NETWORK-ORIENTED DEFINITION OF SPACE AND ITS CONTRIBUTION TO THE UNDERSTANDING OF URBAN BEHAVIOURS

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Abstract

The study of reciprocal relations between urban forms and travel behaviours is a matter of great concern among researchers. In fact, relating travel behaviour models and land-use models into integrated models is one of the strategies deployed to better consider the complexity of urban behaviours.

We propose another perspective of this integration issue, a network-oriented definition of space, which embeds the structure of the transportation network in the modelling process. This is performed by conforming the classical measures of urban form, accessibility and density, to the actual space that supports the daily activities.

Subsequently, four conceptions of the urban space are proposed, from which are derived indexes describing the spatial structure of a particular area. Differences between classical measures (Euclidean distance and gross density) and network-oriented measures are discussed. These conceptions of space are finally appraised around a number of perspectives: examination of classical relations between density and mobility indicators with gross and network densities, estimation of average space occupancy per household (spatial obesity) and review of the dynamical aspect of population density. We believe that network-oriented perspectives have the potential to enhance the relevance of our modelling approaches.

Keywords: Urban forms; Travel behaviours; Density; Accessibility; Greater Montreal Area
Topic Area: F2 Urban Patterns and Transport

1 Introduction

It is well recognised that travel behaviour is the outcome of several urban influences. Evidence of this linkage is the effort to integrate travel behaviour models and land-use models into interaction or integrated models. Several works have confirmed the interest towards those models in the recent years; as a case in point is the paper by Wegener and Fürst (1999) exposing the state of the art in interactions modelling. The study of the reciprocal relations between urban forms and travel behaviours, notably the use of transit, is also a focus of attention. For instance, seven urban form factors acting on the use of transit are identified by Miller and al. (1998): residential density, transit supply, car ownership, socio-economic factors (income, age, gender and occupation), employment density, accessibility and neighbourhood design.

Other perspectives may be examined in order to evolve our modelling approaches of the land-use processes, the travel behaviours and their interdependency. We propose another perspective of the integration issue, a network-oriented definition of space, which embeds the structure of the transportation network in the modelling process. This is performed by conforming the classical measures of urban form, namely accessibility and density, to the actual space that supports the daily activities. Besides, discussions on the validity of the urban density concept (and boundaries of the urban area) will also benefit from the proposed measures that can be uniformly applied over multiple areas and used to compare them (see Richardson and al., 1998).

This study is part of a research on the totally disaggregate modelling of the interactions between urban travel behaviours and spatial dynamics such as urban sprawl. Our research framework is illustrated in Figure 1 and is articulated in ten main interactions which form the conceptual architecture of the urban system. At this point, our research strategy is basically a step-by-step approach seeking to construct multi-perspective understanding of the interactions observed in an urban area. It will eventually lead to the construction of a totally disaggregate model, benefiting from established but somehow fragmentary procedures, as well as from new insights gained from the analytical study of urban interactions.

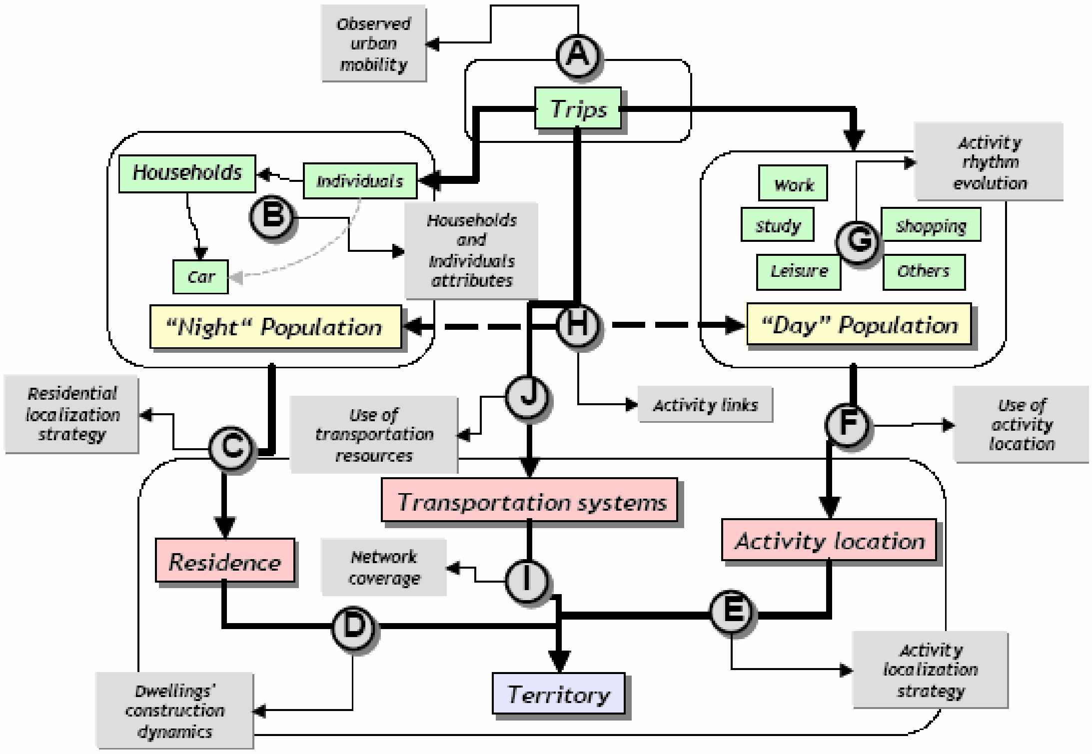


Figure 1 - Schematic representation of the ten main urban interactions

2 Study context

Data from two Large-Scale Origin-Destination Household surveys (1987 and 1998), sampling 5% of the residing households (65 000 households were sampled in 1998), provide detailed information on travel behaviour at the totally disaggregate level: every trip of every individual of a sampled household is precisely characterized. The recent deployment of a high resolution fusion methodology between census data and travel survey data facilitates the introduction of relevant socio-demographic variables in the modelling process (Morency, 2004). Indeed, relevant information on dwellings (periods of construction, type, tenure), households (income) and population (level of schooling, spoken language, mobility, occupation) can contribute to the process of modelling the complexity of travel patterns.

3 Methodology and concepts

Distance to CBD clarifies several spatial trends (socio-demography and travel behaviours). This one dimension, used to simplify the data, is based on the hypothetical radioconcentric nature of the urban area.

« De telles formes géométriques (espace radio-concentrique) ne se rencontrent jamais dans la réalité, ce qui ne signifie pas qu'il faille les rejeter. Elles sont un point de départ nécessaire en analyse spatiale, dans une démarche vers plus de réalisme, l'étape suivante étant l'introduction d'attributs différentiés » Huriot et Perreur (1990).

Actually, notwithstanding the reducing character of this hypothesis, distance to CBD is a key variable in the study of population dispersion over space (and several other urban objects). In fact, this variable can describe, explain and even predict some major urban dynamics. Several researchers make use of radioconcentric models and have proposed some refinements: Peguy (2002), Scheou (1998) and Bonnafous and Tabourin (1998). Hence, it is possible to refine this measure by trading Euclidean distance with network distance and Euclidean space with network space.

Even if the Greater Montreal Area is rather radioconcentric (see Chapleau and Morency, 2004), it differs from this theoretical concept due to the presence of natural barriers. Moreover, urban activities can not be performed over all the area. Actually, only specific sectors, those neighbouring the transportation network or accessible by car and other transportation modes, likely exists for activity purposes.

3.1 Conceptions of space

In order to refine the space concept, when urban functions are subject to analysis, we define four conceptions of the study area (Morency and Chapleau, 2003):

- **Isotropic Uniform Space (IUS)**: radioconcentric space measured around the urban centre, of area 2 *pr* ;
- **Urban Area Space (UAS)**: Greater Montreal Area as delimited for the latest Origin-Destination survey. This area equals the IUS excluding territories outside of the study area (watercourse, area delimitation);
- **Transportation Network Space (TNS)**: surface covered by the transportation network, estimated from a uniform buffer (100 meters) applied on either side of the road segments. The area of this space is the sum of the network bands located inside the radius r.
- **Transit Network Space (PTNS)**: This space is a subset of the TNS since the transit network is generally superimpose over the road network, even in the case of heavy transit (subway, rail) where stations are necessarily linked to the road network. The measure of transit network coverage is more complex since the level of supply fluctuates throughout the day, the week and the season. Hence, this space varies. At the moment, the PTNS is estimated by the application of an accessibility buffer (500 meters) around every bus stop, subway and rail station, notwithstanding the level of service. Only the part of this accessibility buffer located inside the TNS is considered. The 500 meters limit assures the coverage of the space accessible by foot and avoids the integration of non-developed areas (around heavy transit stations).
- Obviously, for a given radius r: $IUS \geq UAS \geq TNS \geq PTNS$.

These four conceptions of space, for the Greater Montreal Area, are illustrated in Figure 2.

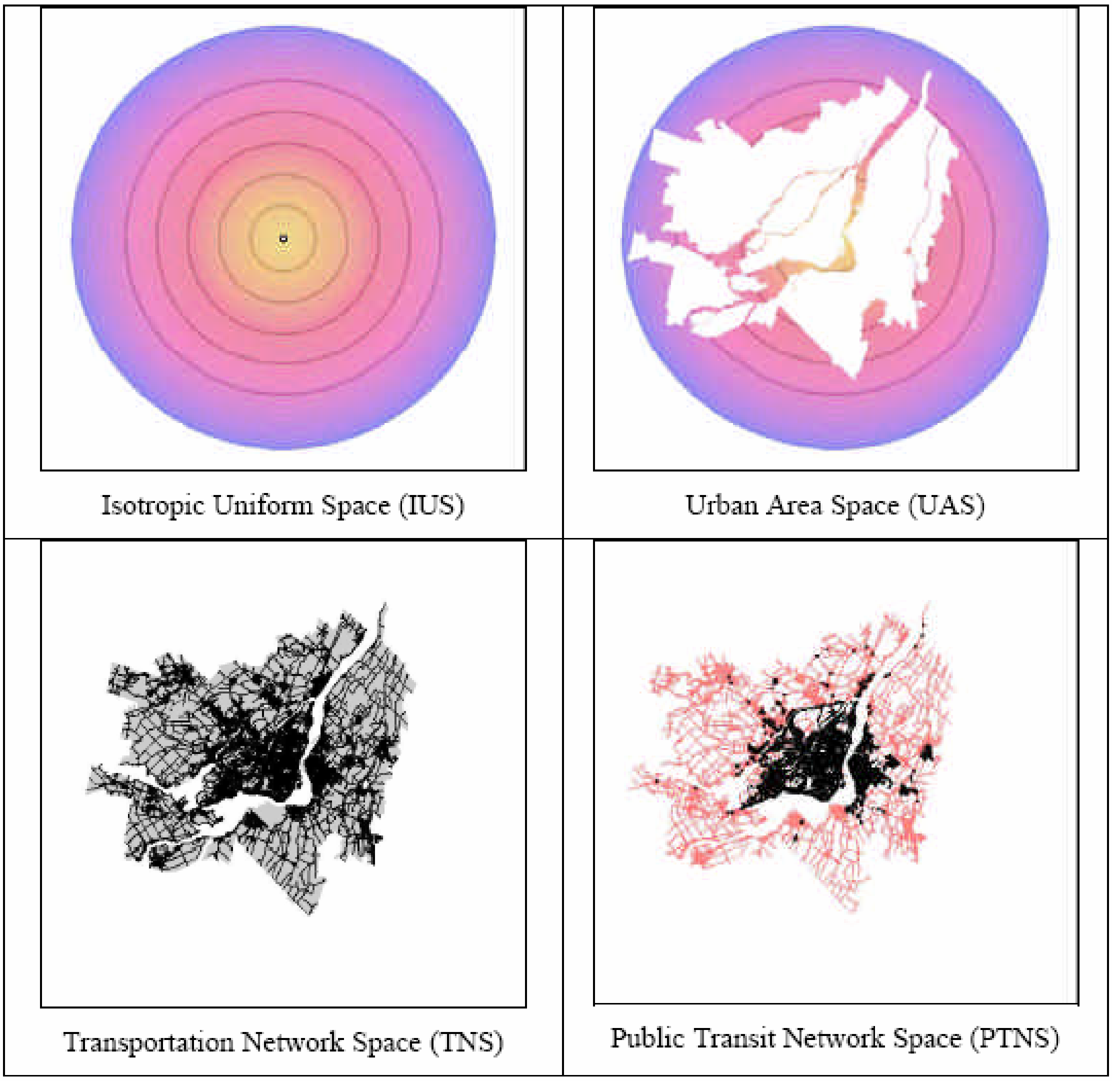


Figure 2 – Four conceptions of the urban space: Isotropic Uniform Space (IUS), Urban Area Space (UAS), Transportation Network Space (TNS) and Public Transit Network Space (PTNS)

3.2 Space occupancy indexes

Relations between these conceptions lead to the definition of three indexes, defining the structure of a specific area. These indexes are estimated by rings (SDI-98, NOI-98 and TNOI-98) and cumulatively (SDI-98-Cum, NOI-98-Cum and TNOI-98-Cum) for the Montreal Area:

- The **Spatial Discontinuity Index (SDI)** measures the proportion of the theoretical isotropic space that is really occupied by the urban area: *SDI(r)=UAS(r)/IUS(r)*. Figure 3 presents this index by kilometre to CBD. It rapidly summarises the differences between the radioconcentric hypothesis and the actual urban area under study. Roughly, the Montreal Area occupies almost 90% of the IUS inside a 20 kilometres radius. This proportion declines gradually beyond 30 kilometres. Globally, the urban area represents less than 40% of the IUS (> 60 km radius from CBD).

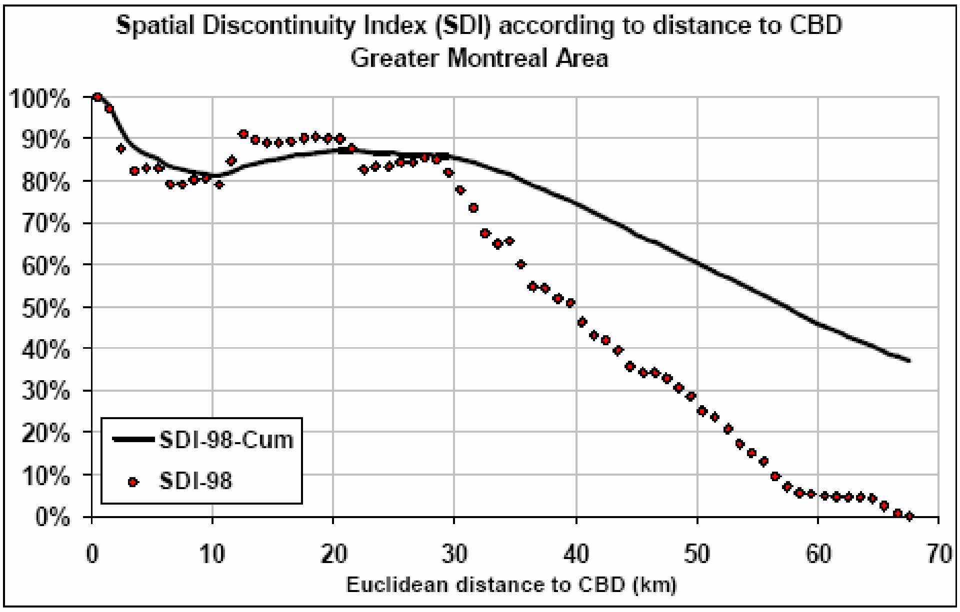


Figure 3 – Spatial Discontinuity Index according to Euclidean distance to CBD for the Greater Montreal Area (1998 perimeter)

• The **Network Occupancy Index (NOI)** reveals the proportion of the Montreal Area that is occupied by the transportation network: *NOI(r)=TNS(r)/UAS(r)*. As presented in Figure 4, about 37.5% of the urban area is covered by the transportation network. This occupation reaches at least 90% inside a 10 kilometre radius from CBD. Figure 5 shows the distribution of NOI estimated for 100 analysis zone. This 3D representation relies on the Transportation Network Space. It confirms the decline of the NOI in space and allows identifying the most urbanised areas.

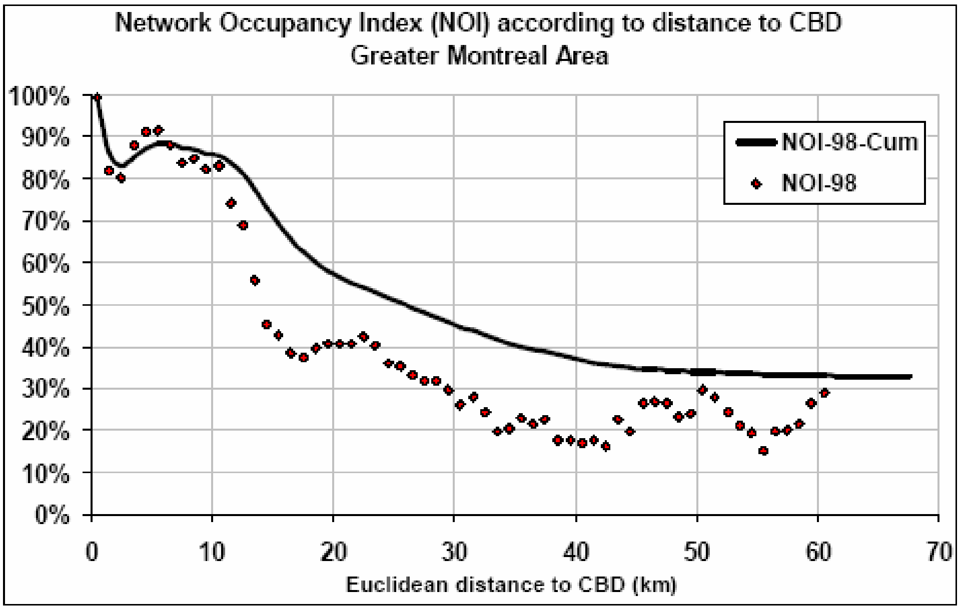


Figure 4 – Network Occupancy Index according to Euclidean distance to CBD for the Greater Montreal Area (1998 perimeter)

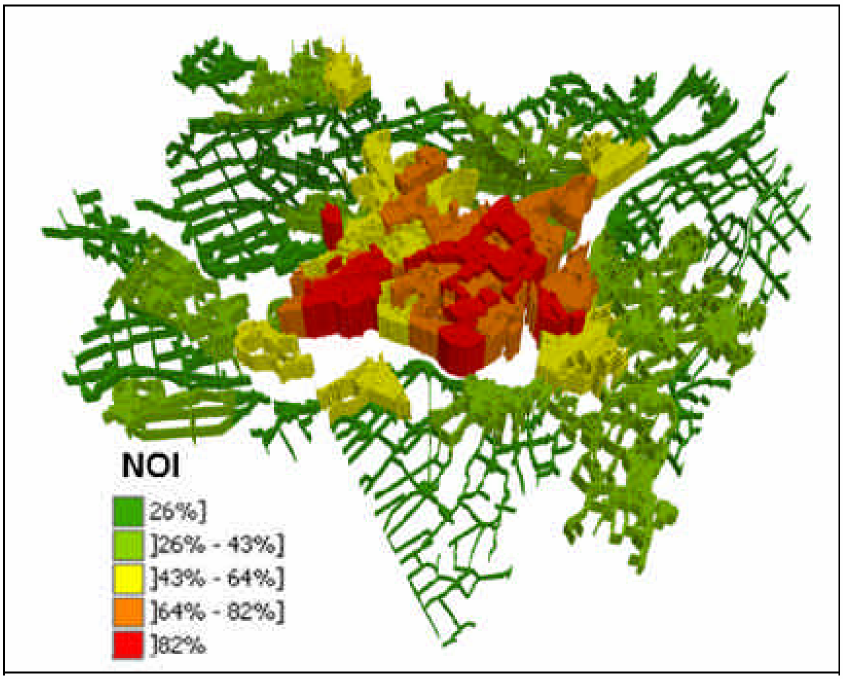


Figure 5 – Network Occupancy Index estimated for 100 analysis sectors

• Finally, the **Transit Network Occupancy Index. (TNOI)** expresses the proportion of the Transportation Network Space where transit services are operating: *TNOI(r)=PTNS(r)/TNS(r)*. Figure 6, witch summarises this index according to distance to CBD, reveals that the transit service rapidly declines beyond a 10 kilometres radius and globally covers 40% of the regional transportation network. In the core area, the transit network practically covers the entire transportation network. This index was also calculated by analysis zone (100 municipal sectors) and is presented in Figure 7. The picture is unequivocal: transit network is basically negligible in suburban areas.

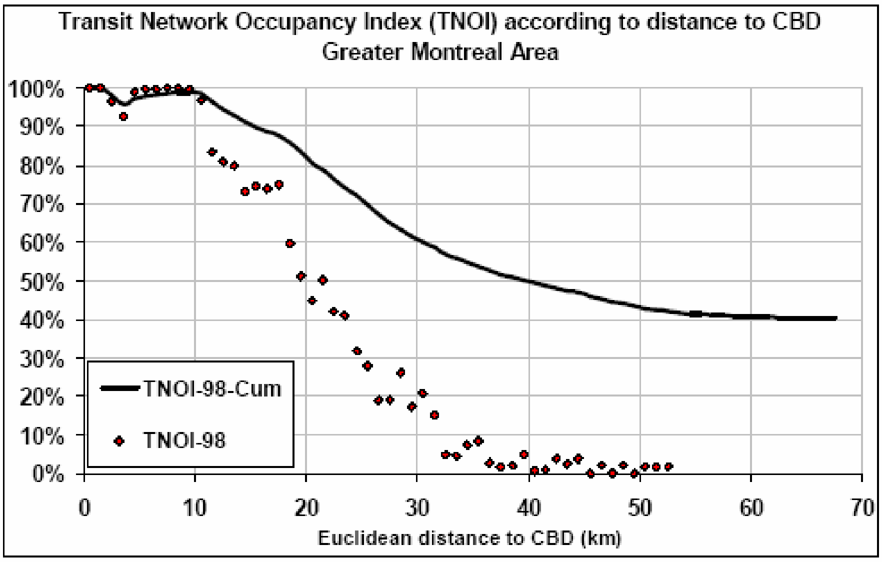


Figure 6 – Transit Network Occupancy Index according to Euclidean distance to CBD for the Greater Montreal Area (1998 perimeter)

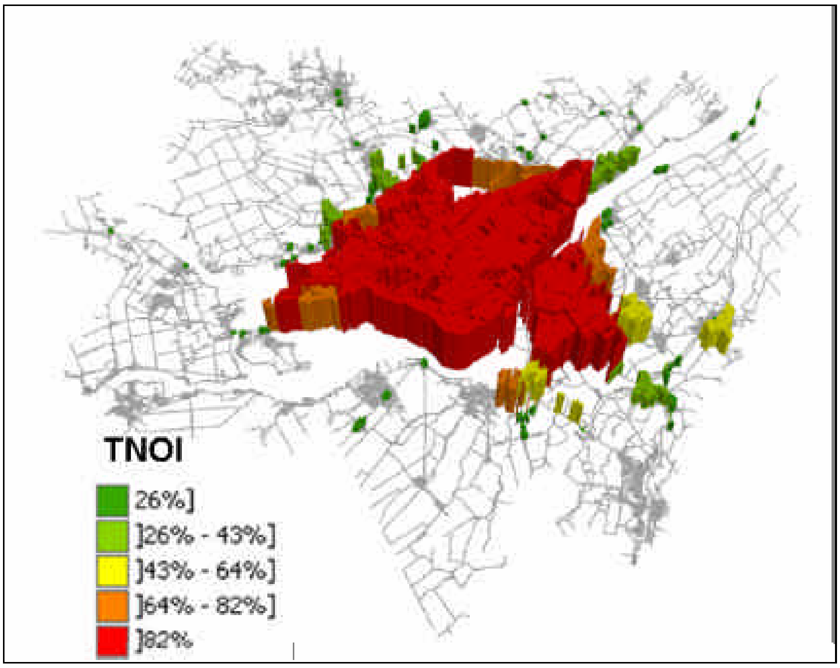


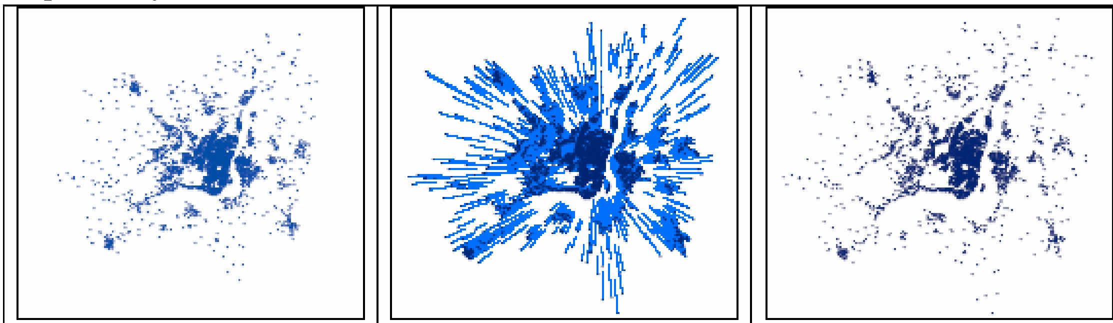
Figure 7 – Transit Network Occupancy Index estimated for 100 analysis sectors

3.3 Impacts of a switch in distance metric

In order to appreciate the impacts of switching from Euclidean distance to network-based distance, a basic spatial transformation was conducted, consistent with the radioconcentric hypothesis. Formally, every urban entity is spatially located by a pair of x-y coordinates. Euclidean distance to CBD is estimated with the classical formula: $D\_CBD_{EUC} = \sqrt{(x_i - x_{CBD})^2 + (y_i - y_{CBD})^2}$. A shortest path calculation algorithm is used to estimate the network-based distance between the same pairs of points (D_CBD_{NET}). The spatial transformation consists in translating every point so that its new x-y position represents its network distance to CBD. Angles are maintained.

As shown in Figure 8, the translated scatter plot is more dispersed $(D\_CBD_{EUC} \leq D\_CBD_{NET}$ and is distorted according to the network accessibility to CBD. Actually, the standard deviation ellipse (SDE), estimated on the basis of transformed point, is 41.5% greater than the SDE estimated over the initial scatter plot (see Figure 9).

Finally, an elongation index, relating Euclidean distance and network-based distance, is estimated for the CBD accessibility. Frankhauser and Genre-Grandpierre (1998) suggest that elongation index measures the extent of the elongation induced by the shape of the transportation network. The Distance Elongation Index of the Montreal Transportation Network $(DELTN = D\_CBD_{NET} / D\_CBD_{EUC})$ was estimated for trips to CBD. Network distance from more than 4 600 origin points (mean centres of Census enumeration areas) were computed and used to illustrate this index (Figure 10). The impact of the transportation structure on the CBD accessibility varies according to spatial location. Actually, the magnitude of the Elongation Index is related to the presence of the major road infrastructures such as highways. Hence, high indexes identify the specific areas clearly disadvantaged by the actual infrastructures. The South Shore is particularly underprivileged by the actual infrastructures, especially bridges, compared to its spatial proximity to CBD.



1) Initial scatter plot: 1986 Census Enumeration Areas (app. 4 000 points)	2) Spatial transformation (for each point)	3) Transformed scatter plot

Figure 8 – Spatial transformation of points according to distance to CBD: 1) Initial scatter plot, 2) spatial translation and 3) transformed scatter plot.

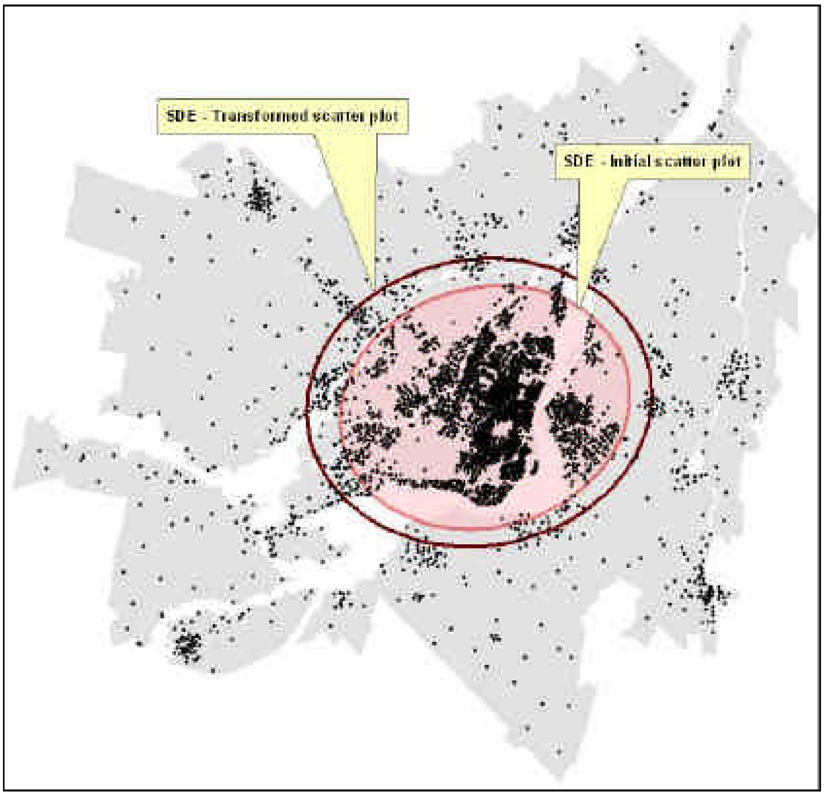


Figure 9 – Comparison between dispersion of Initial scatter plot and Transformed scatter plot using standard deviation ellipses

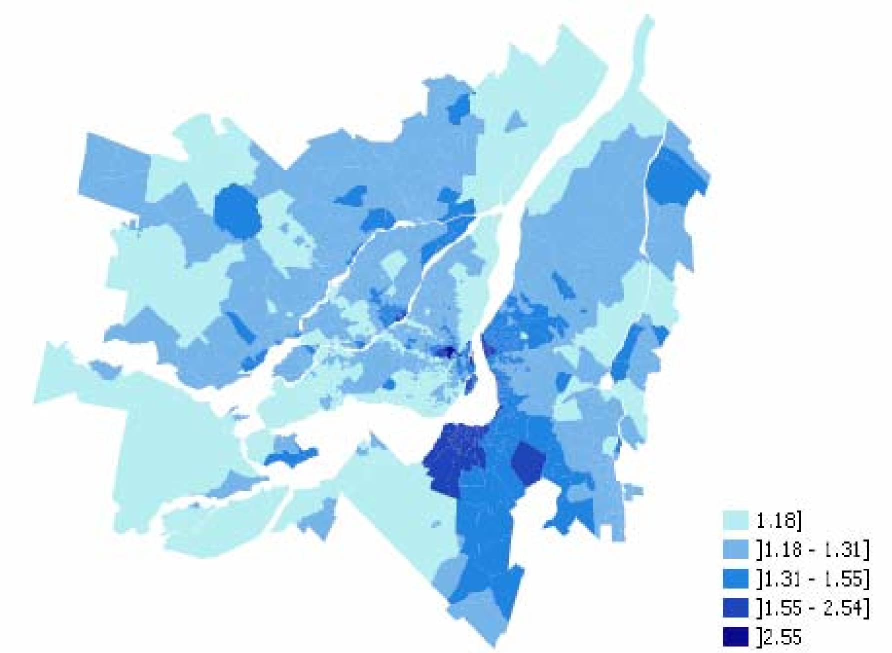


Figure 10 – Distance Elongation Index of the transportation network - CBD accessibility

3.4 Gross density versus network density

The Network Occupancy Index reveals the proportion of the gross area which is occupied by the transportation network. Hence, relation between gross density and network density is related to the magnitude of this index. According to the NOI measured in space (see Figure 4), the difference between gross density and network-density will be small in central areas and will increase with distance to CBD. Besides, network densities will always be higher (or theoretically equal to) than gross densities since network space is smaller or equal to gross space. Figure 11 shows the distribution of Gross and Network population density according to distance to CBD. Data from more than 4 600 analysis zones are used to produce this distribution. As anticipated, the population density declines according to the usual negative exponential model proposed by H. Bleicher (Bonnafous and Tabourin, 1998, Schéou, 1998, Peguy, 2000). In this model, $D(r) = Ae^{-br}$ (where r is the radius to CBD, A is the theoretical density in the CBD (r=0) and b is the density gradient.

A quick estimation of the parameters for the two densities especially reveals a notable difference in density gradients. Indeed, gross density has a higher rate of decline than network density. This is easily observable with the network/gross density ratio illustrated in Figure 11. This ratio is less than 1.5 within 12 kilometres of the CBD and goes up to almost 6.0 at 44 kilometres.

Table 1. Parameters of the Negative Exponential Model of population density, estimated for gross and network densities – 1998 Origin-Destination data

Estimation of the exponential negative model
1998 Data

	A	b	1/b	R^2
Gross Density	9 855.96	0.1089	9.2	0.8778
Network Density	9 945.70	0.0828	12.1	0.9053

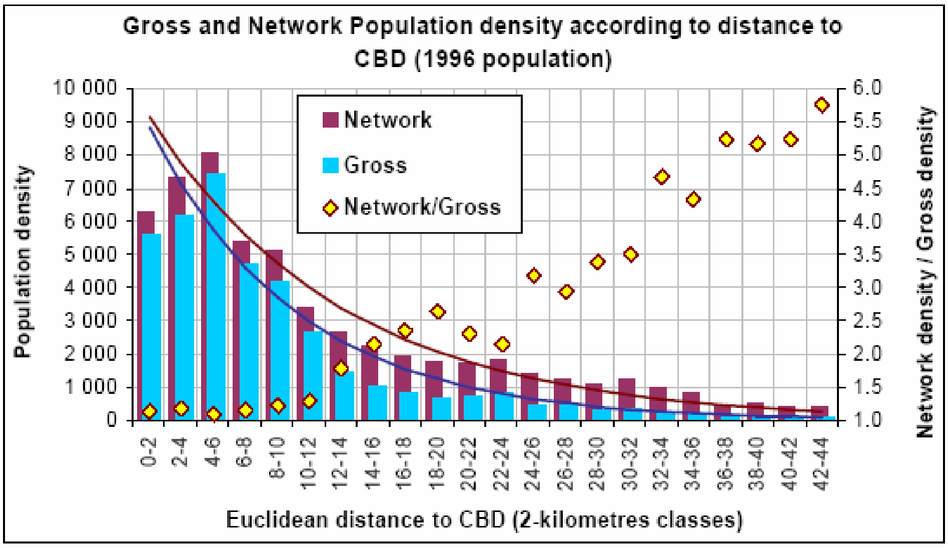


Figure 11. Distribution of Gross and Network population density according to distance to CBD and Network /Gross density ratio 1996 population (Census) - approximately 4 600 analysis zones

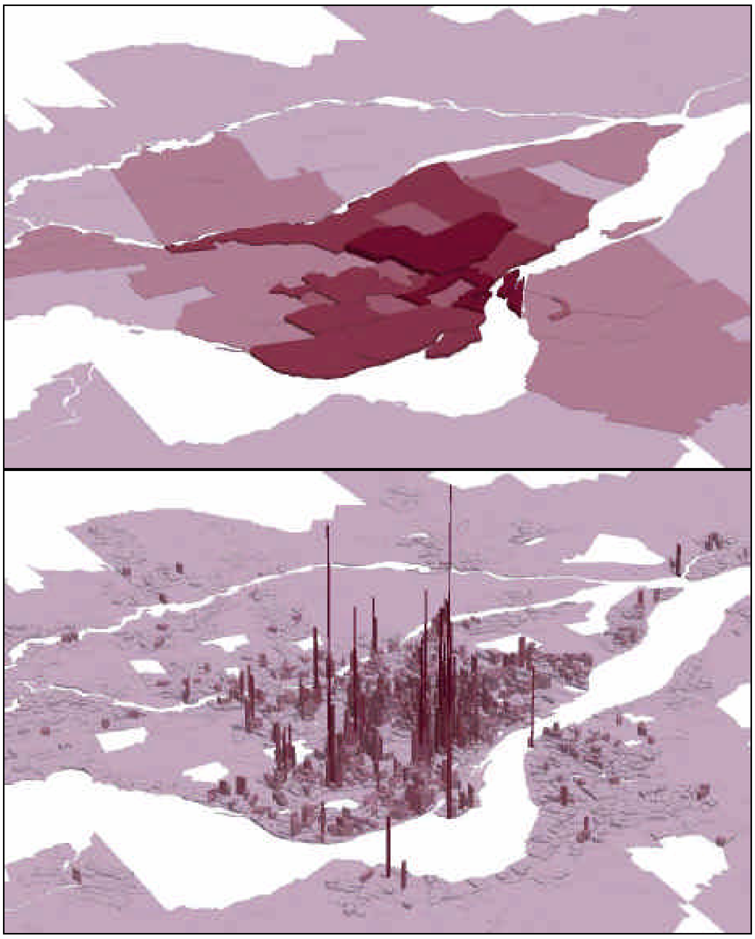


Figure 12 – Comparison between gross population densities estimated with two levels of spatial resolution: 65 municipal sectors (up) and 4 600 enumeration areas (down) – comparable extrusion factors (3D) – 1998 population

4 Relation between urban form and travel behaviours

The classical relation between population density and transit share is examined concurrently with the two concepts of density. The scale of population density is directly related to the zoning system used for analysis. In reality, the measure of population density will evolve in concert with the spatial resolution used for estimation. The previous distribution (Figure 11) was estimated on the basis of more than 4 600 analysis zones called enumeration areas (smallest zones for which census data are disseminated in Canada). With this zoning system, population density reaches values up to 7 000 people per square kilometres near the central areas (more than 85% of enumeration areas are less than 1 square kilometre wide). As illustrated in Figure 12, this level of spatial distribution really enlightens the spatial variability of population distribution over an urban area compared to a more aggregated figure (65 municipal sectors).

Table 2. Correlation matrix between urban form factors and mobility indicators (1987 and 1998)

Correlation matrix between urban form factors and mobility indicators (1987 - 1998)	Survey Year	MS: 65 municipal sectors EA: 4 600 Enumeration areas	Mobility indicators (Y)			Urban form factors (X)			
			Transit Share	Car trips / person	Kilometres / person	Gross Density	Network Density	NOI	TNOI
Transit Share	87	MS	1						
		EA	1						
	98	MS	1						
		EA	1						
Car trips / person	87	MS	-0.868	1					
		EA	-0.763	1					
	98	MS	-0.931	1					
		EA	-0.730	1					
Kilometres / person	87	MS	-0.779	0.771	1				
		EA	-0.441	0.552	1				
	98	MS	-0.792	0.680	1				
		EA	-0.496	0.607	1				
Gross Density	87	MS	0.772	-0.656	-0.661	1			
		EA	0.426	-0.370	-0.300	1			
	98	MS	0.793	-0.720	-0.798	1			
		EA	0.422	-0.363	-0.373	1			
Network Density	87	MS	0.785	-0.675	-0.675	0.987	1		
		EA	0.423	-0.367	-0.296	0.998	1		
	98	MS	0.810	-0.752	-0.810	0.983	1		
		EA	0.075	-0.064	-0.029	0.132	1		
NOI	87	MS	0.624	-0.359	-0.536	0.682	0.627	1	
		EA	0.263	-0.202	-0.261	0.320	0.291	1	
	98	MS	0.562	-0.358	-0.694	0.717	0.644	1	
		EA	0.257	-0.193	-0.369	0.313	-0.181	1	
TNOI	87	MS	0.686	-0.441	-0.688	0.558	0.686	0.825	1
		EA	0.407	-0.260	-0.407	0.257	0.250	0.469	1
	98	MS	0.605	-0.391	-0.719	0.579	0.567	0.822	1
		EA	0.007	-0.005	0.019	0.000	0.723	-0.125	1

The correlation matrix presented in Table 2 also gives a good idea of the interactions between urban form factors and mobility indicators when estimated with those same levels of spatial resolution. As anticipated, correlations between indicators are less significant when the analysis is performed at a high level of spatial resolution since variability is higher. Nevertheless, all the correlations are consistent in terms of direction.

Therefore, the classical relation between transit share and population density is examined with data aggregated according to 65 municipal sectors. They are used to estimate simple regressions involving gross population density and network population density. The correlation matrix reveals that correlations involving network density are similar than those involving gross density. Furthermore, both measures are correlated to the three mobility indicators.

Simple linear regressions are estimated for both gross and network densities. Due to the nature of the density measure (population per area) neither population nor area of zone are used for weighting since it could alter the significance of the regression. The concept of perceived density, proposed by Richardson and al. (1998), addresses some of the measurement issues related to population density. In the present case, every sector is equivalently considered, notwithstanding their size heterogeneity. Consequently, regressions are not weighted.

The plots of transit share as a function of gross and network population density are respectively shown in Figure 13 and Figure 14. They both reveal linear proportional relations: higher residential densities are related to higher shares of transit.

Table 3 summarizes the results of these estimations (AvgVal: average density, Slope: estimated parameters, AvgImp: average contribution of the explanatory variable in the estimation of the transit share). It appears that:

- Both density indicators are positively correlated with transit share and reveal a declining transit share in time (for similar densities);
- Slopes of the plots are similar for network and gross densities;
- For comparable determination coefficients, the importance of the constant in the linear equations is less when network density is used as the explanatory variable.

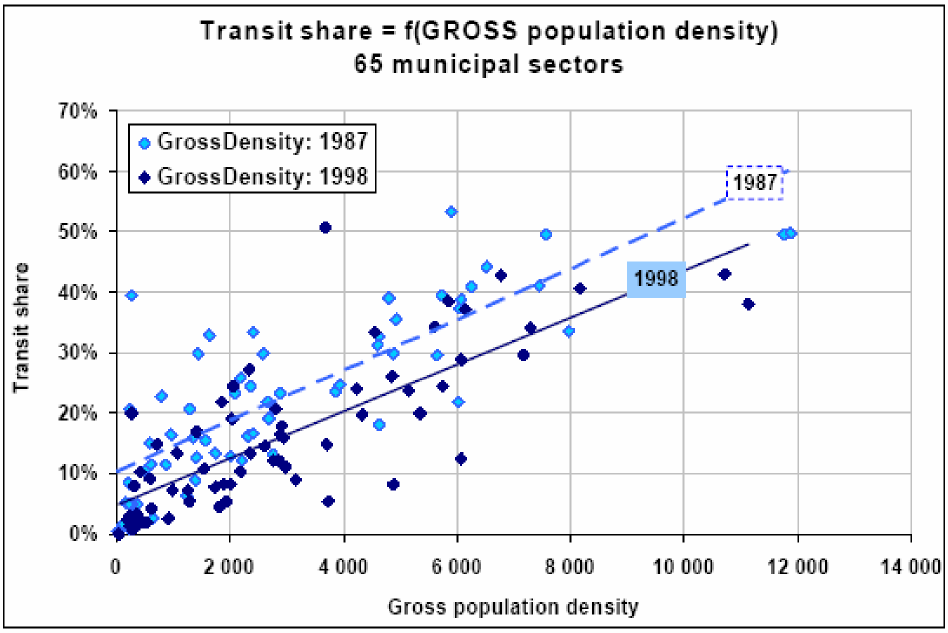


Figure 13 – Relation between transit share and gross population density – data aggregated in 65 municipal sectors – 1987 and 1998 Origin-Destination data

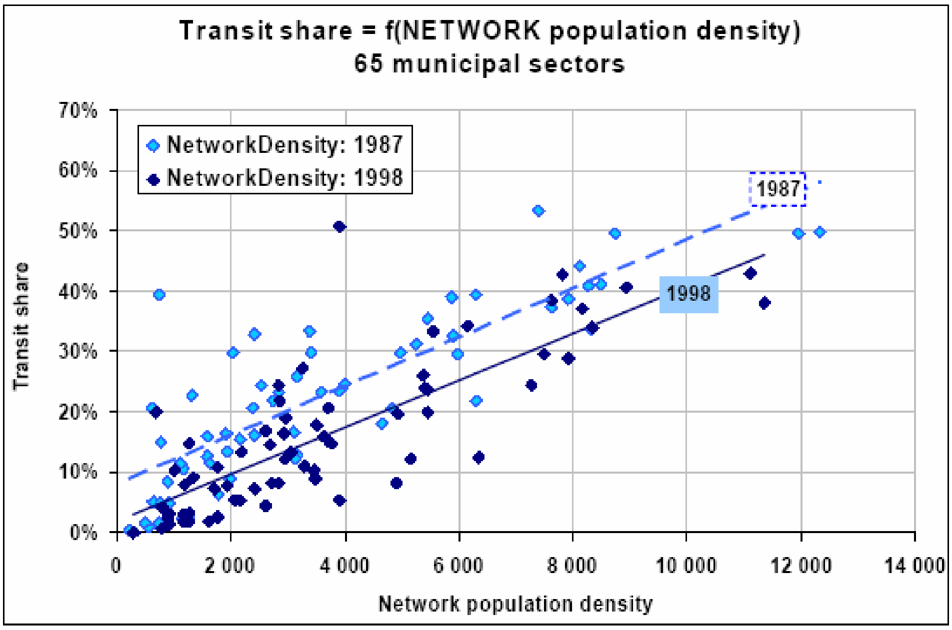


Figure 14 – Relation between transit share and network population density – data aggregated in 65 municipal sectors – 1987 and 1998 Origin-Destination data

Table 3. Results of the estimation of simple linear regressions between transit share and population density (gross and network) (1987 and 1998 Origin-Destination data, estimated with 65 data representing the 65 municipal sectors)

Simple regression models:
Transit share = f (population density)

Transit share: 1987 22.51%
1998 16.30%

Independant variable	Year	AvgVal	Slope	AvgImp	t	Const.	t	R^2
Gross population density	1987	2917.10	0.00419%	12.226%	9.649	10.285%	5.947	0.5964
	1998	2988.14	0.00389%	11.612%	10.345	4.687%	3.178	0.6295
Network population density	1987	3565.79	0.00405%	14.453%	10.046	8.058%	4.377	0.6157
	1998	3703.80	0.00388%	14.377%	10.953	1.922%	1.198	0.6557

5 Other perspectives related to the density concept

Finally, two perspectives related to the measure of density are presented:

- Measure of the average space occupancy by households of different sizes;
- Dynamic evolution of active population density throughout a typical weekday.

5.1 Average space occupancy by population segments

It is possible to convert density into space occupancy and to measure this occupancy for people or households belonging to various population segments. The average gross and network space occupied by households of various sizes was computed and examined according to distance to CBD. The computation is performed at a high level of spatial resolution (more than 4 600 analysis zones) and under the hypothesis that every household residing in a specific analysis zone occupies the same space.

First, the relation between the network space and the gross space occupied by a single household and a single person is examined for different places of residence. As illustrated in

Figure 15, the average occupied network space increases with remoteness from CBD. Furthermore, the lag between network space and gross space increases accordingly.

When this same space occupancy is examined for households of different sizes, it appears that the space usage increases proportionally to the size, notwithstanding the place of residence. The down zoning phenomenon is further confirmed by the important increase of average space occupancy with distance from CBD. Figure 16 displays the "spatial obesity" issue concerning households of every size when residence location drifts out from the central areas. Actually, the average space occupancy is approximately 300 network-square metres in CBD (less than 5 km) while it is more than 2000 network-square metres per household residing at 30 kilometres from CBD.

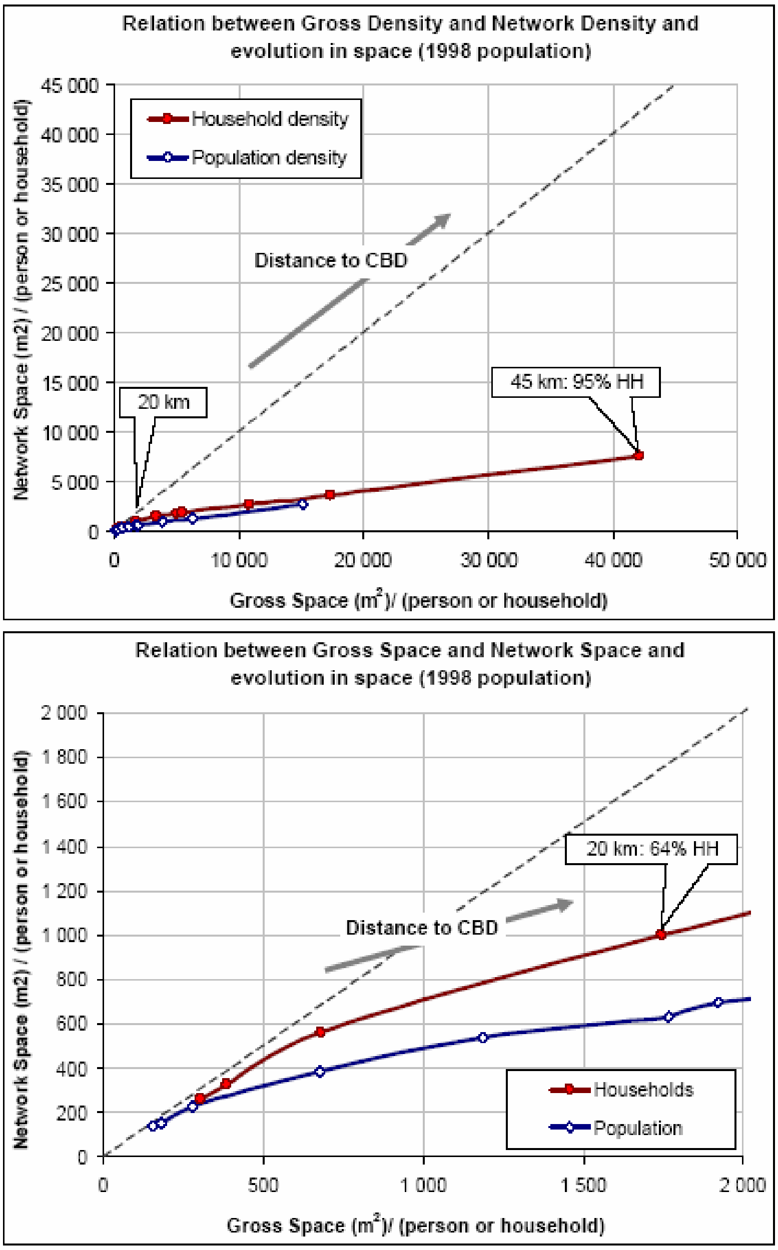


Figure 15 – Relation between Network density and Gross density according to distance to CBD – 1996 population (Census)

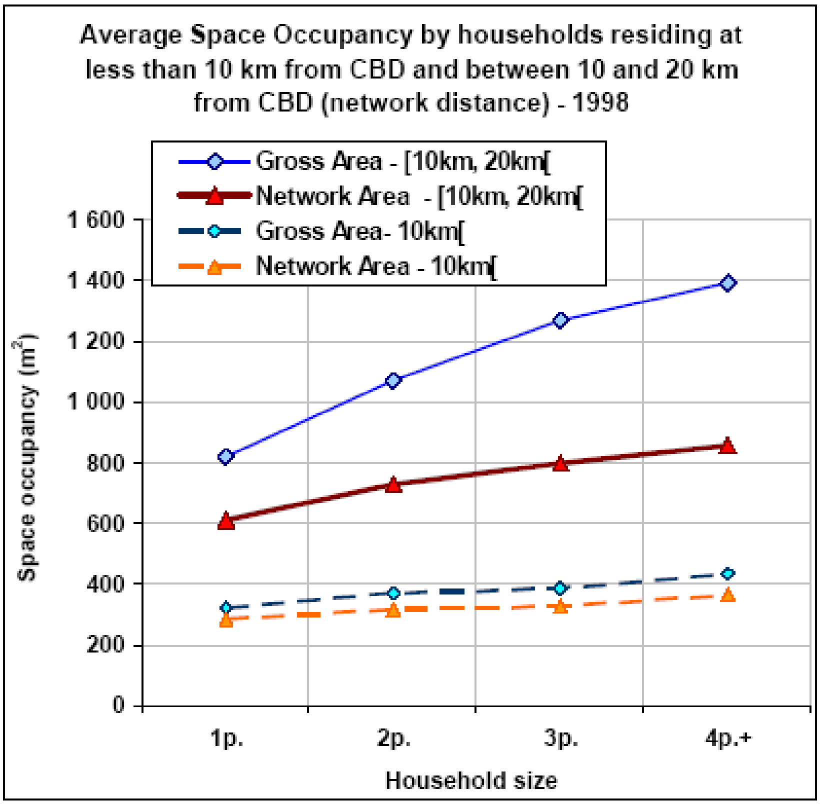


Figure 16 – Average Space Occupancy (Gross and Network) of households of different sizes and residing in different locations (network distance to CBD)

5.2 Dynamical aspect of population density

A last perspective concerning population density is examined. With its daily activities, every person alters the spatial distribution of the overall population. Actually, a large proportion of individuals is mobile and leaves their stable location, their home, for a considerable time during an average weekday. This migration significantly affects the population density in precise areas, especially activity centres near CBD. With totally disaggregate data from OD surveys, it is possible to monitor the active population during an entire day and to appreciate the evolution of population density over the area.

This monitoring was performed with data from the 1998 OD survey. The Montreal Area is represented by one square kilometre cells which allows illustrating the temporal evolution of population in gross density. More than 6 050 cells from which 2 608 are inhabited (residence location) are required to cover the entire area.

Figure 17 shows the dynamics of space usage by the active population. Population density per cell (excluding zero-trippers) is presented for six periods of the day. The importance of the CBD and neighbouring areas for the daily activities is obvious. Furthermore, Figure 18 shows the distribution of gross population density according to distance to CBD. The daily migration movement is confirmed again by the density peak observed around 12h00.

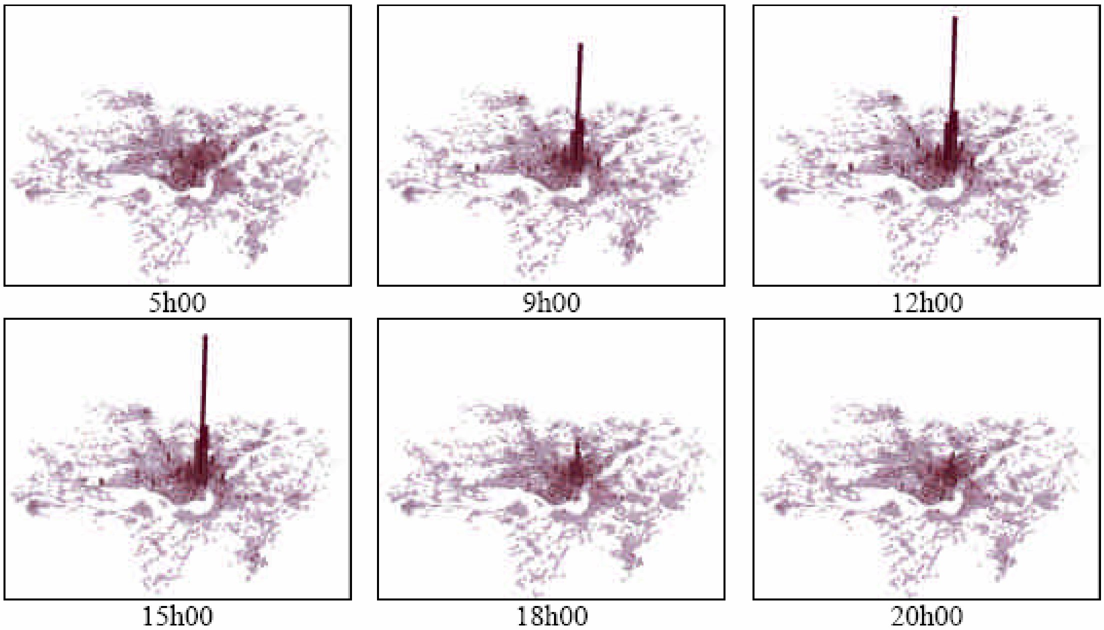


Figure 17 – Chronology of the spatial location of mobile population during an average weekday (1998) – square kilometre cells

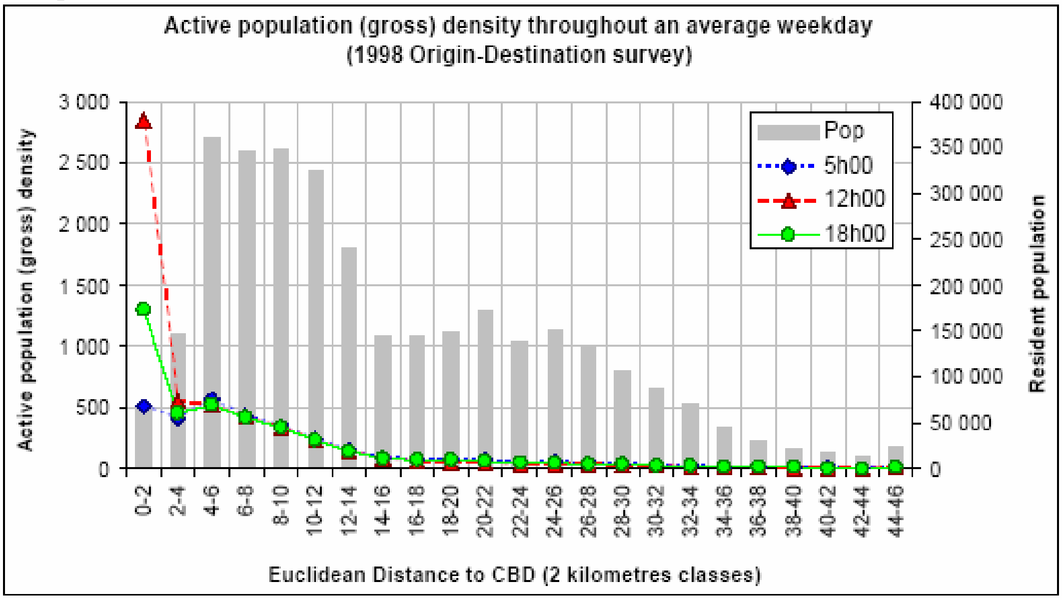


Figure 18 – Dynamical aspect of population density – gross population density estimated per one square kilometre cell at three strategic periods of an average weekday

6 Discussion and conclusion

This paper has discussed the nature of urban space. It has presented some space occupancy indicators aiming at thoroughly characterising the structure of a specific urban area and transportation network. These indexes are likely to permit the comparison between several urban areas and to refine the classical measures which are usually computed without spatial structure discrimination.

This paper has also presented ways to assess the implications of using network distances instead of classical Euclidean distances. The spatial transformation of points, according to CBD, as well as the appraisal of elongation index at a high level of spatial resolution, allows detecting easily the influence, on accessibility to a key location, of the transportation network.

This was followed by the estimation of simple relations linking transit share and density. The purpose of these simple models was to evaluate whether network density was more fitted to explain transit share. Both indicators are similarly related to transit share. More complex models need to be evaluated in order to correctly appreciate the potential contribution of refined measures. Still, a lot of questioning remains regarding the concept of density. This was further brought up with the comparison between population densities estimated at two level of spatial resolution. The impacts of spatial aggregation on parameters estimation are considerable, and even question the validity of such estimations.

The study of space occupancy by people and households has then confirmed that urban sprawl is combined to a "spatial obesity" phenomenon. Finally, it was demonstrated that totally disaggregate data can assist the monitoring of daily activities over an entire urban area. Density concept also needs to evolve towards a dynamical density concept that can appreciate the evolution of population during their daily activities.

Acknowledgments

The authors wish to acknowledge the transport authorities by whom the large-scale surveys, mainly Household Origin-Destination surveys, are conducted. Those surveys authorize the continuation of a travel behaviour observational and analytical culture in the GMA: STM, RTL, STL, AMT and MTQ.

The authors also acknowledge the contribution of two subsidizing organisms: FCAR (Fonds pour les chercheurs et l'aide à la recherche) and NSERC (National Sciences and Engineering Research Council of Canada).

References

Bonnafous, A., Tabourin, E., 1998. Modélisation de l'évolution des densités urbaines, in Données Urbaines n°2, ed. Anthropos, mai 98, pp. 273-285.

Bovy, P.-H. 1999. Structure urbaine et répartition modale, tendances globales et effets sur les transports publics, Transport Public International, Vol. 48, n°1/1999, pp. 8-15.

Chapleau, R., 1998. Free-wheeling urban mobility: a question of densities, motorization, employment and transit decline, World Conference on Transportation Research, Anvers, Belgique

Chapleau, R., Morency, C., 2004. Modelling urban Mobility with Geodemographics, 10th World Conference on Transportation Research, Istanbul, Turquie (to be presented)

Frank, L.D, Pivo, G. 1994. Impacts of Mixed Use and Density on Utilization of Three Modes of Travel: Single-Occupant Vehicle, Transit, and Walking. Transportation Research Record 1466: 44-52, Transportation Research Board, Washington, D.C.

Frankhauser, P., Genre-Grandpierre, C. 1998. La géométrie fractale – un nouvel outil pour évaluer le rôle de la morphologie des réseaux de transport public dans l'organisation spatiale des organisations, les Cahiers Scientifiques du Transport**,** 33, pages 41-78.

Huriot, J.-M., Perreur, J. 1990. Distance, espaces et représentations. Revue d'Economie Régionale et Urbaine (2), pp. 197-237.

Miller, E.J., Kriger, D.S., Douglas Hunt, J. 1998. Integrated Urban Models for Simulation of Transit and Land-Use Policies, TCRP Project H-12, Final Report, 250 pages.

Morency, C., 2004. Contributions à la modélisation totalement désagrégée des interactions entre dynamiques spatiales et mobilité urbaine, thèse soumise pour l'obtention du grade de Ph.D., École Polytechnique de Montréal, 400 pages.

Morency, C., Chapleau, R., 2003. Mesure de diverses expressions de l'étalement urbain à l'aide de données fusionnées d'enquête transport et de recensement: étude multi-perspectives du Grand Montréal, Les Cahiers scientifiques du transport, Lyon, no. 43, pages 3-34

Morency, C., Chapleau, R., 2003. Randonnée analytique à travers les dynamiques spatiales et les comportements de mobilité, 38e Congrès de l'Association québécoise du transport et des routes, Sherbrooke, pages 19.

Péguy, Pierre-Yves 2000. Analyse économique des configurations urbaines et de leur étalement, Thèse pour le Doctorat en Sciences Économiques, mention Économie des Transports, Université Lumière Lyon 2, Faculté de Sciences Économiques et de Gestion, 490 pages.

Richardson, A.J., Brunton, P.J., Roddis, S.M. 1998. The Calculation of Perceived Residential Density, Road & Transport Research, 7, pp.3-15.

Rodrigue, J-P et al. 2003. Transport Geography on the Web, Hofstra University, Department of Economics & Geography, http:://people.hofstra.edu/geotrans.

Scheou, Bernard 1998. L'estimation de la population totale à un niveau communal: utilisation du modèle de René Bussière, Document de travail no 98/01, http://web.mrash.fr/let/francais/indexpub.htm

Wegener, M., Fürst, F. 1999. Land-Use Transport Interaction: State of the Art. Review of Technical issues, Report to the European Commission. Berichte aus dem Institut für Raumplanung 46. Dortmund: Institut für Raumplanung. http://www.inro.tno.nl/transland/Deliverable%202a.pdf