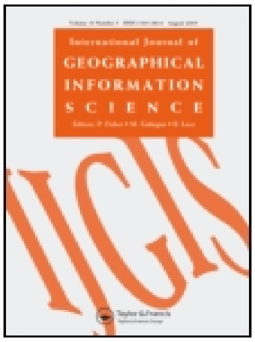

Taylor & Francis
Taylor & Francis Group

International Journal of Geographical Information Science

ISSN: 1365-8816 (Print) 1362-3087 (Online) Journal homepage: http://www.tandfonline.com/loi/tgis20

Intra-urban location and clustering of road accidents using GIS: a Belgian example

T. Steenberghen , T. Dufays , I. Thomas & B. Flahaut

To cite this article: T. Steenberghen , T. Dufays , I. Thomas & B. Flahaut (2004) Intra-urban location and clustering of road accidents using GIS: a Belgian example , International Journal of Geographical Information Science, 18:2, 169-181, DOI: 10.1080/13658810310001629619

To link to this article: https://doi.org/10.1080/13658810310001629619

Published online: 06 Oct 2011.

INT. J. GEOGRAPHICAL INFORMATION SCIENCE
VOL. 18, NO. 2, MARCH 2004, 169–181

Research Article

Intra-urban location and clustering of road accidents using GIS: a Belgian example

T. STEENBERGHEN, T. DUFAYS

SADL/Katholieke Universiteit Leuven R&D, V. Decosterstraat 102, B-3000 Leuven, Belgium; e-mail: therese.steenberghen@sadl.kuleuven.ac.be

I. THOMAS and B. FLAHAUT

National Fund for Scientific Research and Département de Géographie, UCL, Place Louis Pasteur 3, B-1348-Louvain-la-Neuve, Belgium

(*Received 11 September 2002; accepted 30 July 2003*)

Abstract. This paper aims to show the usefulness of GIS and point pattern techniques for defining road-accident black zones within urban agglomerations. The location of road accidents is based on dynamic segmentation, address geocoding and intersection identification. One-dimensional (line) and two-dimensional (area) clustering techniques for road accidents are compared. Advantages and drawbacks are discussed in relation to network and traffic characteristics. Linear spatial clustering techniques appear to be better suited when traffic flows can be clearly identified along certain routes. For dense road networks with diffuse traffic patterns, two-dimensional techniques make it possible to identify accident-prone areas. The operationality of the techniques is illustrated by showing the impact of traffic-calming measures on the location and type of accidents in one Belgian town (Mechelen).

1. Introduction

Methods developed for identifying accident concentrations traditionally apply to *black spots* (Silcock and Smith 1985, Nguyen 1991, Joly *et al.* 1992, Hauer 1996, Vandersmissen *et al.* 1996). The existence of *black zones* comes from the awareness of the evident spatial interaction existing between contiguous accident locations (Flahaut *et al.*, in press). Black zones reveal concentrations and hence suggest spatial dependence between individual occurrences: they may be due to one or several common cause(s). The overall objective of this paper is to present the potential of GIS and point pattern techniques for defining accident concentrations in an urban agglomeration. This enables suggestions for causal dependence, illustrated through the analysis of spatial shifts of accident concentrations by introducing traffic-calming measures.

The most straightforward use of GIS for accident analysis is the examination of spatial characteristics of accident locations. Point-in-polygon overlays combine the characteristics of the surroundings to the characteristics of the accident.

International Journal of Geographical Information Science
ISSN 1365-8816 print/ISSN 1362-3087 online © 2004 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/13658810310001629619

Point-on-line overlays make it possible to add attributes of the road infrastructure. These techniques are useful to find relations between the characteristics of the different key factors of an accident, such as the surrounding, the infrastructure, the vehicles, and the road users. Here, for the analysis of the spatial patterns, a more advanced use of topological relations is required. In the analysis of traffic safety, the spatial patterns can reveal underlying relations between locations in terms of proximity and connectivity.

Proximity is used as a basis for most spatial clustering techniques. The simplest way of defining a cluster is as a localized excess incidence rate that is unusual in that there is more of some variable than might be expected. Spatial clusters can be further used for pattern detection in a GIS environment (Openshaw 1995, Openshaw and Turton 2001). When dealing with spatial concentrations of road accidents, Huguenin-Richard (1999) also examined the issue of contiguity. In the analysis of accidents in Lille (France), she makes a difference between accident concentrations on the same or on adjacent spatial units, and accident concentrations on close but not contiguous spatial units. Proximity can be a matter of time as well as space. Banos developed a flexible tool to analyse proximity in terms of both space and time of the occurrence of accidents (Banos 1999). In the present paper, although time is taken into account by making a distinction between the situation before and after traffic-calming measures, the identification of accident concentrations is primarily based on geographical proximity.

Connectivity is an important concept when dealing with traffic analyses. One way of dealing with connectivity in a GIS environment is the representation of connected points or segments in a network, as parts of routes. In this paper, routes are defined by combining connected roads based on their function and the traffic flows. These routes serve as a basis for the computation of accident concentrations which may be related to traffic flows.

Clustering techniques based on proximity may reveal different potential common causes for the accidents than clustering techniques based on connectivity. In this paper, two-dimensional clustering of road accidents is used to identify concentrations that may reveal common causes based on proximity. Linear clustering of accident locations is used to examine clusters based on connectivity characteristics.

An important issue when dealing with cluster identification is the search radius. In the two-dimensional method based on the commercial GIS software used in this study, Arcview 3.2 (Ormsby *et al.* 1998, based on Silverman 1986), only a fixed search radius is possible. The optimal search radius is obtained by testing different fixed radius lengths. The effect of using a variable search radius on two-dimensional clustering of road accidents is not presently discussed. For the linear clustering technique, a variable search radius was used. The effect is discussed in a companion paper (Flahaut *et al.*, in press).

In Section 2.1 the use of GIS for accident location is detailed. In Section 2.2, the one-dimensional and two-dimensional clustering techniques are explained. After a presentation of the case study area and data used (Section 3), the results of both techniques are then discussed (Section 4).

2. Research methodology

The use of GIS for the definition of accident 'hot spots' involves: (1) the automation of accident locations on a map and (2) the identification of statistically significant spatial clusters of accidents. The physical meaning of the spatial clusters is examined by discussing the impact of traffic-calming measures on the location and type of accident concentrations in the city of Mechelen.

2.1. *Accident location*

In Belgium, for each accident with casualties, more than 100 attributes are registered by the police, and data are centralized at the National Institute of Statistics. Regional authorities are responsible for major roads and the municipalities for local roads. The recording of the location of an accident is different when the accident occurs on a local road or regional road.

The *regional* (numbered) roads are classified by function, such as highway, major regional road and local access road. The function determines the type of traffic and the traffic flows. In the digital road network, routes were defined by the regional road administration. Regional roads have milestones (markers) every hectometre (100 m). The location of such points or segments is not by means of the exact position, but through the position relative to a measurement system in the route. Dynamic segmentation makes it possible to locate accidents in a network, when the position relative to the milestone is known, and other locational data such as co-ordinates or addresses are missing. The location of an accident on the digital network is determined by the road number and the distance to a hectometre marker. Although this method appears to be precise, its implementation limits the number of usable records and may distort the results, such as when the distance to the marker is not accurately measured in the field. A more accurate position is obtained by:

1. Definition of the location at crossroads: in this case, two names of roads are given and the intersection of both roads can be easily computed;
2. Use of a digital map of house numbers: when known, the house number gives more precise information than the hectometre markers, since these are only present every 100 m and are sometimes displaced (e.g. after infrastructure works) or missing (e.g. at crossroads);
3. Removing conflicting data, or very unlikely locations such as accidents located on hectometre markers 0,0 (0,0 is used as the default value when no hectometre marker is recorded in the original accident registration).

Re-matching (by their record number) accidents located by these techniques with the automatically located accidents through dynamic segmentation is used to examine the distortion caused by the automatic location technique.

On the *local* (not numbered) roads, accidents are located by postal address. A reference address is only given in the accident record when there is a visible address near the location. Accidents located on a local (not numbered) road where there was no visible address to refer to, such as in rural areas, could not be located. When those accidents are located on a crossroad, their location is found by selecting the intersection. In the study area (Mechelen), digital cadastral maps provide the possibility to locate addresses on the map. Automation tools for address matching were developed in Arc/View-Avenue. The following sequence is followed: first, the standard address geocoding procedure of Arcview is performed using the addresses of the cadastral plans. In the city, the suburbs and the small centres, this consists mostly of an address matching with very limited spatial interpolation between known addresses. This is normal, since cadastral plans normally include all addresses except very recent buildings (less than 1 year old). Because of the poor quality of the accident data and the high spelling sensitivity of the address match, a human control was built in. Synonyms are automatically stored for later use. Some accidents were located on very short road sections or could be located based on descriptive attributes such as inside or outside built-up areas and pedestrian crossings. When the error was estimated to be smaller than 100 m, these accidents were located manually on the map.

2.2. *Spatial clustering of accidents*

Two spatial clustering techniques are used to identify black zones: two-dimensional clustering and linear clustering.

For the *two-dimensional approach*, the spatial analyst technique of Arcview 3.2, based on the Kernel method is used. After a number of tests, a grid cell size of 20 m by 20 m is selected for the analysis of concentrations in the urban area. There is a considerable literature about the choice for the grid cell size and the search radius. Experimenting with different values to look at variations at different scales for the given population is a practical solution (Bailey and Gatrell 1996, Rushton *et al.* 1996). In the case of accidents on a dense urban network, the grid size providing the best concentration patterns is smaller than the street segments between intersections, but large enough to show accident concentrations. The method uses a fixed search radius (Silverman 1986). A circle with a given radius (r) is drawn around each grid cell, and the number of accidents (X) that fall within the circle is totalled and divided by the circle's area (figure 1).

This method computes the density of point features around each output grid cell. The density (D) of a cell is calculated as the value (number of accidents (n) multiplied by weight) of accidents per unit area. In the present study, all accidents were given a weight of 1 because each accident is a separate record, even when

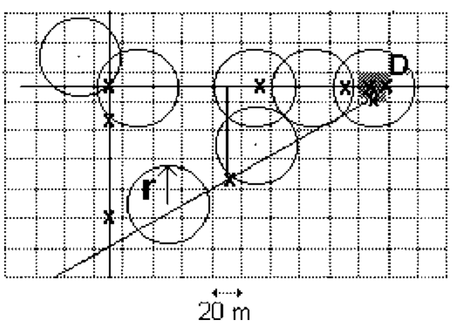

Figure 1. Computation of concentrations (D) of accidents (x) based on the number of points that fall within a circle with a given search radius (r) drawn around grid cells of $20\,\text{m} \times 20\,\text{m}$.

different accidents occur in chains:

$$D = \frac{\sum_{i=1}^{n} X_i}{\pi r^2}$$

With the kernel option, a curved surface is fitted over each point; its value is highest right on the point, and it decreases away from the point, reaching 0 at the radius distance from the point.

For the *linear clustering*, the method involves applying local autocorrelation indices. Global methods for assessing spatial autocorrelation have existed for several decades and mainly stem from the work of Moran (1948; Cliff and Ord 1973, 1981, Griffith 1987, Anselin 1988, Haining 1990). Their application to road accidents has already been discussed (Black and Thomas 1998). Local indices of spatial autocorrelation are more recent (Getis and Ord 1992, Anselin 1995, Ord and Getis 1995, Tiefelsdorf 2000) and their application to road-accident structure quite novel (Flahaut *et al.*, in press). According to Getis and Ord (1992), the Moran index and the Getis–Ord statistic both measure spatial associations between individuals, based on a different approach. The Moran index was preferred in this study because many studies demonstrated a more stable result than other indices. Other advantages are the simplicity of testing, the flexibility of the conditional distribution and the development of theoretical elements related to this index, along with the proven utility in many applications. The local Moran's index I_i computed at any location i is called a *LISA* (Local Indicator of Spatial Association, Anselin 1995) when:

$$I_i = z_i \sum_j w_{ij} z_j$$

and

$$\sum_i I_i = \sum_i z_i \sum_j w_{ij} z_j$$

and

$$\sum_i I_i = \gamma I$$

with

$$\gamma = S_0 m_2$$

$$m_2 = \sum_i z_i^2 / n$$

$$S_0 = m \sum_j \sum_i w_{ij_2}$$

where: n = number of basic spatial units; I = global autocorrelation index.

A *LISA* is an indicator of the extent to which the value of an observation is similar to or different from its neighbouring observations. This allows that a value I_i is associated to location i, and it requires that the notion of neighbourhood (w_{ij}) among the is is specified. Neighbourhood can be simply defined by contiguity (0–1 matrix) or by any other function of distance (Flahaut *et al.*, in press). The local component I_i is the product of the centred local value (z_i), where $z_I = x_i - x_{av}$ and the weighted mean of the centred neighbouring values ($w_{ij} z_j$). The sign of this component is an indicator of the agreement (positive) or disagreement (negative) of the signs of the local centred value and the weighted average of the neighbouring values. Hence, similarly to the global index, I_i can be positive, negative, or equal to zero. It is negative when there is an association of opposite values at neighbouring locations, and positive in the case of spatial association of similar values. In this paper, accident concentrations are identified by the product of two positive values. We refer to a companion paper for more details about this method, its drawbacks and its advantages (Flahaut *et al.*, in press). In the current paper, we are concerned with the operationality of the method *within urban agglomerations*, that is to say, for a dense road network.

For both the linear and the two-dimensional clustering technique, Monte Carlo simulations are used to evaluate the statistical significance of concentrations (Flahaut and Thomas 2002). These simulations are based on a large number of random spatial distributions of points (Hope 1968, Marriott 1979). The significance threshold is a minimum of 0.95.

3. Data

3.1. *Study area*

Mechelen is a city of 75 000 inhabitants, 24 km north-northeast of Brussels. The centre is a typical medieval historic city. The town ramparts, with a diameter of approximately 1.5 km, date from the 14th century and remained until the beginning of the 19th century. After their demolition and replacement by large ring roads, the city began to grow outside the historic walls. First, housing was located near the railway station and later along the ring roads. Densely built areas outside the 14th-century city developed in the twentieth century.

In 1994, the city introduced a *traffic plan*. A crucial element of this plan was the reduction in traffic flows through the city centre by the introduction of loops from the ring road (figure 2). Most of the city centre became a car-restricted area. In order to examine the safety effects of this plan, accidents during the 3 years prior to the introduction are compared with accidents 3 years after the plan became operational. The spatial shift of accident black zones is demonstrated by computing the difference between clusters before and after the introduction of the measures. In addition to the overall concentrations, separate spatial clusters are computed for accidents involving different modes.

3.2. *Accident data*

Using dynamic segmentation, 787 out of the 1587 accidents on numbered roads in this urban area could be located. Comparison between locations using dynamic segmentation by hectometre marker or by address resulted in errors of a maximum magnitude of 100 m. By combining the different location techniques, 2216 accidents out of the 2800 (78.9%) that occurred between 1991 and 1996 in the city of Mechelen could be located.

4. Discussion of the clustering results

4.1. *Accident concentrations*

The two-dimensional method is used to compute spatial clusters of accidents, regardless of the road on which the accident happened. One-dimensional methods result in the identification of road segments with high accident concentrations. Figure 3 illustrates the differences between both methods.

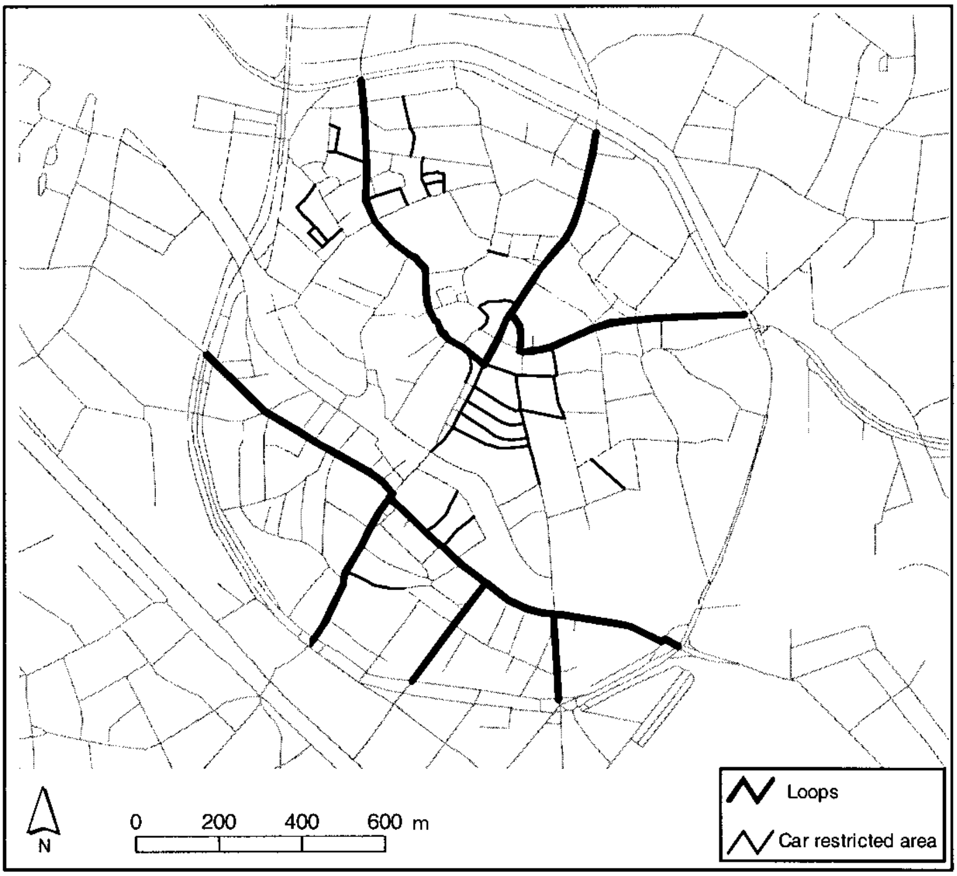

Figure 2. Loops and car-restricted areas of Mechelen.

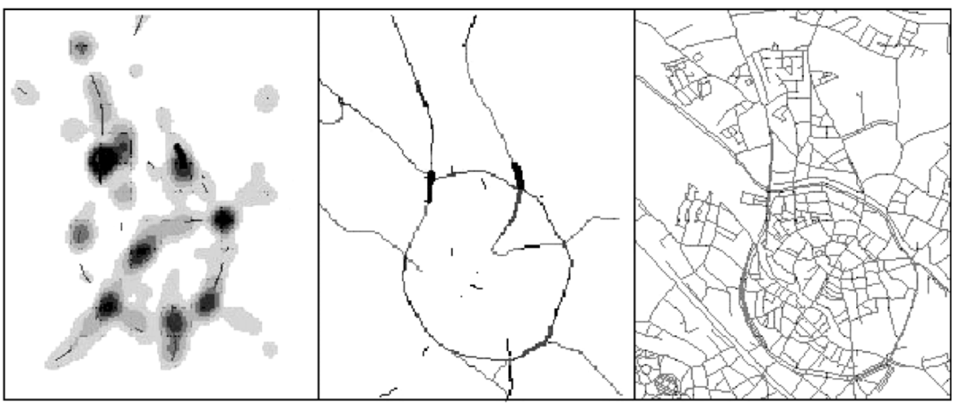

Figure 3. Two-dimensional accident concentrations (left) versus linear concentrations (middle) in a street network (right).

The following advantages and disadvantages were found when applying both techniques for accident clustering in an urban environment:

Advantages of two-dimensional clusters

In an urban environment with a dense road network, accident locations are frequently based on proximity characteristics. In these environments, two-dimensional clusters may suggest causal relationships. An example is the identification of accident concentrations near schools.

Disadvantages of two-dimensional clusters

With two-dimensional clustering techniques, the specificity of traffic flows is not taken into account. On roads with clear traffic characteristics, two-dimensional clusters may even give a false impression of a spatial distribution of accidents.

The identification of spatial clusters by means of circles with a fixed radius creates a problem near the margins of the grid. In grid cells closer to the edge than the diameter of the search radius, the number of points is not computed for the totality of the circle. In Mechelen, the problem was marginal because most accidents are located in and around the centrally located urban centre, while the number of accidents near the city limits is limited. In cases where high concentrations are found near the border of the study area, the problem was overcome by locating accidents outside the study area, in the 'guard area' (Bailey and Gatrell 1996). In Mechelen, this area was delimited by the buffer within a distance to the border equal to the search diameter.

Advantages of linear clusters

Linear clusters give a representation which is consistent with the linear flow of traffic. By computing the linear clusters on routes representing traffic flows, the concentrations of accidents are related to connectivity. This may suggest causal dependence. An example is the location of accident clusters on routes connecting industrial sites with major highways. LISA has the additional advantage of providing precise clusters based on the statistical distribution of the accident locations.

Disadvantages of linear clusters

In the linear method, edge problems occur at the end of each road. For points located closer to the end of the segment than the search radius, no accidents are counted beyond the end of the segment, thus distorting the concentrations near the edges. Without this adjustment, an artificial concentration is created due to double counts of accidents near intersections. Because the roads were combined into routes, the edge problem is reduced to the end of each route. In an urban environment with a dense road network, however, identification of meaningful routes may not be straightforward. For example, in Mechelen, routes had to be defined for the local roads prior to performing the linear clustering. In the inner city, at each intersection, the road with the major function was defined based on the physical and functional characteristics of the road and the angle. Only roads forming an angle of less than 90° were considered to be in prolongation.

With the Moran index, the search radius varies depending on the statistical concentration of accidents. With this approach, accidents on intersections have a strong influence on the search radius. Near intersections, the search radius is very short, and traditional black spots give a better representation of the spatial concentration than a linear clustering technique.

Best results and network characteristics

The Moran index gives the best results for the identification of clusters on roads with a limited number of intersections, and clear traffic flows which can be represented by routes. There, two-dimensional concentration techniques give a false impression of concentration areas. By using the Moran index on routes, the proximity and connectivity characteristics of locations are combined.

The two-dimensional concentrations yield the best results on a dense network with dispersed traffic patterns. In these areas, clusters may exist but may not be discovered by the linear method.

4.2. *Impact of traffic-calming measures in the historic centre of Mechelen*

Traffic-calming measures in Mechelen were introduced in the historic city centre, characterized by a dense road network. Identification of routes with specific traffic conditions was possible on major roads but did not correspond to the dispersed traffic on the smaller intra-city roads. This city centre is an environment where two-dimensional clustering techniques are more appropriate for identification of accident concentrations than linear clustering techniques.

Another important aspect is the objective of the analysis. Loops were introduced to avoid traffic flows through the centre. Part of the new traffic scheme involved changing the routes. The shortening of routes affected the edge effects and thus the resulting linear concentrations. This was an additional reason to examine the effects based on two-dimensional clustering techniques.

The accidents during the period 1991–1993 were compared with the accidents during the period 1993–1996. A significant decrease (9%) in the total number of accidents was observed in the centre of town, including the ring roads (table 1). This is completely due to the evolution in the number of accidents in the historic city centre: before 1993, there were on average nearly 30% more accidents. This is explained by the cutback in motorized traffic and the decrease in speed for the remaining tolerated motorized traffic.

While this decrease appears to be a very good result, the spatial distribution of accident concentrations shows an increase in accidents around the city centre. This is particularly the case for accidents with cyclists (figure 4). Figure 4 shows the difference between the computed density of the accidents with cyclists during the period 1991–1993 and the density of those occurring during the period 1994–1996. The increase is most important for accident concentrations on the new loops within

Table 1. Number of accidents in the city centre by different transport modes.

Historic centre + ring road	Cars	Pedestrians	Cyclists	Total	Historic centre	Cars	Pedestrians	Cyclists	Total
1991	43	18	43	104	1991	14	13	24	51
1992	40	12	59	111	1992	7	10	35	52
1993	50	18	36	104	1993	17	13	23	53
Average	44	16	46	106	Average	12.66	12	27.33	52
1994	37	20	37	94	1994	11	9	18	38
1995	46	10	43	99	1995	5	6	27	38
1996	44	14	37	95	1996	13	7	25	45
Average	42	15	39	96	Average	9.66	7.33	23.33	40.33

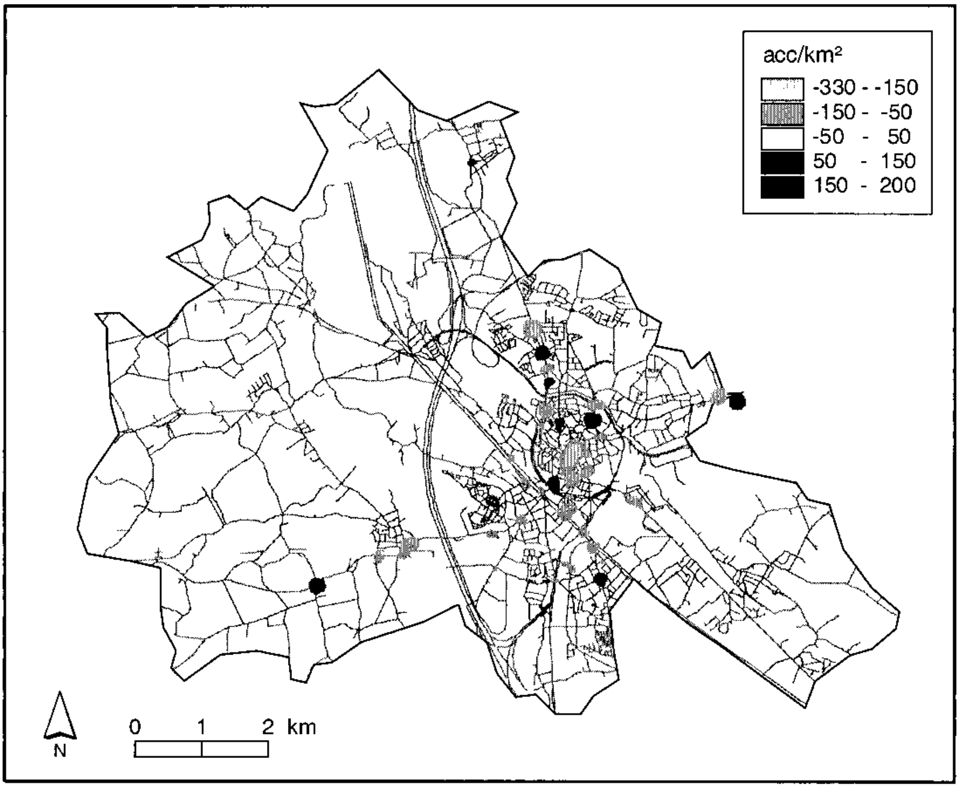

Figure 4. Accidents with cyclists based on two-dimensional clusters before and after the introduction of the plan.

the historic centre and at the beginning of the loops on the ring roads. The new traffic scheme generates new locations of accident concentrations.

A possible explanation for these new accident clusters may be the increase in mix of transport modes without any adaptation of infrastructure. On these roads, pedestrians, cyclists and motorized traffic are concentrated, and the road infrastructure is not adapted to separate the modes (no cycling tracks). By introducing the loops, new roads of this type were created near the edge of the car-free zone.

A large number of accidents occur where the new and the old spatial structures come together (the ring roads). By making the city centre car-free, the ring road increased the mix of local traffic and through traffic. The highest increase in accidents is found at the intersections of the ring road with the loops. On these crossroads, the increased mix of through traffic and traffic generated by the loops is combined with complex conditions for vulnerable traffic, particularly bicycles. On most of these intersections there is a transition between roads with bicycle lanes and roads without bicycle lanes.

5. Concluding remarks

Accident location on a network required a combination of GIS techniques. In urban areas, when an address can be referred to, location by address gives good results, provided there is a database of geo-referenced addresses available. In rural areas, there are currently three alternatives for automatic location: location by address, location on intersection, or location based on the routing system of the numbered routes. Additional location references such as by means of GPS could improve to the current location techniques, but this is not yet the case in Belgium.

Linear methods to compute clusters of accidents appear to perform better on networks where the maze is large. By using the local Moran index on routes, proximity (a shorter search radius where many accidents occur in each other's proximity) and connectivity characteristics (definition of routes) of locations are combined. In an urban area, the roads are short, and there are more edge effects. By working with a variable search radius, the accidents on intersections and on very short roads have a strong effect on the search radius in urban environments.

On dense networks with dispersed traffic, two-dimensional clustering techniques based only on proximity perform better than linear methods. Edge effects are limited to the boundary of the study area.

The case of Mechelen illustrates that the choice of a clustering technique can be affected by both the physical characteristics of the network and the traffic measures to be examined. Traffic measures affecting routes may affect the clustering results as a result of edge effects. The new traffic scheme in Mechelen was able to keep through traffic out of the historic centre. It was thus very positive in terms of road safety, but it increased the concentration of accidents near the edge of the area with restricted car use, on the loops and on the ring road. It seems that in historic centres, further steps should be implemented to separate different types of traffic and other road use. There is insufficient space in the streets for separate tracks. In the past, extra space was made by restructuring traffic with one-way streets. Doing the same exercise of traffic restructuring but for the three different types of road users instead of just motorized traffic, should result in networks, adapted to each mode, with special attention to points where they cross or come together.

Concerning the ring roads, special attention should focus on smoothening the transition between the access roads, and the networks in the centre of town, again taking into account the needs of the different types of road users. All through traffic should be kept out of areas where it does not belong. As a result of further urbanization, in most of our cities, ring roads around the historic centres have long ceased to be the city limit. Long-distance traffic should not pass on these roads, where it is mixed with local traffic on different modes. The use of ring roads for local traffic increases when the city centre is made less accessible to cars.

Traffic safety is the result of a balance between the type of traffic and the road and neighbourhood characteristics. The imbalance results in statistically significant differences in concentrations of accidents. The importance of environmental factors in relation to the traffic characteristics needs to be further researched to better identify which combinations generate higher concentrations.

Acknowledgement

The research presented in this paper was part of the broader research programme on 'Sustainable Mobility' (1998–2001), launched and sponsored by the Belgian Federal Services for Scientifical, Technical and Cultural Affairs (SSTC).

References

ANSELIN, L., 1988, *Spatial Econometrics: Methods and Models* (Dordrecht: Kluwer).

ANSELIN, L., 1995, Local indicators of spatial association—LISA. *Geographical Analysis*, **27**(2), 93–115.

BAILEY, T. C., and GATRELL, A. C., 1996, *Interactive Spatial Data Analysis* (Harlow, UK: Longman).

BANOS, A., 1999, Quelle implication de l'utilisateur dans une stratégie de Data Mining spatial? *Revue internationale de géomatique*, **9**(4/1999), 441–456.

BLACK, W. R., and THOMAS, I., 1998, Accidents on Belgium's motorways: a network autocorrelation analysis. *Journal of Transport Geography*, **6**(1), 23–31.

CLIFF, A. D., and ORD, J. K., 1973, *Spatial Autocorrelation* (London: Pion).

CLIFF, A. D., and ORD, J. K., 1981, *Spatial Processes. Models and Applications* (London: Pion).

FLAHAUT, B., MOUCHART, M., SAN MARTIN, E., and THOMAS, I., 2003, Identifying black zones with a local spatial autocorrelation index and a kernel method. A comparative approach. *Accident Analysis and Prevention*, **35**, 991–1004.

FLAHAUT, B., and THOMAS, I., 2002, Identifier les zones noires d'un reseau routier par l'autocorrelation spatiale locale. *Analyses de sensibilité et aspects operationnels, Revue internationale de Géomatique*, **12**, 245–261.

GETIS, A., and ORD, J. K., 1992, The analysis of spatial association by use of distance statistics. *Geographical Analysis*, **24**(3), 189–206.

GRIFFITH, D. A., 1987, *Spatial Autocorrelation: A Primer* (Washington, DC: Association of American Geographers, Resource Publications in Geography).

HAINING, R., 1990, *Spatial Data Analysis in the Social and Environmental Sciences* (Cambridge: Cambridge University Press).

HAUER, E., 1996, Identification of sites with promise. In *Transportation Research Record 1542, 75th Annual Meeting*, Washington, DC, pp. 54–60.

HOPE, A. C. A., 1968, A simplified Monte Carlo significance test procedure. *Journal of the Royal Statistical Society*, **B30**, 582–598.

HUGUENIN-RICHARD, F., 1999, Identifier les sites routiers dangereux; application de methodes d'analyse utilisant la localisation géographique des accidents. *Revue internationale de géomatique*, **9**(4), 471–487.

JOLY, M-F., BOURBEAU, R., BERGERON, J., and MESSIER, S., 1992, Analytical Approach to the Identification of Hazardous Road Locations: A Review of the Literature. Centre de recherche sur les transports, Université de Montréal, CRT publication No. 815.

MARIOTT, F. H. C., 1979, Barnard's Monte Carlo tests: how many simulations? *Applied Statistics*, **28**, 75–77.

MORAN, P., 1948, The interpretation of statistical maps. *Journal of the Royal Statistical Society*, **10b**, 243–251.

NGUYEN, T. N., 1991, Identification of Accident Blackspot Locations, an Overview. VIC Roads/Safety Division, Research and Development Department, Australia. VIC Discussion Paper (DP/91/4).

OPENSHAW, S., 1995, Developing automated and smart spatial pattern exploration tools for geographical information systems applications. *The Statistician*, **44**, 3–16.

OPENSHAW, S., and TURTON, I., 2001, Geographical analysis machine on the Internet. http://www/ccg.leeds.ac.uk/smart/gam/gam.html.

ORD, J. K., and GETIS, A., 1995, Local spatial autocorrelation statistics: distributional issues and applications. *Geographical Analysis*, **27**, 286–306.

ORMSBY, T., NAPOLEON, E., BRESLIN, P., and FRUNZI, N., 1998, *Getting to Know ArcviewGIS 3.x: The Geographic Information System (GIS) for Everyone* (Redlands, CA: ESRI Press).

RUSHTON, G., and PANOS, L., 1996, Exploratory spatial analysis of birth defect rates in an urban population. *Statistics in Medicine*, **15**, 717–726.

SILCOCK, D. T., and SMYTH, A. W., 1985, Methods of Identifying Accidents Blackspots. Transport Operations Research Group, Department of Civil Engineering, University of Newcastle upon Tyne. TORG Research Report 1985.

SILVERMAN, B. W., 1986, *Density Estimation for Statistics and Data Analysis* (New York: Chapman & Hall).

TIEFELSDORF, M., 2000, *Modelling Spatial Processes. Lecture Notes in Earth Sciences 87* (Berlin: Springer).

VANDERSMISSEN, M. H., POULIOT, M., and MORIN, D. R., 1996, Comment estimer l'insécurité d'un site d'accident: état de la question. *Recherche Transports Sécurité*, **51**, 49–60.