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Evaluating the impact of land-use density and mix on spatiotemporal urban activity patterns: an exploratory study using mobile phone data†

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Abstract. Dense and mixed land-use configurations are assumed to encourage high and prolonged activity levels, which in turn are considered to be important for the condition of urban neighbourhoods. We used mobile phone usage data recorded in Amsterdam, the Netherlands, as a proxy for urban activity to test whether the density in different forms of urban land use increases the level of activity in urban areas, and whether mixed land uses can prolong high levels of activity in an area. Our results indicate that higher densities correspond with higher activity levels, mixed land uses do indeed diversify urban activity dynamics and colocating particular land uses prolongs high activity levels in the evening hours. We proceed to demonstrate that mixed activity provisions and high urban activity levels coincide with urban neighbourhoods that are considered attractive places in which to live and work, while lower activity levels and markedly low activity mixes coincide with neighbourhoods that are considered disadvantaged.

Keywords: mobile phone usage, land-use density, land-use mix

1 Introduction

Since at least the 1990s there has been increasing political support for planning approaches that aim to achieve dense and mixed urban land-use patterns (Grant, 2002; Stead and Hoppenbrouwer, 2004; Vreeker et al, 2004). The desired land-use patterns are expected to improve urban vitality, safety, and quality of life, and make cities more sustainable and attractive (Coupland, 1997). As Hoppenbrouwer and Louw (2005) point out, many of the arguments used in favour of dense and mixed land use are still based on Jacobs (1962), who argued that such land-use configurations increase and prolong activity intensities in a neighbourhood. In her seminal work Jacobs observed that (1) safe and pleasant public spaces are the distinguishing characteristic of vibrant urban neighbourhoods, and (2) public spaces in large cities have very specific requirements in order to function effectively. Jacobs argued that in the public spaces of vibrant urban neighbourhoods an ad hoc social structure exists that maintains order [ie, provides *natural animation* (Petterson, 1997)] and stimulates residents

† The preparation of this paper has been overshadowed by Piet Rietveld's death in November 2013. His thoughts, ideas, and critiques contributed greatly to this article, and with sadness we dedicate this work to him.

to watch or engage in the daily events in public space [ie, provides *natural entertainment* (Montgomery, 1995)]. Such a social structure, upheld by residents and strangers passing by, would emerge naturally when diverse people are almost continuously present on a neighbourhood's streets. Jacobs (1962) argued that, in order to have sufficient, continuous human presence in public space, urban areas need to support activities with sufficient intensity and diversity in terms of temporal participation patterns, so that pedestrians populate the streets for substantial parts of the day.

Dense land-use configurations are expected to contribute to vibrant neighbourhoods by increasing urban activity intensities. One may argue that increasing land-use densities might instead lead to unwanted crowding effects, but perceived crowding and available physical space per capita are often unrelated (Bonnes et al, 1991; Fischer et al, 1975) and perceived crowding depends much more on other factors (Chan, 1999). Mixed land-use configurations are expected to extend activity intensities, and diversify the 'ebbs and tides' of people coming and going into an area to participate in the activities provided (Roberts and Lloyd-Jones, 1997, page 153). Mixed land use is furthermore presumed to generate multiplier effects that help extend activity intensities by retaining people in an area that they initially visited for another activity (Jacobs, 1962; Rodenburg et al, 2003).

Contemporary planners have adopted Jacobs's ideas, and found that encouraging higher and extended activity intensities by developing dense and mixed land-use configurations can have disappointing results. This is particularly unfortunate because dense and mixed developments are often very difficult to achieve [for experiences with establishing such developments, see Coupland (1997), Grant (2002), Majoor (2006), Petterson (1997), Rowley (1996)]. There are reasonable arguments why developing denser and more diverse land uses might not contribute to neighbourhood success at all. First and foremost, there is no proven impact of the physical environment on behaviour, as emphasised by Gans (1991). Another problem is that the demand for the specific type of urban environments at which densification and mixed development aim is presumably limited and, as Gans notes, may stem only from the upper middle class and young urban professionals. Furthermore, existing social environments in the city may already have established a hierarchy of preferred places to which their events and activities are closely tied (Currid and Williams, 2010). If such environments are indeed tied to particular places, the development of new activity spaces is successful only if the new spaces provide additional facilities that do not compete with the established hierarchy, or if a new type of social environment emerges.

Clearly more work is needed to find whether dense and mixed land-use patterns can indeed foster vibrant neighbourhoods. Besides Jacobs's work, only a few case studies have linked land-use density to desirable aspects of vibrant neighbourhoods such as attractiveness (Gadet et al, 2006) and low crime rates (Coleman, 1985; Petterson, 1997). These studies neither yield conclusive evidence on this subject, nor address the overall link between land-use intensity and activity levels. A data source that has recently become available—mobile phone usage data—is used in this paper to evaluate empirically the potential impact of dense and mixed land use on urban activity intensities. We used phone usage densities as a proxy for urban activity intensity and, for each hour of the day, statistically analysed the link between, on the one hand, activity levels and, on the other hand, the densities of various land uses and the interactions between colocated land uses. We did so in order to verify whether higher land-use densities correspond with higher activity intensities, whether the activities associated with those land uses have diverse temporal patterns, and whether multiplier effects exist between particular activities supporting each other when colocated. Subsequently, to test whether high and extended activity intensities do indeed coincide with favourable neighbourhood conditions, we compared observed and modelled phone usage densities in

(1) districts that experts consider successful in attracting members of the creative class, and (2) districts that, according to experts, are accumulating persistent social, economic and physical problems. We must emphasise here that we explored the coincidence of activity patterns and neighbourhood conditions, but have not verified the causal link proposed by Jacobs (1962) between activity intensities and neighbourhood success. In fact, there are many factors affecting the neighbourhood conditions analysed, and a thorough study of the mechanics that govern those conditions is well beyond the scope of this paper. In the following section we expand on the data and methods used; in the subsequent sections we demonstrate our evidence in favour of dense and mixed land-use configurations.

2 Data, methods, and limitations

For this study, mobile phone data recorded between January 2008 and November 2010 have been obtained from KPN, one of the main telecommunication service providers in the Netherlands. Such mobile phone usage data have been emphasised as particularly suitable for urban analysis (Ratti et al, 2006). Recent contributions using such data have explored seasonal migration (Silm and Ahas, 2010) and the composition of traffic flows in Estonia (Järv et al, 2012); linkages between phone usage and city characteristics in Rome (Reades et al, 2009); and the locations of personal ‘anchor’ activity bases in Estonia (Ahas et al, 2010, page 4). The activity patterns that Ahas et al derived are very similar to the spatial distribution of the population as observed in census data, and the authors therefore concluded that mobile phone usage is suitable for studying urban activities. The present study also presumes such a link between human activity patterns and mobile phone usage.

One important issue arises regarding privacy considerations that relate to the storing and analysing of personal communications, such as in the data used. The data obtained contain only aggregate usage statistics per mobile phone cell, and characteristics of the mobile phone users were not recorded. Thus, the data cannot be used to identify individual users and we therefore assume that privacy concerns are not problematic for this study. We elaborate on the mobile phone usage data, the modelled linkages with land-use and activity patterns, and some methodological limitations in the next sections, after addressing the study area. A scheme of this paper’s approach can be found in figure 1.

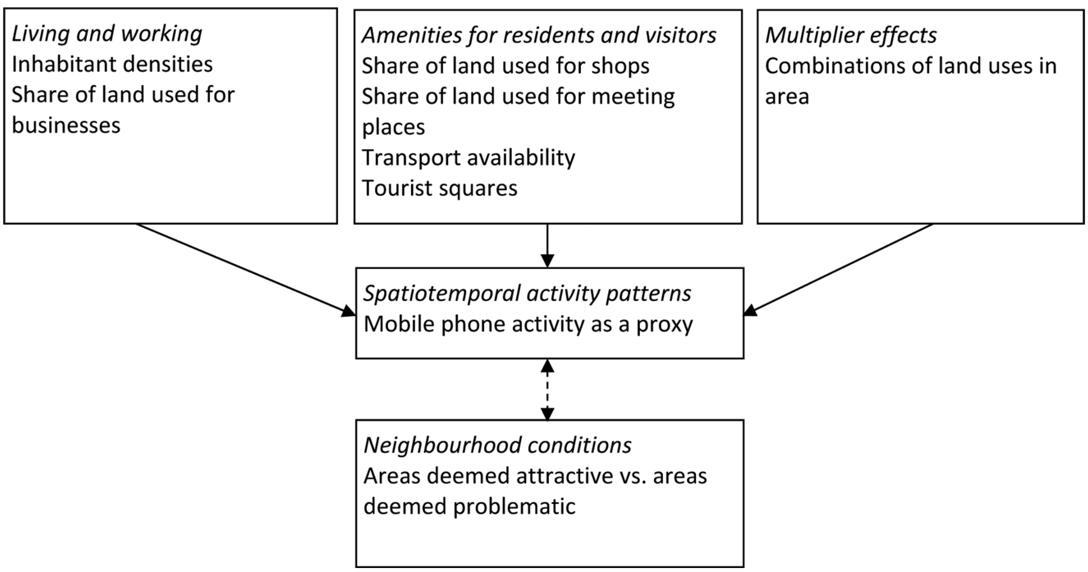

Figure 1. Conceptual scheme for this paper’s analyses, and the operationalisation of the main variables applied.

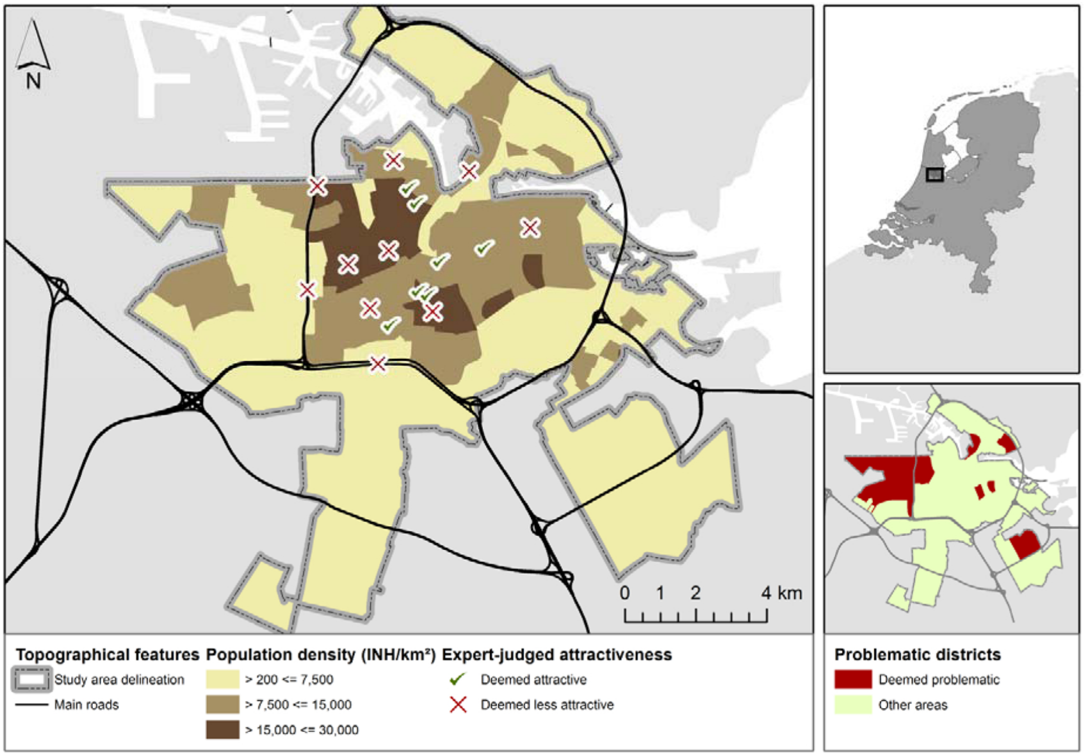

Figure 2. [In colour online.] Amsterdam, its population densities, the boundaries of the studied area, the suggested attractiveness of locations (Gadet et al, 2006), districts deemed problematic (Bicknese et al, 2007), and the location of Amsterdam in the Netherlands.

The city of Amsterdam in the Netherlands, entailing considerable geographical differences in urban density and in the degree of land-use mix, will serve as a case. Because the mixed-use literature seems to concentrate on land-use mixing in residential areas (see, for example, Cervero, 1996; Jacobs, 1962), we also limit our study to areas that have a residential purpose. We therefore use only data from antennas within urban districts with a population density of at least 200 inhabitants per km^2. Note that Amsterdam's average population density is 3800 inhabitants per km^2. Only rural and dominantly industrial areas on the outskirts of the city are excluded: for example, the largest excluded area is the port in Northwest Amsterdam. A map of the study area depicting key variables is shown in figure 2.

2.1 Describing the mobile phone usage data

Mobile phone usage data are spatially explicit because mobile phone network mechanisms make it possible to infer caller locations with more or less accuracy, depending on the characteristics of the available data. In some cases triangulation of individual caller locations is possible (ACA, 2004) and phone usage can be accurately mapped on a fine resolution grid (Calabrese et al, 2007). In other cases usage statistics are available only in an aggregated form per antenna, and then attributed to portions of space where callers using that antenna are presumed to be. Examples are cases in which mobile phone usage has been interpolated into a continuous surface (Ratti et al, 2006) or attributed to superimposed catchment areas (Ahas et al, 2010). The mobile phone usage data provided for this paper are attributed to a similar network-specific zonal topography named 'best-serving cells'. These cells are the results of sampling and subsequently mapping which antennas provide the best connection and they represent the areas that are *usually* connected to a particular antenna. Temporary changes in the network structure are not taken into account. This topology is created by the mobile phone service provider, which unfortunately does not allow disclosure of its mapping work.

Phone usage on the provider's network in the Amsterdam region has been made available for this study, save a number of months for which data are missing. There is a distinction between mobile phone usage data in which all phones *connected to* the network are recorded and data in which only phones that are *using* the network are recorded. The obtained phone usage data describe aggregate use: for example, the number of newly initiated calls per mobile phone cell per hour per day. Figure 3 indicates that, on average, more than two million phone calls were made over the 2G network each day in the observed period in the Amsterdam region.

We observed Y_{it} as the average number of newly initiated mobile phone calls[(1)] per hour (t) through antennas (i) per square kilometre of the best serving cell. The average number of new calls has been computed here as the average number of newly initiated phone calls per hour on all recorded working days from January to June 2010. Those data were used in twenty-four cross-sectional regressions, one for each hour of the day. The analysis centres on observations from that period because they are reasonably close to the land-use data that are available only for 2012, while due to network changes, results from after June 2010 are structurally different (this is also discussed in the following section). We expected that, because of the averaged nature of the dependent variable, sporadically occurring events such as the Queen's Day national holiday would not have a substantial effect on our results. To test the robustness of our findings, we have repeated our analyses with data for all available months.

Some preprocessing has been necessary to use the data. The data originally comprised phone usage statistics from two frequencies (900 and 1800 MHz), of which the antennas have overlapping but differently sized and shaped catchment areas. Network mechanisms such as capacity balancing mean that mobile phone usage statistics of the two frequencies

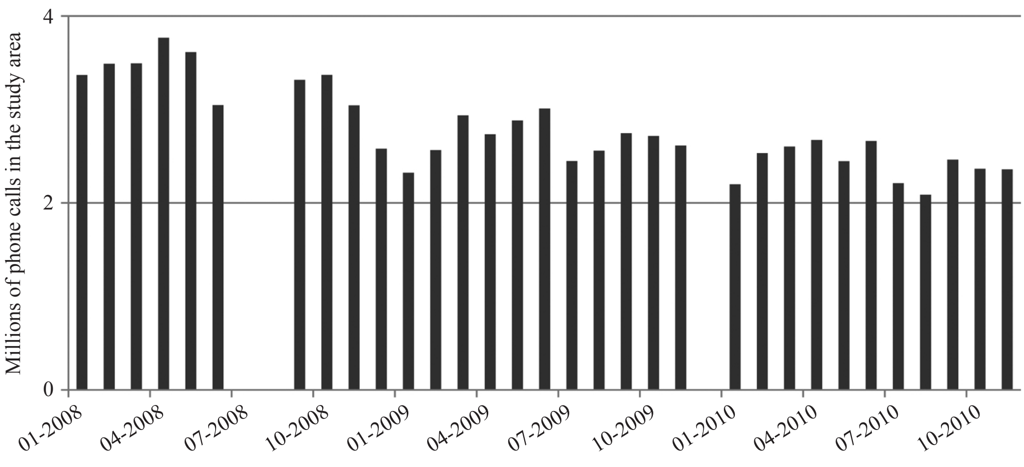

Figure 3. Monthly averages of new calls per day via the 2G network. Data for some intermittent months were not provided. The decrease in phone usage over time is caused by an increasing proportion of calls carried through the 3G network.

[(1)] Other studies (Ratti et al, 2006; Reades et al, 2009) use bandwidth consumption ('Erlang'). We prefer newly initiated phone calls as an approximation of human presence because we expect that this indicator is less biased towards activities that accommodate a disproportional amount of bandwidth. Furthermore, we expect that the portion of calls related to transportation is lower in new phone calls because we assume that people who are travelling (by car or by bicycle) are less likely to initiate a mobile phone call. This is useful because we want to focus on the presence of people in a place, rather than the flows of people in space.

are inextricably related, and therefore need to be analysed together. The data have therefore been integrated into summed statistics for the smaller 900 MHz frequency cells that handle the largest proportion of network traffic. Phone usage statistics of the 1800 MHz frequency have been disaggregated to that topology based on proportions of the overlapping areas.(2)

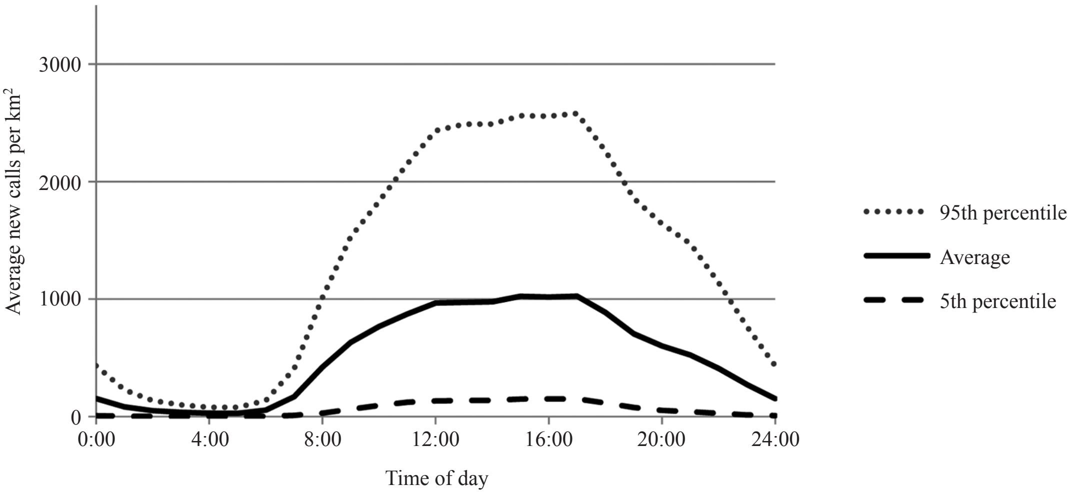

Figure 4. Fifth percentile, 95th percentile, and average number of new calls over the course of the day per km^2.

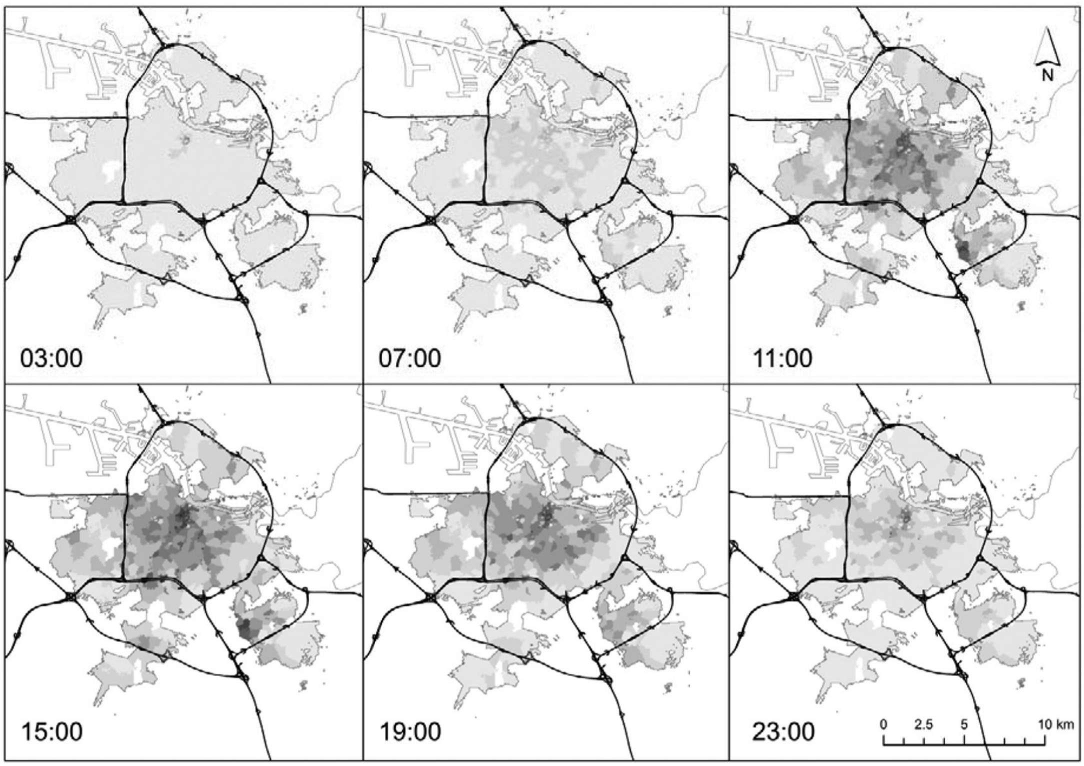

Figure 5. Spatial distribution of new calls per km^2 in Amsterdam and its environs (workday averages 2008–10). Dark black lines indicate motorways. The study area is gray with a darker outline, except for the white areas within it, which indicate missing data.

(2) Thus, if 1% of one 1800 MHz area overlaps one particular 900 MHz cell, 1% of traffic recorded in the 1800 MHz area is attributed to that 900 MHz cell, and so on.

When mapped, the data capture substantial temporal and geographical differences in activity levels (see figures 4 and 5).

2.2 Explaining spatiotemporal patterns in mobile phone usage

We assume that the time and location of mobile phone usage are related to general human activity patterns and the location where these activities take place. The temporal activity patterns in the Netherlands have been rather stable since at least the 1970s (De Haan et al, 2004). The average weekday participation rates of the Dutch population in a selection of activities are shown in figure 6. These national participation rates are likely to differ from the participation rates of the population studied here, but a comparison with figure 4 shows a clear relation between overall participation in activities and mobile phone usage. From figure 6 we can hypothesise that, given the dominant participation rates for working and leisure activities (whether at home or outdoors) throughout the day, these activities will likely have the largest impact on mobile phone usage densities.

The activities distinguished in figure 6 are likely to take place at different locations, so we propose an explanatory framework that combines the basic activities with a spatial representation of the locations where these activities are concentrated. This spatial context is offered by detailed land-use maps that highlight the locations where working, shopping, and leisure activities at home and outdoors are concentrated. In this explanatory framework we fitted mobile phone usage densities on different land-use types that can be associated with the main types of human activity (table 1). This approach allows us to explain spatiotemporal variation in mobile phone usage and provides insight into the importance of land-use density

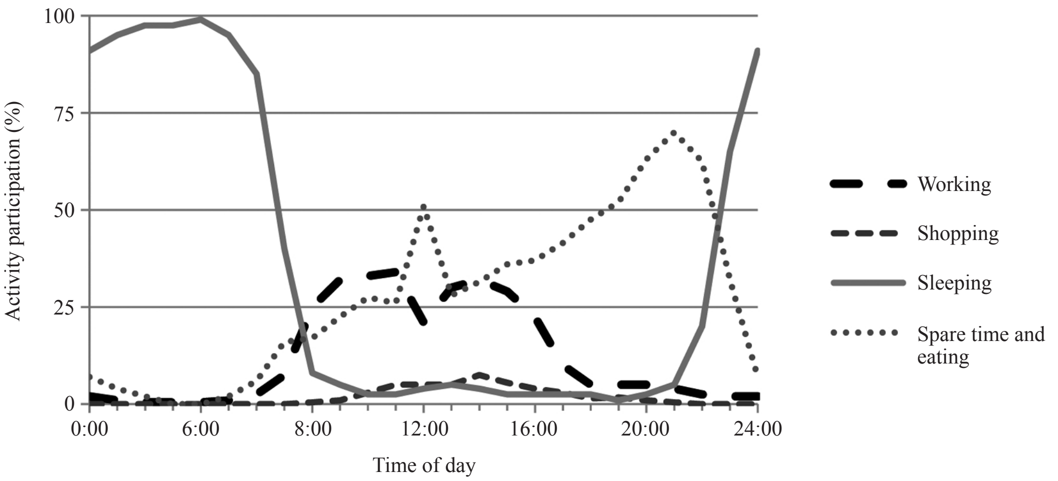

Figure 6. Temporal variation in a selection of weekday activities by percentage of Dutch people older than 12 years of age who participate in them (sources: Breedveld et al, 2006; Cloïn et al, 2011).

Table 1. Land-use types and their definition.

Leisure at home	Inhabitants per square kilometre, reflecting leisure opportunities at home
Working	Proportion of area used by factories, offices, and schools, reflecting working opportunities
Shops	Proportion of area used by shops, reflecting shopping opportunities
Outdoor leisure	Proportion of area used by various building types dedicated to social meetings such as cafés, restaurants, churches, conference rooms, and discotheques, reflecting outdoor leisure opportunities

in generating the concentrations of people active in the urban environment. By specifically looking at the impact of different combinations of land-use types, we are also able to assess the importance of land-use mixing in generating urban activity.

The land-use data are obtained from two data sources. Activities at home are observed by means of inhabitant densities per km^2, aggregated to the best serving cells from approximately 18 000 postcodes in the study area (Statistics Netherlands, 2006). Working, shopping, and social activities are approximated by means of land-use densities that are computed as the summed sizes of partial or total building footprints designated to a particular land use versus the total area of the catchment area. The building footprints and designations are derived from detailed building footprint data (Kadaster, 2013) in which the land-use designations of all independent units (eg, apartments or offices) within all buildings in the Netherlands are recorded. To compute land-use densities from those independent units, the total areal footprint of buildings is distributed equally over all the independent units that a building contains, and the total footprints of those independent units are summed per land-use type per mobile phone cell. Thus, if a building with a 60 m^2 footprint contains three independent units, of which two are designated to land use A and one to land use B, 40 m^2 of the building's footprint is attributed to A and 20 m^2 is attributed to B. We must acknowledge that information on floor space per independent unit is not included in these data, which may possibly skew the density figures because building heights will be higher in particular areas of the city. However, the data applied still provide a much more detailed description of land uses than the remotely sensed data that are often used in land-use studies, and we believe that the data used are a workable alternative as long as more accurate sources such as information on floor space are unavailable.

2.3 Methodological limitations

The data used impose a number of important limitations. A first limitation is that some activities likely encourage phone use more than other activities. Thus, mobile phone usage is presumably biased towards certain activities. We assumed this is not problematic because all activities are captured to some degree in the modelling exercise, which is sufficient for this study. Another limitation is that, while neighbourhoods supposedly need pedestrians, the data used do not discern callers who are outdoors or indoors. We thus have to assume that higher activity intensities and more diverse temporal activity patterns lead to more pedestrian activity. This likely holds true in Amsterdam, a city that actively discourages private car use.

Another concern related to the mobile phone data used is that only phone usage data from the so-called 2G network have been obtained, while, during the observed period, mobile phone services were provided in the Amsterdam region by both second-generation (2G) and third-generation (3G) network technology. Especially in 2010 a substantial share of mobile phone usage, 36%, has used the 3G network (see KPN, 2011), which causes the previously mentioned shift in results after June 2010. Nevertheless, the majority of phone calls used the 2G network even in 2010, and we therefore believe that the shift in traffic from 2G to 3G has not severely affected our findings.

Other limitations are related to the spatial nature of phone usage data. The zones used cover an area of 0.5 km^2 on average, and are thus of a relatively fine spatial resolution, but still much larger than the streets and blocks analysed in other studies of land-use mixing (Hoppenbrouwer and Louw, 2005; Jacobs, 1962; Rodenburg et al, 2003). Because of the fixed resolution of the available data, the detail of those previous studies cannot be repeated here, and we cannot account for relevant aspects of urban land-use configuration such as street connectivity and grain size. We nevertheless expect that the spatial and temporal comprehensiveness of the data used is valuable for understanding the effects of land-use density and mix on activity levels. Another difficulty of using data based on presumed antenna catchment areas is that, because the antenna providing the best connection to one place may vary with temporal conditions, changes in the built environment, or even chance reflections in water, the link between caller location and the connecting antenna is of a stochastic rather than deterministic nature. Thus, callers are often falsely attributed to neighbouring catchment areas (see also Ahas et al, 2010). We presume that this is one cause of spatial autocorrelation in the data. To overcome spatial autocorrelation in the data, a spatial error model is applied (see Anselin, 2001; LeSage and Fischer, 2008). Furthermore, the use of discretely bordered areal units brings forth the modifiable areal unit problem (Openshaw, 1984), of which the differences in areal sizes of zones in particular can bias statistical findings (Arbia, 1989). These biases can in part be overcome by normalising observations by average cell size [see Jacobs-Crisioni et al (2014) for a recent overview], which we do by means of equation (1):

$$S_i = A_i \Big/ \left(\frac{1}{n}\sum A_i\right), \tag{1}$$

where weight S is computed for each cell i by means of geographical area A.

3 The impact of land-use density and mix on hourly urban activity patterns

To estimate the impact of land-use densities and mixes on mobile phone usage in zones ($i = 1, 2, .., 362$), we fit the spatial error model shown in equation (2) repeatedly on the selected time frame's averaged new call densities for one hour of the day ($t = 0, 1, \ldots, 23$):

$$\begin{aligned} Y_{i,(t=0,1,\ldots,23)} = {} & \beta_0 + \beta_1 \mathrm{INH}_i + \beta_2 \mathrm{BUS}_i + \beta_3 \mathrm{SH}_i + \beta_4 \mathrm{MP}_i + \beta_5 (\mathrm{BUS}_i \times \mathrm{MP}_i) \\ & + \beta_6 (\mathrm{SH}_i \times \mathrm{MP}_i) + \beta_7 (\mathrm{BUS}_i \times \mathrm{SH}_i) + \beta_8 \mathrm{TS}_i + \beta_9 \mathrm{METRO}_i \\ & + \beta_{10} \mathrm{STATION}_i + \beta_{11} \mathrm{MWAY}_i + \rho W_{ij} \varepsilon_j + \mu_i , \end{aligned} \tag{2}$$

in which the observations i are additionally weighted with the weighting values S_i discussed in section 2.1. In our approach the impacts of densities of inhabitants (INH), businesses (BUS), shops (SH), and meeting places (MP) on phone usage levels are estimated. Furthermore, potential interaction effects between different land uses are captured. We are aware that land-use mix is an ambiguous concept which in all cases has to do with land-use diversity within cities, but which can occur on varying scales and with varying impacts on activity dynamics (Rowley, 1996). Unsurprisingly, there are many methods to measure degrees of land-use mixing; for an overview, we refer to Manaugh and Kreider (2013). We model land-use mixes by means of interaction effects between the densities of particular land uses colocated within one areal unit. On a side note, aggregate indicators of land-use mix based on the Herfindahl concentration index have also been tested, but did not yield useful results. The reason is no

Table 2. Descriptive statistics of new call densities and explanatory variables.

Variable	5th percentile	Mean	95th percentile
New mobile phone calls per km^2 (Y)	123.79	641.83	1487.82
Inhabitants per km^2 (INH)	0.00	6546.88	17050.99
Fraction of areas used for businesses (BUS)	0.05	3.04	8.87
Fraction of areas used for shops (SH)	0.00	0.82	3.59
Fraction of areas used for meeting places (MP)	0.00	0.82	3.24
Colocated businesses and shops (BUS×SH)	0.00	4.75	23.82
Colocated businesses and meeting places (BUS×MP)	0.00	4.09	21.16
Colocated shops and meeting places (SH×MP)	0.00	2.67	13.39

Note: $N = 362$; areal fractions have been multiplied by 100 in this table for better legibility.

Table 3. Spatial error model estimation results of impacts on average new call densities per hour from recorded working days from January to June 2010.

Hour	Constant	Inhabitant density	Business density	Shop density	Meeting place density	ρ	Pseudo-R^2
0	17.34 (0.82)	1.61** (8.77)	1.03 (0.36)	8.14 (0.86)	9.92 (1.12)	0.63** (16.34)	0.29
1	10.48 (0.68)	0.83** (6.19)	0.32 (0.15)	4.82 (0.70)	4.51 (0.70)	0.62** (16.54)	0.29
2	8.09 (0.72)	0.47** (4.75)	0.15 (0.10)	1.92 (0.37)	3.06 (0.63)	0.58** (14.73)	0.28
3	7.58 (0.83)	0.34** (4.21)	−0.20 (−0.15)	1.87 (0.43)	0.19 (0.05)	0.54** (12.81)	0.25
4	5.60 (1.01)	0.26** (5.32)	0.10 (0.12)	2.76 (1.03)	1.16 (0.46)	0.53** (12.10)	0.22
5	6.66 (1.73)	0.25** (7.10)	0.41 (0.69)	2.34 (1.13)	1.49 (0.78)	0.36** (6.39)	0.12
6	17.55** (3.23)	0.39** (7.83)	2.08* (2.41)	3.62 (1.18)	2.50 (0.90)	0.29** (4.51)	0.08
7	46.75** (3.43)	1.19** (9.51)	10.40** (4.71)	9.89 (1.24)	9.38 (1.30)	0.22** (2.92)	0.07
8	99.64** (2.60)	2.80** (7.98)	33.52** (5.61)	22.18 (1.06)	20.64 (1.07)	0.33** (4.65)	0.11
9	119.89 (1.78)	4.00** (6.49)	59.41** (5.74)	41.30 (1.15)	40.61 (1.23)	0.38** (5.20)	0.12
10	118.37 (1.46)	5.21** (7.03)	70.93** (5.65)	57.65 (1.31)	54.69 (1.36)	0.35** (4.72)	0.11
11	115.16 (1.26)	6.25** (7.48)	77.58** (5.45)	70.86 (1.41)	62.49 (1.36)	0.33** (4.33)	0.12
12	122.81 (1.28)	7.06** (8.01)	78.69** (5.21)	90.31 (1.69)	59.33 (1.22)	0.31** (4.25)	0.13
13	116.38 (1.19)	7.06** (7.87)	77.53** (5.02)	95.78 (1.75)	69.06 (1.38)	0.29** (4.00)	0.14
14	109.10 (1.11)	7.20** (7.98)	75.70** (4.85)	97.31 (1.75)	71.94 (1.42)	0.28** (3.72)	0.15
15	121.21 (1.21)	7.67** (8.34)	74.09** (4.64)	93.97 (1.64)	84.24 (1.63)	0.26** (3.47)	0.15
16	125.34 (1.27)	7.74** (8.55)	68.57** (4.36)	81.22 (1.45)	77.13 (1.51)	0.26** (3.56)	0.16
17	137.05 (1.38)	7.90** (8.65)	64.68** (4.11)	57.93 (1.03)	72.04 (1.41)	0.28** (4.11)	0.16
18	110.85 (1.36)	8.07** (10.79)	37.00** (2.87)	34.42 (0.75)	61.52 (1.48)	0.30** (4.58)	0.18
19	88.76 (1.47)	7.24** (13.11)	16.03 (1.70)	37.98 (1.15)	50.99 (1.68)	0.33** (5.38)	0.22
20	76.33 (1.48)	6.51** (13.79)	7.81 (0.98)	36.01 (1.31)	39.66 (1.57)	0.38** (6.59)	0.24
21	64.00 (1.35)	5.78** (13.46)	6.21 (0.87)	27.41 (1.12)	34.39 (1.53)	0.44** (8.01)	0.25
22	45.82 (1.12)	4.48** (12.20)	5.25 (0.89)	23.79 (1.19)	30.76 (1.66)	0.52** (11.02)	0.26
23	28.91 (0.89)	2.92** (10.17)	3.24 (0.72)	14.57 (0.97)	21.54 (1.53)	0.59** (14.02)	0.28

Table 3 (continued).

Hour	Businesses×shops	Businesses×meeting places	Shops×meeting places	Tourist square	Metro station	Railway station	Motorway
0	−4.67** (−4.21)	6.72** (3.90)	2.82* (2.03)	174.61* (2.01)	50.22 (1.38)	33.62 (0.55)	−4.98 (−0.25)
1	−3.36** (−4.16)	5.51** (4.39)	1.47 (1.45)	107.27 (1.70)	24.32 (0.92)	3.93 (0.09)	−1.96 (−0.14)
2	−2.18** (−3.58)	3.85** (4.06)	1.18 (1.54)	63.14 (1.34)	13.37 (0.67)	−1.95 (−0.06)	−1.60 (−0.15)
3	−1.49** (−2.94)	3.46** (4.37)	0.71 (1.10)	45.15 (1.16)	14.41 (0.86)	−7.25 (−0.26)	−1.53 (−0.17)
4	−1.04** (−3.32)	2.05** (4.19)	0.37 (0.95)	26.50 (1.11)	17.81 (1.73)	−5.98 (−0.34)	−0.47 (−0.08)
5	−0.37 (−1.56)	0.81* (2.17)	0.06 (0.21)	12.48 (0.72)	19.20* (2.47)	−3.42 (−0.25)	−0.68 (−0.16)
6	−0.49 (−1.41)	0.40 (0.73)	0.28 (0.62)	28.04 (1.14)	33.74** (2.97)	2.81 (0.14)	1.17 (0.19)
7	−1.06 (−1.17)	0.43 (0.30)	1.36 (1.17)	61.73 (0.99)	87.07** (2.97)	29.19 (0.56)	4.22 (0.27)
8	−2.46 (−1.03)	0.84 (0.22)	6.61* (2.16)	85.74 (0.50)	233.65** (2.98)	71.37 (0.52)	15.99 (0.38)
9	−2.00 (−0.49)	2.54 (0.39)	7.89 (1.50)	116.51 (0.39)	338.62* (2.51)	−15.72 (−0.07)	18.65 (0.26)
10	−1.79 (−0.36)	5.05 (0.64)	8.32 (1.30)	175.39 (0.48)	391.67* (2.38)	−18.48 (−0.06)	20.24 (0.23)
11	−1.24 (−0.22)	7.95 (0.88)	10.42 (1.43)	212.23 (0.52)	419.79* (2.24)	−8.85 (−0.03)	20.60 (0.21)
12	−1.28 (−0.21)	13.08 (1.37)	13.40 (1.72)	257.85 (0.59)	448.43* (2.26)	58.98 (0.17)	29.98 (0.28)
13	0.10 (0.02)	13.71 (1.40)	14.47 (1.81)	300.18 (0.68)	455.21* (2.24)	39.66 (0.11)	26.96 (0.25)
14	1.21 (0.19)	14.18 (1.43)	16.03* (1.98)	331.69 (0.75)	451.16* (2.19)	48.78 (0.13)	30.49 (0.28)
15	2.61 (0.40)	13.20 (1.29)	17.65* (2.12)	371.30 (0.82)	446.36* (2.11)	95.80 (0.26)	34.39 (0.31)
16	2.68 (0.42)	14.62 (1.46)	21.57** (2.64)	303.00 (0.68)	481.23* (2.31)	132.04 (0.36)	44.21 (0.40)
17	0.96 (0.15)	15.60 (1.56)	27.42** (3.36)	339.46 (0.75)	542.10** (2.61)	241.80 (0.66)	51.24 (0.46)
18	−1.30 (−0.25)	17.13* (2.10)	20.05** (3.02)	360.17 (0.98)	402.16* (2.37)	231.85 (0.78)	24.72 (0.27)
19	−4.47 (−1.18)	15.59** (2.62)	11.14* (2.31)	355.39 (1.31)	223.44 (1.81)	196.09 (0.91)	−16.45 (−0.25)
20	−5.48 (−1.74)	14.71** (2.97)	7.90* (1.96)	294.29 (1.27)	161.34 (1.56)	166.00 (0.92)	−27.16 (−0.49)
21	−6.58* (−2.35)	13.41** (3.05)	7.40* (2.08)	264.27 (1.26)	147.61 (1.60)	163.20 (1.03)	−26.46 (−0.53)
22	−7.36** (−3.18)	11.19** (3.09)	6.03* (2.07)	243.39 (1.38)	133.62 (1.76)	124.93 (0.96)	−15.04 (−0.37)
23	−6.52** (−3.72)	9.42** (3.45)	5.23* (2.38)	172.95 (1.27)	98.73 (1.71)	71.29 (0.73)	−8.18 (−0.26)

* Significant at the 0.05 level; ** significant at the 0.01 level.

Note: Z–scores are reported in parentheses. $N = 362$ for each hour of the day. Spatial dependencies in the error term are expressed by ρ. Inhabitant densities are divided by 100 for better legibility.

doubt that such aggregate indicators do not distinguish individual land-use interactions, while our results show that different interactions can even have contrary effects on urban activity levels at a given time. This problem with aggregate land-use diversity indicators is also noted by Manaugh and Kreider. The proximity of two squares that are popular tourist destinations is also modelled, because the other variables presumably underestimate the attraction that these locations have. This variable (TS) indicates whether a zone is within 250 m of Amsterdam's 'Dam' or 'Museum' squares. Lastly, because transit places may affect the recorded dynamics of phone usage, the presence of metro stations (METRO), major railway stations (STATION), and motorways (MWAY) within a zone is estimated.

We repeatedly fitted phone usage densities per hour on cross-sectional data; thus, temporal shocks and dependencies are not explicitly modelled. We must acknowledge that this is an unusual approach to tackling longitudinal data compared with more common time-series methods. Although the method applied does not allow us to explore the causes that drive the dynamics of phone usage explicitly, it does allow us to explore how land-use configuration is related to phone usage, while spatial dependencies can be included in a relatively straightforward manner and serial autocorrelation should not problematically affect the results. Although land-use configurations are assumed to be static, one may expect that, in the longer run, they do respond to changes in activity levels; we ignore this in our modelling effort, but stress that further research on interdependencies between spatial configuration, land use, and human presence is needed.

As explained in section 2.1, a spatial error model is applied. That model is fitted by separating the white noise error term μ from the spatially interdependent unobserved variables of contiguous neighbours (j) in ε. Spatial relations are defined as first-order contiguity according to the queen's case, and are observed in the spatial weighting matrix $\mathbf{W}$. As a sensitivity analysis strategy, alternative modelling approaches have been tested. Ordinary least squares (OLS) estimations yielded fairly similar results, but geographically weighted regression yielded rather unstable estimators with various variable or kernel settings. This is presumably because of local multicollinearity in the explanatory variables (see Wheeler and Tiefelsdorf, 2005). Note that, although multicollinearity may be problematic in geographically weighted windows, global multicollinearity is not problematic for this work's results (see online appendix A, http://dx.doi.org/10.1068/a130309p).

Summary statistics of all variables are given in table 2; other characteristics of the explanatory variables are given in appendix A. The estimation results are presented in table 3; estimated contributions of average land-use densities on phone usage are shown in figure 7. The last are computed by multiplying the estimated effects of land uses by the average land-use densities in table 2, thus showing the average impact of the presence of various types of land use.

We find that inhabitant densities contribute to new call densities throughout the day. Nevertheless, this effect varies over time and peaks between 15:00 and 18:00 hours, which is the period in which workers are coming home (see figure 6). Business densities contribute most to phone usage during common Dutch working times. Shop densities contribute to phone usage chiefly between 11:00 and 17:00 hours and peak at 14:00 hours, resembling common Dutch shopping times. In comparison with shops, meeting places contribute to phone usage over a longer period of time during the day, which may be related to the heterogeneity of activity types covered in this category. The colocation of businesses and meeting places increases human presence after working hours. The colocation of shops and meeting places increases human presence throughout the day, even before and after shopping times but peaking from 14:00 hours, when shopping participation is on the decrease. The colocation of shops and businesses does not significantly increase human presence. Amsterdam's tourist squares are associated with relatively high phone usage densities throughout the day; this

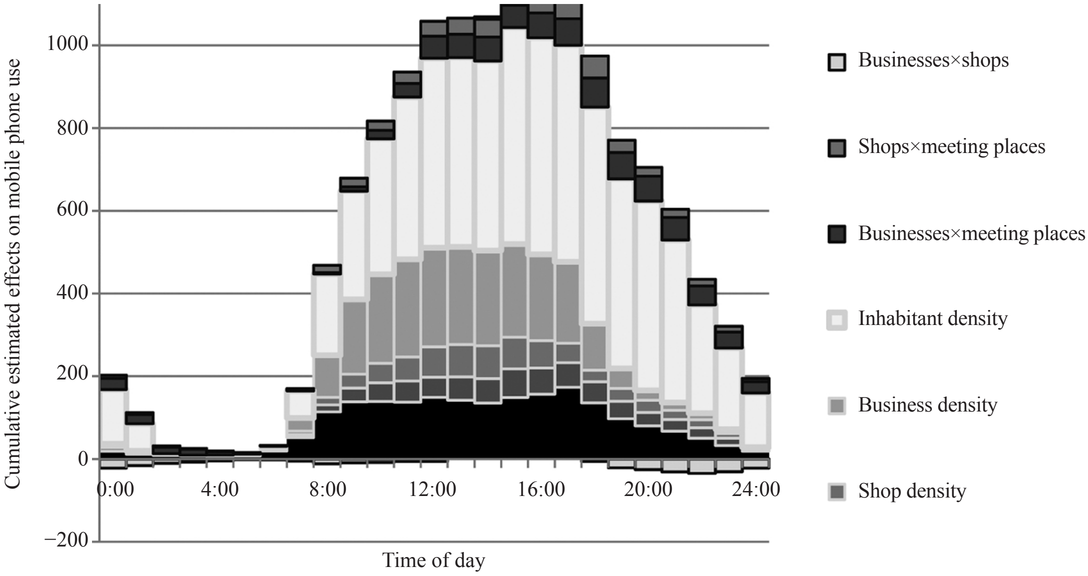

Figure 7. Estimated mobile phone usage in a zone in Amsterdam with average scores for inhabitant density, land-use densities, land-use colocation, and other estimators. For the sake of simplicity, spatial interdependencies are ignored here.

highlights the central function those squares have as public meeting places. Metro stops, motorways, and railway stations are associated with phone usage most of the day, peaking in the afternoon rush hour from 16:00 to 18:00 hours. Unfortunately, the analysis yields disappointing explained variances; this is presumably caused by aspects of the spatial econometric specification, which in any case requires that pseudo-R^2-values are treated with caution (see Anselin and Lozano-Gracia, 2008). In fact, OLS estimations yielded similar coefficients, but much higher R^2-values.

The above results show clear differences in the rhythms of the activity intensities associated with the modelled land uses. Thus, mixed land uses cause more diverse activity dynamics. Furthermore, the results confirm that mixing shops and businesses with meeting places has an additive effect on activity levels; in particular during times that shops and businesses per se do not cause much activity. This shows that local provisions of leisure opportunities outside the home are vital for any effort to extend activity intensities. We interpret the additive effect of meeting places as a multiplier effect of colocation that isolated land uses cannot produce, which indicates a change in the population's activity patterns. All in all, our results confirm Jacobs's (1962) expectations that mixed land uses can cause diversity in activity dynamics and, by means of multiplier effects, can extend activity intensities. Lastly, the results show that some home-related activity in neighbourhoods remains throughout the day; thus, even in the most monofunctional residential areas, daytime activity levels can be increased by densification.

To verify the robustness of our results, we have repeatedly executed the same analysis with average workday phone usage densities for every available month with reasonably consistent results. All results obtained have the same order of magnitude from 2008 to the first half of 2010. After June 2010 somewhat different results are obtained, but those still support our general conclusions. A selection of results is available in online appendix B.

4 Comparing activity patterns in advantaged and disadvantaged neighbourhoods

Dense and mixed land uses contribute to increasing and extending activity intensities, but do the desired activity patterns correspond with advantaged urban environments? In this section we compare phone usage densities in different areas, of which particular indicators of neighbourhood conditions have been evaluated by experts. We use results from Amsterdam's planning department (Gadet et al, 2006), which evaluated from a subset of potentially attractive locations whether particular streets are able to draw new residents and businesses working in the creative sector. We consider the intended residents and businesses characteristic of the category of urbanites who for various reasons are able to choose their place of residence, and we consider urban districts that are able to attract such settlers advantaged. On the other side, we compare phone usage densities in urban districts that according to the former Dutch Ministry of Housing, Neighbourhoods and Integration are accumulating persistent social, economic, and physical problems, and in fact are considered some of the most problematic neighbourhoods in the Netherlands (Bicknese et al, 2007). All in all, we compare temporal variations in phone usage in three groups of phone cells and in the study area on average. To do so we crudely classify the results of Gadet et al into highly attractive and somewhat less attractive streets, and subsequently average phone usage densities in the cells that contain those streets. We furthermore average phone usage densities in the cells that have their centroid in a problematic neighbourhood. The list of locations can be found in online Appendix C; observed temporal variation in phone usage intensities in all groups is shown in figure 8.

The phone usage intensities in the locations used by Gadet et al (2006) coincide with their distinction as highly attractive and less attractive streets. Higher urban activity levels correspond with more attractive urban environments, while in comparison disadvantaged neighbourhoods have lower phone usage densities throughout the day. Disadvantaged neighbourhoods nevertheless have above-average phone usage densities, indicating that poor neighbourhood conditions do not necessarily correspond with low activity intensities. One explanation may be that in problematic districts reasonably high urban densities do provide anonymity to dwellers in public space, but the provision of activities is still inadequate to promote sufficient and continuous and human presence.

Figure 9 shows average hourly effects of activities at home computed using inhabitant densities and their hourly estimated effects on phone usage divided by 24 versus the similarly computed effects of all other modelled activities. This figure clearly shows that

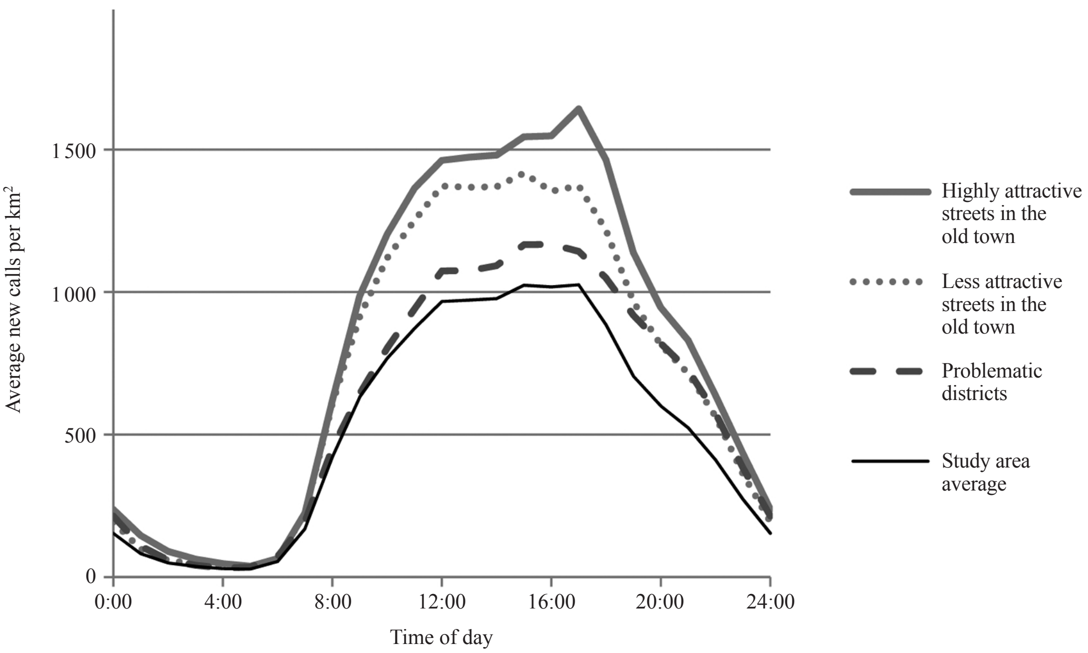

Figure 8. Observed average phone usage per km^2 in the environs of Amsterdam streets classified by Gadet et al (2006), in Amsterdam's most problematic districts and in the study area on average.

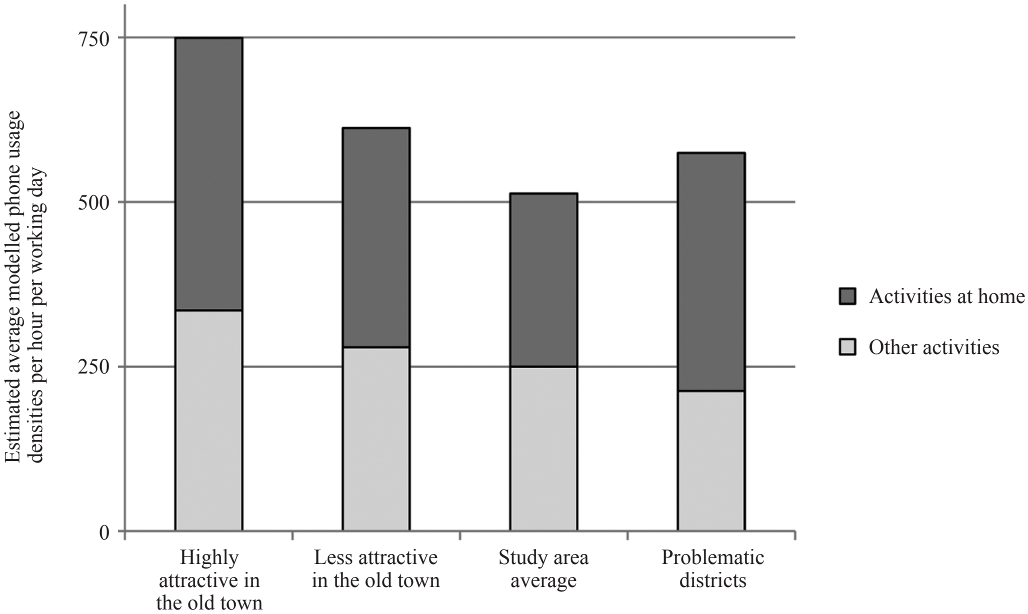

Figure 9. Estimated average hourly contribution per day of activities at home and other activities to phone usage in the environs of Amsterdam streets classified by Gadet et al (2006), in Amsterdam's most problematic districts and in the study area on average. For the sake of simplicity, spatial interdependencies are ignored here.

neighbourhood attractiveness corresponds with land-use configurations that cause higher activity intensities and a greater degree of activity mixing. Here, in more attractive areas, there is a more equal distribution between home-related activities and other activities. On the other side of the coin, in Amsterdam's most problematic districts, activities away from home contribute much less to local activity intensities than they do on average in the study area. We conclude that neighbourhoods that fare better coincide with urban areas that, due to their land-use configurations, have higher activity intensities and more equal activity mixes. This agrees with Jacobs's (1962) observations.

5 Conclusions and discussion

In this paper we use mobile phone usage data recorded in Amsterdam, the Netherlands, to investigate expectations originally posed by Jacobs (1962) that dense and mixed land-use configurations are related to higher and prolonged urban activity intensities. Our evidence confirms that land-use densities are associated with activity levels; that different land uses are associated with different activity dynamics; and that colocated land uses have synergetic or multiplier effects that prolong activity levels. We additionally test Jacobs's expectation that neighbourhoods accommodating higher activity levels and mixed activity provisions coincide with advantaged neighbourhoods. Our results confirm that areas that are considered attractive have higher urban activity intensities, while in such areas the more mixed provision of activities stands out; in contrast, activity intensities are much lower and activities at home are overrepresented in Amsterdam's most disadvantaged districts.

Although the evidence uncovered supports the development of dense and mixed land uses, a number of factors need consideration before prompting such developments. First of all, the economic value of higher and prolonged urban activity levels is difficult to estimate, and its impact on vitality is unclear. The development of dense and mixed-use environments is complex and costly, and real estate developers therefore prefer simpler projects (Coupland, 1997; Majoor, 2006). Thus, especially in times of weak real estate markets, dense and mixed land-use projects are unlikely to be considered. We therefore agree with Rowley (1996) that, above all, it is important that urban planners should strive to preserve those urban areas where land-use patterns encourage high and extended activity intensities, and perhaps apply flexible zoning schemes that allow new mixed land-use patterns to emerge.

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