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Patterns of sustainable mobility and the structure of modality in the Randstad city-region

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Abstract:
The sustainable mobility vision for city-regions proposes a more integrated and 'seamless' multi-modal public transport system around quality neighborhoods, shifting mobility to soft transportation modes and to public transport at various scales. Existing models of sustainable urban form address this challenge focusing on the location, density and diversity of activities, on the composition of the street layout, and on the presence of transport nodes and the quality of the public transport service. In order to better understand the relation between urban form and sustainable mobility patterns we propose to additionally measure the structure of mobility networks, including network proximity, density and accessibility, for different transport modes. The analysis of a multi-modal network model of the Randstad region in the Netherlands, integrating private and public transport infrastructure networks and land use information, reveals the structures of modality in the city-region. These structures are used to identify a typology of 'modality environments' that tested against travel survey data demonstrate support for specific patterns of mobility, i.e. walking, cycling, car use, local and regional transit.

This classification can contribute to a new urban form based method for evaluating the potential of neighborhoods for sustainable mobility.

Keywords: *Network analysis, multi-modal networks, sustainability, mobility patterns.*

1. Introduction

The Randstad region in the Netherlands is one of the paradigmatic polycentric city-regions in Europe (Hall and Pain 2006), comprising the four largest cities in the country (Amsterdam, Rotterdam, The Hague and Utrecht) and a series of middle size cities (Amersfoort, Haarlem, Leiden, Dordrecht and Hilversum) that together constitute its Daily Urban Systems (DUS) against a background of suburban neighborhoods and a mostly preserved rural and natural area at the centre called the "Green Heart" (van Eck and Snellen, 2006).The Randstad urban centres and their suburbs are served by an established multi-modal mobility network of local walking and cycling infrastructure, comprehensive road and public transport networks, and connected by rail and motorway networks. The Randstad's combination of mobility infrastructure networks with land use concentration and mix should offer the baseline conditions for sustainable mobility patterns within the local neighbourhoods and across the region (Figure 1).

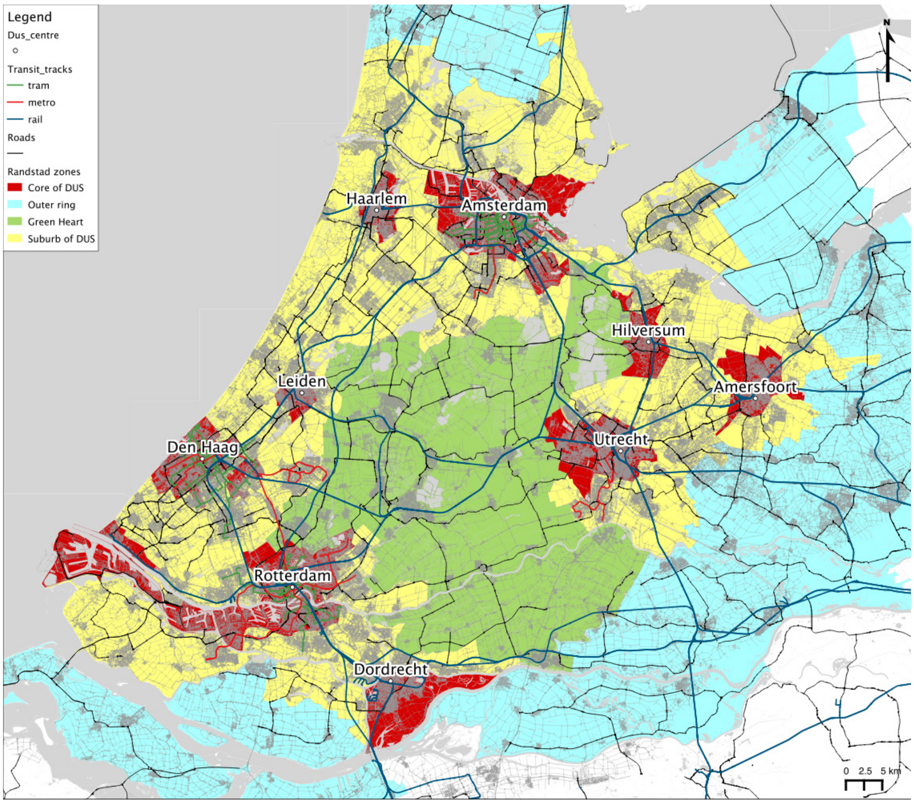

Figure 1. *Map of the Randstad city-region, showing its areas, main urban centres and main mobility network infrastructure.*

The Randstad's current configuration is the result of a long spatial planning tradition based on carefully planned neighborhood development since World War II (Wassenberg 2006) that over the decades has evolved from implicit to explicit sustainable urban development (Goedman et al. 2008), reflected in policy documents since the late 1980s (Buijs 1992, VROM 2001, VROM 2008). The Fourth Spatial Planning Framework Extra, also known as VINEX, introduced a program of urban expansion of new residential areas focusing on the core concepts of sustainable neighborhood development and sustainable mobility in particular. The Fifth Spatial Planning Framework, the latest spatial strategy for the Netherlands, sets as key objectives the reduction of traffic congestion, the intensification of land use and the development of the network for multi-modal transport provision (VROM, 2001; Snellen and Hilbers, 2007) with the aim of achieving a more sustainable mobility. Understanding the spatial conditions that support these policy objectives is a primary concern.
Some of the main VINEX objectives have in general not been achieved, i.e. increase in walking and cycling in the neighborhood, use of public transport for commuting or reduction of car use. In particular, the locations in green field sites do not lead to more sustainable mobility patterns when compared to other parts of the country and continue to perform worse than new and old inner city locations (Hilbers and Snellen, 2005).

While this can in part be explained by differences in socio-economic profile between these different locations, for a particular type of location one might find a consistent trend of mobility pattern. With the aim of exploring this assumption we look at empirical evidence from a mobility survey and at network structure characteristics of the city-region within a framework of sustainable mobility indicators. This paper follows from previous research analyzing public transport networks using the space syntax configurational approach (Gil and Read 2012), which revealed the structure and hierarchy of each network and of their integrated effect, towards assessing the potential of different neighborhoods to support sustainable mobility patterns.

2. Sustainable mobility patterns in the Randstad city-region

The general sustainable mobility vision for city-regions proposes a more integrated and 'seamless' multi-modal public transport system around quality neighborhoods and vibrant city centres, with land use distribution matching the needs of population, business and institutions, shifting mobility to soft transportation modes such as walking and cycling and to public transport for long distance travel (Banister 2005). These objectives can be monitored through the use of sustainable mobility indicators, like the ones found in numerous urban from and travel studies and policy documents,such as distance traveled per mode or per person, modal share and number of journeys (Cervero and Kockelman 1997; Newman and Kenworthy 1999;Banister 2008;Bruun, E., Schiller, P.L.L. &Litman, T., 2012; Gilbert, R., Tanguay, H., 2000;European Commission, 2001). Using empirical data from the Netherlands Mobility Survey from the years 2004 to 2009 (MON 2004-2009) containing 282,543individual home based journeys between the 4-digit postcodes of the Randstad city-region,one can identify the sustainable mobility patterns of the population according to a collection of sustainable mobility indicators (Table 1). In this table, the mean, minimum and maximum values for each indicator are given for the whole Randstad, providing baseline against which one can compare the performance of specific postcodes.

From the mean values in Table 1 one can observe certain mobility trends in this city-region. The overall number of cycle journeys share is high at 25%, even higher than walking, but this depends on the distance traveled because more than half of the short local journeys are done by walking, followed by the bicycle at 30.66%.Transit share is on average very low, which is surprising considering the extensive public transport infrastructure, however many locations away for the larger urban centres are not served by a variety public transport modes, and in urban areas public transport share can be as high as 36% of the journeys. Despite the relatively high values of some sustainable mobility indicators, the car journeys share is the highest on average 44%, approaching a 75% share when it comes to total distance traveled. For that reason, there are policies in place to reinforce the positive change towards sustainable mobility, represented in Table 1 by the symbols in the 'Sustainability direction' column.

One aspect that can be found in the data set is the close relation between multi-modal journeys and overall public transport journeys. While the large majority of multi-modal journeys use public transport (86%) either in one or more legs of the journey, the other legs are mostly walking (54% at origin and 71% at destination), cycling (13%) and with the car (8,5% as driver and 5% as passenger).

Table 1. *Selection of sustainable mobility indicators. The 'Sustainability direction' column shows the intended direction of the indicator in relation to general sustainable mobility objectives.*

Indicator	Sustainability direction	Randstad		
		Mean	.Min	.Max
Share of short[1] walk journeys	+++	% 54.17	0.00	100.00
Share of walk journeys	+++	% 22.64	0.00	59.42
Share of short[1] cycle journeys	+++	% 30.66	0.00	93.75
Share of medium[2] cycle journeys	+++	% 33.14	0.00	81.82
Share of cycle journeys	+++	% 25.59	0.00	51.37
Share of short[1] car journeys	---	% 14.23	0.00	100.00
Share of medium[2] car journeys	--	% 52.33	0.00	100.00
Share of long[3] car journeys	-	% 78.01	20.00	100.00
Share of car journeys	---	% 44.65	3.42	88.71
Share of car distance	--	% 74.87	17.96	98.47
Share of car duration	--	% 56.16	6.50	93.99
Share of medium[2] local transit journeys	++	% 6.19	0.00	53.33
Share of local transit journeys	++	2.55%	0.00	20.00
Share of long[3] train journeys	++	% 14.82	0.00	65.00
Share of train journeys	++	% 2.13	0.00	17.59
Share of transit distance	++	% 12.64	0.00	65.33
Share of transit duration	+	% 7.91	0.00	41.39
Mean journey distance	-	km 10.2	2.99	28.38
Mean daily distance per person	-	km 34.5	8.70	102.01
Mean daily journeys per person	-	3.40	2.46	6.00

[1]up to 1.5km; [2]between 1.5km and 10km; [3]longer than 10km

What is clear from the minimum and maximum values in Table 1 is that there is a large amount of variation for certain mobility indicators, which is suggestive of a local variation in conditions that support specific mobility patterns. We can map the sustainable mobility indicators in the region using scaled values centred on the Randstad's mean value, with red showing indicator values below the baseline and green indicator values above the baseline (Figure 2).Looking at the variation of indicator values on the maps, they present clear spatial patterns, further reinforcing the notion that urban form and configuration characteristics can be used as indicators of sustainable mobility especially in planning.

3. The configuration of multi-modal urban networks

Existing models of sustainable urban form, such as transit-oriented development (TOD), and of sustainable accessibility, such as'Multi-modal urban regional development' (Bertolini and Clercq 2003), relate specific urban form characteristics to sustainable mobility patterns. In terms of urban form characteristics, these models focus on the presence of transport nodes, on the public transport's network size and service quality, and on the location, density and diversity of activities. They use node, density and accessibility measures (Cheng et al. 2012) where the network provides the connection between opportunities (land use units or transportation nodes) and is used to measure the distance to them (accessibility) and their number or size (density) reachable from a given location.

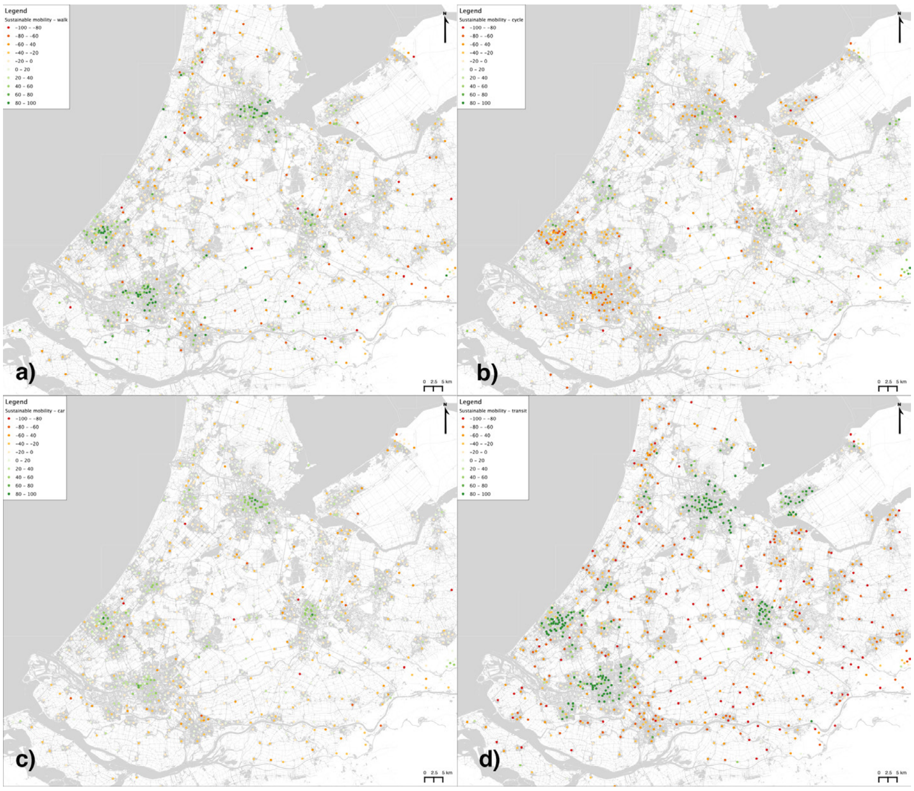

Figure 2. *Maps of the spatial patterns of sustainable mobility indicators, with green for values above and red for values below the Randstad baseline mean value, for a) walking b) cycling c) car and d) public transport share.*

Other urban form models focus on the characteristics of the street network itself, measuring the composition of the street layout (Marshall 2005), network reach (Peponis et al. 2008) and network centrality (Hillier and Hanson 1984),providing the network affordances of all locations assuming that the opportunities are the same everywhere in a general form of accessibility(Batty 2009). These street network models are used in the context of sustainable development to describe and measure the configuration of urban areas and can extend to cover entire cities and city-regions.

In order to better understand the complex relation between urban form and sustainable mobility patterns it isproposed that the city-region needs to be measured according to the configuration characteristics of its mobility infrastructure networks, and for that we need integrated urban network models. These models canaddress the organising role of the mobility infrastructure networks, where these whole,integrated structures define the relational condition of urban areas in a city-region (Read et al. 2007; Read and Gil 2012).

3.1 Multi-modal network models inspace syntax research

The spatial network developed in space syntax theory most used in urban and regional studies is the ‘axial map’ (Hillier and Hanson 1984; Hillier 1996), and its derivatives that split the lines of the map into smaller segments producing the‘segment map’ (Turner 2001; Hillier and Iida 2005) or merging lines based on their angular connectivity producing the ‘continuity map’ (Figueiredo and Amorim 2005). The most conventional geographic representation of the street network in GIS is the road centre line, with linear segments drawn along the middle of the street or of the individual traffic lanes. The resolution of the 'road centre line' based models is at the level of the street segment and the crossing node. Inlarge-scale studies, and to allow the use of publicly available street databases, methods have been developed to apply space syntax centrality analysis to road centre line networks (Dalton, Peponis, and Conroy Dalton 2003; Turner 2007; Peponis, Bafna, and Zhang 2008; Chiradia et al. 2008; Jiang and Liu 2009). Both the road centre line and the axial map representations are used to describe the street networks used by private transport, i.e. pedestrian, bicycles and cars.

As for the public transport networks, their representation is a standard feature in transportation network models, where the public transport stops are represented as nodes on the network with the links connecting these stops along the service routes or tracks. There are some examples of adding public transport networks to the models based on the 'axial map' (Chiaradia, Moreau, and Raford 2005; Gil 2012; Law, Chiaradia, and Schwander 2012), most of the times opting for a simplified topological representation linking the stops and stations directly, and considering additional topological links for transfer between modes.

The power of these street and multi modal network models can be further increased by integrating the activity and land use information using the buildings or building plots and connecting these to the nearest street (Ståhle et al. 2005; Marcus 2005; Sevtsuk 2010).

Beyond aspects of network representation, the analysis of network models uses the concept of network distance, which can take different forms (Hillier et al. 2010). This can be physical distance based on the length of the street segment, topological distance where every change of direction counts as one topological step, or angular distance where the angle of direction change is taken into account and a 90-degree change of direction is equivalent to one topological step (Turner 2001; Dalton 2001; Hillier and Iida 2005).In the case of the public transport network, the focus is on the network structure and the impedance is simply topological, with network transfers representing additional topological steps. However, when one starts working with multi-modal networks where flows happen at different speeds, one should also consider temporal distance where physical distance takes travel speed into account.

3.2 Measuring multi-modal network models

Table 2 provides a summary of different network metrics that can be calculated to characterize the mobility conditions of local urban areas using a multi-modal network model.

Proximity is the distance to the nearest element of the mobility network infrastructure of each mode, e.g. distance to the nearest train station or trunk road, and allows assessing the local network in terms of availability or convenience of a given mode.

Density measures provide an assessment of the availability and intensity of a given mobility mode (network reach) or land use activity (location density) in the local network. Network reach (Peponis et al. 2008) gives the amount of elements of the mobility network infrastructure within a given distance from a source location, e.g. number of crossings, total street length or cycle lanes length. Location density (Ståhle et al. 2005; Marcus 2005) gives the amount of activities available within a given distance from a source location, e.g. number of shops or total area of office space. It can be calculated for a variety of activities, such as offices, retail or education.

Table 2. *Summary of five types of urban network measures calculated on the multi-modal network model.*

Concept	Measure	Definition	Examples
Proximity	Node Proximity	Network distance to the nearest access node or to an infrastructure element of each mode	Distance to nearest train station, or to nearest trunk road
Density	Network Density / Reach	Network length or absolute number of nodes within a fixed network distance, per mode	Street network length or number of tram stops within 10 minutes walking
	Activity Density	Total area of activities within fixed network distance, per mode	Total office area or number of retail units within 10 minutes cycling
Accessibility	Network Centrality	Mean distance to or path overlap between every network node, using a specific mode	Mean closeness centrality of the street segments within 15 minutes walking
	Activity Accessibility	Mean distance to activities, weighted by their number and size, using a specific mode	Closeness to retail within 15 minutes driving

Accessibility is a more abstract concept that measures the relative importance of a location based on the distance to other locations on the network and to opportunities associated with activities (Batty 2009). Network centrality is a general type of accessibility that uses measures from network theory to describe the configuration of networks based on their topological relations (Freeman 1978). It calculates the mean distance of shortest routes to (closeness) and the frequency of shortest routes through (betweenness) a location. In space syntax closeness is called 'integration' and described as 'to movement', and betweenness is called 'choice' and described as 'through movement'. The results are the hierarchy, attraction and flow potential of individual elements of the network, e.g. junctions, street segments or rail stations. Activity closeness is the 'classic' accessibility, combining the mobility infrastructure networks with land use. It calculates the physical distance to locations on the network, weighed by the size or number of activities at those destinations, and uses a negative quadratic distance decay factor (Hansen 1959).

In a multi-modal network model, these urban network metrics can be calculated for the different mobility modes - walking, cycling, car, local public transport (tram, metro and bus) and rail - because each mode is based on different infrastructure elements, and must be calculated differently because each mode has different principles of use, e.g. reach, purpose or integration with other modes.

4. The multi-modal urban network model of the Randstad

The multi-modal network model of the Randstad integrates the various mobility infrastructure networks of the urban neighbourhood, i.e. pedestrian, bicycle, car, bus, tram and metro, with those of the city-region, i.e. motorways and railways, together with land use units. This is a disaggregate model with the smallest spatial units being respectively the street segments, the public transport stops and the individual buildings. Three different data sets have been used to build the model (Figure 3). The private transport system data was extracted from the OpenStreetMap (OSM) data set of the Netherlands (dump from January 2012) (http://www.openstreetmap.org/); the public transport system data was partly derived from OSM, partly from the public transport time table database of the OpenOV project (http://openov.nl/), and complemented with information from route maps of the various network operators; the land use data was extracted from the Basis register Addressen (BAG) data set (http://bag.vrom.nl/).

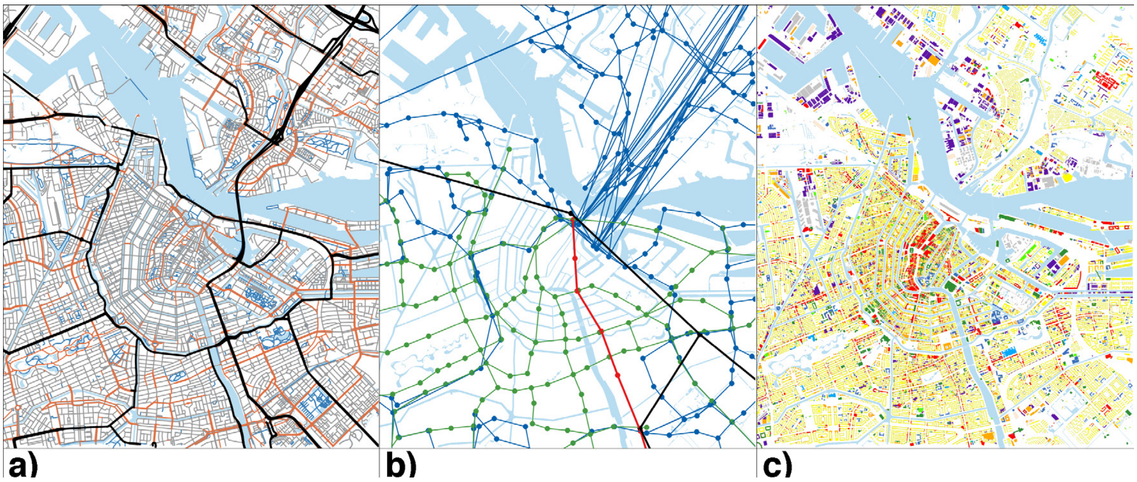

Figure 3. *Overview of the three main systems of the multi-modal network model centred on Amsterdam: a) private transport system (blue – pedestrian routes, orange – cycle routes, black motorways, grey – general roads), b) public transport system (black – rail, red – metro, green – tram, blue – bus), and c) land use system (colours according to the LBCS classification).*

4.1 The structure of the model

The different modes work in different ways, have specific geographic representations and need to be modelled differently. For this reason the components of the model are grouped in different systems, namely the private transport system, the public transport system and the land use system. In addition, the model has a layer of components connecting the systems together. Each of these systems is illustrated in Figure 4, and described next.

The private transport system is based on the street network and caters for the free and individual movement of pedestrians, bicycles and cars that together share the large majority of the network. This system also constitutes the public space structure of the urban environment and represents the main interface to the other systems: it is through the street network that one gains access to public transport and buildings. For that reason it is the core system onto which all others must connect.

The private transport system is modelled using the road centre line representation of the street network, with nodes at every level intersection or junction of two roads and the road segments linking the nodes. By default the street segments are general and accessible to all private modes - grey segments in Figure 4a. However, each segment has an attribute indicating if any of the private modes is not allowed to circulate and if the segment is specifically designed for a specific mode - blue for pedestrians, orange for bicycles and black for cars in Figure 4a. The street segments also have attributes related to their geometry, namely length and shape, and to the time of travel dependent on the speed of the associated mode. The nodes layer has attributes relating to the topology of the crossing and the number of different modes allowed to use the crossing.

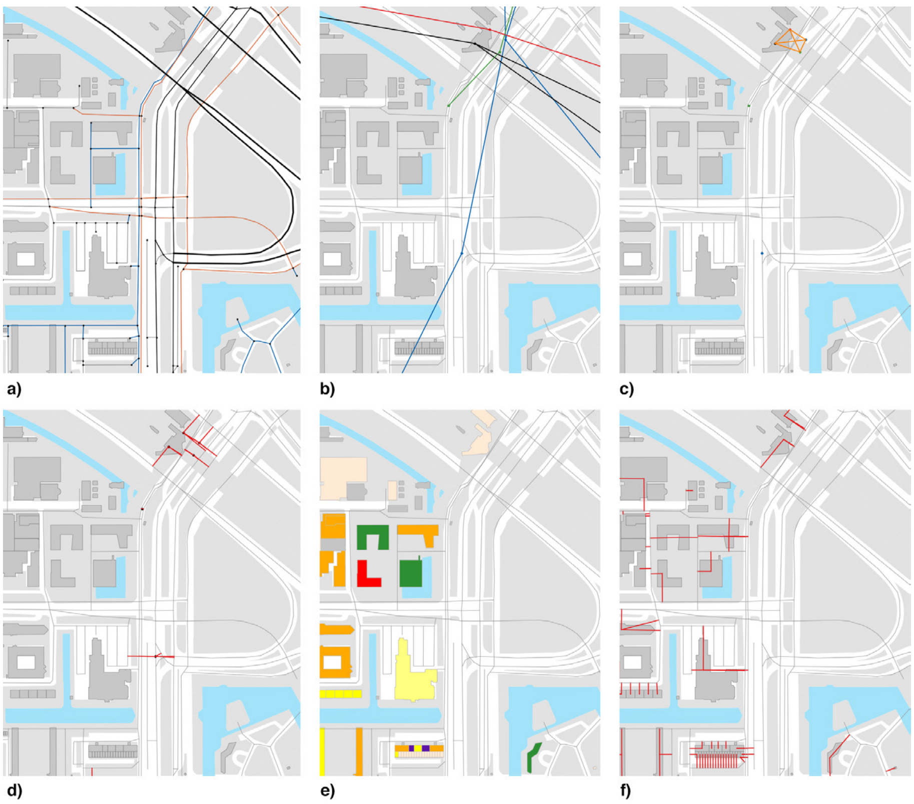

***Figure 4.** The systems of the multi-modal network model: a) private transport,* b) public transport, e) land use; and the interfaces between systems: c) multi-modal transit interfaces, d) transit and roads interfaces, f) buildings and roads interfaces.

The public transport system offers managed and collective movement of persons on metro, tram, buses and rail, most of the time using specific infrastructure for each mode. The technology and use of each public transport mode is different, not only requiring different types of tracks to run and stops for boarding and alighting, but also offering different speeds, ranges of movement and consequently different intervals between stops, increasing from bus to rail. These infrastructure networks cross and converge at particular locations where the stops of different modes share the same name, to allow interchange and multi-modal travel.

The public transport system consists of a nodes layer representing stops or stations of each public transport mode, and a links layer connecting these where a service exists between two stops of the same mode – black for rail, red for metro, green for tram and blue for bus in Figure 4b. The resulting public transport networks are further interconnected by 'modal interfaces' (Gil 2012; Gil and Read 2012), i.e. links connecting stops of different modes with the same name – orange links in Figure 4c.

The land use system offers the activities that are most often at either end of travel and that motivate travel in the first place. For this reason, although it is not strictly a component of the multi-modal transportation system, it is an integral part of mobility, accessibility and urban form and is therefore included in the model.

Contrary to the other systems, the land use system is composed only of a polygons layer representing the buildings, which can also be represented by nodes at the centroid of the buildings' geometry (Figure 4d). These buildings have land use attributes for different categories that result from the aggregation of the units and areas of each category I the building.

For multi-modal network analysis, the different systems of the model need to work together as an integrated whole and therefore there are 'modal interfaces' connecting the public transport nodes to the street network segments (Figure 4e) and the buildings to the adjacent street segment(s) (Figure 4f). These 'modal interfaces' provide direct links to the private transport system, and indirect links to the land use system and public transport system respectively.

To create these connections, links are drawn from the node, building perimeter or building centroid to all adjacent street segments of different private transport modes. Only links crossing other buildings and/or waterways are discarded. It is thus possible to have multiple links for one node, to account for the multi-lane road centre line representation and to the variety of options in reaching those nodes.

4.2 The analysis of the model

The geographic representation of the multi-modal network model,described in the previous section,needs to be translated into a graph representation for analysis. Here, the option of creating a primal or a dual graph is available. The proposed model uses an undirected graph that tries to reflect the nature of each system, and combines both dual and primal graph representations (Figure 5). On the one hand, in the private transport system, while the primal graph is simpler to obtain from a road centre line, the model uses a dual graph with the street segment as the main spatial unit of analysis providing the graph vertices, and the crossing nodes providing the edges. On the other hand, the public transport system has a more direct translation because the main spatial unit of analysis are the stops or stations, and these provide the graph vertices, with the connections between them providing the edges. The land use system only has nodes that become vertices in the graph. Both public transport and land use vertices are then linked to the street segment vertices with the various 'modal interfaces' edges.

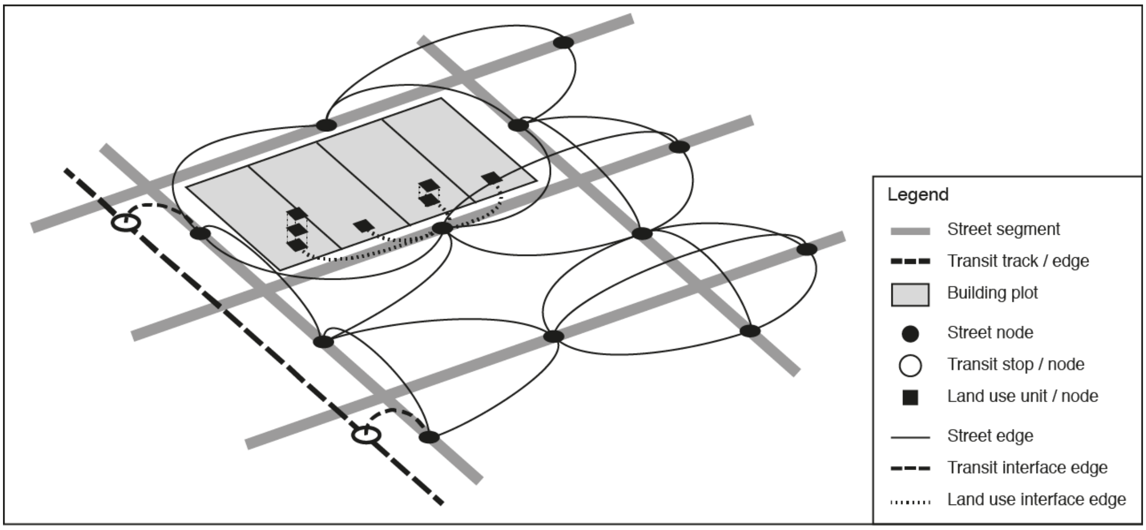

Figure 5. *Diagram of the graph representation of the multi-modal network model.*

The geographic representation of the model, in combination with the selected graph representation, supports different conceptions of distance, namely actual distance (physical and temporal), topological distance (segment, axial and directional) and angular distance.

In a first phase, the various types of distance are calculated for every street segment based on its geometry. Physical distance is simply the length of the segment in metres, while temporal distance multiplies the length by a factor of speed based on the averages taken from the mobility survey, for different modes and types of street segment, e.g. normal roads and main roads/motorways have different values (see Table 3). Topological distance is a constant value of 1 (one) in the case of segment distance, and a multiple of 1 depending on the number of changes of direction along the segment that are greater than a specific threshold, e.g. 15 degrees, in the case of axial and directional distance (Ozbil et al. 2011;Peponis et al. 2008). Angular distance is the sum of the angles between all sub-segments in a street segment, a method implemented in the sDNA software (Chiaradia, Webster, and Cooper 2012).

In a second phase, the impedance of the dual graph edges is calculated at the moment of conversion from network representation to graph representation

$$D(e(i,j)) = di/2+dj/2+te(i,j) \qquad (1)$$

where D is the impedance of edge e between vertices i and j, with di and dj being the impedance value of each vertex and t the turn cost of edge e between vertices i and j. The graph links have the same types of distance as the network links, and the impedance results from adding half of the distance of each of the vertices together with the turn cost component of the link. The turn cost component tis calculated based on the angle between two segments and varies depending on the type of distance. In physical and temporal distance t has a value of 0 (zero), in topological distance a value of 1 (one), and in angular distance the angle's value.

Table 3. *Network characteristics of the different modes, in terms of average speed and distance of 'modal interfaces'. Based on data from the mobility survey of the Netherlands (Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, and DienstVerkeer en Scheepvaart, 2011).*

Mode	Avg. Speed	Topological interface with transit	Temporal interface with transit	Topological interface with streets	Temporal interface with streets
main roads	60 km/h	-	-	-	-
car	40 km/h	-	-	-	-
bicycle	15 km/h	-	-	-	-
pedestrian	5 km/h	-	-	-	-
rail	80 km/h	2		1	3 min.
metro	25 km/h	2	5 min.	1	3 min.
tram	25 km/h	2	5 min.	1	½ min.
bus	30 km/h	2		1	½ min.

In the public transport system, with links that are straight lines, physical or temporal distance is based on the link's geometric length, while topological and angular distance have a constant value of 1 (one). Because these network links are only represented in primal form there is no further transformation. The impedance of 'modal interfaces' is calculated as in the previous cases for physical and cognitive distance and has pre-defined constant values for topological and temporal distance, depending on the transport mode (Table 3).

5. The structure of modality of the Randstad

5.1 Network proximity structure

The Randstad region has a comprehensive public transport network comprised of railway, metro (or light rail), tram and bus networks. If we map the shortest distance of every street segment to the nodes of each of the public transport networks we obtain the network proximity structure of the region. Proximity can be calculated using any of the concepts of distance mentioned earlier, but here we adopt the concept of physical distance, which is simpler and frequently used to define the walking catchment area from a location. The resulting mapsin Figure 6give the availability of each public transport mode at every location, or conversely the physical reach of every mode within the city-region. This reveals the environment of possible movement afforded by different mobility infrastructure networks.

While the railway clearly has reach across the whole city-region, linking its various centres and sub-centres, the tram and metro networks are contained in the four main urban centres, and the bus network is a local presence throughout the city-region. The three latter networks have a complementary role in their coverage, converging in the mobility hubs of the main urban centres where they also interface with the railway.

This analysis can be synthesised in a map of the public transport environment of the Randstad (Figure 6d), showing a different hue for the different combinations of public transport covering a location, a bright white colour where all these modes overlap, and black where there is no public transport reaching the location.

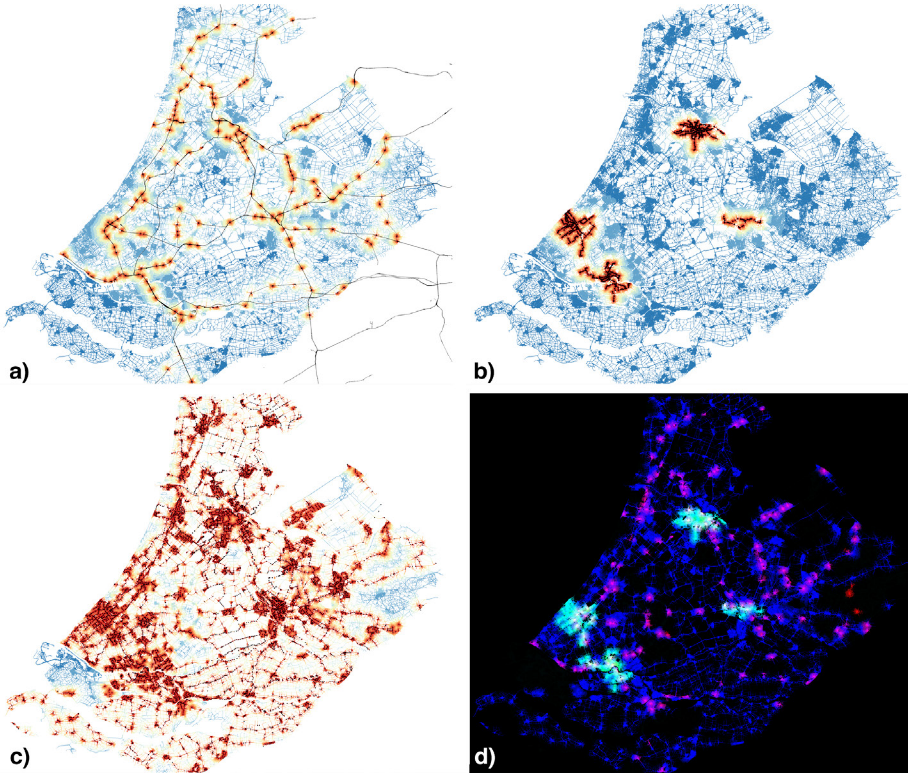

Figure 6. *Public transport modality in the Randstad region. Maps of proximity to public transport, showing the physical distance of every street segment to a a) rail station, b) tram stop and c) bus stop. The red to orange colour range corresponds to a 'walkable' distance of 400 to 1600m. Map d) shows a composite image where each colour highlights one mode, white indicating a concentration of modes and black the absence of public transport.*

5.2 Network centrality structure

Network centrality analysis reveals the hierarchy of places and the hierarchy of routes in an urban area, city or region. It is usually carried out on a complete model that does not differentiate between mobility modes, eventually using varying radii to capture different grains or scales of this hierarchy. However, the different modes are an essential aspect of measuring sustainable mobility

(Table 1), and for that reason it is useful to explicitly measure the centrality structure of models representing different modes. Figure 7 shows angular closeness analysis of the region at the global (radius N) scale. The grey area represents the buffer of the study area that is part of the calculations but for which the results are 'hidden'.

If we only consider the network of roads and paths accessible to pedestrians, which excludes the motorways, angular closeness analysis reveals a pattern with the integration core concentrated in the 'Green Heart' of the Randstad, instead of its urban centres (Figure 7a). Of course, this analysis of pedestrian movement is not realistic, as no pedestrians would walk the distances required to traverse the region. A solution to capture 'walkable' centralities would be to constraint the analysis to 'local' radii.

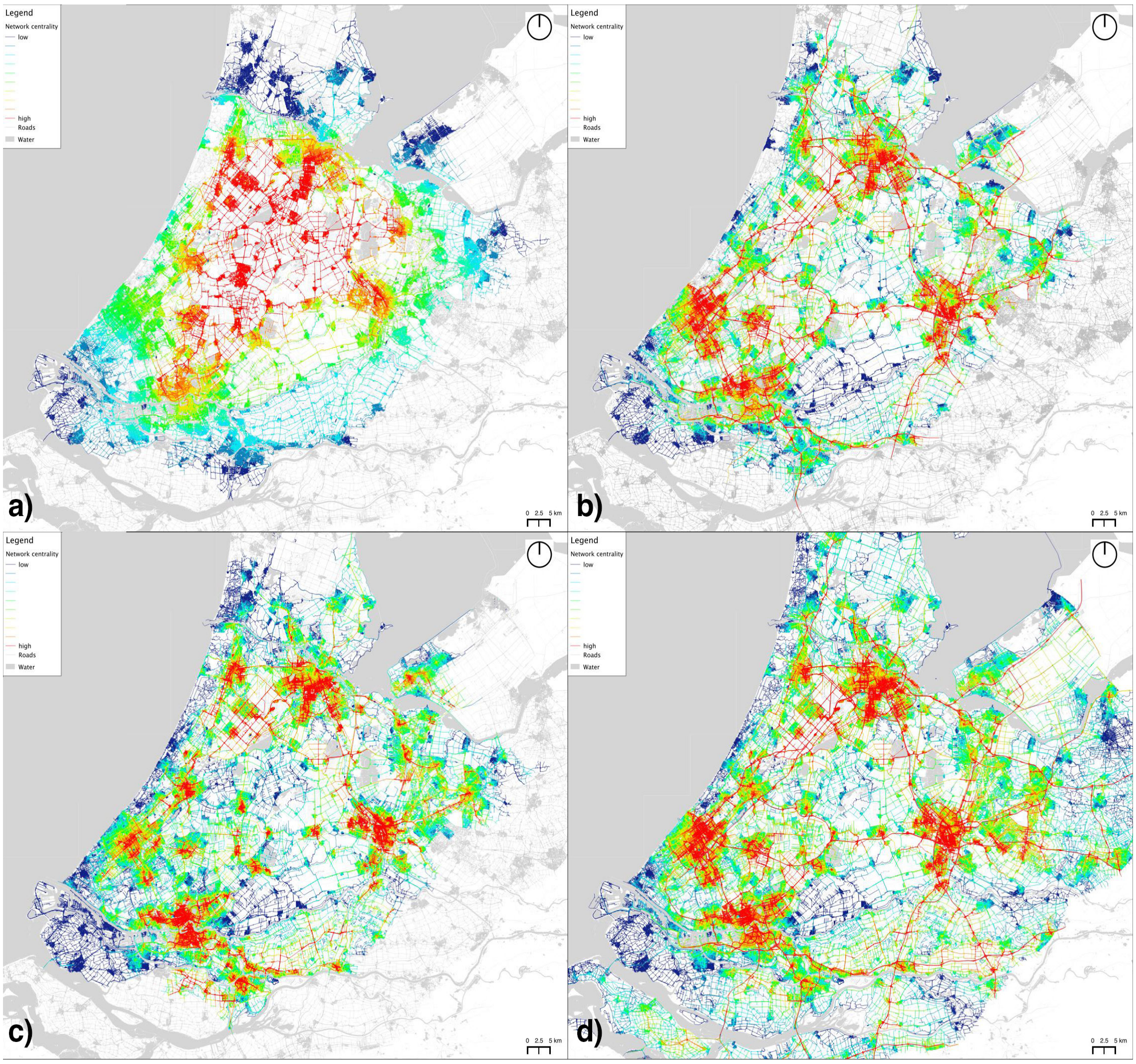

Figure 7. *Network centrality analysis of angular closeness at radius N, for different modes: a) non-motorised, b) private transport, c) public transport, d) all modes combined.*

However, what this map also shows is that there have been other mobility infrastructures, or modes (i.e. canals, ports, roads for horse and carriage), that allowed the region to historically form in the polycentric structure that we find today, otherwise the analysis would be 'correct'. If we run the same analysis integrating the present day mobility networks of car (Figure 7b) and public transport (Figure 7c) a new hierarchy emerges that already highlights local centralities. In the case of the car it captures the urban peripheries and out of town retail parks, while with public transport it captures the more traditional urban centres and suburbs. The final analysis (Figure 7d) is a composite of all non-motorised and motorized modes.

In these multi-modal centrality analyses, we have used angular distance with the private transport networks and topological distance with the public transport networks, the land use system and the 'modal interfaces' connecting these. Other combinations have been tried, however there should be a relation between the different concepts of distance being combined, as is the case with a topological turn equating to a 180 degree angle change, otherwise a complex process of calibration is required. On the other hand, temporal distance should be used as the cut-off distance for radius and catchment areas in multi-modal analysis measurements because this accounts for the different speeds of the different modes.

5.3 The relation between modality and mobility in the Randstad

Given the measurements proposed in Table 2, we can calculate a range of modality characteristics for the Randstad region using the multi-modal network model demonstrated so far. As the previous analyses have shown, there are several parameters for each measurement, such as network layers used, network distance type, catchment distance or modal interface costs. This opens the door to a potentially endless list of possible measures. In order to identify a set of urban form indicators that is relevant to sustainable mobility assessment we have calculated the modality characteristics of 839 postcode locations of the MON survey, and correlated these with the mobility indicators from Table 1.

The first step was to reduce the set of possible indicators to a set of meaningful indicators. This was achieved by identifying and eliminating co-variant measures of the same type, and selecting those that also showed greater inequality with the Gini coefficient, as they are more differentiating. The second step was to correlate the modality characteristics with the mobility patterns summarized in Table 1, in order to identify the most relevant urban form indicators. This resulted in the set of urban form indicators, summarized in Table 4.

The result of simple bivariate correlation between modality and mobility characteristics(Table 5) shows that twelve of the modality indicators have medium correlation with one or more of ten sustainable mobility indicators. From these results one can confirm some well known relations, such as higher density is an indicator of more walking and public transport use, and less driving. However, the rest of the mobility indicators remain unexplained, namely those relating to cycling, and urban form indicators do not show a sizable nor significant correlation. One should not forget that each mobility indicator represents a complex mobility pattern influenced by many factors and it would be impossible to get a single urban form characteristic to explain all that happens.

As a next step, one could use multivariate regression models to explore the combined influence of urban form characteristics in determining each mobility indicator, considering the many possible combinations of urban form variables.

Table 4. *List of selected urban form measures used to characterize the modality of urban areas in the Randstad.*

			Randstad postcode locations			
Measure	**Distance**	**Range**	**Mean**	**.Min**	**.Max**	**Gini**
Network Proximity						
Cycle network metric distance	Metric	-	274	0	3388	0.5901
Main road segment distance	Metric	-	1542	0	8611	0.4548
Motorway distance	Metric	-	3262	0	17396	0.3731
Rail station distance	Metric	-	4181	102	30416	0.4703
Local transit stop distance	Metric	-	503	0	17800	0.6336
Network Density / Reach						
Pedestrian network length	Metric	800m	2826	0	18393	0.5632
Cycle network length	Metric		4221	0	18469	0.4334
Cul-de-sacs count	Metric		14.36	0	50	0.4290
Crossings (X and T) count	Metric		148	1	523	0.3570
Local transit stops	Metric		5.23	0	24	0.4300
Rail stations	Metric	1600m	0.34	0	3	0.7355
Non-motor network reach	Angular	180°	6615	62	70947	0.5134
Car network reach	Angular		4725	62	102226	0.5512
Location Density						
Residential area	Metric	800m	254,880	164	966,080	0.3897
Activity area	Metric		29,429	0.00	467,770	0.6079
Work area	Metric		40,971	0.00	934,775	0.6779
Education area	Metric		13,877	0.00	335,879	0.6416
Network Centrality						
Car closeness mean	Angular	800m	0.000206	0.00	0.000240	0.0502
Non-motor closeness mean	Angular / topo		0.000312	0.000001	0.0003137	0.0027
Local transit closeness mean	Angular / topo		0.000274	0.00	0.0003139	0.1248
Rail closeness mean	Angular / topo	1600m	0.000093	0.00	0.0003141	0.7028
Location accessibility						
Car activity accessibility	Angular	-	2,034,127	88,363	226,490,500	0.7653
Car work accessibility	Angular	-	9,249,206	3,904,583	622,935,100	0.8008
Transit activity accessibility	Angular / topo	-	722,325	32,173	40,776,020	0.6321
Transit work accessibility	Angular / topo	-	243,9811	35,321	63,318,680	0.5909

Table 5. *Correlation between modality characteristics of postcode areas and sustainable mobility indicators of the same area. In bold are correlations of large size, with R >= 0.5, and in italic correlations of medium size, with 0.5 > R >= 0.3. For all values p < 0.01, except the value in brackets with p = 0.089.*

Measure	**Share of short walk journeys**	**Share of walk journeys**	**Share of medium car journeys**	**Share of car journeys**	**Share of car distance**	**Share of medium transit journeys**	**Share of transit journeys**	**Share of long transit journeys**	**Share of train journeys**	**Share of transit distance**
Rail station distance	-0.142	-0.187	*0.311*	*0.354*	*0.355*	-0.236	*-0.32*	*-0.39*	**-0.565**	*-0.384*
Cycle network length	*0.332*	*0.301*	*-0.321*	*-0.354*	*-0.324*	*0.441*	*0.477*	*0.345*	0.233	*0.37*
Crossings count	0.182	*0.339*	*-0.39*	*-0.466*	*-0.359*	*0.345*	*0.344*	*0.317*	0.213	*0.343*
Local transit stops	*0.322*	*0.405*	*-0.39*	*-0.447*	*-0.368*	*0.473*	*0.437*	0.293	0.122	*0.362*
Residential area	*0.309*	*0.429*	*-0.432*	**-0.511**	*-0.421*	*0.477*	*0.489*	*0.423*	0.254	*0.452*
Activity area	0.244	*0.463*	*-0.444*	**-0.543**	*-0.386*	*0.344*	*0.322*	*0.31*	0.223	*0.339*
Work area	0.236	*0.368*	*-0.404*	*-0.492*	*-0.379*	*0.308*	*0.308*	0.294	0.244	*0.324*
Education area	0.275	*0.344*	*-0.452*	*-0.471*	*-0.407*	*0.451*	*0.493*	*0.403*	*0.343*	*0.448*
Non-motor closeness	0.296	*0.331*	*-0.369*	*-0.416*	*-0.33*	*0.405*	*0.428*	*0.34*	*0.32*	*0.382*
Rail closeness	0.218	0.289	*-0.346*	*-0.374*	-0.199	*0.308*	*0.329*	0.189	(0.102)	0.223
Car activity accessibility	0.203	*0.31*	*-0.358*	*-0.42*	-0.299	*0.35*	*0.324*	0.256	0.239	*0.321*
Transit activity accessibility	0.178	0.229	*-0.343*	*-0.379*	-0.293	*0.324*	*0.338*	0.297	*0.372*	*0.347*

But only some of these combinations correspond to recognizable urban forms on the terrain, and given the spatial diversity one should not expect to find a unique statistical model that is capable of explaining the mobility patterns that occur throughout the region. For this reason, it is proposed to identify a set of modality profiles in the region that correspond to the different urban areas based on the modality indicators from Table 4. This is achieved applying unsupervised data classification methods, in particular k-medoid clustering, used in previous urban morphology studies (Gil et al. 2012; Serra, Gil and Pinho 2012). In this case, the method has led to the identification of 15 different modality environment types, summarized in Table 6. Their urban form profile provides a composite, multivariate description of each location. Their spatial distribution, illustrated in Figure 8, confirms the location and concentration of different types, highlighting the differentiated urban form and structure affordances of the different areas of the region.

By charting, for each of these modality environment types, the mean value of the sustainable mobility variables from Table 1, one can clearly identify how the different modality types support different mobility patterns (Figure 9).

Types 2 and 15 clearly show a reduced use of the car, with a high level of walking and use of public transport. In types 1, 8, 9, 12 and 13 the car

Table 6. *Summary description of the 15 modality environment types identified for the Randstad region based on the modality characteristics of Table 4.*

ID	Name	Summary description
1	Active multi-access core	High non-motorized network density, reach and centrality, proximity to main roads, dense local transit network, high mixed-use density and accessibility.
2	Regional transit hub	Highest non-motorized network density, reach and centrality, regional car and rail accessibility, high mixed-use density, with focus on non-residential activity.
3	Active local access cluster	Non-motorized network present with interrupted layout, average car and local transit access, but no rail, high residential and active land use density.
4	Car location	Average private transport presence and network density, but no rail and basic local transit, low residential and education densities.
5	Low access transit area	Low non-motorized and car infrastructure availability in sparse and segregated network, without rail but close to local transit, low active land use density.
6	Sparse car area	Low non-motorized and car infrastructure availability in sparse network without crossings, reduced presence of public transport, low active land use density.
7	Residential car area	Low non-motorized and car infrastructure availability, but high regional centrality, in sparse network of limited reach, reduced presence of public transport, mostly residential land use.
8	Live-work multi-access cluster	High non-motorized network density, reach and centrality, close to motorways with high car centrality and regional accessibility, high residential and work density and high regional accessibility to active land uses.
9	Residential multi-access cluster	High non-motorized network availability close to motorways, high public transport availability and centrality, dense residential and educational street network, with high regional accessibility to other land uses.
10	Residential transit cluster	Average private transport availability in structured network, presence of rail, high residential density and high regional accessibility to other land uses.
11	Residential island	Segregated private and public transport network, some presence of rail, mostly residential land use with low active land use density.
12	TU Delft North ((outlier	Available but segregated non-motorized network, many cul-de-sacs and high density of education land use.
13	Multi-access active (core (Utrecht	High street network density, reach, and centrality, local transit availability and centrality, high mixed-use density and highest regional accessibility.
14	Low access area	Sparse and segregated private and public transport network, lowest local density and lowest regional accessibility to active and work land uses.
15	Regional transit (hub (Utrecht	High non-motorized network density and centrality but low reach, far from car network infrastructure, high public transport availability and centrality, high residential density, with high regional accessibility to other land uses.

doesn't dominate, with transit (in the first three) and the bicycle (in the last two) taking higher prominence. Types 4, 6 and 7 show the average pattern of the Randstad dominated by the car, followed by the bicycle, while the similar types 3, 10 and 11 show some use of public transport and increased levels of walking. Types 5 and 14 are absolutely dominated by the car with an increased distance and frequency traveled. These mobility patterns are consistent with the location of the neighbourhoods and what would be expected from their modality environment description.

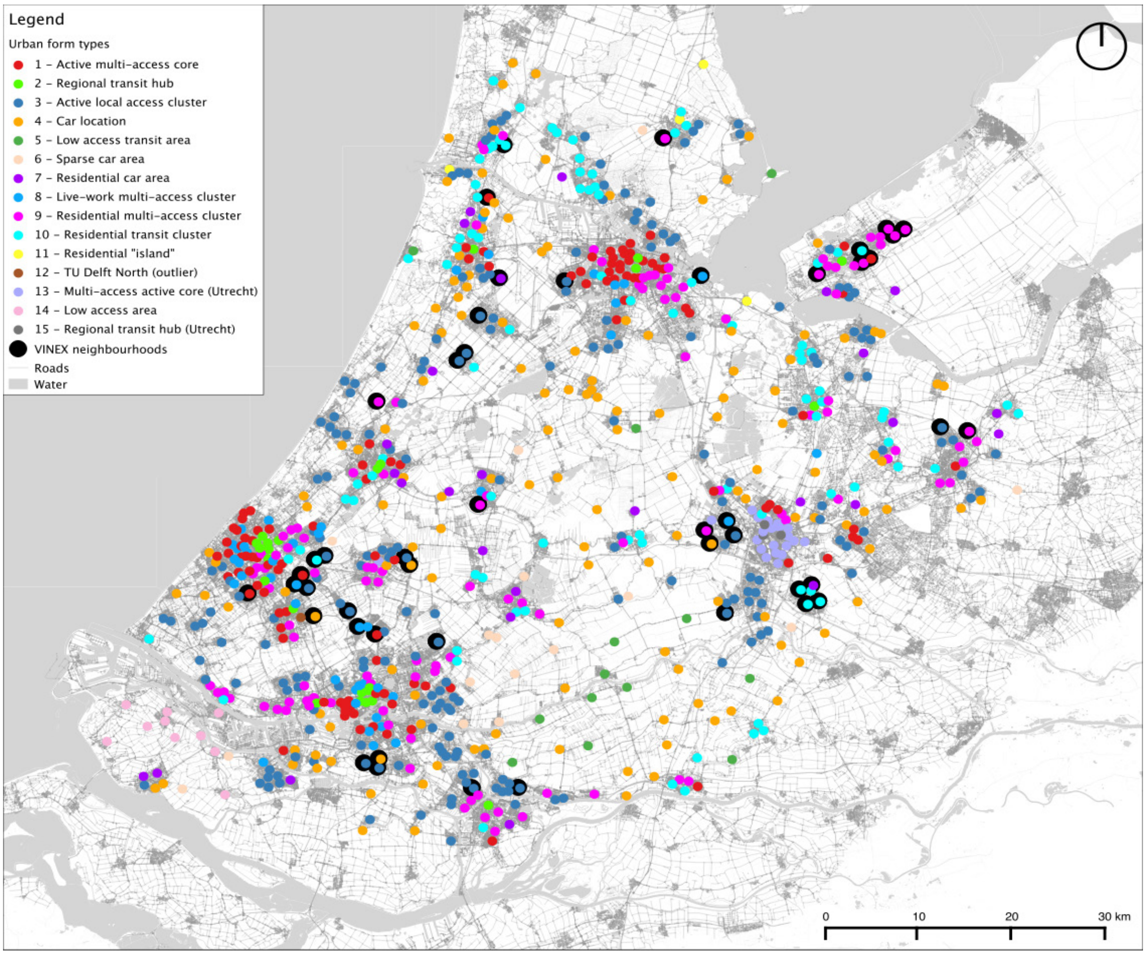

Figure 8. *Map of the location of the 15 different modality environment types described in Table 6. Each of these environments has specific urban form and structure affordances that are expected to support different types of mobility.*

The affordances of the different modality environment types enable or constraint the use of specific modes, at varying travel distances and journey frequency. Each of these mobility patterns defines the potential of a location, of a given modality type, to fulfill sustainable mobility objectives.

This approach can be used as an evaluation method of the sustainable mobility potential of neighbourhoods in this region, for ex-ante decision support during planning stages of new neighbourhoods, or ex-post decision support for monitoring performance and propose policy and planning interventions on existing neighbourhoods. Further work is required to explore the performance potential of each sustainable mobility dimension, namely walking, cycling, transit and driving, in relation to each individual modality type, and identify trends and similarities between these types with regards to specific mobility performance.

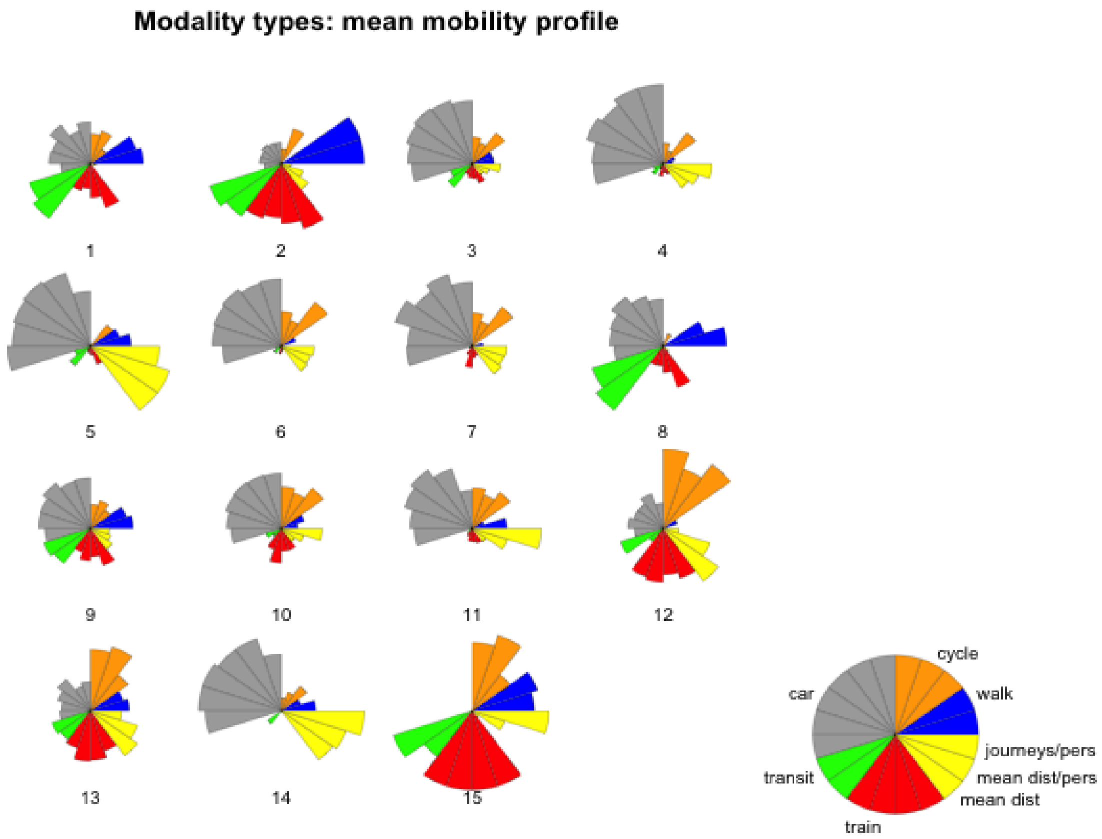

Figure 9. *Mobility profile of each of the 15 modality environment types described in Table 6 and located in Figure 8, using the sustainable mobility variables identified in Table 1.*

6. Conclusion

In this paper we introduce a multi-modal network model to explore the relation between urban form characteristics of urban areas that relate to different modes of movement. The relational network model is high-resolution, and integrated,combining three systems (private transport, public transport, and land use), differentiating the network links that are accessible to each mode of transport. Using this model we were able carry out analyses and measurements of the infrastructure network of the different modes,namely,the proximity to access nodes, the network density of infrastructure, the activity density within reach, regional accessibility to work and active land uses, and the regional network centrality of nodes. These analyses reveal the structures and hierarchies of urban form in the city-region that support the different modes of mobility.

From the large set of resulting measurements, we proceed to identify a reduced set of urban form indicators that are independent, and can describe the urban areas in the region based on a variety of proximity, density and accessibility dimensions. Upon correlation with empirical mobility data,we were able to confirm some of the accepted urban form principles of sustainable mobility, such as the relation between high network and active land use density and higher pedestrian movement and lower car use.

However,these bivariate relations are not sufficient to explain the full range of mobility patterns. Using a k-means clustering algorithm on the same dataset of urban form indicators, we obtain a typology of urban areas in the region, which we call modality environments because they have specific signatures in terms of the mobility patterns that they support. This typology of urban areas can contribute to new a relational and multi-scale urban form based method for evaluating the sustainable mobility potential of neighbourhoods in the city-region.

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