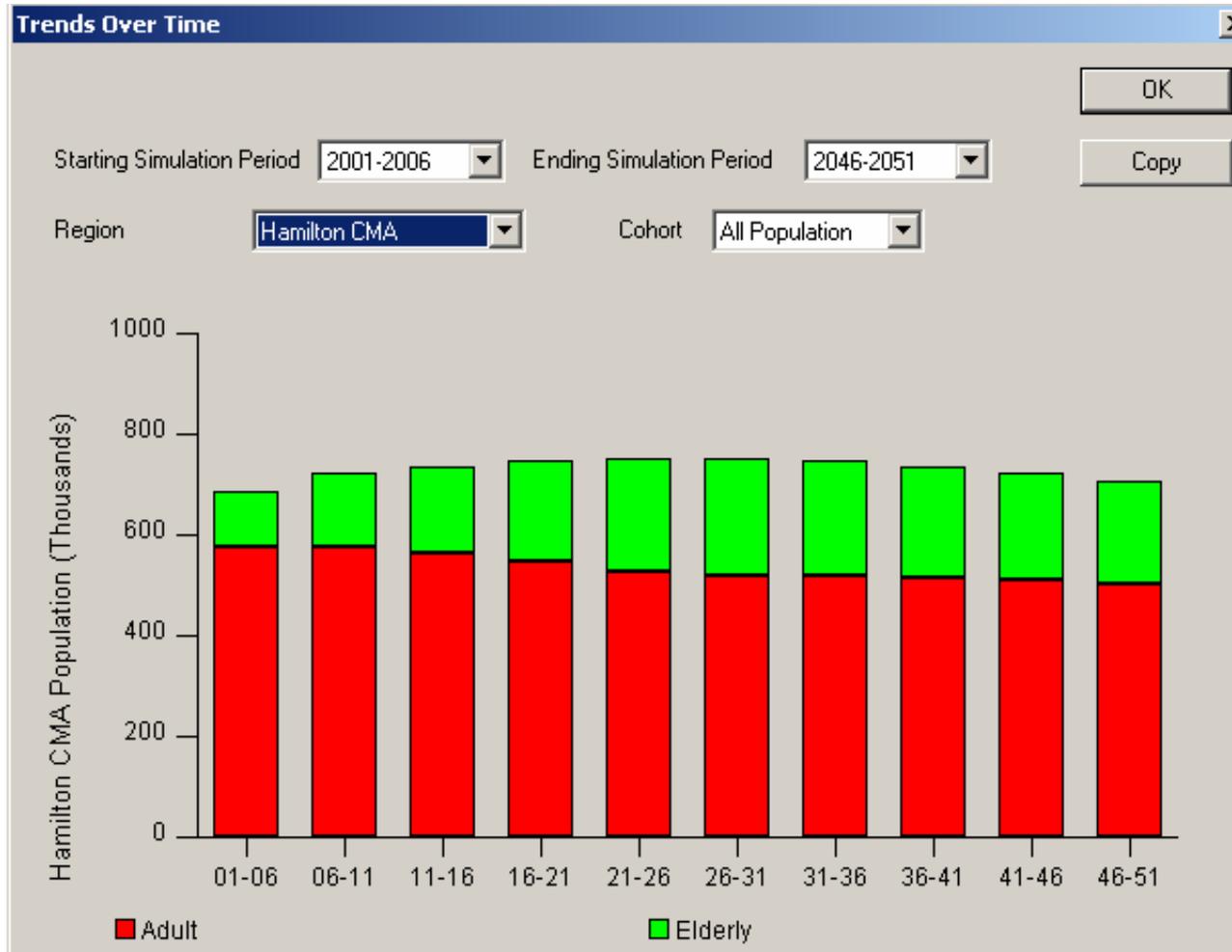


Figure 9: Projected Population in the Hamilton CMA, 2001 – 2051

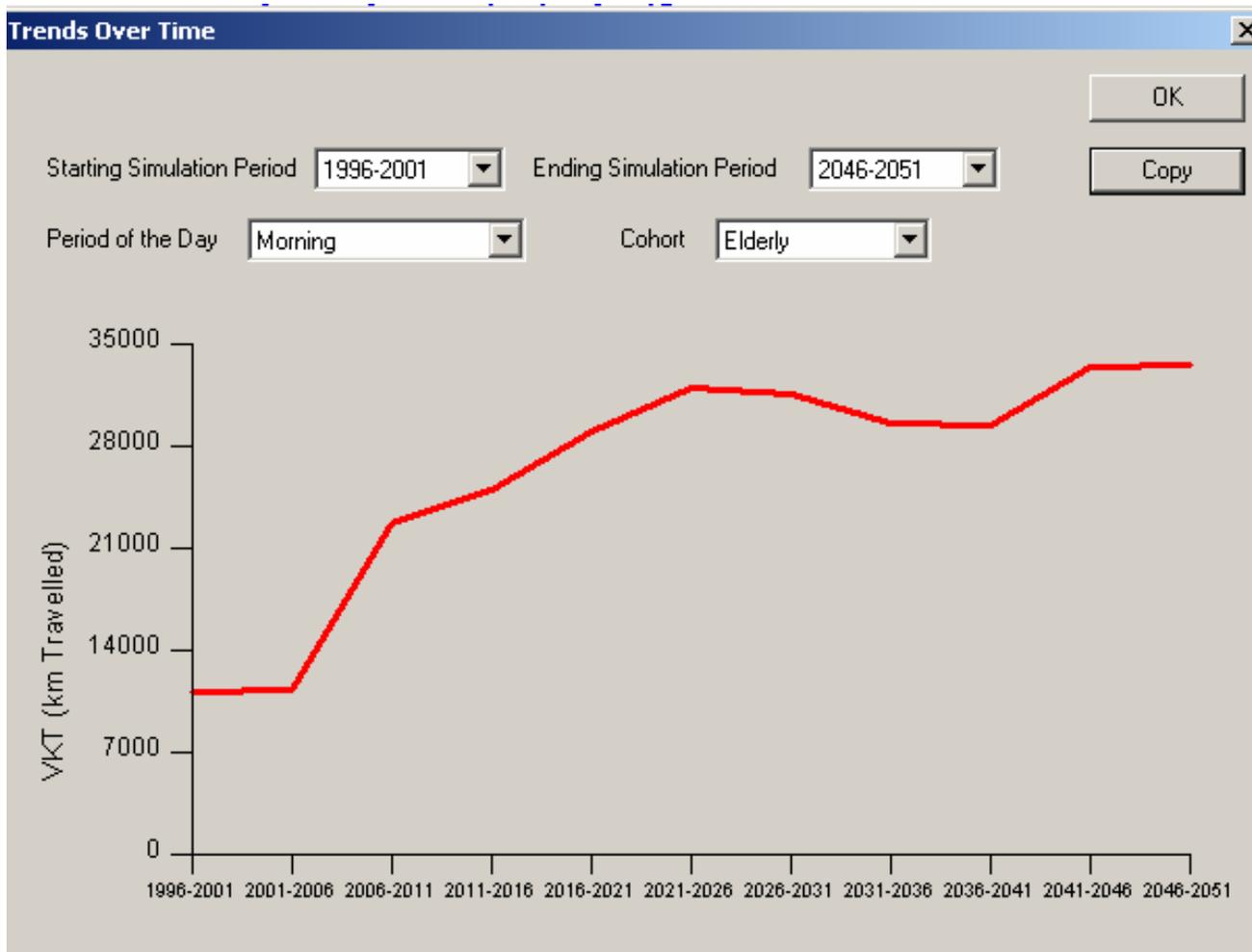


Figure 10: Vehicle Kilometers Traveled by the Elderly population in the morning, 2001 – 2051

6. CONCLUSION

This paper reported on the work we are conducting to develop a GIS-based decision support tool (DST) to study the impact of elderly population on the transportation system in the Hamilton CMA. In recent years, advancements made in geomatics have revolutionized the development of spatial software. For instance, tools like MapObjects allow the development of efficient spatially oriented decision support tools, by offering a wide range of functionalities to manipulate and analyze spatial data without the need to rely on a commercial GIS platform.

An innovative and cost-effective approach has been adopted to develop the DST. We re-used many of the functionalities already built in the IMULATE urban land use and transportation model (Buliung et al., 2005). The result is a simulation model with an intuitive GIS-based graphical user interface that is built using MapObjects and Visual C++.

The developed tool will help us to conduct research that will advance our knowledge on the likely impacts of an expanding older population coupled with its increased automobility on the Hamilton's CMA urban environment. The system also serves as a prototype that can be followed in studying similar demographic and transportation processes in other Canadian cities.

REFERENCE

Anderson, W., Kanaroglou, P. Miller, E. and Buliung, R.. (1996) Simulating automobile emissions in an integrated urban model, *Transportation Research Record*, 1520: 71-80.

Buliung, R., Kanaroglou, P. and Maoh, H. (2005) "GIS, Objects and Integrated Urban Models" In: *The Behavioral Foundations of Integrated Land use and Transportation Models*, eds. M. Lee-Gosselin and S. Doherty, Amsterdam, Elsevier.

Cheng, W. and Stewart, G. (1992) Incorporation of a Transportation/Pollutant Model within the EMME/2 Framework" presented at the 7th Annual EMME/2 International Users Conference, Vancouver.

ESRI (1996). *Building Applications with MapObjects*, Environmental Systems Research Institute, Redlands CA.

Ferguson, M. and Kanaroglou, P. (1997) An empirical evaluation of the aggregated spatial choice model, *International Regional Science Review* 20(1&2): 53-65.

Kanaroglou, P. and Ferguson, M. (1996) Discrete spatial choice models for aggregate destinations, *Journal of Regional Science* 36: 271-290.

Kanaroglou, P. and Scott, D. (2001) Integrated urban transportation and land-use models for policy analysis, in M. Dijst (eds.) *Governing Cities on the Move: Functional and Management Perspectives on Transformations of Urban Infrastructure in European Agglomerations.*, Ashgate, pp. 43-75.

Kanaroglou, P. and South, R. (1999) Can urban form affect transportation energy use and emissions? An analysis of potential growth patterns for the Hamilton Census Metropolitan Area, *Energy Study Reviews*, 9: 22-40.

Meyer, M. and Miller, E. (2001) *Urban Transportation Planning: A Decision-Oriented Approach*, Second Edition. New York: McGraw-Hill.

Paez, A., Scott, D., Potoglou, D., Kanaroglou, P. and Newbold, B. (2006) *Elderly Mobility: Demographic and Spatial Analysis of Trip Making in the Hamilton, CMA*. Accepted for publication in *Urban Studies*

Rogers, A. (1995) *Multiregional Demography: Principles, Methods and Extensions*. New York: Wiley.

Rosenbloom, S. (2001) Sustainability and automobility among the elderly: An international assessment. *Transportation*, 28: 375-408.

Scott, D., Kanaroglou, P. and Anderson, W. (1997) Impacts of commuting efficiency on congestion and emissions: a case of the Hamilton CMA, Canada, *Transportation Research Part D*, 2: 245-257.

Sheffi, Y. (1985) *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Prentice-Hall Inc., New Jersey.

Southworth, F. (1995) A technical review of urban land use-transportation models as tools for evaluating vehicle travel reduction strategies, ORNL-6881, The Office of Environmental Analysis and Sustainable Development, U. S. Department of Energy.

Statistics Canada (2001) *General Social Survey: An Overview*. Catalogue Number: 89F0115XIE. Statistics Canada (2002)

Wegener, M. (2004). Overview of land use transport models. In: *Handbook of transport geography and spatial systems* (Eds, Hensher, D., Button, K., Haynes, K. and Stopher, P.), Elsevier, pp. 127-146.

Hensher, K. Button, K. Haynes and P. Stopher (eds.) *Handbook of transport geography and spatial systems*, Amsterdam: Elsevier, pp. 127-146.