# Energy and Urban Form: Special Feature

# Can Urban Form Affect Transportation Energy Use and Emissions?

## *An Analysis of Potential Growth Patterns for the Hamilton Census Metropolitan Area*

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*The debate on the type of urban form that is the most efficient with respect to transportation energy consumption and the associated pollutant emissions has produced ambiguous results. This paper contributes to the debate through an analysis of the efficiency of simulated urban forms for the time period 1991-2021 with the help of IMULATE, an Integrated Transportation and Land Use Model for the Hamilton Census Metropolitan Area. The urban forms analysed are obtained by varying the spatial distribution of the projected household growth in the region. The status quo is compared to a compact urban form and to two multi nucleated forms. The results, albeit ambiguous, demonstrate that the way future scenarios are developed can have a significant impact on inferences drawn from such studies.*

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1. INTRODUCTION

The transportation sector is a major source of harmful emissions contributing to the deterioration of air quality in urban areas. It is also a major consumer of fossil fuels and generator of greenhouse gas. Unlike stationary emission sources, such as industry and the residential and commercial sectors, emissions from mobile sources are difficult to observe and measure. Research indicates that although over the last two decades technological improvements have reduced significantly emissions per Vehicle/Kilometre Travelled (VKT), overall emissions are on the rise because of increases in VKTs. This is primarily because of the rising prominence of discretionary trips relative to work trips. Furthermore, the longer and more frequent automobile trips lead to congestion in urban highways, which is directly associated with higher level of emissions per VKT (Anderson et. al., 1996)

Increase in VKT has been linked, among other things, to the spatial arrangement of interacting activities in urban areas. Environmental buzzwords and catch-phrases, such as holistic and sustainable development, have now become common in the urban literature. The recent growth of this research focus has led to the inevitable fusion of issues that had formerly been studied in isolation. Two research areas that have recently been linked together, via their common focus on the issue of sustainable development, are urban form and the emissions and energy consumption of automobiles (Breheny, 1992, 138).

An issue that has been debated extensively within the urban form-transportation literature is whether the spatial arrangement of activities within an urban area has a large impact on the levels of pollutants emitted and energy consumed by private automobiles. Research on this issue consists of either empirical studies, which are based on direct observations, or of simulation studies that project the impacts of several hypothetical growth patterns and policy initiatives for a given urban area. The results of these studies have been mixed, rendering any relationship between urban form and transportation emissions highly ambiguous.

The research presented in this paper contributes to the urban form-transportation literature in two ways. First, we add to the debate by presenting the results of a simulation study designed to project the effect of four alternative growth strategies on automobile emissions and energy consumption. These results were obtained with the use of an urban simulation model developed for the Hamilton Census Metropolitan Area (CMA) (see Figure 1). Second, we demonstrate that the way in which a particular scenario is defined can alter the simulation results significantly. Suggestions for dealing with this problem are also addressed. It is important to emphasize here that although the scenarios being modelled represent hypothetical growth patterns, we try to ensure that they are feasible. Political or economic feasibility, however, of the most efficient scenarios is not examined.

The remainder of the paper is organised into four sections. The next section provides a review of the literature and debate surrounding the issue of urban form and automobile energy use and emissions. Then we discuss our analytical approach and describe of the urban simulation model employed in this analysis. We then describe the four scenarios, or hypothetical growth patterns, that are simulated, outline their data requirements and present their results. Lastly, we offer some concluding remarks and directions for future research.

## 2. THE URBAN FORM-TRANSPORTATION RELATIONSHIP: A REVIEW

The spatial organisation of urban land uses (i.e., urban form) and the nature of the intra-urban transportation system have both changed significantly over time, particularly in North American cities. The evolution of transportation and land use has been symbiotic: urban form has a large impact on transportation network performance and vice versa (Kelly, 1994, 137). As a result, any discussion that focuses on the spatial and temporal evolution of urban areas would be incomplete if it did not also discuss the development of the urban transportation system.

In the 1800s, cities were characterised by high densities and mixed land uses. Evidence of this is provided by Lewis who, in a study of residential and employment locations in Montreal between 1861 and 1901, found that workers, constrained to walking as the predominant mode of travel, were inclined to live close to their place of employment (Lewis, 1991, 144-146). In the late-1800s and early-1900s, the onset of public transportation, such as cable cars, allowed for greater separation between land uses (Anderson *et al.*, 1996, 12; Olson, 1991, 251). As a result, cities became more dispersed and urban land became more segregated (e.g., commercial, industrial and residential zones). The process of rapid suburbanisation in North American cities, a well documented phenomenon, did not begin until the 1950s (e.g., Bourne, 1991; Yeates, 1990). The substantial growth that has occurred in the outlying regions of urban areas since the 1950s can be attributed to a number of factors, including a general increase in the affluence of the population, the cost of land in peripheral areas and a desire for low-density housing. However, the single most important determinant of the 'urban sprawl' phenomenon was society's universal acceptance of the private automobile as the preferred mode of travel (Carley, 1992; Wegener, 1995, 1). With the private automobile being a highly flexible and fast mode of travel, the need for a close spatial association between complementary land uses declined.

Although suburban residential developments offer several benefits, such as quiet neighbourhoods and larger homes and lots, the outward and exclusionary growth associated with these areas has several negative repercussions. These include increases in the number and length of automobile trips, congestion, noise pollution, automobile energy consumption and emissions, and the permanent transformation of natural and farmland to urban use (Carley, 1992, 207; Wegener, 1995, 1). Olson (1991, 253) argues that the dispersion and separation of activities in an urban area lead to an increase in its metabolic rate due to the fact that "... continuous inputs of energy are required to cover the greater distances". As a result, dispersed settlements with a high degree of separation between different activities consume greater amounts of energy and generate more waste (i.e., emissions). This problem is particularly acute in Canadian cities as approximately 50% of the energy used by the average Canadian household is expended while driving an automobile (Olson, 1991, 254).

Research indicates that improvements in transportation technology can have a dramatic impact in reducing automobile fuel consumption and emissions (Kanaroglou and Anderson, 1997). It has been argued, however, that technological fixes alone will not be sufficient for reaching levels of emissions that are deemed sustainable (Carley, 1992, 208). Improvements in technology must be supported by changes in human behaviour (i.e., reduced use of the private automobile) and government policy initiatives (e.g., development of efficient public transportation, fuel taxes, land use planning) that facilitate this behavioural change. One strategy advocated by urban researchers and planners is the reorganisation of urban activities such that the structure of modern cities more closely resembles that of 19th-century cities (i.e., higher densities and mixed land uses).

While there is consensus that, other things being equal, dispersed settlements consume more energy than compact ones, the same level of unanimity does not exist with respect to the particular urban form[1] (e.g., concentric, radial, multi-nucleated) that is the most efficient at decreasing the levels of energy use and emissions. Anderson *et al.* (1996) and Breheny (1992) provide comprehensive reviews of studies addressing these issues. Depending on their methodological approach these studies can be classified as either empirical or simulation.

Perhaps the best known empirical study of urban form / transportation relations is by Newman and Kenworthy (1989) whose cross-sectional analysis of 32 world cities, 10 of which are in the United States, shows a strong relationship between energy consumption and population and employment densities. The remedy they propose is to encourage urban areas to implement development strategies that focus on the reurbanisation of established areas instead of continuing to expand into peripheral regions. This strategy, in turn, will facilitate the development of efficient transit systems and promote non-motorised forms of commuting.

Gordon and Richardson (1989, 342-343) are sceptical of the results and suggestions of Newman and Kenworthy. They present data which show that commuting times are shorter in decentralised cities. This relationship, they suggest, is the direct result of the considerable amount of commuting that takes place between and within suburbs, which reduces congestion on roads that lead to the city centre. They advocate the development of multi-nucleated cities and the implementation of a fuel tax as more practical strategies than those proposed by Newman and Kenworthy. Gordon *et al.* (1991, 418) provide support to these arguments by demonstrating that average commuting times in 18 of the 20 largest American cities decreased between 1980 and 1985. This finding, they suggest, confirms that firms and commuters are making locational adjustments that are resulting in shorter work trips and less congestion. Thus, they call for municipal governments to facilitate the decentralisation process by loosening restrictions on land use (e.g., zoning by-laws).

Banister *et al.* (1997) and Cervero (1996) both present results that support the arguments of Newman and Kenworthy. Banister *et al.* (1997) analyse the energy efficiency of six urban settlements of varying sizes in the United Kingdom and the Netherlands. Cervero (1996) analyses data

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[1] Types of urban form include concentric, with a single, central commercial district; multi-nucleated, with several commercial nodes scattered throughout the metropolitan area; and radial with development concentrated along transport corridors extending from the centre.

for households in eleven American cities in order to determine the relationship between land use organisation at the neighbourhood level (i.e., mixed/segregated) and the commuting patterns of neighbourhood households. Banister *et al.* (1997) show that higher densities and mixed land uses can both lead to decreases in energy use, while Cervero (1996) demonstrates that the likelihood of non-motorised commuting increases with higher urban densities and the presence of non-residential activities in a given neighbourhood.

Additional evidence has been generated using urban simulation models.[2] Two of the most notable studies are those presented in Rickaby (1987; 1991) and Wegener (1995). The study conducted by Rickaby (1987; 1991) involved the creation of a fictitious 'archetypal' city by combining data that were collected for twenty British cities. Using an urban simulation model called TRANUS (see de la Barra, 1989), Rickaby simulated six different growth patterns of the archetypal city for a 25-year period. The overall conclusion was that while the concentrated land use pattern is the most energy efficient, it is also the most costly due to increases in congestion. As a result, Rickaby advocates an urban form where a cluster of nodal developments are strategically located around the existing city.

Wegener (1995)used his model for the city of Dortmund to analyse scenarios of changes in the cost and speed of travel. The results show that modal choices and trip lengths are both sensitive to these types of changes. He concludes that restructuring the spatial organisation of cities is not the only alternative for achieving reductions in the use of the private automobile, but he cautions that these results may not be applicable to more dispersed cities that are not adequately served by public transportation (e.g., North American cities).

This brief review demonstrates that what is known about the relationship between urban form and transportation energy use and emissions is ambiguous. Although it is clear that the relationship does exist, it is not clear which urban form is the most environmentally benign and energy efficient. To some extend the simulation results presented in the following sections of this paper reinforce the ambiguous nature of the urban form-transportation relationship. However, our results will demonstrate that in simulation studies the way scenarios are defined could be the key factor contributing to ambiguous results.

## 3. METHODOLOGY

The analysis presented in this paper has been conducted using an urban simulation model called IMULATE[3] (**I**ntegrated **M**odel of **U**rban **LA**nd use and **T**ransportation for **E**nvironmental analysis), which has been designed to simulate the spatial assignment of automobile trips for the morning rush hour period in the Census Metropolitan Area (CMA) of Hamilton, which is located approximately 100 kilometres south-west of the city of Toronto (Figure 1). In this model, the number as well as the origin/destination of trips are conditional on the spatial configuration of land uses. One of the purposes of the model is to estimate the levels of energy demand and environmental emissions generated by these automobile trips.

The general structure of IMULATE is outlined in Figure 2. The core procedures of IMULATE are contained within four interrelated submodels: POPMOB, TRANDEM, TRAFFIC ASSIGNMENT and TRAVEL TIMES. The first module, POPMOB, simulates the process of residential mobility as well as the performance of the housing market. The second module, TRANDEM, uses the results of POPMOB to generate estimates of inter-zonal automobile trips for work, school and discretionary purposes. The variables used by the first two modules are all defined for the set of census tracts contained within the Hamilton CMA (see Figure 3a). The TRAFFIC ASSIGNMENT submodel allocates the estimates of inter-zonal transportation demand to the road network of Hamilton-Wentworth. Based on this assignment of automobile trips and the resultant congestion effects, inter-zonal travel times are calculated by the module TRAVEL TIMES. TRANDEM, TRAFFIC ASSIGNMENT and

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Simulation studies differ from empirical studies in that they base their conclusions on the results of projections by simulation models rather than direct observation of past trends.

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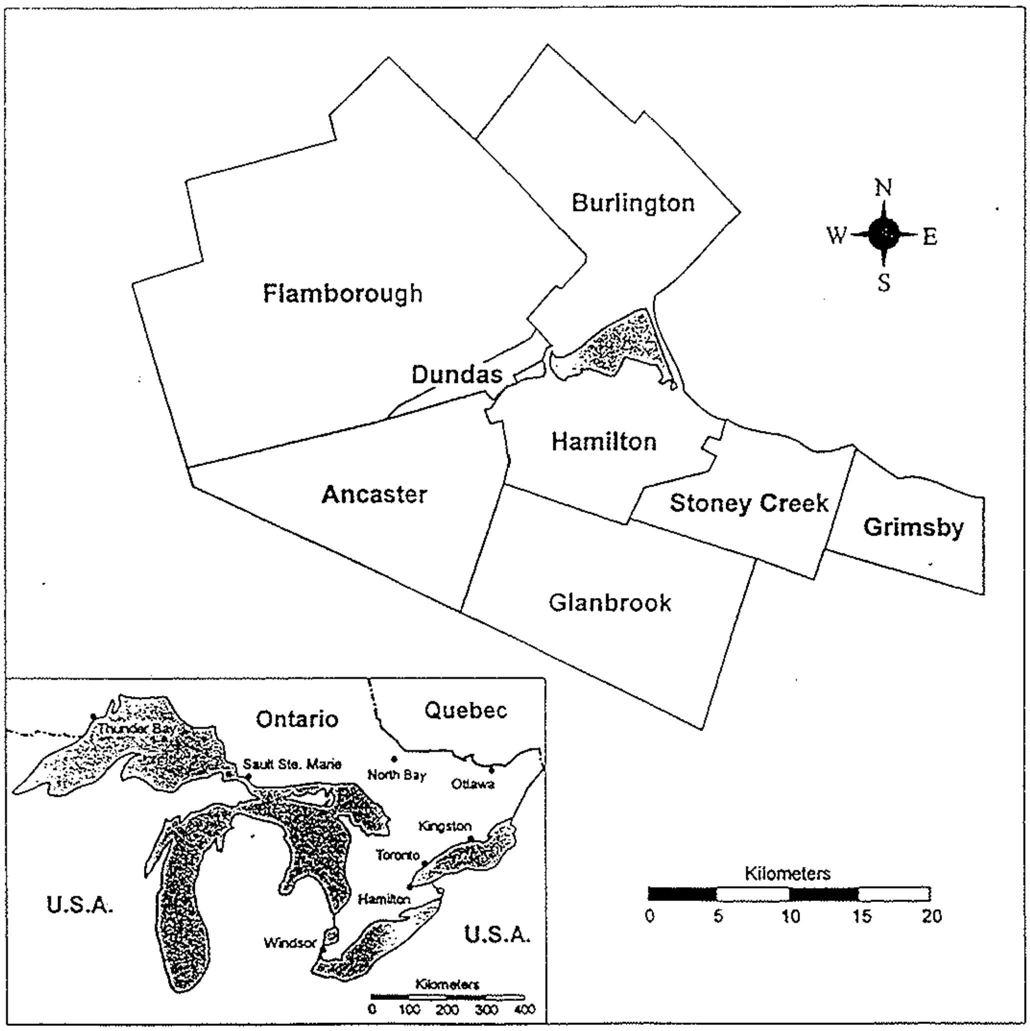
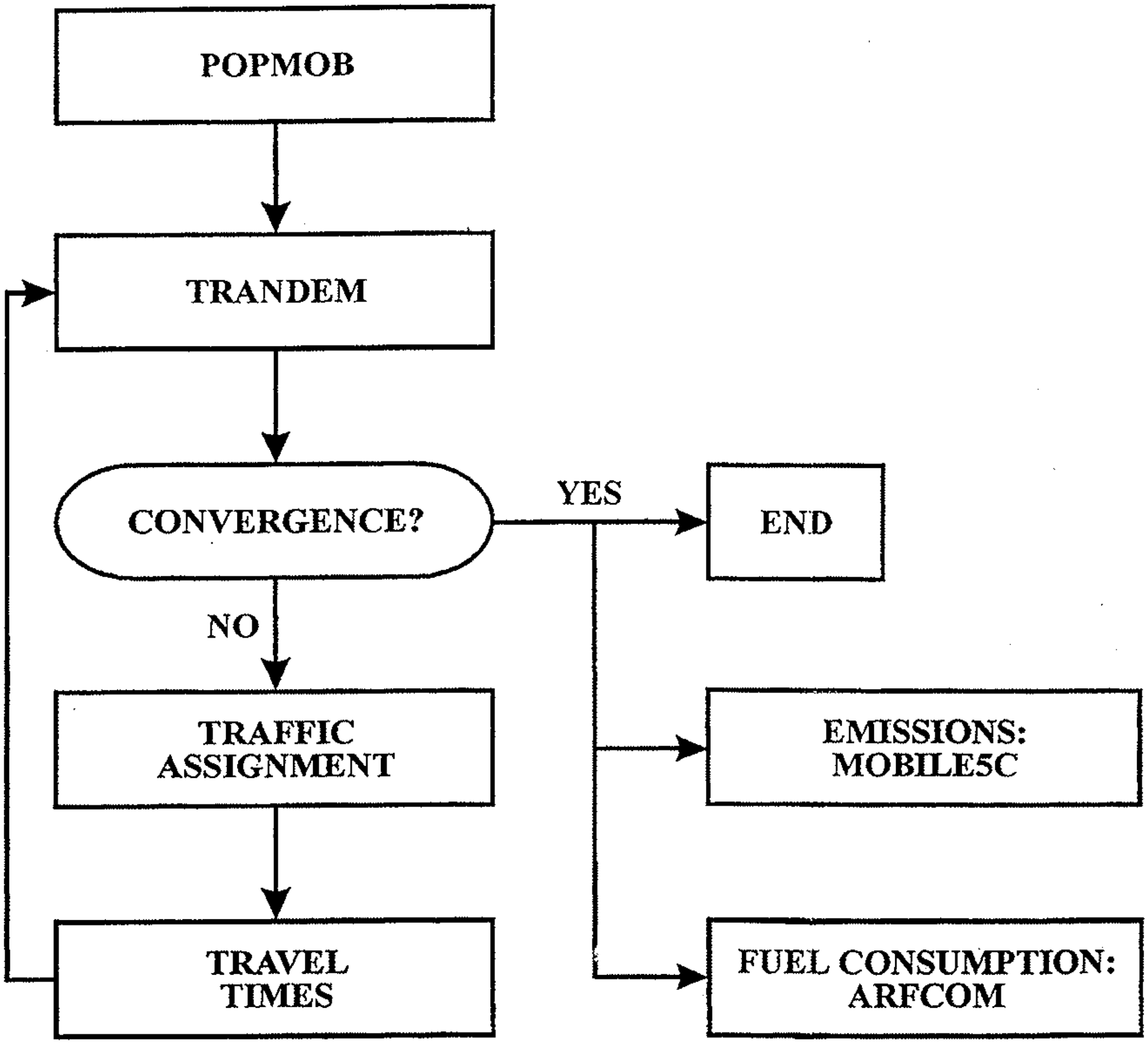
IMULATE has been developed at the McMaster University Institute for Energy Studies. The description of the IMULATE model given here is based on the comprehensive discussions of Anderson *et al.*, 1994; Kanaroglou *et al.*, 1996; and Scott, 1996.

**Figure 1: Hamilton-Wentworth, Burlington and Grimsby**




Source: Scott (1996).

**Figure 2: General Structure of IMULATE**




Source: Anderson *et al*. (1994).

TRAVEL TIMES work together in an iterative fashion until a network equilibrium (convergence) has been achieved. Once convergence is established, the EMISSIONS and FUEL CONSUMPTION modules are engaged to estimate the levels of emissions and fuel consumption that correspond to the network equilibrium.

To begin the simulation of a given scenario, IMULATE requires four types of data. First an initial distribution of households and employment over the census tracts of the Hamilton CMA is obtained from the 1986 Census of Canada (Statistics Canada, 1986). Thus, 1986 is the starting point in time for all the simulations. Second, the 'place of residence/place of work' (PORPOW) and 'place of residence/place of school' (PORPOS) matrices, which are sets of conditional probabilities, $W_{j|i}$, that a worker (student) living in zone *i* works (attends school) in zone *j* are obtained from a travel survey.[4] Third, information is required relating to the number of new households (or dwelling units) added to each census tract between time *t* and *t*+1. To simulate the future impacts of a given scenario, multi-zonal population projections are used to estimate the distribution of new households for the year(s) of interest. The final requirement is a spatial database representing the Hamilton road network, which has been constructed within a GIS package called Transcad (see Figure 3b). All of the IMULATE modules have been interfaced with Transcad so that the spatial data generated by the model can be displayed in graphical form.

Using the data pertaining to the initial distribution of households and the number of new households added to each zone, the POPMOB submodel estimates changes in the spatial distribution of households between times *t* and *t*+1. In addition to intra-urban migration, POPMOB also simulates the processes of household formation and dissolution. Once these changes are simulated, the PORPOW and PORPOS matrices are updated based on the new distribution of households.

The TRANDEM submodel uses the PORPOW and PORPOS matrices to calculate the total number of trips, $T_{ij}$, between a given origin zone *i* and a given destination zone *j*. This is accomplished by multiplying the number of workers and students in each zone by the probabilities defined in PORPOW and PORPOS. In order to produce a crude representation of discretionary trips, TRANDEM employs the use of a simple linear regression model to estimate trip generation and a doubly-constrained gravity model to distribute these trips between zones.[5] The final task of the TRANDEM module is to sub-divide $T_{ij}$, with the use of a multinomial logit model, into four modes: driver, passenger, transit and walk/bike. The modal split routine is based on inter-zonal free flow travel times and socio-economic attributes of the population.

The total number of driver trips between zones *i* and *j*, estimated by the modal split routine, represents the number of automobiles that must be assigned to the network by the TRAFFIC ASSIGNMENT model. These trips are allocated to specific sets of links on the Hamilton road network with the use of a *stochastic user equilibrium* assignment procedure (See Sheffi, 1985). Once this equilibrium is achieved, the TRAVEL TIMES module is engaged to estimate a new set of inter-zonal automobile travel times ($t_{ij}$), which are calculated based on estimates of link speeds. This new matrix of travel times is passed back to TRANDEM and is used to generate a new matrix of car trips. This iterative process continues until travel times do not change between iterations, at which point convergence is considered to have been achieved.

When a convergence is reached, IMULATE calculates a measure of accessibility for households living in zone *i* ($I_i$), which depends upon the equilibrium values of $t_{ij}$ weighted by $W_{j|i}$. $I_i$ represents the transportation utility that an individual derives from living in zone *i* and is used by POPMOB in the next time period as a measure of mobility potential for households in *i*.

IMULATE has been linked with two environmental models, MOBILE5C and ARFCOM,

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The initial PORPOW and PORPOS matrices were defined with information on inter-zonal travel obtained from the 1986 Transportation Tomorrow Survey (see Transportation Tomorrow Survey, 1988).

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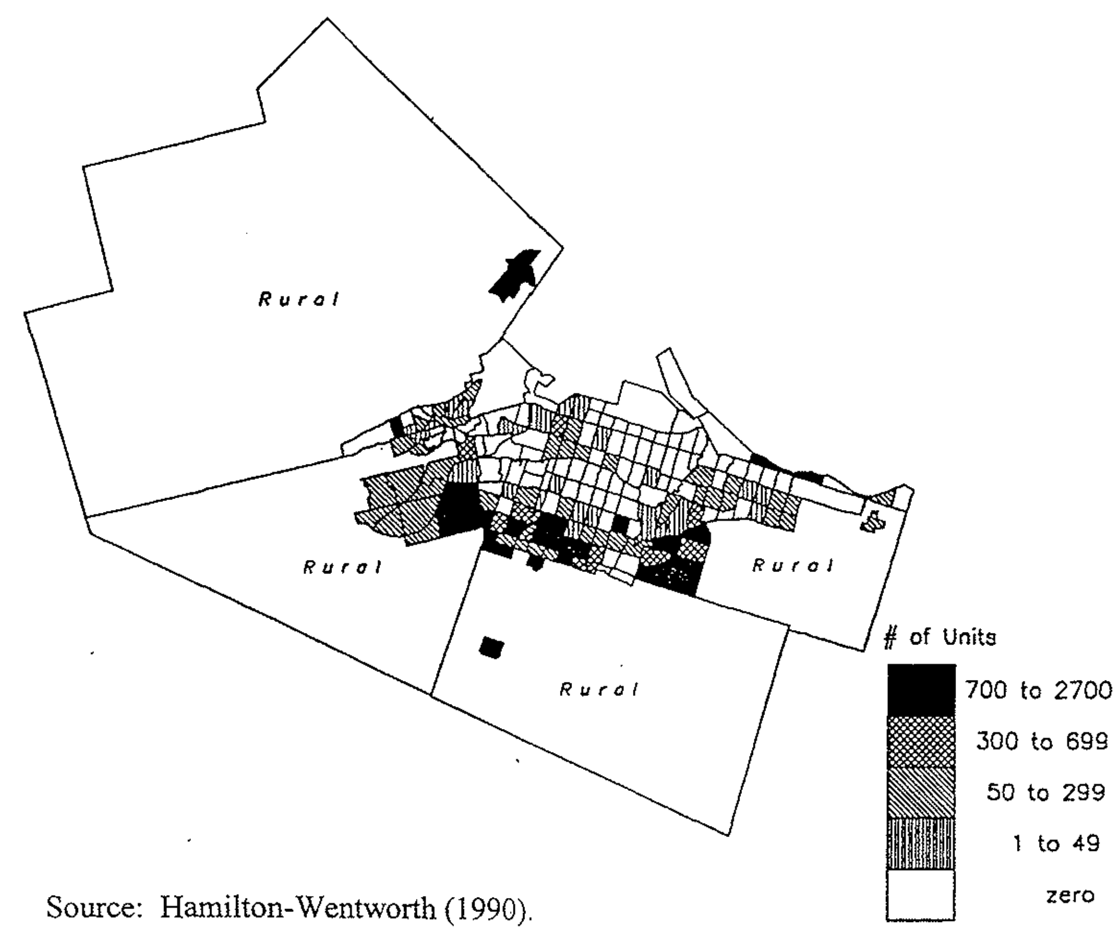
Anderson *et al.* (1994) justify the use of this simple model because of the fact that discretionary trips account for a small proportion of the total automobile trips during the morning rush hour period.

**Figure 4: Estimated Housing Unit Potential by Planning District**




Source: Hamilton-Wentworth (1990).

which are respectively used to generate link specific estimates of automobile emissions (i.e., carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide ($NO_x$)) and fuel consumption. These models base their estimates on the predicted number of flows and congested travel speeds for the individual links in the Hamilton road network. Both models can be employed once a network equilibrium is reached.

## 4. SCENARIOS AND DATA REQUIREMENTS

The starting point for all simulations is the urban form of the Hamilton CMA in the year 1986. Scenarios simulate growth patterns that give rise to different types of urban form to the year 2021. All the scenarios have three common characteristics. First, they all project the same level of population growth between the years 1986 and 2021; the difference between the scenarios is the spatial distribution of this growth. Second, the development policies implied by each of the scenarios are assumed to take affect at the end of the first simulation period (i.e., in 1991). This measure ensures that all of the scenarios share the same starting point. Third, to isolate the effects of changes in urban form, it is necessary to hold the other variables in the model constant; these variables include the road network and the emissions factors used by MOBILE5C.

Four alternative growth strategies, described below, have been defined and simulated within the IMULATE model: a *base* scenario, a *compact* alternative and two scenarios for *multi-nucleated* urban forms. The two multi-nucleated schemes will be used to demonstrate the impact that scenario definition can have on simulation results.

### 4.1 Base Scenario

The base scenario represents the growth pattern that would occur if the status quo is projected into the future. It represents the most dispersed growth strategy in which the vast majority of urban expansion occurs in the peripheral areas of the region. Construction of the scenario required two types of information. The first were the population projections for each of the simulation time intervals, provided by the Regional Municipality of Hamilton-Wentworth (Appendix I). The projected population figures were transformed into estimates of the number of households by dividing the population by projections of average household size for the region, also provided by the regional government. The number of new households $H(\Delta t)$ added in the study area within each simulation period $\Delta t$ was calculated by subtracting the households in the beginning of the time period from those in the end.

The second type of information required was estimates of the potential of census tracts for development of new housing units. The Regional Municipality of Hamilton-Wentworth provided the relevant data, along with the map in Figure 4 which shows the approximate number of new housing units that can be constructed within each planning district in the region. Estimates of housing unit potential by census tract were obtained by aggregating the planning districts to the census tract level. The proportion $P(x)$ of the total regional housing unit potential that can be located in census tract $x$ is used to allocate the regional increase in households to census tract x:

$$H(x;\Delta t) = P(x) * H(\Delta t), \qquad (1)$$

where $H(x;\Delta t)$ is the number of new households in census tract $x$ within the time period $\Delta t$. Thus, the distribution of unit potential displayed in Figure 4 represents the growth pattern modelled in the base scenario.

### 4.2 Compact Scenario

The compact scenario has been designed to represent the most dense urban form of the four alternatives. This growth strategy calls for a moratorium on future development in peripheral areas at the end of 1991 and, as a result, all of the new households that were designated for these areas in the base scenario had to be redistributed as infill development in the established sections of the city, as shown in Figure 5. The redistribution was done with the help of equation (1) by redefining $P(x)$ over the established census tracts only.

Another important difference from the base case scenario is that the compact scenario simulates a higher level of mixed land uses. This is achieved by adjusting the Place Of Residence Place Of Work (PORPOW) matrix to reflect a closer correspondence between places of residence and employment. [6]

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This adjustment involved several steps. First, a diagonal matrix (CHANGE) of the same dimensionality to PORPOW was

**Figure 3a: Census Tracts in Hamilton Region**

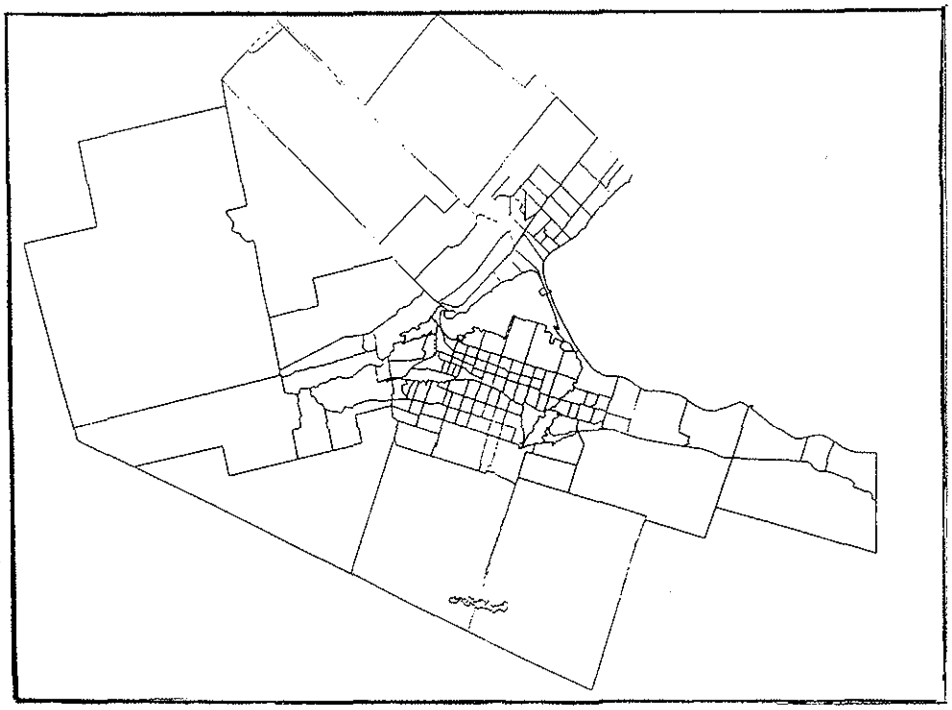


**Figure 3b: Road Network in Hamilton Region**

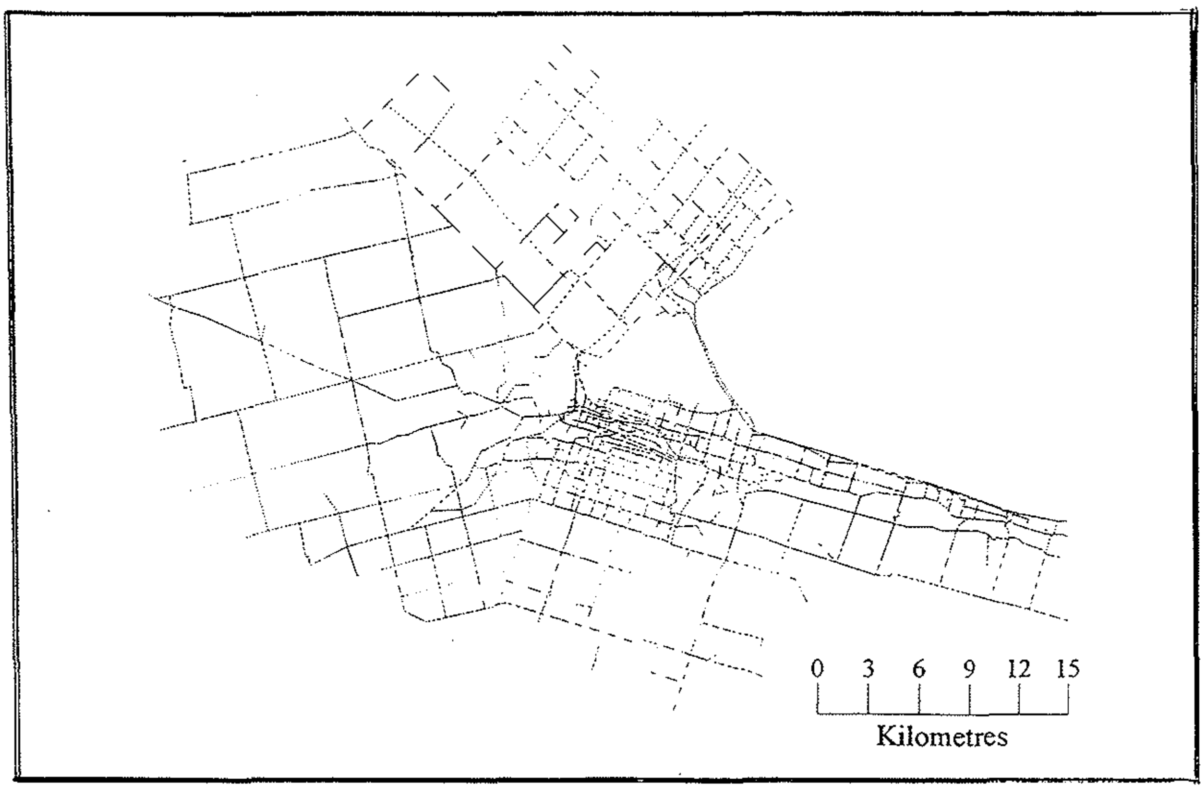


Figure 5: Census Tracts Included in Compact Scenario

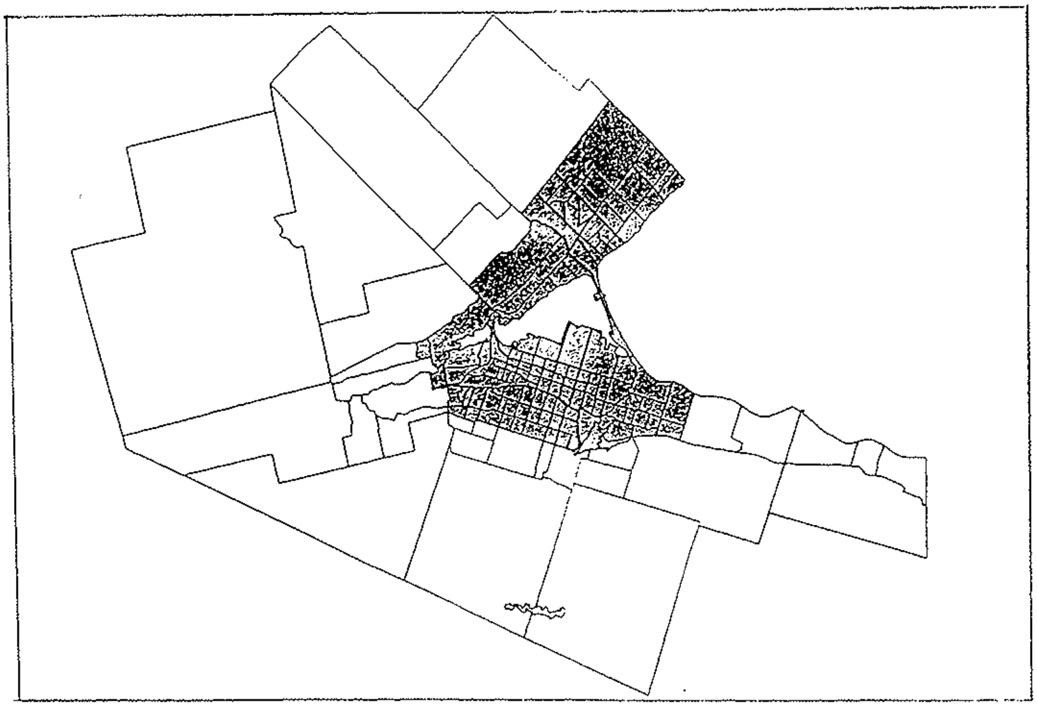
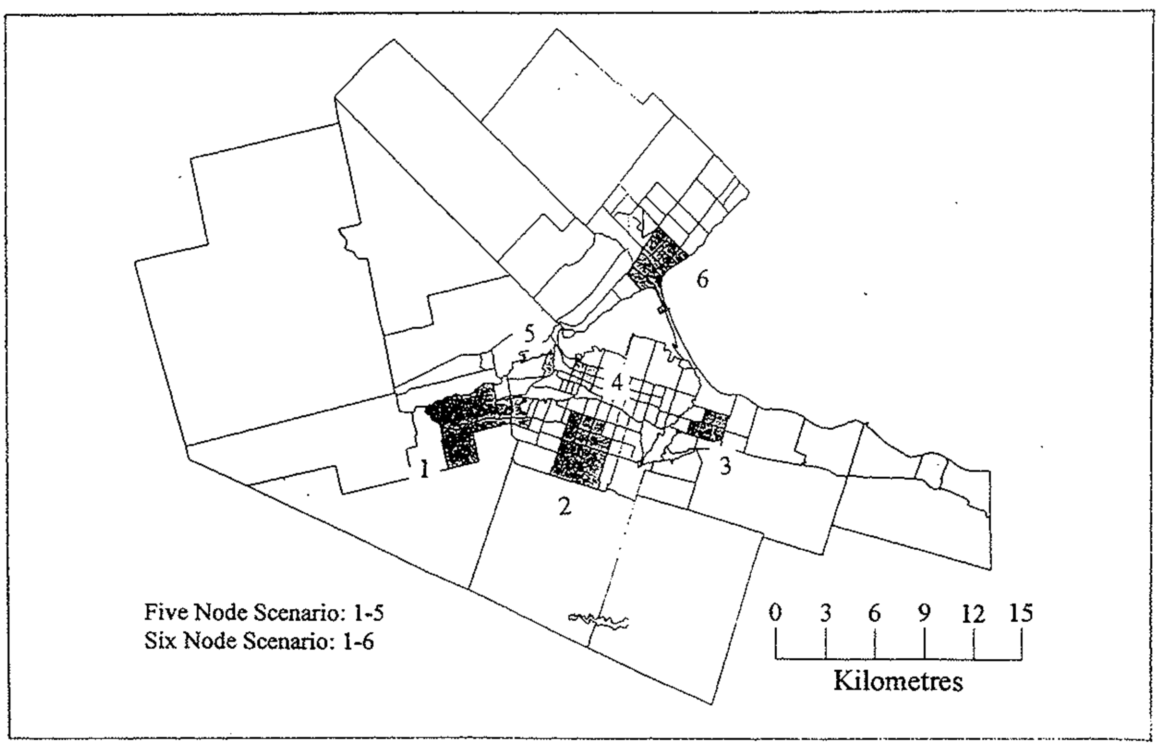


Figure 6: Census Tracts Included in Multi-Nucleated Scenarios



### 4.3 Multi-Nucleated Scenarios

Two multi-nucleated alternatives were defined in which certain areas of the region (i.e., groups of census tracts) were targeted for development in 1991. The first of these scenarios limits growth to five nucleations while the second limits growth to six nodes as shown in Figure 6. These nucleations are concentrated around features that promote reductions in automobile travel, such as the downtown core, major malls and important places of employment. The densities of these two scenarios fall between those of the base and compact scenarios, as the nodal developments include a combination of established and peripheral census tracts.

The adjustments made to the base scenario, in order to define the two multi-nucleated alternatives, are very similar to the modifications discussed for the compact scenario. The first modification involved redistributing the new households originally assigned to non-nodal census tracts to the nodal zones. This procedure employed the use of equation 1, with P($x$) being defined for the nodal census tracts only. The second adjustment was the generation of a new PORPOW matrix to represent the fact that all of the new development within the region is now focused on a small number of segregated zones. Similar to the compact scenario, the new PORPOW matrix includes a closer correspondence between places of residence and employment.

defined, whose diagonal elements represent the increase in the probability of living and working in the same zone. This increase was based on each census tract's proportion of the total new households. Second, another matrix (SUM) was created by adding the CHANGE and PORPOW matrices together. The third, and final, step in this adjustment process involved normalising matrix SUM so that the probabilities would add up to one. This procedure was accomplished by summing across each row of the SUM matrix and then dividing each element of a row by the row total. The end result was a new PORPOW matrix which incorporates a higher degree of association between places of residence and work.

## 5. RESULTS

Detailed results of the four scenarios can be found in Appendix II. All of the scenarios start from the same point in 1991, after which the policies of the compact and multi-nucleated alternatives come into effect. The percentage changes reported in the last column of Appendix II are all defined over the same 1991 values and, therefore, these changes provide measures of the relative differences between the alternative growth strategies. For convenience, the percentage changes of the key variables have been summarised in Table 1.

Table 1 reveals the following general trends. First, the base scenario generated the largest increases for all of the variables. Therefore, as expected, the most dispersed pattern of urban growth results in the highest levels of emissions and fuel consumption. Second, the compact and nodal growth patterns produce reductions in all of the variables compared to the results of the base scenario. A comparison of these three scenarios shows the following: the compact alternative generates the smallest changes in congestion and nitrogen oxide, the five node alternative produces the lowest levels of hydrocarbons, carbon monoxide and fuel consumption, and the six node growth pattern is the most wasteful of these three options in terms of emissions and fuel use.

These results demonstrate three important points. First, urban form can and does have an impact on automobile emissions and fuel consumption. Paired sample t-tests over the network links reinforce this assertion as indicated in Table 2. The t-test results show that, with the exception of a few instances, the alternative growth patterns produce outcomes for the year 2021 which differ by statistically significant amounts.

Second, there is ambiguity surrounding the issue of which urban form is the most effective at achieving reductions in emissions and fuel consumption. For some variables the compact scenario achieved the best results while for others the most effective option was the five node alternative. The uncertainty in these results is heightened by those of the paired sample t-tests. For several of the variables (e.g. cHC, cCO and Fuel), the estimates of the compact scenario and the nodal options do not differ by statistically significant

**Table 1: Percentage Changes in Selected Variables, 1991-2021**

| Scenario | VKT^ | VMT† | Avg. Congestion* | cHC‡ | $cNO_x$‡ | cCO‡ | Fuel |
|---|---|---|---|---|---|---|---|
| Base | 40.76 | 92.71 | 40.00 | 92.93 | 42.35 | 95.85 | 67.92 |
| Compact | 28.07 | 76.57 | 26.67 | 78.41 | 32.51 | 81.34 | 57.33 |
| 5 Node | 29.95 | 69.66 | 33.33 | 76.66 | 34.89 | 78.98 | 51.54 |
| 6 Node | 30.75 | 73.24 | 31.67 | 81.87 | 36.11 | 84.55 | 59.04 |

^ VKT refers to total "vehicle kilometres travelled".
† VMT refers to total "vehicle minutes travelled".
* Congestion measured as a ratio between link volume and link capacity.
‡ The prefix "c" represents the word "congested".

levels. Therefore, it is not possible to draw conclusions which assess the effectiveness of a particular urban form in reducing the levels of automobile emissions and fuel consumption. It can only be stated that, for the Hamilton (CMA) the compact urban form leads to congestion and nitrogen oxide levels which are significantly lower than the magnitudes of these variables in the five node scenario, while the levels of hydrocarbons, carbon monoxide and fuel consumption in the five node scenario are not significantly lower than the estimates of these same variables in the compact scenario.

This statement prompts an interesting question: Why are the levels of all the variables not minimised under the same scenario? Since higher levels of congestion result in speed reductions and more idle automobiles, two conditions which tend to increase emissions and fuel usage, it is intuitive to conclude that the scenario which generates the highest (lowest) level of congestion will also result in the highest (lowest) estimates of emissions and fuel consumption. However, as the figures in Table 1 indicate, this general rule does not always hold.

First, consider the results for the two multi-nucleated urban forms. The five node scenario generates a higher congestion level but lower estimates of emissions and fuel consumption. This situation occurs because, compared to the five node urban form, the six node scenario is more dispersed and, as a result, leads to longer automobile trips in terms of distance (VKT) and minutes (VMT) travelled.

Now consider the percentage changes for the compact and five node scenarios. In this instance, the rule for congestion described above holds only for emissions of nitrogen oxides. All the other variables (i.e., cHC, cCO and Fuel) are lower in the five node scenario. This anomaly can be explained by examining the VKT and VMT estimates for these scenarios. As expected, the total kilometres travelled in the compact scenario is less than that of the five node alternative. However, in terms of total minutes travelled, the opposite is true. This suggests that although the compact form gives rise to an overall lower level of congestion than the five node scenario, there are certain areas in the region where link congestion is considerably higher than that of the nodal alternative (see Figures 7a and 7b). An analysis of these figures reveals that the five node scenario, compared to the compact urban form, produces a more uniform spatial distribution of congestion. In the compact form, extremely high levels of congestion, concentrated within the downtown section of the city and along the two major highways, cause severe speed reductions as well as increased emissions and fuel use along the effected links. However, due to the fact that fuel requirements, and the resultant emissions of hydrocarbons and carbon monoxide, are extremely sensitive under conditions of heavy congestion, this means that, along the effected links, fuel consumption and the emissions of these pollutants will increase in a greater proportion than the

**Table 2: Results of t-Tests for Paired Samples^**

| Variable | Scenario 1 | Scenario 2 | Degrees of Freedom | t Value |
|---|---|---|---|---|
| Congestion | Base | Compact | 1524 | 13.98§ |
| | Base | 5 Node | 1524 | 9.44§ |
| | Base | 6 Node | 1524 | 9.95§ |
| | Compact | 5 Node | 1524 | -6.87§ |
| | Compact | 6 Node | 1524 | -7.78§ |
| | 5 Node | 6 Node | 1524 | 0.99* |
| cHC | Base | Compact | 1524 | 5.50§ |
| | Base | 5 Node | 1524 | 6.40§ |
| | Base | 6 Node | 1524 | 5.86§ |
| | Compact | 5 Node | 1524 | 0.47* |
| | Compact | 6 Node | 1524 | -1.25* |
| | 5 Node | 6 Node | 1524 | -3.50§ |
| $cNO_x$ | Base | Compact | 1524 | 10.66§ |
| | Base | 5 Node | 1524 | 8.44§ |
| | Base | 6 Node | 1524 | 7.93§ |
| | Compact | 5 Node | 1524 | -2.18† |
| | Compact | 6 Node | 1524 | -4.33§ |
| | 5 Node | 6 Node | 1524 | -2.64§ |
| cCO | Base | Compact | 1524 | 5.14§ |
| | Base | 5 Node | 1524 | 6.20§ |
| | Base | 6 Node | 1524 | 5.63§ |
| | Compact | 5 Node | 1524 | 0.58* |
| | Compact | 6 Node | 1524 | -1.07* |
| | 5 Node | 6 Node | 1524 | -3.49§ |
| Fuel | Base | Compact | 1524 | 4.34§ |
| | Base | 5 Node | 1524 | 6.52§ |
| | Base | 6 Node | 1524 | 2.80§ |
| | Compact | 5 Node | 1524 | 1.53* |
| | Compact | 6 Node | 1524 | -0.45* |
| | 5 Node | 6 Node | 1524 | -2.43† |

^ Based on results for 2021; § Significant at the 99% confidence level; † Significant at the 95% confidence level; * Not significant.

**Figure 7a: Congestion - Compact Scenario, 2021**

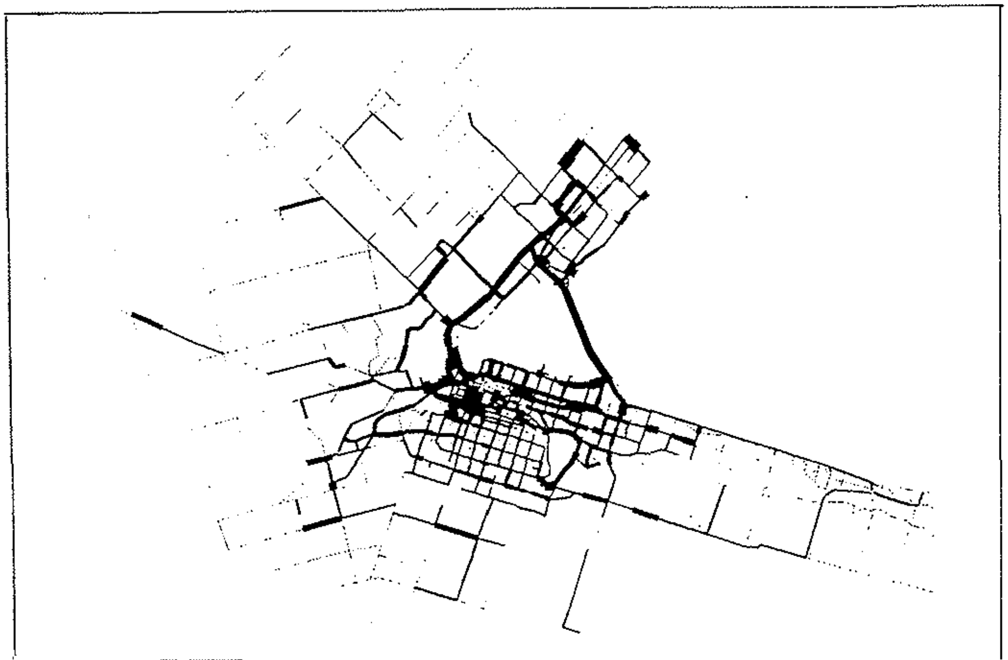
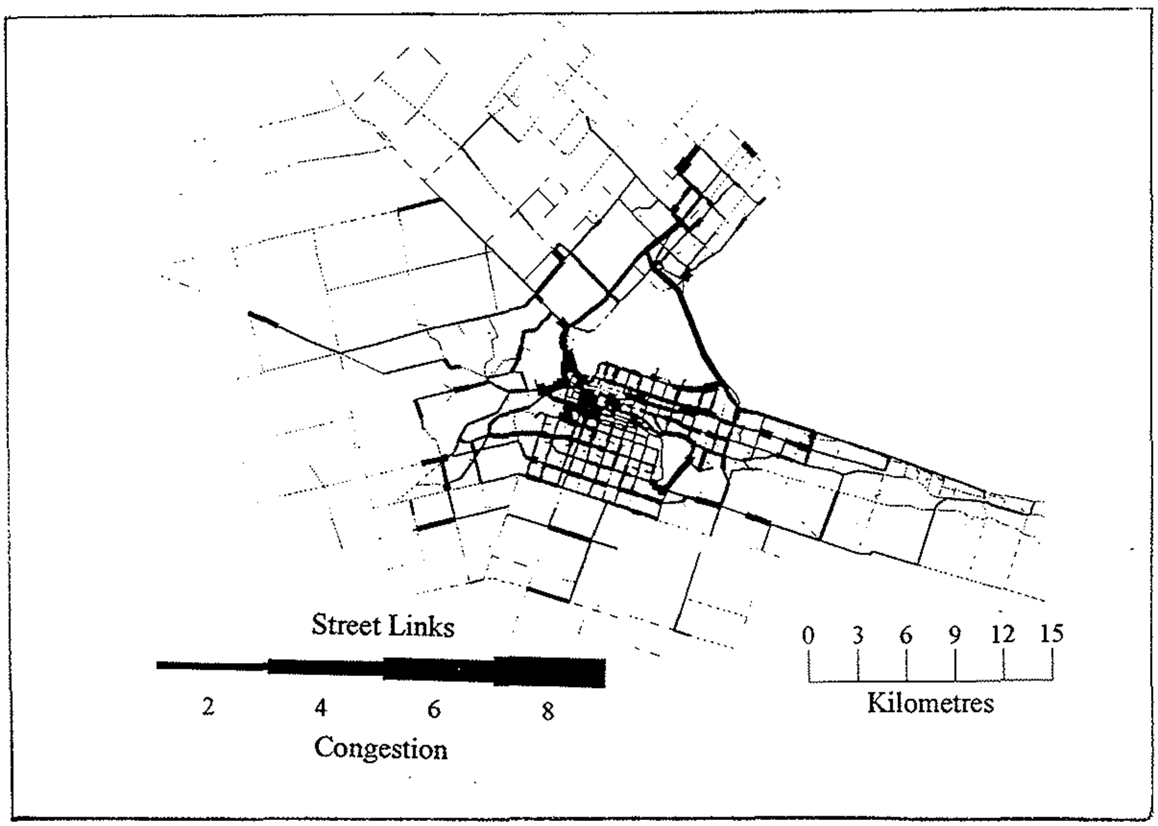


**Figure 7b: Congestion - Five Node Scenario, 2021**



corresponding decrease in speed. As a result, the estimates of fuel usage and emissions (i.e., cHC and cCO) are higher in the compact scenario.

The third issue that the results in Table 1 demonstrate is the impact of scenario definition. In the case of urban form, this problem involves the spatial distribution of urban growth (i.e., the sections of a city that will be developed and the intensities of these developments). The effect of this factor can be seen through an examination of the results produced by the two multi-nucleated scenarios. Although these two scenarios represent the same general urban form, they have been defined differently and, as a result, generate estimates of fuel consumption and emissions that deviate from each other significantly (see Table 2). The six-node multi-nucleated urban form is, with the exception of the base scenario, the least effective growth pattern, while for the five-node alternative with respect to most of the measures used, the opposite is true. This illustrates that the way in which a particular scenario is defined can substantially influence conclusions drawn with respect to the effectiveness of different urban forms in reducing energy consumption and emission levels. For example, if the analysis presented above did not include the results of the five node scenario, a very different conclusion would have been derived.

The preceding analysis has shown that urban development strategies could be used for achieving reductions in automobile fuel consumption and emissions. However, the results of the four simulations reinforce the ambiguous nature of these changes under alternative policy initiatives. This ambiguity partially stems from the issue of scenario definition. As illustrated above, the way in which a particular scenario is constructed can significantly alter the outcome of a simulation.

## 6. CONCLUSIONS

As the twentieth century comes to end, urban planners have started to realise that policies involving changes in urban form can play a significant role in strategies designed to fulfil the environmental needs of the near and distant future. Urban morphologies that allow for decreases in society's dependence on the private automobile (i.e., dense settlements with mixed land uses) also lead to significant reductions in energy use and emissions levels. However, as the results in this paper indicate, research efforts have not been able to identify an ideal urban form to which all cities should aspire. Thus, in order to make informed decisions about the future growth patterns of their cities, planners must carefully consider the likely results of alternative urban structures. In this regard, urban simulation models can be extremely useful in planning decisions.

Urban simulation models afford decision makers with the opportunity to isolate the future impacts of growth policy strategies, something that is impossible to achieve otherwise. The information gained from simulations can then be used to help determine which urban form is the most effective at achieving policy objectives, conditional on the economic and political realities of the local government. When decisions of this nature are being made, simulation models are not decision making 'substitutes'. They are tools that provide policy makers with information to be used in the decision process. Also, users of simulation models should recognise that these analytical tools have several limitations, one of which is scenario definition. The research presented above demonstrates the large impact that this problem can have on simulation results. Therefore, to reduce the chance of making a spurious conclusion, the user of a simulation model should consider several different formulations of the same scenario.

Urban simulation models provide analysts with large volumes of detailed data which are already being used effectively in decision making. However, we should not lose sight of the fact that these models have a number of limitations. By gaining a thorough understanding of these shortcomings, those who employ the services of urban simulation models will be able to make better use of a valuable tool for policy analysis.

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## APPENDIX I: POPULATION AND HOUSEHOLD DATA

| Variable | 1991 | 2001 | 2011 | 2021 |
|---|---|---|---|---|
| Population | 592560 | 639960 | 674134 | 708258 |
| Avg. Household Size | 2.67 | 2.60 | 2.52 | 2.44 |
| Total Households | 221849 | 246138 | 268045 | 290389 |

Source: Hamilton-Wentworth (1992; 1996).

## APPENDIX II: RESULTS OF SCENARIOS

| Scenario | Variable | 1991 | 2001 | 2011 | 2021 | % Change 1991-2021 |
|---|---|---|---|---|---|---|
| Base | VKT^ | 815644.42 | 938215.84 | 1043000.91 | 1148090.75 | 40.76 |
| | VMT† | 3923296.27 | 4962997.42 | 6113972.70 | 7560733.32 | 92.71 |
| | Avg. Link Flows | 1882.96 | 2149.34 | 2384.14 | 2623.04 | 39.30 |
| | Avg. Congestion* | 0.60 | 0.68 | 0.76 | 0.84 | 40.00 |
| | cHC‡ (g/km) | 7375559.12 | 9401310.47 | 11609739.53 | 14229471.13 | 92.93 |
| | $cNO_x$‡ (g/km) | 6547476.21 | 7480394.28 | 8371854.87 | 9320639.45 | 42.35 |
| | cCO‡ (g/km) | 79663143.03 | 101918448.41 | 126520014.71 | 156022064.82 | 95.85 |
| | Avg. Speed (km/h) | 33.29 | 32.17 | 31.11 | 30.06 | -9.70 |
| | Fuel (l/km) | 291886.59 | 349640.06 | 416079.55 | 490148.49 | 67.92 |
| Compact | VKT | 815644.42 | 899466.12 | 971289.52 | 1044620.65 | 28.07 |
| | VMT | 3923296.27 | 4807055.95 | 5717124.12 | 6927518.91 | 76.57 |
| | Avg. Link Flows | 1882.96 | 2081.24 | 2255.53 | 2437.26 | 29.44 |
| | Avg. Congestion | 0.60 | 0.66 | 0.71 | 0.76 | 26.67 |
| | cHC | 7375559.12 | 9144249.97 | 11013696.02 | 13158826.23 | 78.41 |

| Scenario | Variable | 1991 | 2001 | 2011 | 2021 | % Change 1991-2021 |
|---|---|---|---|---|---|---|
| Compact | $cNO_x$ | 6547476.21 | 7264711.77 | 7942319.80 | 8675850.15 | 32.51 |
| | cCO | 79663143.03 | 99312414.04 | 120272291.44 | 144458972.02 | 81.34 |
| | Avg. Speed | 33.29 | 32.49 | 31.81 | 31.12 | -6.52 |
| | Fuel | 291886.59 | 340185.00 | 398444.78 | 459226.59 | 57.33 |
| Multi- Nucleated (5 Nodes) | VKT | 815644.42 | 905875.81 | 984289.24 | 1059950.46 | 29.95 |
| | VMT | 3923296.27 | 4769454.61 | 5631525.69 | 6656323.69 | 69.66 |
| | Avg. Link Flows | 1882.96 | 2104.32 | 2301.75 | 2498.17 | 32.67 |
| | Avg. Congestion | 0.60 | 0.67 | 0.73 | 0.80 | 33.33 |
| | cHC | 7375559.12 | 9197633.76 | 11049814.67 | 13029701.11 | 76.66 |
| | $cNO_x$ | 6547476.21 | 7326422.54 | 8070212.80 | 8831771.86 | 34.89 |
| | cCO | 79663141.03 | 99764806.13 | 120377797.10 | 142579346.59 | 78.98 |
| | Avg. Speed | 33.29 | 32.39 | 31.56 | 30.70 | -7.78 |
| | Fuel | 291886.59 | 337612.96 | 390512.71 | 442328.89 | 51.54 |
| Multi- Nucleated (6 Nodes) | VKT | 815644.42 | 906780.79 | 987732.76 | 1066444.61 | 30.75 |
| | VMT | 3923296.27 | 4788185.36 | 5696513.80 | 6796798.84 | 73.24 |
| | Avg. Link Flows | 1882.96 | 2106.06 | 2308.56 | 2511.93 | 33.40 |
| | Avg. Congestion | 0.60 | 0.67 | 0.73 | 0.79 | 31.67 |
| | cHC | 7375559.12 | 9230305.98 | 11221111.02 | 13414088.57 | 81.87 |
| | $cNO_x$ | 6547476.21 | 73332307.35 | 8107711.05 | 8911720.86 | 36.11 |
| | cCO | 79663143.03 | 100127404.01 | 122338837.18 | 147015468.77 | 84.55 |
| | Avg. Speed | 33.29 | 32.39 | 31.56 | 30.70 | -7.78 |
| | Fuel | 291886.59 | 339886.84 | 395835.22 | 464203.58 | 59.04 |

^ VKT refers to total "vehicle kilometres travelled".
† VMT refers to total "vehicle minutes travelled".
* Congestion measured as a ratio between link volume and link capacity.
‡ The prefix "c" represents the word "congested".