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Author(s)	Vega, Amaya
Publication Date	2009
Repository DOI	<a href="https://doi.org/10.1016/j.tra.2008.11.011">DOI 10.1016/j.tra.2008.11.011</a>

# **A methodological framework for the study of residential location and travel-to-work mode choice under central and suburban employment destination patterns**

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## **Abstract**

The aim of this paper is to contribute to the methodological questions that arise from the study of the simultaneous choice of residential location and travel-to-work mode under central and non-central or suburban employment patterns. Geographic Information System (GIS) visualisations and network analysis are used to generate a choice set based on the definition of spatially aggregated alternatives. Discrete choice models specified as cross-nested logit (CNL) are estimated for each of the two different types of employment patterns and direct and cross elasticities are presented. The analysis is carried out for the Greater Dublin Area, a metropolitan region that is a recent example of rapid employment suburbanisation and residential sprawl in a European context. A simulation exercise, tracing the extent of mode switching and location switching behaviour is undertaken using the framework developed.

*Keywords:* Residential location; Travel mode choice; Employment suburbanisation; Discrete choice analysis; Geographic Information Systems

JEL Codes: R41; R14; C25

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Acknowledgements: the authors wish to thank Frank McCabe and other staff at the Dublin Transportation Office for their help in providing data and discussion for this research. The authors also wish to thank two anonymous referees for helpful suggestions and points of clarification.

## **1. Introduction**

There is a strong correlation between the process of suburbanisation of employment and residential sprawl, and the increase in car-based commuting travel due to lower transport costs (Nechyba and Walsh, 2004). The Greater Dublin Area (GDA) is a recent example of this global trend within the European context.

This paper presents a modelling framework that combines standard discrete choice models with GIS network analysis for the integrated study of residential location and travel mode decisions. The research objectives are to contribute to the methodological questions that arise from the simultaneous study both decisions and to analyse the differences in home location and commuting mode choice arising from the process of employment suburbanisation when this is compared to the traditional monocentric city case scenario.

Some recent studies of the simultaneous choice of residential location and travel mode argue that the extent to which travel costs affect residential location depends primarily on the number of alternatives of travel-to-work available for the commuter (Eliasson and Mattsson, 2001). Under the assumption of constant public transport provision, location and travel mode choice patterns are expected to differ considerably among those commuting to the Central Business District (CBD) and those travelling to suburban job locations. This paper explores these relationships in the context of the GDA.

The combination of residential and employment suburbanisation with sustained low levels of investment in the public transport network and the existence of a predominantly radial public transport system have contributed to the consolidation of the private car as the main mode of travel to work in the GDA. This has had major implications for commuting time and traffic congestion and it makes the Dublin

region an attractive case study for the comparative analysis of residential location and travel mode choice behaviour across central and suburban employment destinations.

Direct and cross elasticities with respect to the main travel-to-work attributes are computed and a simulation exercise is carried out to analyse the extent to which increasing car travel costs affect home re-location and travel mode switching across employment destinations.

The discrete choice analysis presented builds on the empirical literature introduced by Lerman (1976), which applies random utility maximisation (RUM) theory and discrete choice modelling to empirically estimate joint probability choice models of residential location and other household mobility decisions. Within this modelling framework, the Multinomial logit (MNL) and Nested logit (NL) models are considered the most broadly used model structures to estimate the joint probability choice of residential location and travel mode choice. Geographic Information System (GIS) network analysis is used to generate an aggregated spatial choice set, which is based on the definition of service areas around each employment centre.

The next section reviews the main contributions to the study of the simultaneous choice of residential location and travel mode. The conceptual framework for the analysis is presented in the next section, followed by the data sources and variable specifications. Section 5 describes the empirical model structure and Section 6 presents the CNL estimation results and direct and cross elasticities for CBD and suburban commuting. In Section 7, an increase in travel costs is simulated as a final application of this modelling framework. The final section outlines the main conclusions and discusses the policy implications of the analysis presented.

## **2. Existing research**

During the last three decades, most of the research presented in the literature dealing with the simultaneous choice of residential location and travel mode has applied random utility maximisation (RUM) theory and discrete choice modelling to empirically estimate joint probability choice models.

The simultaneous choice of residential location and travel mode is supported by early theoretical contributions that acknowledged the need for integrating both decisions in transport and land use models (Le Roy and Sonstelie, 1983; Brown, 1986). Since the mid-1970s, the most significant contributions to the study of this relationship come from empirical studies of residential location and other household's decisions, including the choice of workplace.

Empirical contributions to the simultaneous choice of residential location and travel mode are strongly influenced by Lerman (1976). Discrete choice models of residential location are often estimated as models of mobility bundles, defined by Lerman (1976) as all the household decisions that affect the choice of residential location, i.e. location, housing, automobile ownership and mode of travel to work. Most of the empirical contributions reviewed in this paper explore the various factors affecting joint probability models that include all or some of the above household decisions.

Investigation of residential location and travel mode choices has not been limited to empirical research. Theoretical papers have also contributed to the understanding of this relationship. The introduction of mode choice and commuting cost into the Alonso-Muth model is found to be fundamental for the understanding of the spatial distribution of residences by income (LeRoy and Sonstelie, 1983). Brown (1986) suggests that travel mode and residential location are not independent goods and, therefore, demand for either good needs to be modelled considering the other.

DeSalvo and Huq (2005) in a recent theoretical study support the findings of previous theoretical studies of residential location and travel mode choice. These findings suggest that high income individuals use faster modes and travel short distances to work and those commuting long distances, use faster modes and experience lower marginal commuting costs<sup>2</sup>. The model results also suggest that if housing is a normal good, households with higher non-wage incomes are more likely to live further away from the CBD.

In modelling spatial choices such as residential location, a number of difficulties may arise. Ben-Akiva and Lerman (1986) identifies two main problems related to the application of discrete choice models to the study of residential location. The first problem arises when the choice set is too large, making the process of data management and model estimation very arduous for the analyst. The most widely applied solution to this problem was proposed by McFadden (1978). Estimates obtained by sampling from the full set of alternatives, including a set that comprises the chosen alternative and a sample of non-chosen alternatives are consistent if the choice set is described by a MNL model and the sampling strategy satisfies some specific conditions (see Ben-Akiva and Lerman (1985) for details). The second problem relates to the lack of information on the *elemental alternatives*. It is difficult to determine what constitutes an elemental alternative, particularly when using highly disaggregated residential location data at the dwelling or street level. In general, highly disaggregated spatial data are unavailable and available data tend to be aggregated into some sort of geographic unit such as census tracts or traffic zones. This is one of the most common problems when modelling the choice of residential

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<sup>2</sup> The results presented in DeSalvo and Huq (2005) are affected by a number of restrictive assumptions in the formulation of their theoretical model. This could explain why some of these results differ from those found in other recent empirical studies that consider the effects of income on travel patterns (Carlsson-Kanyama and Lindén, 1999; Glaeser et al., 2000).

location using census data and it provokes one of the best-known problems in spatial quantitative analysis known as the modifiable areal unit problem (MAUP). As such, MAUP may cause unreliable estimation results that depend on the definition of the data areal units (Fotheringham et al., 2000).

One of the main assumptions of discrete choice models for non-spatial contexts is that individuals are able to evaluate all potential alternatives. In other words, it is assumed that individuals have full information on all possible alternatives. In the case of the spatial choice, individuals are not likely to evaluate a large number of alternatives all at once. Instead, they are more likely to identify a series of clusters from where they choose first and then, they evaluate alternatives within that particular cluster (Fotheringham, 1988, Fotheringham et al., 2000).

Hierarchical choice behaviour can be handled by using well-defined NL models. However, the definition of precise clusters or nests is a difficult task. In a spatial context, it is not clear how mental clusters of alternatives are formed, whether their boundaries are physical, perceptual or entirely subjective (Fotheringham and Curtis, 1999).

Due to data restrictions, most empirical studies present some sort of aggregation of residential location alternatives. The aggregation varies from geographical units such as census tracts or traffic zones found in Ben-Akiva and Bowman (1998), Rappaport (1997), Sermons and Seredich (2001) and Waddell (1993; 1996), to alternative aggregations based on the characteristics of the dwelling, neighbourhoods or communities. These aggregations are believed to fit better the research objectives of the particular model (see Boehm (1982) and Tu and Goldfinch (1996)). In some cases, already grouped alternative locations are clustered again into larger units to reduce the already large data sets. Examples are found in Levine (1998) and Sermons and

Seredich (2001). A number of empirical studies of residential location and other household mobility decisions contain highly disaggregate data, allowing them to model the choice of residential location at the dwelling level (see Quigley (1985) and Sermons and Koppelman (2001) as examples).

One of the debates that emerged from the estimation of discrete choice models of residential location and travel mode is whether job location should be modelled simultaneously with residential location or assumed to be exogenous. There are studies that assume that the influence of residential location on job location decisions is as important as the influence of job location on residential location. Both decisions are treated simultaneously in recent empirical papers (Abraham and Hunt, 1997, Freedman and Kern, 1997, Romani et al., 2003, White, 1988). Simpson (1987) proved that models introducing simultaneous estimation of home location and workplace explain commuting behaviour more accurately than those that only consider one of the decisions. On the other hand, Deitz (1998) presented empirical evidence on the relationship between employment and residential location and proved that access to work was not the main determinant of residential location. Other factors such as neighbourhood characteristics were found to be more likely to influence location decisions.

Regarding the effect of the workplace on location and travel patterns, little empirical work has been done to explore the impact of issues related to societal change and transport. The incidence of workplace-related changes due to the introduction of information and telecommunications technologies has been identified as one the most promising areas of research for residential location and travel (Giuliano and Gillespie, 1997). These impacts are concerned not only with the quantity and nature of travel-to-work patterns, but also with the location of workplaces. Given the possible increase in intensity of the above effects on

location and travel, assumptions of fixed job location in simultaneous choice models of residential location and travel mode may be seen as unrealistic.

In spite of this, many of the empirical studies reviewed in this paper assume fixed job location and estimate residential location choices as a function of travel variables to work or non-work locations, i.e. travel distance, travel time, or parking costs (Lerman, 1976, Levine, 1998, Quigley, 1985, Sermons and Seredich, 2001). Based on previous research, Waddell (1993) places job location on the upper nest of a NL model as the marginal choice. Following Lerman (1976), Abraham and Hunt (1997) consider job location as part of the choice set. The difference in this model is that it is not a joint logit model as in Lerman, but an NL model where residence and employment location choices are placed in the upper nest and travel mode choice probabilities are assumed to be conditional on location.

A recent methodological contribution to the application of discrete choice modelling to the spatial choice is by Bhat and Guo (2004). The Mixed Spatially Correlated Logit (MSCL) is developed as a closed-form Generalised Extreme Value (GEV) model with flexible correlation structure and random coefficients to capture spatial autocorrelation and random heterogeneity across individuals. In spite of recent advanced methodological contributions like the MSCL model, the MNL and NL are still the most widely applied model structures for policy analysis. A model structure that allows for a more flexible correlation of the error term - the CNL model - is used in this paper to study the simultaneous choice of residential location and travel mode in the GDA.

### **3. The conceptual framework**

We follow the conceptual framework introduced by Lerman (1976). A number of factors influence residential location and travel mode decisions. Land-use characteristics of the chosen residential area and the socio-economic characteristics of the commuter in terms of family structure and lifestyle have long been identified as main influencing factors on mobility decisions (Boarnet and Crane, 2001; Cervero, 2002).

In contrast to some other studies of residential location and travel mode choice, in this paper the location of employment is not part of the choice set. Job location, understood as the spatial pattern of employment and the level of wages, is assumed to be exogenous. Travel time and the travel cost are computed as a function of the commuting distance, that is, the distance between residential and employment location.

Residential location and travel behaviour are studied under two case scenarios: central and suburban employment. The case of central employment is the classic example of a monocentric city, where all the jobs are located at the CBD. Vega and Reynolds-Feighan (2008) carried out an extensive analysis of origin-destination commuting trips in the GDA and identify and characterise four key employment sub-centres in the region. The suburban employment case shows all jobs concentrated into these four employment sub-centres identified outside the CBD.

Differences between central and suburban scenarios are based on the location of jobs for the sample of commuters considered in each case. The definition of the spatial choice set for both groups of commuters is based on road distance to work. A number of studies have examined location and commuting decisions for households with two workers. Due to the characteristics of the data discussed in the next section, this

model is limited to household mobility decisions made at the individual level and not at the household level. Hence, the unit of analysis is the individual, who selects from several combinations of distance to employment and mode of travel to work.

In the case of central employment destinations, the residential location choice set is based on a series of concentric road-distance rings around the CBD. The suburban employment destination scenario responds to a similar spatial choice set based on concentric road-distance rings, but this time including road-distance measures to each employment sub-centre in addition to those computed to the CBD. Spatial employment patterns for the central and suburban commuting trips are shown in a stylised manner in Fig. 1.

[Fig. 1 here]

## **4. Data**

### *4.1. Data sources*

The area selected for this analysis is the GDA and it includes the four inner counties of Dublin: Dublin City, South Dublin, Dun Laoghaire-Rathdown and Fingal, and the four adjacent counties to Dublin: Kildare, Meath, Wicklow and Louth. Fig. 2 shows a map of the GDA and the location areas.

[Fig. 2 here]

The primary source of data for the analysis is the *Place of Work Sample of Anonymised Records* (POWSAR). This is the only source of disaggregate origin-destination travel-to-work data in Ireland. POWSAR is a 30% sample of the 2002 Irish Census of Population and it provides socio-economic information on individuals who at the time of the census were (i) enumerated in a private household; (ii) 15 years old or over; (iii) enumerated at home, and (iv) their present principal status was

working for payment or profit. It also provides information on the characteristics of the households, means of travel, distance and journey times to work as well as place of residence and place of work<sup>3</sup>.

In addition to the 2002 Irish Census of Population, three additional sources of data are used in the analysis: origin-destination travel time and cost matrices by car and public transport from the Dublin Transportation Office (DTO) transportation model; the 2003 Permanent / ESRI National House Price Index with information on property prices by postal code and county and digital data for GIS analysis, provided by URBIS<sup>4</sup> and licensed by Ordnance Survey Ireland. These data sources are discussed in the next paragraphs.

Origin-destination travel time and travel cost matrices are provided by the DTO at the electoral district level for all possible origin-destination trips by both, car and public transport. Car travel costs are computed as the monetary costs associated with fuel consumption and they are a function of travel distance, parking charges at the destination and other parking restrictions. Public transport costs consist of a system of varying fares with distance that includes a boarding penalty measure to account for the fact that the bus is an inferior mode in relation to rail<sup>5</sup>. Car and public transport travel times are computed for the morning peak period and they include walking time to stop/station and waiting time at the stop/station for public transport and in-vehicle time in minutes for public transport and private car travel.

Property prices data come from the Irish Permanent / ESRI National House Price Index. The index follows the methodology developed by Fleming and Nellis (1985) in

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<sup>3</sup> 2002 Irish Census of Population. Place of Work Sample of Anonymised Records (POWSAR) User Guide. ([www.cso.ie/census/documents/PlaceofWork-SARUserGuide2002.pdf](http://www.cso.ie/census/documents/PlaceofWork-SARUserGuide2002.pdf))

<sup>4</sup> University College Dublin's integrated Urban Information System (URBIS)

<sup>5</sup> The boarding penalty measure is part of the data set generated by the DTO transportation model.

the Halifax Index, which is based on the hedonic model approach. Further details on the construction of this index can be found in Conniffe and Duffy (1999).

Additional data sources used for the GIS analyses include digital data obtained from URBIS at University College Dublin and licensed by Ordnance Survey Ireland. URBIS digital data includes digital boundaries for electoral districts and counties and the geometric transport network for the region.

There are well known difficulties arising from the use of census data when modelling spatial choices: In this paper, these relate to the aggregated nature of the Irish census data into electoral districts. This is also the case for the DTO travel data, that are spatially aggregated into the same units.

#### *4.2. Variable specification*

The variables used for the analysis can be classified into three groups: socio-economic characteristics, property prices and travel-related attributes.

A number of socio-economic variables are used for the analysis. These include household size (i.e., number of usual residents in the household), household composition or structure, nature of occupancy (i.e., whether the individual's accommodation is owner occupied or rented), number of cars or vans available in the household, gender, age and socio-economic and industrial group. The classification by socio-economic group aims to bring together persons with similar social and economic statuses on the basis of the level of skill or educational attainment required. In the case of the industrial group, this corresponds to the Industry group that the individual's employer belongs to as coded by the Irish Central Statistic Office (CSO). Based on the view that the value of access tends to be capitalised into property prices, Srour et al. (2002) explore the importance of access on property values and assess the effect of access on residential location choices. Land prices are found to be a potential

valuable measure of access for residential location modelling and they are used in this analysis as an explanatory variable<sup>6</sup>.

Travel variables include travel times and travel costs by car and public transport computed from each electoral district to each employment location, i.e., the CBD and the employment sub-centres considered as suburban job destinations.

Additional individual-specific dummy variables are created for each of the employment centres<sup>7</sup> and for car availability. Table 1 provides descriptions for the entire set of independent variables used in the modelling process.

[Table 1 here]

## 5. Model structure

A discrete choice model specified as a CNL model is formulated for the joint probability choice of residential location and travel-to-work mode of transport. The decision maker is the Dublin commuter, defined as an individual travelling to work on a daily basis by a motorised mode of transport, i.e. car or public transport.

GIS Network Analysis is used to generate road distance service areas, which are the spatial unit of analysis for the residential location choice set. Service areas, also known as buffers, have been traditionally defined using simple methods such as the circular Euclidean distance or the mutually exclusive Thiessen polygons. However, these methods create service areas with no relation to the geometry of the transport network.

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<sup>6</sup> This differs from most transport papers where access is usually modelled through transportation performance functions that represent the average cost from a given origin to a number of destinations (Cascetta, 2001).

<sup>7</sup> Employment centres correspond to those identified and characterised in a previous study carried out by the authors (Vega and Reynolds-Feighan, 2008). Four employment centres are included: a relatively centric employment centre (N11) and three peripheral employment locations (Clondalkin-Tallaght, Airport and Blanchardstown)

The ESRI's ArcGIS Network Analyst extension provides network-based spatial analysis that facilitates the generation of service areas based on the geometry of any given digital road transport network. This is used to generate service areas defined as road-distance-based polygons from previously defined points in the road transport network.

In order to analyse spatial choice at the electoral district level, the ESRI's ArcInfo Overlay toolset is used for the geometric intersection of the spatial data sets describing service areas and electoral district boundaries<sup>8</sup>. Each service area is constructed by considering a number of road distances to each employment centre as catchments areas using all the accessible motorways, national primary, secondary and regional roads as the geometric transport network.

Following Ben-Akiva and Lerman's (1986) general theory for aggregation of alternatives, an aggregation bias correction term is introduced in the model. This is a zone-specific term representing the size of the aggregate alternatives computed as the natural log of the number of occupied households by the chosen tenure type.

The  $t$  travel mode choice sub-set consists of two motorised modes of travel to work: the private car and public transport. The  $r$  residential location sub-set has 3 alternatives in the case of central employment and 6 alternatives for the suburban case<sup>9</sup>. Therefore, the model choice set  $C = c_1, \dots, c_N$  is defined as the joint choice set of  $r = 3$  or  $r = 6$  and  $t = 2$ , which creates a set of  $N = 6$  alternatives for central employment destinations and  $N = 12$  alternatives for suburban employment.

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<sup>8</sup> See ArcGIS Desktop Help 9.2 at [www.esri.com](http://www.esri.com) for details on this methodology and Appendix C for the specific steps followed for in the GIS network analysis carried out in this dissertation.

<sup>9</sup> Given the short road distances between suburban employment sub-centres, the spatial choice sub-set in this model is more detailed for suburban destinations than for CBD destinations, thereby capturing more comprehensive location behaviour around each employment sub-centre.

Under the RUM framework, a decision-maker  $i$  facing a choice among  $N$  alternatives obtains a certain level of utility  $U_{in}$ ,  $n = 1, \dots, N$  from selecting alternative  $n$ . The decision maker will select alternative  $m$  if and only if the utility provided by alternative  $m$  is the largest utility, i.e.  $U_{im} > U_{in} \forall n \neq m$ .

Utility is modelled as the sum of a systematic component and a random component. The systematic component  $V_{in}$  is a function of the attributes of the alternatives and of the characteristics of the decision maker, while the random component  $\varepsilon_{in}$  captures all other factors unobserved by the researcher,

$$U_{in} = V_{in} + \varepsilon_{in} \quad (1)$$

In this particular model, the simultaneous choice of residential and travel mode is specified as follows:

$$V_{irt} = f(tt_{irt}, tc_{irt}, hp_r, se_i) \quad (2)$$

The systematic utilities for each of the alternatives are a function of their travel and land use attributes, i.e. travel time  $tt$ , travel costs  $tc$ , property prices  $hp$  and the socio-economic characteristics of the decision maker  $se$ . Additional bias correction terms for the endogenous stratification of the sample (Ben-Akiva and Bowman, 1998) and the aggregation of alternatives are also included in the model specification. These variables are not truly components of the systematic utility function, but allow the estimates to be consistently estimated.

The application of the CNL structure in this particular model has two main advantages. Firstly, it provides a more flexible correlation structure of the error term that allows the potential spatial correlation between alternatives that belong to contiguous rings to be captured. Secondly, similar to the MNL and NL model

structures, the CNL model has a closed-form expression derived for the calculation of its probabilities.

The CNL model can be seen as an extension of the NL model designed for choice situations where each of the alternatives may belong to one or more nests. The CNL model is one of the various models developed from McFadden's (1978) GEV model and specified for overlapping nests.

The term *cross-nested logit* model was first introduced by Vovsha (1997) in a mode choice model for the Tel Aviv Metropolitan Area and it has been further extended by Bierlaire (1998), Ben-Akiva and Bierlaire (1999), Papola (2004) and Bierlaire (2006) to refer to a series of models with overlapping nests.

Wen and Koppelman (2001) offer a comprehensive review of the most significant developments for models with overlapping nests and an account of the differences and similarities between them. They present the Generalised Nested Logit (GNL) model and show other cross-nested logit models as special cases of the GNL model, providing a formulation for direct and cross elasticities.

In this paper, Bierlaire's (2006) CNL model formulation is followed and Wen and Koppelman's (2001) direct and cross elasticities are presented.

A set of allocation parameters with a value between 0 and 1 is defined for each nest and alternative. These parameters represent the degree of membership of each alternative to each nest and can be estimated or assumed to be fixed. A value zero indicates that the alternative does not belong to the nest at all. For interpretation purposes, it is usually specified that the allocation parameters for a given alternative  $i$  must sum to unity over all nests.

Fig. 3 illustrates the general correlation structure of the model with overlapping nests, where some alternatives belong to more than one nest. Dissimilarity parameters<sup>10</sup> are estimated for each nest, capturing the correlation of contiguous spatial units. The allocation parameters are estimated for each alternative that belongs to more than one nest and the linear constraint  $\sum_m \alpha_{im} = 1$  is imposed in the model.

[Fig. 3]

## 6. Empirical results

The simultaneous choice of residential location and travel to work mode is analysed for individuals whose job location is at the CBD and at various suburban employment locations in the Dublin region. The objective is to study the effect of socio-economic variables on the joint probability choice and to analyse the effect of travel cost and time across employment destinations.

First, a monocentric city model is estimated for a sample of commuters travelling to the CBD. This is based on the assumption that all employment is located within a radius of 5 kilometres from the CBD. Three concentric rings constitute the spatial choice set at road distances defined at less than 5 kilometres, 5 to 20 kilometres and more than 20 kilometres from the central employment location.

As part of the preliminary analysis, a series of models was estimated for various road distance concentric rings at different cut-off points. The three-ring model was found to be the best model specification and it is presented in this section. Fig. 4 shows the

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<sup>10</sup> Dissimilarity parameters are often referred to as “logsum” or “mu” parameters.

complete (six ring) GIS network analysis carried out for central employment location in the GDA.

[Fig. 4]

The nest correlation structure is shown in Fig. 5. Alternatives 3 and 4 are spatially adjacent to alternatives 1 and 2 and to alternatives 5 and 6 and they belong to nests A and B respectively. In order to allow for this correlation structure, a CNL model is estimated<sup>11</sup>.

[Fig. 5]

CNL model estimation results are reported in Table 2. The entire series of models presented here are estimated using the freely available optimisation package Biogeme<sup>12</sup> (Bierlaire, 2003).

[Table 2]

The CNL estimated coefficients for the attributes of the alternatives confirm initial expectations in terms of their sign, with negative signs for travel time and travel cost variables. House prices also show negative estimates. Expected signs are obtained from socio-economic variables. Older individuals are found to be more likely to live closer to the CBD than younger individuals. This can be seen as an income-related effect given the existent declining rates in property prices as distance to the CBD increases (ESRI-Permanent TSB, 2003). The same effect is found for single individuals, with a higher probability of choosing residential locations further from

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<sup>11</sup> In this paper we assume that there is a correlation among adjacent residential areas. Unsuccessful attempts were made to estimate similar two-level CNL models with correlation among common modes, i.e. < 5 Kilometres, Car; 5-10 Kilometres, Car, etc. This correlation structure may be accommodated by using more complex CNL structures. Daly (2001) and Daly and Bierlaire (2006) generalise the GEV model family and the multi-level tree logit model with the CNL model as a special case.

<sup>12</sup> CNL estimation with Biogeme uses the CFSQP optimisation algorithm developed by E.R. Panier, A.L. Tits, J.L. Zhou and C.T. Lawrence. CFSQP is licensed to AEM Design that kindly distributed a copy for its use in conjunction with Biogeme.

the CBD. The positive sign for the estimate of the household size shows that larger families are more likely to select alternatives further away from the CBD.

Non-significant estimates are found for gender, for the number of available cars in the household and for the socio-economic group 3, i.e. a dummy variable indicating manual skilled, semi-skilled and non-skilled labour. The positive coefficient obtained for the aggregate bias correction term is intuitive, implying greater probability that larger residential location areas are chosen in the model. The scale parameters of the random terms associated with nests A and B are consistent with random utility theory<sup>13</sup>.

Disaggregate direct and cross elasticities with respect to travel time and cost are presented in Table 3 for a randomly selected commuter. Direct elasticities represent the variation in an individual's choice probability due to a change in one of the attributes affecting that alternative. Similarly, cross elasticities are the variation in the choice probability due to a change in an attribute affecting another alternative. In this case, cross elasticities for each alternative respond to a change in travel times and costs of the alternative mode of travel to work within the same distance ring. For example, the car travel time cross elasticity for alternative 1 (i.e., alternative 1 corresponds to residential location at less than 5 kilometres from the CBD and commuting by car to work – see Fig. 5) shows the change in the choice probability of alternative 1, due to a 1% change in travel times for public transport at that same distance to work. Elasticities in Table 3 have been computed for all alternatives.

[Table 3]

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<sup>13</sup> The inequality  $\frac{\mu}{\mu_m} < 1$  with  $\mu = 1$  is tested against the values (0,1).

Direct time elasticities for car travel increase the greater the distance to work<sup>14</sup>. Travel costs affect car and public transport probabilities in a different way, with larger elasticities for public transport than for car choice. In general, commuters are more sensitive to changes in travel times, which increase considerably with distance to work.

Cross elasticities are negative for alternatives within the five-kilometre distance ring to the CBD. Given their size, their effect on choice probability can be considered as negligible. This implies that the effect of increasing car travel times within the CBD has practically null effects on the probability choice of public transport and vice-versa. Cross time elasticities are greatest for the middle-distance ring, i.e. 5 to 20 kilometres. This implies that variations in car (public transport) travel times are expected to have a relatively large effect on public transport (car) choice probabilities.

Using the same choice set, the model is estimated again for those individuals with suburban employment destinations. Under this scenario, all employment is concentrated in more than one destination (in a multi-centre employment location pattern) outside the CBD.

The model remains unchanged, but the sample now includes those commuting trips to suburban employment destinations. Once individuals in the sample are allowed to work in more than one location and these locations are not in the CBD, their commuting trips are not necessarily assumed to be radial<sup>15</sup>. Location and travel mode effects due to changes in travel variables are expected to be different under this scenario.

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<sup>14</sup> The same trend is found for public transport, but at a lower rate.

<sup>15</sup> Commuting trips to the CBD may not be radial either, but it is known with certainty that there is an available radial route to work by car and public transport. Commuting trips to suburban employment centres may still be radial if commuters decide to cross the CBD in their journey to work instead of using orbital road routes. Unfortunately, no data on route choice is provided in the 2002 Irish Census of Population and therefore, the percentage of non-radial commuting trips to these suburban employment destinations cannot be determined.

A detailed spatial choice set is produced for the dispersed employment model with 6 road-distance concentric rings: at less than 5 kilometres; between 5 and 10 kilometres; between 10 and 20; 20 and 30; 30 and 40; and more than 40 kilometres from each of the employment sub-centres and the CBD. Fig. 6 illustrates the GIS network analysis carried out for the employment sub-centres. As with the CBD employment case, several initial models were estimated for various road distances at different cut-off points. The estimation results correspond to the best fitted model. Service areas show a more heterogeneous shape with the shortest distance rings (less than 5 kilometres) located around each employment sub-centre<sup>16</sup>.

[Fig. 6]

Fig. 7 illustrates the model's nest correlation structure for a total of 12 alternatives with the definitions of each alternative. Given the more detailed definition of spatial alternatives in the suburban employment destination case, several alternatives belong to more than one nest. In fact, all the alternatives belong to two nests except for alternatives 1, 2, 11 and 12. Estimation results are reported in Table 4.

[Fig. 7]

[Table 4]

Coefficients for the attributes of the alternatives and the socio-economic variables present similar signs to those obtained for the CNL model in the CBD employment destination sample. Comparing these results to those presented in Table 2, the number of cars available in the household is now significant, but gender and socio-economic group 3 (manual skilled, semi-skilled and non-skilled employment) remain non-significant.

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<sup>16</sup> The Airport employment sub-centre does not present a less than 5 kilometre residential location due to planning restrictions around the Airport area.

Cost coefficients for travel time, travel cost and house prices are negative and in the case of property prices, these are highly significant. The sign of the coefficient for the employment centres dummy variables indicate similar behaviour across employment centres showing those individuals working at peripheral suburban locations as more likely to live further away from the CBD. Finally, correlation of the unobserved part of the utility function for long-distance commuting alternatives (Nest E) is found to be zero.

As for the monocentric city scenario, disaggregate direct and cross elasticities with respect to travel time and cost are presented in Table 5 for a randomly selected commuter.

[Table 5]

One of the most salient features of Table 5 is that public transport choice probabilities are particularly sensitive to changes in public transport fares for long- distance commuting trips. Alternatively, public transport choice probabilities at locations close to work, i.e. less than 5 kilometres distance, are not particularly sensitive to changes in travel times or costs. In general, public transport use to suburban employment destinations is more sensitive to changes in travel cost than to changes in travel time. Travel times have greater effects on car choice probabilities than on public transport, increasing in both cases as distance to work rises.

Cross elasticities are predominantly low, with negative signs for locations at less than 5 kilometres and between 10 and 20 kilometres to the suburban employment sub-centre. Changes in public transport fares are found to have the largest cross negative effects at these locations. Overall, negligible effects are found on choice probabilities due to changes on travel costs and times of the alternative mode of travel available within the same distance-to-work ring.

Differences found in the computed direct and cross elasticities for suburban employment commuting can be seen as a symptom of the relatively poorer provision of public transport to these employment destinations. It also shows the need for multi-mode use in order to reach the employment destination.

## **7. Simulation tests**

A major feature of this modelling framework lies in its potential use to test the impact of a change in travel attributes on re-location and travel mode switching. The objective of this analysis is to identify which spatial employment pattern is more sensitive to variations in car travel-to-work attributes. Increases in car travel costs are simulated for all routes for central and suburban employment destinations. The analysis is carried out assuming a closed city and perfectly elastic housing supply<sup>17</sup>.

Monocentric cities are assumed to experience centralising effects when travel costs increase (Eliasson and Mattsson, 2001). Re-location effects are analysed in relation to mode switching effects for central and non-central employment destinations. Eliasson and Mattsson (2001) suggest that the extent to which increasing travel costs affect residential location is largely dependent on the options commuters have to counteract these effects. Increased travel costs can be compensated by re-location, but also by changing the mode of transport. Under the assumption of dispersed employment and well-functioning public transport systems, Eliasson and Mattsson find small re-location effects relative to travel mode switching effects.

In the present study, sample enumeration is used as the aggregate forecasting technique. Based on the parameters presented in Tables 2 and 4, sample enumeration

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<sup>17</sup> The assumption of closed city means that the population is given and it is assumed to locate within the limits of the city. The assumption on perfectly elastic supply can be seen as fairly unrealistic, but it helps the researcher to simplify the simulation process for presentation purposes by avoiding the introduction of additional assumptions on residential land use development across the spatial choice set.

calculates the choice probability for each of the commuters using the data samples for CBD and suburban commuting as representative of the population (see Ben-Akiva and Lerman (1986) for details). Monte-Carlo simulation is used to produce correct predicted probabilities for all alternatives<sup>18</sup> (see Small et al. (2002) for an application of sample enumeration procedures to the study of travel behaviour).

A sensitivity analysis is presented to evaluate the effects on location and travel mode choice of a simulated increase in car travel costs. Results for one-euro, three-euro and six-euro increase in car travel costs are reported in Table 6 for the CBD and in Table 7 for suburban employment destinations. Each cell represents the percentage of commuters over the base scenario (predicted shares) that moves or remains at each alternative after the increase has taken place. Hence, the diagonal values represent the percentage of commuters for each alternative that remain at that alternative after car travel costs have increased.

[Table 6]

[Table 7]

The actual and predicted shares illustrate the potential of the CNL model to accurately represent the choice shares in the study area. In the case of CBD commuting, increasing car travel costs have a dramatic effect on mode-switching. Re-location effects are found to occur for increases of three-euro and six-euro in car travel cost, but they are moderate in size relative to the changes obtained for mode-switching. Decentralising effects are found from the CBD to the middle-distance ring. This is particularly evident as car travel costs increase to three and six euro. Centralising effects are found as distance to the CBD increases with significant residential re-location from the outer ring to the middle ring. Public transport alternatives at a

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<sup>18</sup> Biogeme package is used to perform sample enumeration (Bierlaire, 2003)

commuting distance below 5 kilometres experience the largest growth for six-euro increases in travel costs.

In terms of suburban commuting, the most salient feature is the extraordinary effect of an increase in car travel costs on car choice probabilities. Mode-switching within the same distance ring is less prominent than for the monocentric city case, with strong re-location effects found into the adjacent inner rings. Centralising effects are mainly found for long-distance commuting and in particular, for those individuals travelling more than 30 kilometres to work.

Results from this analysis illustrate the different ways in which commuters can neutralise the effects of increasing travel costs under centralised and decentralised employment patterns assuming constant public transport provision. The relatively stronger public transport provision to the CBD (radial routes) facilitates mode switching such that commuters can achieve approximately the same level of utility by switching modes of travel to work without having to change residential location.

Suburban travel to work mode switching is effective up to a certain distance to work. From that point, re-location is the most likely response to increasing car travel costs. Centralising effects are present, but they are unevenly distributed across the various residential location rings with large numbers of commuters changing from the furthest commuting distance locations to the shortest distance rings.

The relative lack of efficient public transport provision to suburban employment centres to/from the city centre and the main suburban residential areas in Dublin, can be seen as one of the main influencing factors on the different results found for suburban employment destination patterns.

## **8. Conclusion and further research**

The objective of this paper is to analyse the simultaneous choice of residential location and travel-to-work mode and to explore the effects of car travel variables on re-location and travel-to-work mode switching in the Dublin region.

Employment location has long been identified in the literature as a critical variable in the analysis of the so-called mobility decision process. In this paper, job location is assumed to be fixed and a road-distance to work spatial choice set is generated using GIS for the CBD and for various employment sub-centres in the region.

A combination of data sources are used to estimate a closed-form discrete choice model for the Dublin region specified as a CNL model. This model provides a more flexible correlation structure of the error terms than other closed-form discrete choice models such as the MNL and NL models and it allows for the potential correlation of adjacent spatial alternatives.

Estimation results and direct and cross elasticities are presented for central and suburban employment. Results from this analysis suggest that commuters to the CBD are quite responsive to more time-consuming travel. Similar results are obtained for suburban commuting where increasing travel times have a greater effect on car choice probabilities than on public transport. Cross elasticities are generally low, but they show particularly small values for suburban commuting trips, which mean very low levels of potential mode switching due to changes in travel variables.

A simulation exercise for increasing travel costs uses sample enumeration to forecast the variation in aggregate choice probabilities for central and suburban employment scenarios. Significant mode switching effects are found for the monocentric city case with centralising effects from the outer ring to the middle-distance ring. Strong re-

location effects are found for suburban commuting destinations with significantly less pronounced mode switching effects.

Results suggest that, given the current provision of public transport in the GDA and keeping everything else equal, transport policies aimed at reducing traffic congestion by increasing car travel costs may have larger effects on home re-location than expected if individuals affected by these policies are working at suburban employment locations. These results are influenced by the fact that a number of land use assumptions were made to simplify the simulation exercise.

Considering realistic land use planning restrictions for the development of new residential areas in Dublin and new land use planning programs for residential and employment development in future extensions of this model will provide more accurate representations of expected residential location and commuting patterns.

Provision of a sound public transport system at suburban destinations and the effective integration of land-use and transport policies are needed in order to avoid raising traffic congestion levels as a result of an increasingly dispersed employment and residential location.

The introduction of road user charging in Dublin has been seen by some academics and urban planners as the solution to traffic problems in the city. A potential application of the modelling framework presented in this paper is the study of the location and travel mode choice of a hypothetical road user charging scheme for the city of Dublin. Further extensions of the framework developed here might look at a dynamic analysis, taking account of the incremental impacts of new public transport initiatives being gradually introduced in the city.

## Appendix A

### [Table A]

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Table 8: Variables used in the residential location and travel mode choice model

<b>Name</b>	<b>Description</b>
Property prices	2003 average house prices from the Permanent / ESRI House Price Index
<i>Socio-economic characteristics</i>	
Gender	Female commuter =1
Age group 2	Individuals between 35 and 54 years old (reference category: individuals between 15 and 34 years old)
Age group 3	Individuals over 55 years old (reference category: individuals between 15 and 34 years old)
Socio-economic group 1	Education and employment status (socio-economic group as defined by CSO). Employers, managers and professionals (reference category: non-manual)
Socio-economic group 3	Education and employment status (socio-economic group as defined by CSO). Manual skilled, Semi-skilled and Unskilled (reference category: non-manual)
Number of cars	Car availability for use in the household
Household size	Number of residents in the household
Household type	Dummy variable indicating if the individual is single. Single =1
Nature of occupancy	Dummy variable indicating whether the individual owns a house Owner = 1
Employment centre	Dummy variable for each suburban employment centre, i.e. Blanchardstown, Clondalkin-Tallaght and Airport (reference category: N11)
<i>Travel attributes</i>	
Travel time Car and public transport in minutes	In-vehicle travel time for car and public transport. Walking time and waiting time to station/stop for public transport provided by the DTO. Peak traffic congestion included.
Travel costs Car and public transport in euro	Travel costs for car and public transport fares as a function of distance provided by the DTO
<i>Bias correction measures</i>	
Geographic stratification bias correction term	Zone specific variable computed as the natural log of the ratio of the aggregate zone's sample proportion to its proportion in the population.
<b>Size aggregation bias correction term</b>	<b>Zone-specific variable computed as the natural log of the number of occupied households by chosen tenure type.</b>

Table 9: CNL estimation results for the monocentric city

VARIABLES	COEFFICIENTS (T-STAT)
Total Travel Time (in minutes)	-0.05 (-12.80) **
Total Travel Cost (in euro)	-0.33 (-6.02) **
Age group 2	-0.38 (-7.60) **
Age group 3	-0.26 (-3.41) **
Socio-economic group 1	-0.26 (-4.69) **
Socio-economic group 3	-0.09 (-1.17)
Number of cars	-0.03 (-1.09)
Gender	0.03 (0.67)
Property prices	-0.85 (-17.60) **
Nature of occupancy (owner=1)	-0.31 (-4.68) **
Household size	0.09 (5.65) **
Household type (single=1)	-0.37 (-3.80) **
Aggregation correction bias	0.89 (19.84) **
Nest A	3.03 (3.61) **
Nest B	1.48 (5.99) **
Number of observations	10 980
Null log-likelihood	-19 182.1
Final log-likelihood	-14 253.6
Adjusted rho-square	0.26

**\*\* indicates a parameter is significantly different from 0 (or 1 in the case of the nest parameter) at the 95% confidence level.**  
**Alternative 1 is the reference category**  
**Allocation parameters are shown in Table A in the Appendix**

Table 10: Disaggregate direct and cross elasticities for a random individual in the monocentric city

	Direct elasticities				Cross elasticities			
	Travel time elasticity		Travel cost elasticity		Travel time elasticity		Travel cost elasticity	
Rings	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport
<5 Km	-0.316	-0.036	-0.030	-0.017	-0.002	-0.005	-0.001	0.000
5-20 Km	-0.912	-0.471	-0.116	-0.150	0.518	0.562	0.142	0.070
>20 Km	-3.681	-2.291	-0.461	-1.170	0.190	0.284	0.087	0.040

Table 11: CNL model estimation results for suburban employment

<b>VARIABLES</b>	<b>COEFFICIENT (T-STAT)</b>
<i>Total Travel Time (in minutes)</i>	-0.01 (-9.11) **
<i>Total Travel Cost (in euro)</i>	-0.45 (-12.38) **
<i>Age group 2</i>	-0.16 (-5.99) **
<i>Age group 3</i>	-0.15 (-3.20) **
<i>Socio-economic group 1</i>	-0.09 (-4.39) **
<i>Socio-economic group 3</i>	-0.05 (-1.72)
<i>Number of cars</i>	-0.05 (-3.89) **
<i>Gender</i>	0.01 (0.43)
<i>Dummy Blanchardstown (N11 ref. category)</i>	0.37 (5.99) **
<i>Dummy Airport (N11 ref. category)</i>	0.27 (7.21) **
<i>Dummy Clondalkin-Tallaght (N11 ref. category)</i>	0.16 (4.63) **
<i>Property prices</i>	-0.19 (-12.41) **
<i>Stratification correction bias</i>	0.33 (2.90) **
<i>Nature of occupancy (owner=1)</i>	-0.12 (-5.15) **
<i>Household size</i>	0.04 (4.55) **
<i>Household type (single=1)</i>	-0.10 (-2.08) **
<i>Aggregation correction bias</i>	0.76 (15.70) **
Nest A	8.92 (8.22) **
Nest B	4.60 (7.86) **
Nest C	4.17 (7.52) **
Nest D	8.66 (1.99) **
Nest E	1.00 (0.00)
<i>Number of observations:</i>	5 894
<i>Null log-likelihood:</i>	-14 436
<i>Final log-likelihood:</i>	-10 695.5
<i>Adjusted rho-square:</i>	0.26

**\*\* indicates a parameter is significantly different from 0 (or 1 in the case of the nest parameter) at the 95% confidence level.**

**Alternative 1 is the reference category**

**Allocation parameters are shown in Table A in the Appendix**

Table 12: Disaggregate direct and cross elasticities for a random individual in suburban employment

	Direct elasticities				Cross elasticities			
	Travel time elasticity		Travel cost elasticity		Travel time elasticity		Travel cost elasticity	
Rings	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport
<5 Km	-0.142	-0.042	-0.196	-0.086	-0.001	-0.011	-0.020	-0.157
5-10 Km	-0.147	-0.102	-0.204	-0.198	0.001	0.001	0.012	0.020
10-20 Km	-0.223	-0.140	-0.332	-0.312	-0.001	-0.011	-0.024	-0.160
20-30 Km	-0.560	-0.175	-0.655	-0.482	0.000	0.008	0.001	0.092
30-40 Km	-0.725	-0.760	-1.464	-2.720	0.000	0.002	0.015	0.050
<b>&gt;40 Km</b>	-1.092	-0.966	-1.776	-4.184	0.000	0.003	0.012	0.046

Table 13: Sensitivity analysis for 1 euro, 3 euro and 6 euro increase in car travel costs – CBD employment

<b>CBD employment destination</b>				<b>&lt; 5 Km</b>		<b>5 - 20 Km</b>		<b>&gt; 20 Km</b>	
<i>One-euro increase in travel costs</i>				Car	Public transport	Car	Public transport	Car	Public transport
Location	Travel mode	Actual shares	Predicted shares						
< 5 Km	Car	9.29%	9.20%	<b>74.1%</b>	<b>25.3%</b>	0.6%	0.0%	0.0%	0.0%
	Public transport	5.27%	5.08%	0.0%	90.9%	9.1%	0.0%	0.0%	0.0%
5 - 20 Km	Car	47.25%	47.97%	0.0%	0.4%	<b>85.5%</b>	<b>14.0%</b>	0.0%	0.0%
	Public transport	21.61%	21.28%	0.0%	0.0%	0.0%	99.1%	0.9%	0.0%
> 20 Km	Car	11.03%	11.28%	0.0%	0.0%	0.0%	0.9%	<b>83.7%</b>	<b>15.4%</b>
	Public transport	5.55%	5.19%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
<i>Three-euro increase in travel costs</i>				Car	Public transport	Car	Public transport	Car	Public transport
Location	Travel mode	Actual shares	Predicted shares						
< 5 Km	Car	9.29%	9.20%	<b>28.6%</b>	<b>65.6%</b>	5.7%	0.0%	0.0%	0.0%
	Public transport	5.27%	5.08%	0.0%	89.1%	10.9%	0.0%	0.0%	0.0%
5 - 20 Km	Car	47.25%	47.97%	0.0%	1.9%	<b>52.6%</b>	<b>45.5%</b>	0.0%	0.0%
	Public transport	21.61%	21.28%	0.0%	0.0%	0.0%	97.0%	3.0%	0.0%
> 20 Km	Car	11.03%	11.28%	0.0%	0.0%	0.0%	3.5%	<b>51.5%</b>	<b>45.0%</b>
	Public transport	5.55%	5.19%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
<i>Six- euro increase in travel costs</i>				Car	Public transport	Car	Public transport	Car	Public transport
Location	Travel mode	Actual shares	Predicted shares						
< 5 Km	Car	9.29%	9.20%	<b>2.4%</b>	<b>90.8%</b>	6.5%	0.3%	0.0%	0.0%
	Public transport	5.27%	5.08%	0.0%	91.6%	8.1%	0.4%	0.0%	0.0%
5 - 20 Km	Car	47.25%	47.97%	0.0%	4.3%	<b>18.2%</b>	<b>77.5%</b>	0.0%	0.0%
	Public transport	21.61%	21.28%	0.0%	0.0%	0.0%	95.4%	2.8%	0.0%
> 20 Km	Car	11.03%	11.28%	0.0%	0.0%	0.0%	8.6%	<b>15.7%</b>	<b>45.0%</b>
	Public transport	5.55%	5.19%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

Table 14: Sensitivity analysis for 1 euro, 3 euro and 6 euro increases in car travel costs – Suburban employment

Suburban employment destinations				<5 Km		5 - 10 Km		10 - 20 Km		20 - 30 Km		30 - 40 Km		> 40 Km	
<i>1 euro increase in travel costs</i>				Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport
Location	Travel mode	Actual shares	Predicted shares												
< 5 Km	Car	18.88%	20.55%	<b>24.3%</b>	<b>56.9%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.6%	10.7%	3.5%
	Public transport	5.89%	6.28%	0.0%	99.7%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5 - 10 Km	Car	31.95%	29.52%	0.0%	5.5%	<b>59.0%</b>	<b>35.5%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Public transport	6.77%	6.14%	0.0%	0.0%	0.0%	99.4%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10 - 20 Km	Car	16.66%	16.76%	0.0%	0.0%	0.0%	6.8%	<b>62.9%</b>	<b>30.4%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Public transport	3.36%	3.73%	0.0%	0.0%	0.0%	0.0%	0.0%	97.3%	2.7%	0.0%	0.0%	0.0%	0.0%	0.0%
20 - 30 Km	Car	6.21%	6.50%	0.0%	0.0%	0.0%	0.0%	0.0%	5.7%	<b>84.1%</b>	<b>10.2%</b>	0.0%	0.0%	0.0%	0.0%
	Public transport	0.75%	0.97%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.3%	94.7%	0.0%	0.0%	0.0%	0.0%
30 - 40 Km	Car	4.61%	5.40%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	11.3%	<b>88.4%</b>	<b>0.0%</b>	0.0%	0.0%
	Public transport	0.75%	0.93%	0.0%	83.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	16.4%	0.0%	0.0%
> 40 Km	Car	3.65%	2.92%	0.0%	97.7%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	<b>0.0%</b>	<b>0.0%</b>
	Public transport	0.53%	0.31%	0.0%	83.3%	5.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	11.1%
<i>3 euro increase in travel costs</i>				Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport
Location	Travel mode	Actual shares	Predicted shares												
< 5 Km	Car	18.88%	20.55%	<b>0.0%</b>	<b>76.5%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	16.4%	4.7%	2.5%
	Public transport	5.89%	6.28%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5 - 10 Km	Car	31.95%	29.52%	0.0%	23.7%	<b>2.5%</b>	<b>73.8%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Public transport	6.77%	6.14%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10 - 20 Km	Car	16.66%	16.76%	0.0%	0.0%	0.0%	41.5%	<b>3.3%</b>	<b>55.2%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Public	3.36%	3.73%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

	transport														
20 - 30 Km	Car	6.21%	6.50%	0.0%	0.0%	0.0%	0.0%	0.0%	68.9%	<b>16.4%</b>	<b>14.6%</b>	0.0%	0.0%	0.0%	0.0%
	Public transport	0.75%	0.97%	0.0%	0.0%	0.0%	0.0%	0.0%	24.6%	5.3%	70.2%	0.0%	0.0%	0.0%	0.0%
30 - 40 Km	Car	4.61%	5.40%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	3.1%	53.8%	<b>39.9%</b>	<b>0.0%</b>	0.0%	0.0%
	Public transport	0.75%	0.93%	0.0%	83.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	16.4%	0.0%	0.0%
> 40 Km	Car	3.65%	2.92%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	<b>0.0%</b>	<b>0.0%</b>
	Public transport	0.53%	0.31%	0.0%	88.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	11.1%
<b>6 euro increase in travel costs</b>															
Location	Travel mode	Actual shares	Predicted shares	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport	Car	Public transport
< 5 Km	Car	18.88%	20.55%	<b>0.0%</b>	<b>73.7%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.2%	1.3%	2.7%
	Public transport	5.89%	6.28%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5 - 10 Km	Car	31.95%	29.52%	0.0%	29.7%	<b>0.0%</b>	<b>70.3%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Public transport	6.77%	6.14%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10 - 20 Km	Car	16.66%	16.76%	0.0%	0.0%	0.0%	56.3%	<b>0.0%</b>	<b>43.7%</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Public transport	3.36%	3.73%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20 - 30 Km	Car	6.21%	6.50%	0.0%	0.0%	0.0%	0.0%	0.0%	94.8%	<b>0.0%</b>	<b>5.2%</b>	0.0%	0.0%	0.0%	0.0%
	Public transport	0.75%	0.97%	0.0%	0.0%	0.0%	0.0%	0.0%	42.1%	0.0%	57.9%	0.0%	0.0%	0.0%	0.0%
30 - 40 Km	Car	4.61%	5.40%	0.0%	0.0%	0.0%	0.0%	0.0%	12.6%	0.0%	78.9%	<b>8.5%</b>	<b>0.0%</b>	0.0%	0.0%
	Public transport	0.75%	0.93%	0.0%	83.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	16.4%	0.0%	0.0%
> 40 Km	Car	3.65%	2.92%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	<b>0.0%</b>	<b>0.0%</b>
	Public transport	0.53%	0.31%	0.0%	88.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	11.1%

Table A: Allocation parameters from the city and suburban employment destination scenarios

<b>ALLOCATION PARAMETERS</b>	
<b>SCENARIO 1: CENTRAL EMPLOYMENT DESTINATIONS</b>	
<b>ALPHA (T-STAT)</b>	
$\alpha_{1,A}$	= 1.00 (fixed)
$\alpha_{2,A}$	= 1.00 (fixed)
$\alpha_{3,A}$	= 1.00 (0.00) *
$\alpha_{4,A}$	= 0.88 (30.10)
$\alpha_{3,B}$	= 0.00 (0.00) *
$\alpha_{4,B}$	= 0.12 (4.18)
$\alpha_{5,B}$	= 1.00 (fixed)
$\alpha_{6,B}$	= 1.00 (fixed)
<b>SCENARIO 2: SUBURBAN EMPLOYMENT DESTINATIONS</b>	
<b>ALPHA (T-STAT)</b>	
$\alpha_{1,A}$	= 1.00 (fixed)
$\alpha_{2,A}$	= 1.00 (fixed)
$\alpha_{3,A}$	= 0.00 (0.00) *
$\alpha_{4,A}$	= 0.22 (11.47)
$\alpha_{3,B}$	= 1.00 (17.09)
$\alpha_{4,B}$	= 0.78 (41.54)
$\alpha_{5,B}$	= 0.00 (0.00) *
$\alpha_{6,B}$	= 0.15 (7.84)
$\alpha_{5,C}$	= 1.00 (14.23)
$\alpha_{6,C}$	= 0.85 (43.99)
$\alpha_{7,C}$	= 0.31 (12.67)
$\alpha_{8,C}$	= 0.50 (22.81)
$\alpha_{7,D}$	= 0.69 (27.57)
$\alpha_{8,D}$	= 0.50 (23.01)
$\alpha_{9,D}$	= 0.69 (13.53)
$\alpha_{10,D}$	= 0.56 (13.00)
$\alpha_{9,E}$	= 0.31 (6.12)
$\alpha_{10,E}$	= 0.44 (10.09)
$\alpha_{11,E}$	= 1.00 (fixed)
$\alpha_{12,E}$	= 1.00 (fixed)

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\* indicates allocation parameter is non-significant

Fig. 7: Spatial employment patterns analysed in the model for the CBD and suburban employment locations, as well as the direction of the commuting trip

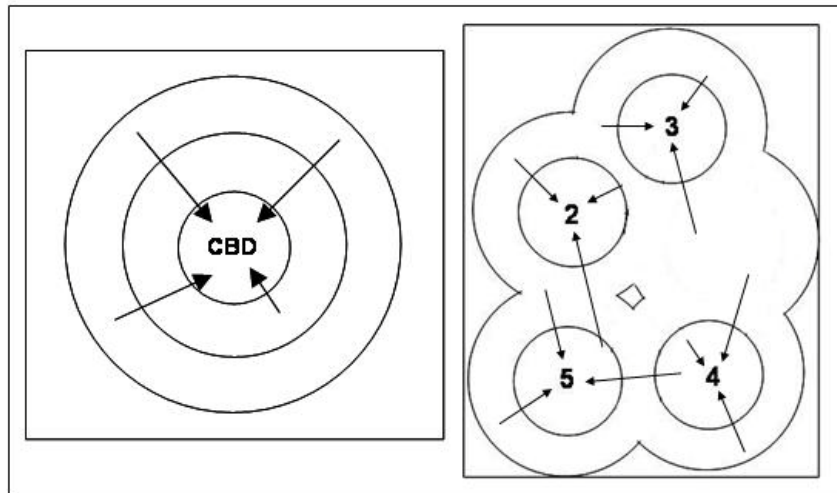


Fig. 8: Study Area

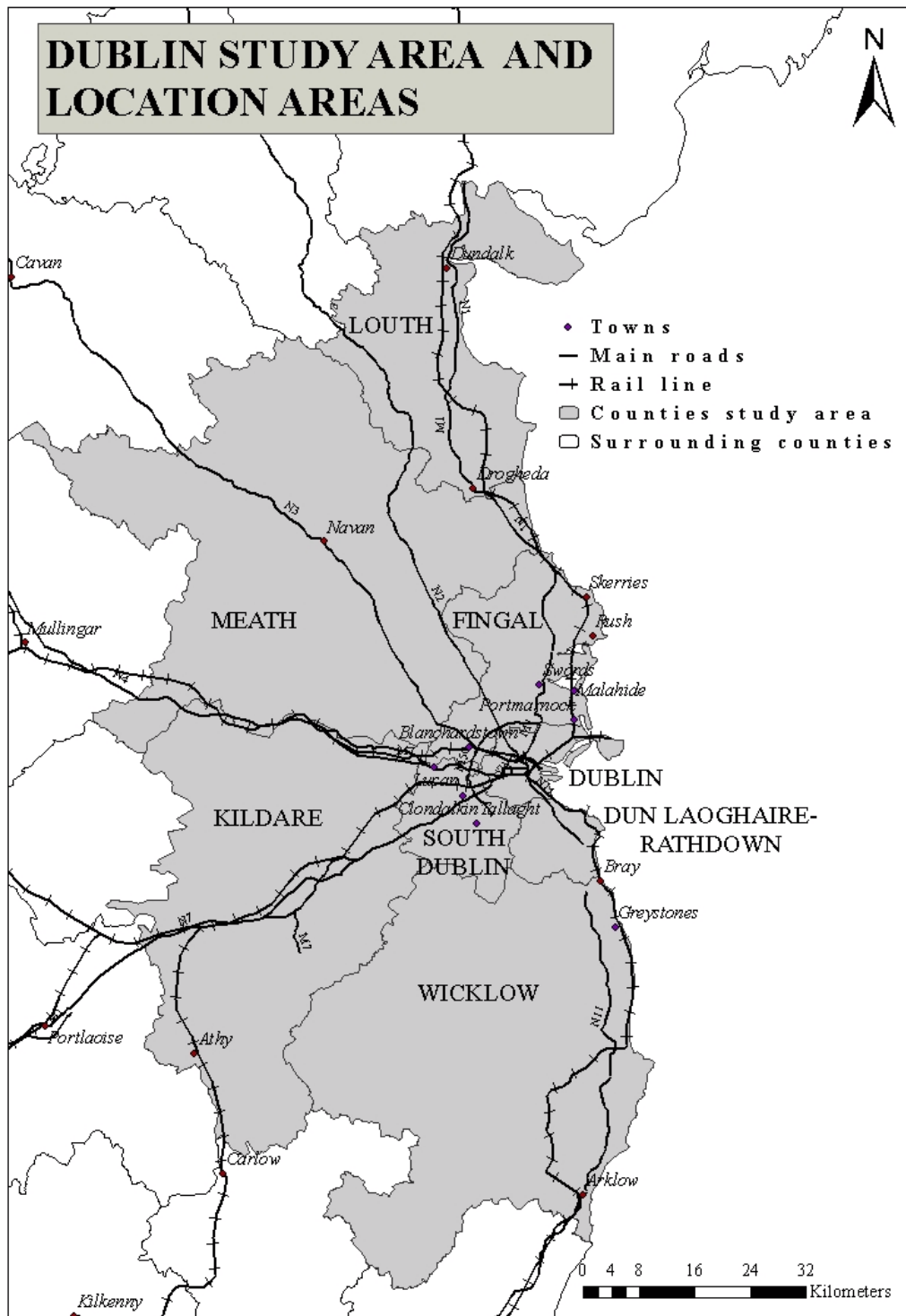


Fig. 9: CNL nesting structure based on spatial contiguous zones

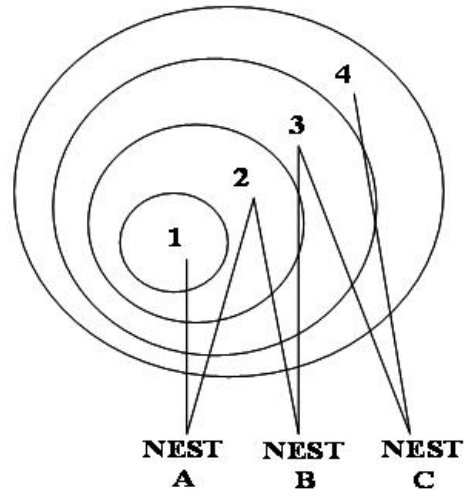


Fig. 10: Service areas computed for the monocentric city

## Service Areas

Service areas based on road distance with universal turns for the Central Business District  
Data source: Geometric network provided by URBIS - Urban Institute Ireland  
Digital boundaries provided by Ordnance Survey Ireland

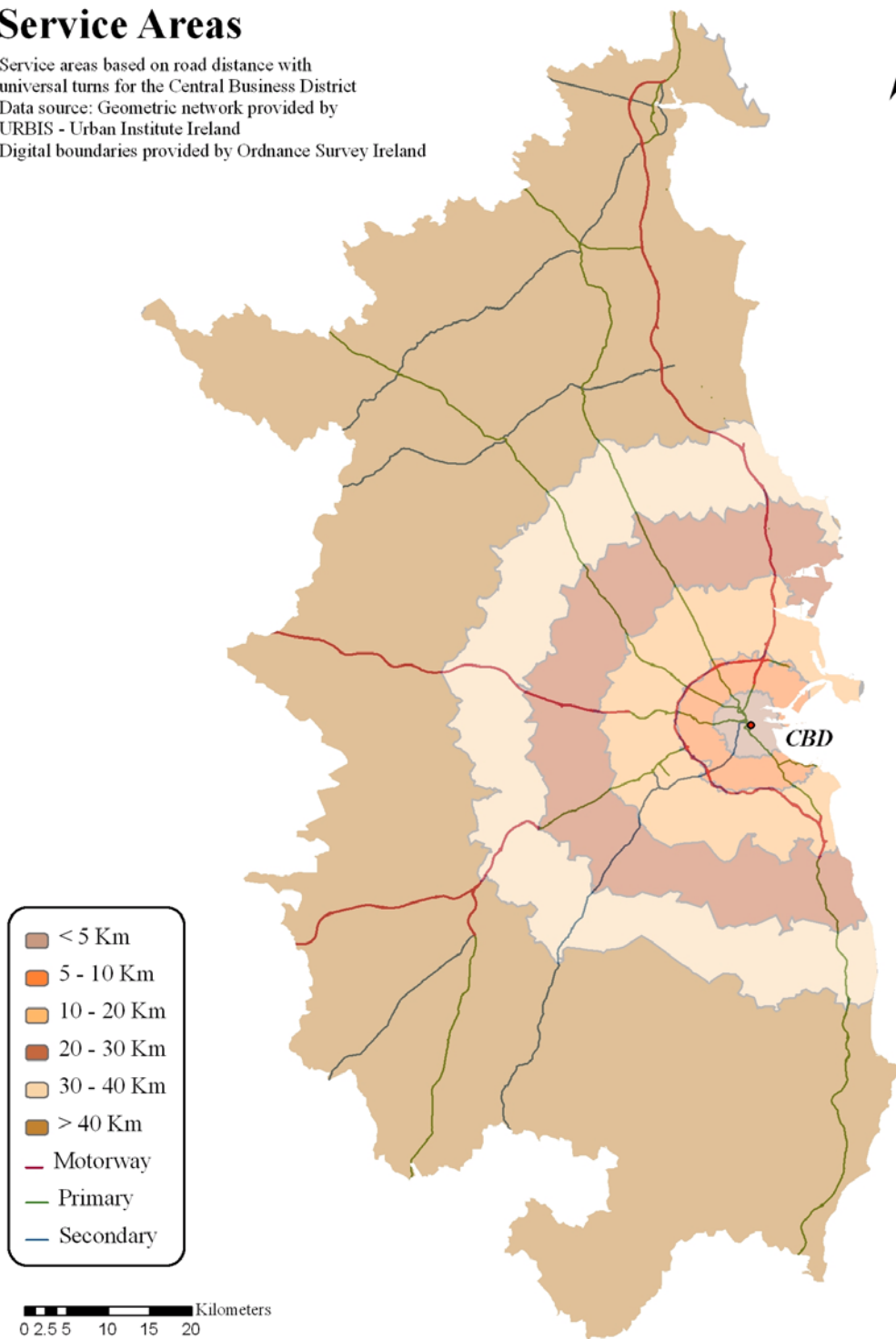


Fig. 11: CNL nesting structure based on spatial contiguous zones

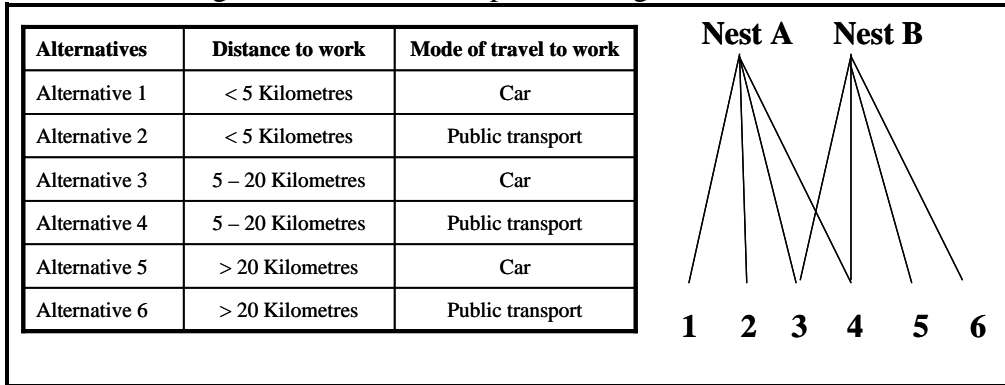


Fig. 12: Service areas computed for the suburban employment destinations

## Service Areas

Service areas based on road distance with universal turns for each employment sub-centre  
Data source: Geometric network provided by URBIS - Urban Institute Ireland  
Digital boundaries provided by Ordnance Survey Ireland

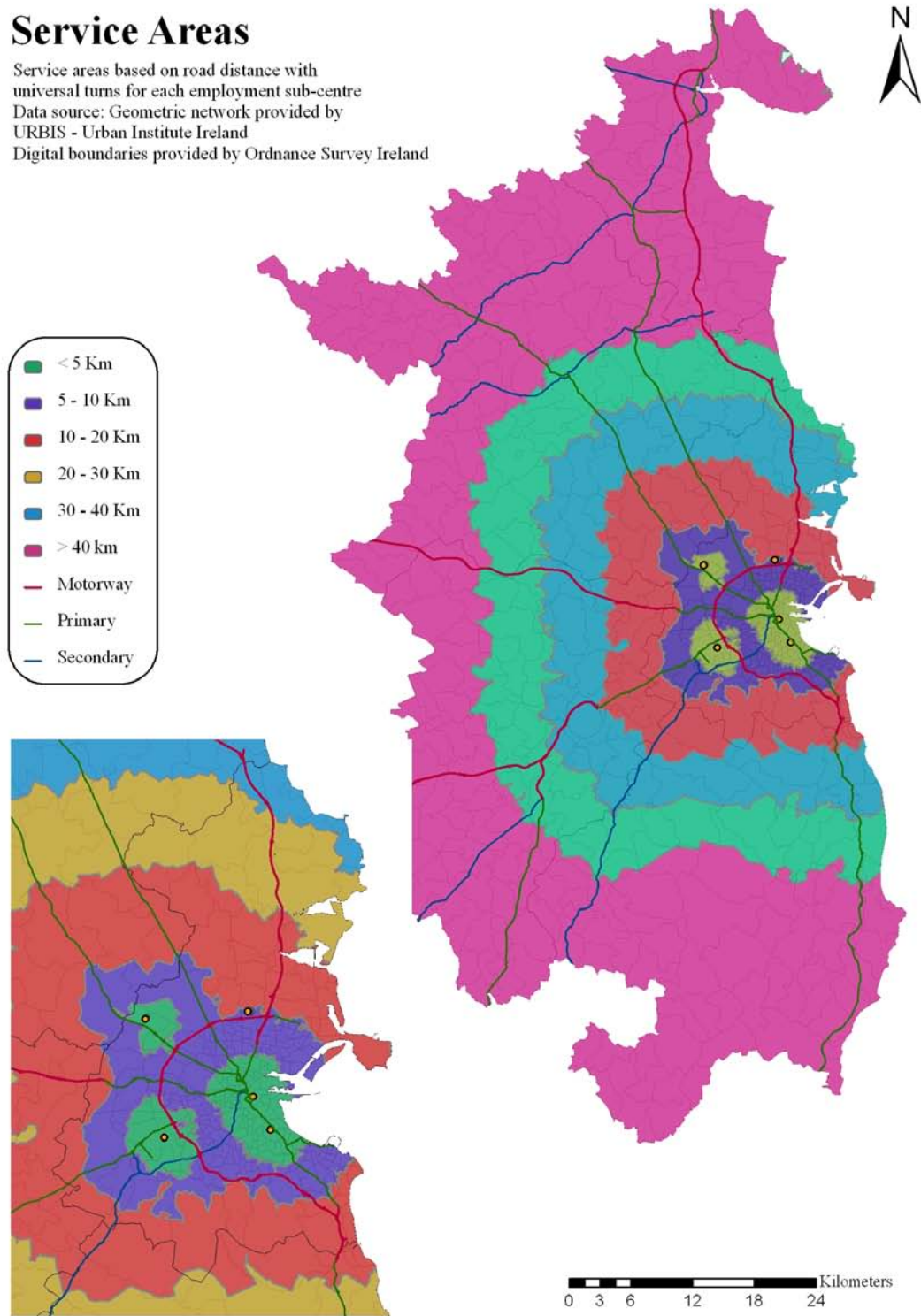


Fig. 7: CNL nesting structure based on spatial contiguous zones for the suburban employment

