A GIS-BASED CONTEXT SENSITIVE SOLUTION FOR MULTIMODAL ROAD PLANNING

EDWARD BEUKES and MARIANNE VANDERSCHUREN

University of Cape Town, Department of Civil Engineering
Private Bag X3, Rondebosch 7701, South Africa
Email: ebeukes@ero-engineers.co.za
Tel: 021 975 6200, Fax: 021 975 6400

Abstract

Context sensitive design (CSD) has been identified as a key mechanism to address the mounting safety and sustainability problems transportation presents in urban areas in the developed world, and an intensive research effort is currently underway to understand the implications for planning practice. However, CSD is relatively unknown in the developing world, where arguably, the concept has even more potential to improve conditions.

One of the main weaknesses of the method is that it tends to rely on qualitative processes, when much of transport planning and design practice is quantitative in nature. This paper introduces a new road planning methodology that draws on the concepts underlying CSD and, using a GIS-based spatial decision support system, quantifies a range of contextual inputs to develop planning recommendations for urban roads. The method is demonstrated by means of a case study conducted along an arterial route in Cape Town.

1. CONTEXT SENSITIVE DESIGN

In recent years, Context Sensitive Design (CSD) has been promoted by both AASHTO and the FHWA as a best practice. CSD provides a systematic and comprehensive approach to project development from inception and planning through operations and maintenance. Its goal is to achieve a project development process that provides an outcome harmonizing transportation requirements with community needs and values (Stamatiadis et al., 2009).

There are a number of definitions of CSD. According to FHWA, for example, CSD is “…a collaborative, interdisciplinary approach that involves all stakeholders to develop a transportation facility that fits its physical setting and preserves scenic, aesthetic, historic and environmental resources, while maintaining safety and mobility” (FHWA, 2007). The New York State Department of Transportation defines CSD as “a philosophy wherein safe transportation solutions are designed in harmony with the community” (De Cerreño and Pierson, 2004).

Complete streets initiatives are another example of CSD. In the USA, the National Complete Streets Coalition (NCSC) highlights that complete streets are “…designed and operated to enable safe access for all users” (NCSC, 2010). The approach to implementing complete streets policies vary, but generally encompass adoption of a complete streets policy, the generation of a set of guidelines or manuals, such as that of...
the American Planning Association (McCann and Rynne, 2010), and possibly legislation to support the policy.

The need for CSD arose in part from the realisation that the majority of urban streets serve multiple roles, having to accommodate the needs of multiple modes of transport and needs related to mobility (through users) and access (local users). As a result, a certain amount of flexibility in design is required to meet all these needs (see Hebbert, 2005). In addition, urban streets may perform a variety of civic, ceremonial, political, cultural and social roles, as well as commercial and economic roles, in addition to their movement roles (Svensson, 2004). This multiplicity of roles implies that the functions performed by the road, and the needs of those who are expected to use it, must be thoroughly evaluated and understood, before an appropriate planning recommendation can be made.

Current road and network design methods that rely almost exclusively on traffic and transportation information to recommend service levels and design parameters have been found to significantly impact mode choice (Cervero and Radisch, 1996) in favour of private cars as well as vehicle miles travelled (Holtzclaw, 1990; Kitamura et al., 1997). This paper posits that contextual factors are equally as important as traffic and transportation factors when planning roads, and their inclusion would facilitate the planning of a more balanced multimodal transport system. Consequently, it is important to take all of these factors into consideration when developing designs.

Each mode in use in a road has its own specific characteristics and needs, and these determine the design parameters for that mode. Also, each location in a network or along a road is defined by a set of contextual parameters that determine how and by whom it is most often used. It is at the intersection between these modal characteristics and locational factors, or the needs of a mode and the use of a location, that an ideal planning solution can be found. Accordingly, certain modes are better suited to a certain set of contextual circumstances than others. Therefore, under a given mix of contextual circumstances, certain modes should be given a higher priority than the rest.

However, in order to determine a priority, or a rank order, it is necessary to quantify the context in terms of its impact on each mode. The remainder of the paper describes a method developed to achieve this.

2. METHODOLOGY

Context can be defined as including aspects related to the adjacent land uses, the socio-economic profile along the route, the environmental (ecological and cultural) landscape along the route and the traffic and transportation characteristics of the route. It is evident that these contextual aspects will vary spatially and temporally.

GIS has emerged as a useful platform to analyse the spatial complexities of urban planning and transport planning problems. Planners are often confronted with alternative scenarios to assess, and these assessments are often driven by a range of both quantitative and qualitative variables, with numerous stakeholders and viewpoints to be considered. GIS is well suited to evaluating large databases of spatial information (Eastman et al., 1995). GIS-based spatial decision support tools, particularly spatial multiple criteria evaluation (SMCE) tools have emerged as effective techniques to assess these cumulative impacts and to carry out suitability analyses in order to evaluate the alternatives (Laaribi, 1996). SMCE has been successfully used to assess alternatives in a range of areas including environmental impact assessment (Blaser et al., 2004; Brown and
To evaluate the suitability of one mode over another, a SMCE was conducted using the five main road based modes commonly found in Cape Town: private vehicles, freight, pedestrian, public transport and bicycle, as the alternatives.

Variables were selected from each of the four contextual categories (land use, socio-economic, environmental and transportation) to describe the context of each location along the route. The variables that are considered relate specifically to the what, who and how questions that can be asked of any locality:

1. What are the characteristics that define the locality?
2. Who are the people using the locality?
3. How are these people using the locality?

To describe the location, land use type, property density and property values were used. Land use encompasses issues related to the activities conducted at a particular location and the intensity of activity at that location. Commonly used parameters include zoning, density, diversity and land value (Cervero, 1994; Ewing and Cervero, 2001; Frank and Pivo, 1995; Handy, 1996; Zhang, 2004). In terms of road planning, these parameters provide information on the expected number of trips and the modal split at a location.

To describe the people using the location, demographic information such as income levels (using education level as a proxy) and the proportion of vulnerable road users were used. The socio-economic profile along the route encompasses issues related to, amongst others, neighbourhood demographics, such as age and gender, income levels and employment levels. This information is critical to the route context since it details the types of users, their levels of ability and the modal split at a location.

The proximity to environmentally sensitive or historically significant sites and wetlands were used to describe the environmental qualities of the location. The environmental profile along the route speaks to the environmental and cultural or heritage sensitivity along the route. In terms of the National Environmental management Act (DEAT, 2006), infrastructure provision must give consideration to the physical, biological, social, economic and cultural aspects of the environment that may be affected by the proposed activity. Road infrastructure must, therefore, be planned so as to minimise the expected impacts it may have in this regard.

The demand for public transport and the demand for private vehicle transport (derived from the OD matrix for the area) as well as the proximity to public transport stops was used to describe the traffic and transport characteristics of the location. Demand in terms of traffic volume, and supply in terms of capacity, as well as travel speed are the primary parameters that typically dictate road design. However, traffic and transportation factors that inform context also includes modal split and the location of public transport stops.

The open source software ILWIS v3.31 was used to conduct the SMCE analysis. In the context of transportation planning, SMCE is typically used to identify suitable routing alternatives (e.g. Farkas, 2009; Keshkamat et al., 2009; Sharifi et al., 2006) for a particular mode of transport. In the case of this research, the route is predefined (either existing or planned), and instead, it is the suitability of the various modes that use the route that must be determined.
Spatial datasets were constructed using the available data sources and converted to raster images to conduct the SMCE in ILWIS. Each mode was evaluated individually, thereby producing a set of five preference or suitability maps, one for each mode. Image processing techniques were then used to aggregate the results along the route centreline for each map. This information was exported to a spreadsheet programme for further analysis.

The data sources used included data from the 2001 South African National Census, the 2003 South African National Household Travel Survey, and data acquired from the City of Cape Town’s Corporate GIS department. Case study roads were selected from routes that initially displayed a wide variety of land use, social, economic and environmental characteristics along their length, and that were known to have high accident rates.

A mode is more suited to a particular location if the numerical score it achieves through the SMCE at that location is greater. The numerical score is calculated from the formula:

\[ P_j = \sum w_i x_i \]  

(1)

where \( P_j \) is priority (or contextual suitability) for mode \( j \), \( w \) is the weight of factor \( i \) and \( x \) is the criterion score of factor \( i \). The inputs to the process are raster maps of the criterion scores, and each cell of the raster is evaluated for each mode.

As with any MCE process, the criterion score of factor \( i \) is calculated by standardising (generally to unity) the input values in relation to a relevant cost or benefit structure, since these inputs may all have different measurement units and it is also necessary to bring them to an equivalent scale (if one criteria is in billions, and another in tens, a dramatic change in the latter will not make major difference to the total score). Increased household densities, for instance, may be standardised as a benefit to transit and NMT, but as a cost to freight and private vehicles.

The standardisation approach was designed to be as simple as possible, using linear functions to map criteria scores to a scale between 0 and 1. The approach varied depending upon whether the criteria was perceived as a spatial cost or benefit for that mode, and whether the data was to be standardised in relation to the maximum data point in the set or in relation to a set interval.

For standardisation in relation to the maximum data point in the set, used for datasets where there is a continuous increase or decrease in preference in relation to the data value, the benefit function is defined as:

\[ P_j = \frac{x_i}{x_{imax}} \]  

(2)

The cost function is defined as:

\[ P_j = 1 - \frac{x_i}{x_{imax}} \frac{x_{imin}}{x_{imax}} \]  

(3)

For standardisation in relation to an interval, used for datasets where there is a discontinuity in the preference value in relation to the data value (where, for instance,
above or below a certain threshold value benefits or costs no longer accrue) the benefit function is defined as:

$$P_j = \frac{x_i - x_{imin}}{x_{imax} - x_{imin}}$$  \hspace{1cm} (4)

The cost function is defined as:

$$P_j = 1 - \frac{x_i - x_{imin}}{x_{imax} - x_{imin}}$$  \hspace{1cm} (5)

where $P_j$ is the standardised preference score for the mode, $x_i$ is the measured value at the point of interest, $x_{imax}$ is the maximum value in the dataset and $x_{imin}$ is the minimum value in the dataset. The same method was used to standardise all the criteria besides land use, which is a categorical variable, and the environmental criteria, which are binary (yes/no). Categorical variables were scored qualitatively, by ranking preference for each mode, binary variables either score 1 for a positive cell (there is a wetland/environmentally sensitive area) or 0 for negative cell.

The weights used in the procedure can be calculated using the Analytical Hierarchy Process (AHP) as introduced by (Saaty, 1980). However, to investigate the contextual differences along the case study route, and the influence that the criteria have on the suitability of the various modes, a uniform weighting regime was used so as not to introduce any biases within the criteria set. The results therefore only reflect the summation of transformed criterion scores along the route.

The nature of the SMCE method means that the introduction of weights will have an impact on the results produced. Since it is undesirable that slight changes in weighting lead to radically differing results, and conversely, that significant changes in weighting do not have any noticeable impact on the results, a sensitivity analysis was conducted to test the impact of changes in the weighting scheme. The analysis involved increasing the weighting of each category of criteria by 20% and then comparing the results using non-parametric correlation and a dependent t-test (see Beukes et al., 2010).

The analysis found that for each mode, the adjusted results were very strongly correlated to the base case result. It was concluded, especially when considering the strong correlations between the base and weighted cases for all the test pairs, that the method produces results that are robust enough to produce reliable results. The dependent t-test results showed that the method is able to produce results that are flexible to variations in weighting schemes without inducing radically altered outcomes.

Voortrekker Road from Salt River in the west of Cape Town to Kuilsriver in the east of Cape Town was selected as a case study route, as it is one of the corridors with severe safety issues. Voortrekker road is a major arterial that links suburbs in the west of Cape Town with suburbs in the east. The section of the route selected for the study is approximately 17 kilometres long. A variety of modes, land uses, intensity of land use and population groups are served along it. For the large majority of the study section (>90% of the route length), the road comprises of a two lane, dual carriageway roadway, with a narrow central median and is flanked by sidewalks of varying width. This uniformity of cross-section is striking given the range of locational contexts the road passes through.
3. RESULTS

The evaluation was conducted using the criteria discussed in Section 2. The evaluation revealed that spatial contextual variation along the route produced significant variability in the preference for each mode. However, clearly defined stretches were identified where relative modal preferences can be said to be constant. In order to conduct a comparative evaluation of the results for Voortrekker road, the pixel values were aggregated along the centreline. The method used involved calculating the average value for a matrix of 20 by 20 pixels centred around each individual pixel in turn. Since each pixel represents a 5 by 5 metre area, this represents a 10000m² (1 hectare) area. This average is then applied to the pixel being evaluated. In this manner an average is calculated for each pixel in the raster and an averaged raster is generated. This process is conducted for each mode’s preference map. The values along the centreline of the road are extracted and exported to a spreadsheet programme. The resultant output for each mode is then plotted on a line chart to show the relative priority of each mode.

Having generated the SMCE results and plotted them in a spreadsheet, the data was clustered using a two step clustering algorithm as developed by Zhang et al. (1996). The algorithm is based upon the hierarchical clustering method, but has the benefit of being able to efficiently manage large multi-dimensional datasets and cope with outliers reliably. However, it was selected primarily because the optimal number of clusters is automatically derived from the dataset itself (see Fraley, 1998).

![Figure 1: Modal Suitability Clusters](image)

The output from this exercise is shown in Figure 1. Although there is significant variability in the results, this has to a large extent already been tempered by averaging the initial results. The remaining variability is a consequence of the inherent variations in the original input criteria raster images. Despite the variability, large sections of the route present a reasonably stable ranking profile. Three distinct sections can be identified from the results along the route.
The first section of the route (km 0 to 7.5) initially runs through an industrial area (km 0 to 1.5). Here the modal priorities are for public transport, car and freight. This is followed by a stretch of commercial area (approximately km’s 1.5 - 3.5), where the priority for freight decreases and that of pedestrian increases. Towards the end of this section of the route (km’s 4 to 6) it is flanked by a cemetery to the south and undeveloped land to the north, which is listed as being a wetland of moderate importance. Here there is a clear priority recommended for public transport and car. This section is followed by an industrial park where the priority of bicycle, pedestrian and freight increases again (km 6 to 7.5).

The second seven kilometre section of route has less variation than the first section. The model recommends that public transport, pedestrian and car modes receive equal priority for much of the route. Bicycle and freight receive relatively low preference from km 7.5 to 10.5, but their scores improve somewhat between km’s 10.5 and 13. This area is characterised by mixed land uses, comprising of middle income medium density apartments, shops and offices fronting the road. There are frequent bus stops and rail stations along the route.

Between km’s 13 and 15, the route is flanked by low density residential areas to the north and heavy industrial land uses to the south. This explains the improvement of the car and freight mode scores in this area. Thereafter (km 15 to 16.7), the route is flanked by medium density high income residential area, which accounts for the preference for the public transport mode.

The method allows for a large range of inputs and their various effects on the different modes to be assessed coherently. It is apparent that although the priority scores are sensitive to fluctuations within the criteria set, as can be seen by the variability within the scores, distinct patterns can be identified for different sections of the route. This shows that there are indeed contextually distinct areas along the road and that, consequently, location specific context should be considered when planning roads.

The clustering analysis produced seven unique clusters. In Figure 1, the horizontal sections of the line "Two-step clustering" show sections of the route belonging to the clusters numbered on the secondary vertical axis. Each cluster represents a different modal suitability regime along the route. Clusters are in many cases repeated in various sections of the route. This indicates that these sections, although not adjacent to each other, share many contextual characteristics that influence the suitability of the various modes moving through them. Each modal suitability regime is defined by the mean score of each of the five modes for that section of the route. These cluster specific mean mode scores can be extracted and plotted for further analysis of the clusters themselves.

Using the mean scores for each mode by cluster, it is possible to assess the relative suitability of each mode in each cluster, and then from this begin to assess what type of infrastructure should be provided to accommodate that mode in accordance with its suitability score. Figure 2 shows the differences between clusters. The scores for each mode, and the ranking of modes within each cluster, vary considerably from cluster to cluster. It can therefore be concluded that the clusters represent unique combinations of modal suitabilities across the route.
These mode suitabilities can be assessed by planners in relation to proposed developments along the route, or can be used to guide planners when developing proposals for infrastructure for the route. They provide insight into the needs of the various modes that use the road as these needs vary along the length of the route.

Figure 3 shows how the clusters relate to each other and the surrounding road network. It is interesting to note that clusters tend to segment at major intersections or where the adjacent road network density or layout pattern changes. These changes are usually indicative of a change in the predominant land use pattern. Often, this impacts across many of the criteria used to describe the context. This explains why there would be a change in the clusters at these points. Also, the figure shows that the outlier points (where clusters change over very short distances) correspond with large intersections along the route. The implication is that the priorities at these intersection areas are unique and that they therefore warrant special treatment.
Figure 3: Clusters plotted on road network
4. CONCLUSIONS

The method developed in this paper is able to take a large range of location specific information and aggregate it to reveal the contextual differences along a route. The context along the route varies significantly from one location to another, and consequently should influence decisions made around the infrastructure built to serve that location. These contextual differences can be assessed in terms of the implications they have for the various modes traversing the route. Because it is implicitly multimodal, the method forces planners to think about the road from a multimodal point of view. Also, since the method relies on location specific contextual information, the method very effectively integrates the transport planning process with land use, societal, economic and environmental concerns. The method can be used in combination with established tools in planning and design guidelines to inform decisions around infrastructure provision, project prioritization and road classification.

REFERENCES


Hebbert, Michael 2005, ‘Engineering, Urbanism and the Struggle for Street Design’, 

Holtzclaw, J. 1990, Manhattanization versus Sprawl. How Density Impacts Auto Use 
Comparing Five Bay Area Communities, in ‘Proceedings of the Eleventh International 

transport route planning alternatives: a spatial decision support system for the Via 
Baltica project, Poland’, Journal of Transport Geography 17(1), 54–64.

and travel in five neighborhoods in the San Francisco Bay Area’, Transportation 
24(2), 125–158.


McCann, Barbara, Suzanne Rynne 2010, ‘Complete Streets: Best Policy and 
Implementation Practices’.


Rescia, Alejandro J, Elizabeth N Astrada, Julieta Bono, Carlos A Blasco, Paula Meli, 
Jorge M Adámoli 2006, ‘Environmental analysis in the selection of alternative corridors 
in a long-distance linear project: a methodological proposal.’, Journal of environmental 


Sharifi, M A, L Boerboom, K B Shamsudin, Loga Veeramuthu 2006, Spatial Multiple 
Criteria Decision Analysis In Integrated Planning For Public Transport And Land Use 
Development Study In Klang Valley , Malaysia, in ‘ISPRS Technical Commission II 
Symposium, Vienna’.

Stamatiadis, Nikiforos, Kirk Adam, Hartman Don, Hopwood Theodore, Pigman Jerry 2009, 
‘Quantifying the Benefits of Context Sensitive Solutions’.

Svensson, Å se, ed. 2004, Arterial Streets for People: Guidance for planners and decision 
makers when reconstructing arterial streets., European Commission Fifth Framework 
Programme. www.tft.lth.se/artists

Zhang, Ming 2004, ‘The Role of Land Use in Travel Mode Choice: Evidence from Boston 

Zhang, Tian, Raghu Ramakrishnan, Miron Livny 1996, BIRCH: An Efficient Data 