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Context sensitive multimodal road planning: a case study in Cape Town, South Africa

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ABSTRACT

Road planning practice relies almost exclusively on parameters related to traffic factors, such as private vehicle speeds and volumes. In many developing countries the requirements for public transport and non-motorised transport are not explicitly integrated into the planning process, despite the fact that these form the primary mode of transport for the majority of the population. This affects the mobility opportunities for these sectors of the population and contributes to poor road safety, especially with regards to pedestrians. The research outlined in the paper posits that, in order to assess the usage and needs of the road holistically, other factors related to the adjacent land uses, socio-economic characteristics of the population the road serves, and the environmental context within which the road is located, factors heavily in how the road is used and should, therefore, be considered within the planning process. The paper describes a methodology to include these factors in the planning of roads. The method attempts to prioritise amongst the five primary road based modes (public transport, car, freight, walking and cycling) based upon a combination of traffic and non-traffic factors. The method employed uses a geographic information system (GIS) based spatial multiple criteria evaluation (SMCE) model with inputs from widely available data sources such as census, household travel surveys, land use and environmental data to arrive at solutions for modal priorities. A case study is conducted along an arterial route in Cape Town, South Africa, providing infrastructure planning recommendations and audit possibilities for the future. Since weighting is an important driver in the SMCE process, a sensitivity analysis is conducted to investigate the effect of alternative weighting schemes on the outputs from the method.

1. Introduction

In developing countries, such as South Africa, mode choice is often dictated by income. Specifically, lower income people are generally captive to public transport (PT) and non-motorised modes (NMT), while higher income people are more likely to use private motorised transport (NDoT, 2005). Furthermore, even in metropolitan areas the overall levels of car ownership are low relative to developed countries, which is symptomatic of the high proportion of low income earners and the high numbers of unemployed (Dargay, 2001). The South African National Household Travel Survey (NDoT, 2005) found that 42% of respondents used public transport as their primary mode of travel to work, and that 30% either walked or cycled to work. The remaining 28% used private vehicles. This highlights the importance of PT and NMT to trip making in South Africa.

In this context, it would be fair to assume that road planning practice in South Africa is sensitive to the demand for facilities for NMT and PT. However, this is not the case. There is a lack of infrastructure and facilities that inhibits NMT use and NMT is not successfully integrated in all aspects of planning (CoCT, 2005a). This is despite legislation and policy documents calling for PT to be given higher priority in planning and infrastructure provision and for NMT to be promoted as the preferred mode over appropriate distances (NDoT, 2006).

The authors contend that one of the primary reasons for this continuing in planning practice is that many of the guidelines commonly used by planners and designers are outdated, and were not developed to comply with current policies (e.g. CUTA, 1989). Guidelines are fragmented between modes and road categories, and consequently fail to provide the planner with a modally integrated perspective on the needs of all road users who may use the facility being planned. In most instances there is very little, if any, explicit guidance given on infrastructure provision for mixed use roads, despite more recent literature defining these as

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constituting the majority of urban streets (CSIR, 2000). Although guidelines specifically state that they do not preclude the use of innovative engineering practices (CSIR, 2000), planners seldom deviate from their recommendations. It is, therefore, unsurprising that road planning practice in South Africa continues to produce infrastructure that is biased towards the needs of private motorised transport.

This paper investigates the role that contextual influences such as land use, socio-economic and environmental factors can play in eliminating the disjuncture between planning for private vehicles and planning for NMT and PT, and proposes a GIS based method that relies on a spatial multiple criteria evaluation (SMCE) to include these factors in the transport planning process.

2. Context and design

2.1. Needs assessment in road planning

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). 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 planning practices in South Africa do not facilitate an assessment of this nature. Practice currently involves the classification of the route into one of five hierarchical categories, generally related to the expected volume of vehicular traffic on the road, but also to its location in the road network. Each category is characterised by a set of norms related to operating and design speeds, cross sectional parameters and modal inclusivity (which modes are allowed to operate where). Access is defined as access to properties, and theoretically all roads are said to lie somewhere on a spectrum between mobility only routes (such as freeways and motorways) and access only routes (such as cul-de-sacs) (FHWA, 2004). These norms are then expanded to derive a range of appropriate design parameters, which are applied when developing design recommendations so as to meet at least a minimum acceptable level of service (LOS).

This generalized approach to road planning has limited the influence that location specific contextual factors can have on the final plans produced. In addition, the current system of rating transportation quality, LOS, is primarily concerned with vehicle mobility. The evaluation of transportation needs based solely on this criterion often leads to construction of larger roadways which may not always be necessary or desired by the users (TRB, 2009).

2.2. The role of context in road planning

Contextual factors play a significant role in determining how a street is used, and by whom. It is often the case that contextual realities dictate a facilities use irrespective of the limitations imposed by the design. It is in these instances that dangerous situations may occur. City authorities in Cape Town found that of the ten roads with the highest recorded number of pedestrian fatalities, half are officially completely restricted to pedestrians, and the remainders are primarily vehicle mobility routes, with limited access allowed for pedestrians (CoCT, 2005b). The (unwanted) pedestrian activity along these routes demonstrates the impact of contextual realities manifested as travel needs despite a lack of infrastructure.

According to the US Federal Highway Administration (FHWA), context sensitive design (CSD) (also referred to as context sensitive solutions) 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 principles of CSD and methods for quantifying and measuring the performance of projects in relation to CSD principles are further detailed in 15 principles outlined in TRB (2009), but include amongst others, the use of interdisciplinary teams, the need to address all alternative modes, the need to maintain environmental harmony and the need to utilize the full range of design choices. However, CSD as it is presented is mainly a project development and project management approach to use existing geometric design standards to develop socially and environmentally sensitive infrastructure.

In recent years the use of GIS as a platform to analyse the spatial complexities of urban planning and transport planning problems has increased dramatically. Planners are often confronted with alternative scenarios to be assessed, and these assessments are often driven by a range of both quantitative and qualitative variables, with numerous stakeholders and viewpoints to be considered. 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 (Keshkamat et al., 2009). SMCE has been successfully used to assess alternatives in a range of areas including environmental impact assessment (Blaser et al., 2004; Affum and Brown, 2002), public transport and land use development planning (Sharifi et al., 2006), mapping potential biodiversity of new woodlands (Van der Horst and Gimona, 2005) and routing problems for pipelines and roads (Rescia et al., 2006; Keshkamat et al., 2009). The latter study used a range of criteria including transport factors, ecological factors, social and safety factors and economic factors to define a routing for a motorway across Poland under a number of assessment scenarios. The study demonstrates the impact that these contextual factors can have on project planning outcomes at the macro (regional) scale, and presents an interesting contrast to the FHWA CSD planning approach. The question can then be asked, how do these contextual factors vary on the micro or neighborhood scale, and how, if at all, could these contextual variations be accounted for in road planning at this scale?

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. As mentioned, the aim of the developed tool is to improve livability through context sensitive road planning. The selection of context specific criteria was, therefore, a major step in the development of the tool. Land use was identified as the first context sensitive relevant criteria. 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; Handy 1996; Ewing and Cervero 2001; Frank and Pivo 1994; Zhang 2004). In terms of road planning, these parameters provide information on the expected number of trips and the probable modal split at a location. Neighborhood demographics, such as age, gender, income and employment levels of inhabitants were the second group of attributes selected. These attributes were summarized in the criteria, called socio-economic profile. This information is critical to the route context, since it details the types of users, their levels of ability and the probable modal split at a location (NDoT, 2005). Sustainable road space management and context specific road planning is not possible without the inclusion of the environmental profile along the route which relates to the environmental and cultural or heritage sensitivity along the route. In terms of the National

Environmental management Act (DoEAT, 1998), 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. Finally, it was decided to include the more traditional transport specific attributes. 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.

3. Method development

3.1. Problem framing

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) and vehicle miles travelled (Holtzclaw, 1990; Kitamura et al., 1994). This research posits that contextual factors, such as those described in Section 2.2 are equally as important as traffic and transportation factors when planning roads. 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 in the intersection between the modal characteristics and the 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.

Therefore, the planning problem that this research addresses is to identify what infrastructure needs to be developed given the order of priority of the various modes, as recommended by a set of contextual and modal factors. Framing the problem in this way allows one to derive possibilities for a contextually appropriate mix of service levels to be given to the various modes along the road.

3.2. Methodology

A GIS based approach was used to bring together all of the information needed to assess the context of each location along the route. GIS is well suited to evaluating large databases of spatial information (Eastman et al., 1995). To evaluate the suitability of one mode over another, a spatial multiple criteria evaluation was conducted using the five main road based modes: private vehicles, freight, pedestrian, public transport and bicycle, as the alternatives. The criteria that were selected are discussed in detail in Section 3.3. The output from the evaluation is a ranking or score for each mode at each (raster based) location.

The most prevalent procedure for multiple criteria evaluation is the weighted linear combination (Voogd, 1983, p.120). With a weighted linear combination, factors are combined by applying a weight to each followed by a summation of the results to yield a suitability map, i.e.:

$$P = \sum w_i x_i \qquad (1)$$

where P is priority, w is the weight of factor i and x is the criterion score of factor i. The weights used in the procedure can be calculated using the Analytical Hierarchy Process (AHP) as introduced by Saaty (1980). 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 the linear combination of 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 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 (Farkas, 2009; Keshkamat et al., 2009; Sharifi et al., 2006). In the case of this research, the route is predefined (either existing or planned), and instead, it is the relative priority 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. 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. 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 during the development of the methodology.

3.3. Criteria selection

Multiple criteria analysis methodologies require that criteria be standardized in order to be evaluated. Standardization involves reducing the variables to a common base (usually 1) so that arithmetic operations can be performed on it. This presents a challenge, as some variables can be described as being continuous (such as densities, incomes) while others are presented in discreet categories (land uses, environmental sensitivity). Furthermore, variables must be evaluated as being either a cost or a benefit. As will be seen, this is often dependent upon the evaluator's viewpoint.

The variables needed to assess the locational context of a road can be classified into the four categories mentioned previously that define the characteristics of a specific location. The variables that are considered relate specifically to the what, who and how questions that can be asked of any locality. What are the characteristics that define the locality? Who are the people using the locality? How are these people using the locality?

To describe the location, land use type, property density and property values were used. 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 proximity to environmentally sensitive or historically significant sites and wetlands were used to describe the environmental qualities of the location. 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. The case of land uses (discreet categories) and household densities (continuous) are used to illustrate the approach adopted.

3.3.1. Land use

Various land uses have differing characteristics in the type and volume of traffic that they generate, the time of day and day of the week that peak volumes are generated, and the traffic needs specific to the land use (NDoT, 1995). Consequently, when planning infrastructure to service any particular land use, these differences need to be considered and the design altered as required. By considering land use as an explicit variable in the criteria tree, these differences and the costs or benefits attributed to each mode as a result of them, can be captured.

These costs and benefits can vary according to the viewpoint. For example, in an industrial area it is reasonable to expect high volumes of heavy vehicles. In fact the businesses in these areas depend upon the ease of access provided to these vehicles. From this viewpoint, maximising mobility for heavy vehicles (and in fact all motorised vehicles) is important. However, these areas also see high levels of non-motorised traffic (workers walking to work, etc.). The conflicts between non-motorised road users and vehicles are a significant cost from the perspective of NMT road users.

The question centres around the values that are imposed on the evaluation. These values are translated into impacts or modal priorities through value statements. In the example given, the following statement could be used to interpret the values from the perspective of NMT road users:

> *“We want to maximise the safety of all road users”*

In order to maximise safety, it is necessary to afford priority to the most vulnerable road users, limit vehicle speeds and minimise potential conflict points. Maximising safety is a benefit function, and the safety of each mode is expressed qualitatively in terms of vulnerability and travel speed. This yields an impact vector as shown in Table 1:

Alternatively, since an industrial area is being considered, the position can be taken that mobility and access for delivery vehicles is of paramount importance. The value statement could be expressed as:

> *“We want to maximize the mobility of delivery vehicles”*

In order to maximise mobility for delivery vehicles the highest priority must given to speed, in which case the impact vector will look as follows, with the fastest mode receiving the highest preference (see Table 2):

Clearly, with each land use, multiple value positions could be taken that would each yield different impact vectors. Furthermore, since the concerns around traffic vary across land uses (the concerns in a commercial district are different to that of a residential district) (NDoT, 1995), it is not possible to assume one value position for all land uses. Instead, the impact vector must be individually defined for all land uses. The result can best be described as a value matrix. Each land use option is assessed from the value position that is perceived to be best suited to it. This yields an ordinal scale of benefits as seen in Table 3.

Table 1
Safety maximisation impact vector.

Mode	Car	Public transport	Pedestrian	Bicycle	Freight
Impact	++	+++	+++++	++++	+

Table 2
Mobility maximisation impact vector.

Mode	Car	Public transport	Pedestrian	Bicycle	Freight
Impact	++++	+++	+	++	+++++

In Table 3, different value statements (to be read as: “We want to maximize [value] by giving priority to the mode with the [indicator]”) are used to express priorities varying between safety, access and mobility. In this case only two indicators, speed of mode and volumes by mode are used to distinguish between alternatives in terms of the value statement. Different impacts can be developed for different land use options despite the fact that the same indicator is used.

The reason for adopting an ordinal, rather than a cardinal scale is that the primary objective of the evaluation is to derive a modal priority or modal preference ranking for each segment. The disadvantage of the ordinal scale approach is that the extent of preference is lost. Also, it is not possible to confer the same rank to different alternatives (in this case these are modes). In order to assign weights, the preference rankings must be standardized to preference scores. In the example, the highest preferred mode gets one point and the lowest gets 0.

3.3.2. Household density

Higher density areas are better suited to a more intense activity mix, and can support better quality public transport (CoCT, 2009). Density is often cited as an indicator of trip frequency and trip length (Chen et al., 2008; Chatman, 2006). Density is also an indicator of modal split, in that in less dense regions, with a higher uniformity of land uses, trips are more often made using motorised modes that are better suited to longer trips, whereas in high density areas with a higher mix of land uses, trips can be shorter, and so better suited to public transport and non-motorised modes (Limtanakool et al., 2006; Kockelman, 1996; Zhao et al., 2002).

Density is therefore important in defining the character of a location in relation to which mode should receive a higher priority. In low density residential environments, it is not unreasonable to assume that many trips will be made using private vehicles, especially when trip attractors such as shops or work places are far away, and especially when public transport facilities are unavailable. So, although mobility may not be the overriding concern in that context, if density were the only evaluation criteria the lower density gives justification to considering the needs of the private automobile as primary.

Returning to the value statements that were used to identify indicators for the criteria, if density is assumed to be a continuum of some range of values from high to low, then in higher density areas a higher preference is given to NMT and PT and in lower density areas a higher preference is given to private vehicles. The value statement can be stated as:

> *“We want to maximise the mobility of the majority of road users”*

So, in high density areas where the majority of road users can be expected to be either pedestrian, cyclist or public transport users, they should receive priority, whereas in low density areas where most people could be expected to be driving, private automobiles should receive priority.

The relationship between density and modal priority can be modelled as a simple linear function. Each mode is modelled in terms of its preferred modal priority given a certain density. Fig. 2 conceptually illustrates how modal priorities shift with increasing densities. The specific modal priority values selected are a reflection of the subjective values imposed on the evaluation by the decision maker.

If, as discussed, density were defined as being a continuum between a measureable low and high value, the relationships defined

Table 3
Land use value matrix.

Criteria	Option	Value	Indicator	Car	Public transport	Pedestrian	Bicycle	Freight
Land use	Residential	Safety for NMT	Lowest speed	0.25	0.5	1	0.75	0
	Commercial	Access for patrons	Highest volume	0.5	0.75	1	0.25	0
	Industrial	Mobility for vehicles	Highest speed	0.75	0.25	0.5	0.25	1
	Education	Safety for learners	Lowest speed	0.25	0.5	1	0.75	0
	Sports and recreation	Access for spectators	Highest volume	0.25	0.5	1	0.75	0
	Vacant land	Mobility for passersby	Highest speed	1	0.75	0	0.25	0.5
	Medical	Access for patients	Highest volume	0.25	0.75	1	0.5	0
	Office	Access for workers	Highest volume	0.5	0.75	1	0.25	0

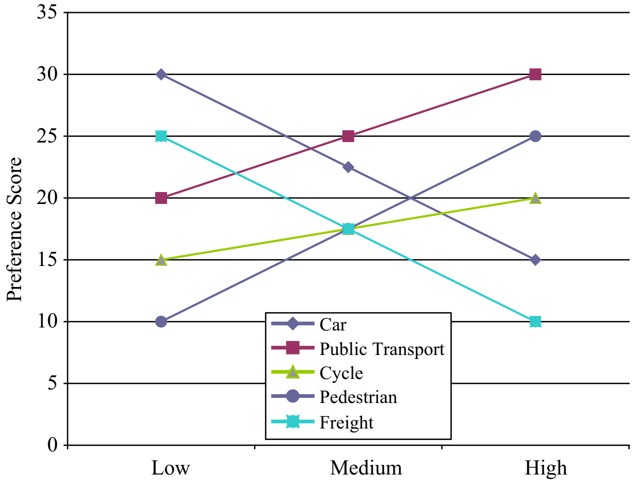

Fig. 1. Modal preference in relation to density.

above can be applied to each location to determine the appropriate modal mix in terms of the value function as shown in Fig. 1.

Similar methods as described in Sections 3.3.1 and 3.3.2 were used to standardize remaining factors. Care was taken to avoid including highly correlated criteria wherever possible, without losing important contextual detail, so as to avoid biasing one mode over another. Table 4 gives an overview of the criteria used and the standardizations that were applied to each.

4. Study route description

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 km long, and was selected on the basis of the variety of modes, land uses, intensity of land use and population groups it serves. 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.

5. Results

The evaluation was conducted using the criteria discussed in Section 3. The evaluation revealed that spatial contextual variation along the route produced significant variability in the preference for each mode. However, clearly defined stretches can be identified where modal preferences can be said to be constant. Fig. 2 presents graphical representations of the modal preference for each mode as output from the analysis. The colors are a representation of the score given to each pixel, with zero being the worst score, represented by red, and one being the best, represented by green.

In order to conduct a comparative evaluation of the results for Voortrekker road, the pixel values have to be 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 m area, this represents a 100 by 100 m area in reality. 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 result. Since the evaluation strip is centred along the road centreline, the values along the centreline of the road now represent an average of the area surrounding it. These values are collated 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.

The output from this exercise is shown in Fig. 3. 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 (0–7.5 km) initially runs through an industrial area (0–1.5 km). Here the modal priorities are for public transport, car and freight. This is followed by a stretch of commercial area (approximately 1.5–3.5 km), where the priority for freight decreases and that of pedestrian increases. Towards the end of this section of the route (4–6 km) 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 (6–7.5 km).

The second 7 km 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 7.5 to 10.5 km, but their scores improve somewhat between 10.5 and 13 km. 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 13 and 15 km, 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 (15–16.7 km), the route is flanked by medium density high income residential area, which accounts for the preference for the public transport mode.

By analysing the results in relation to what is known about the route (photographs have been included in Fig. 3 to give the reader some insight into the character of the various sections along the route), the reasons for the variations in the priority scores become

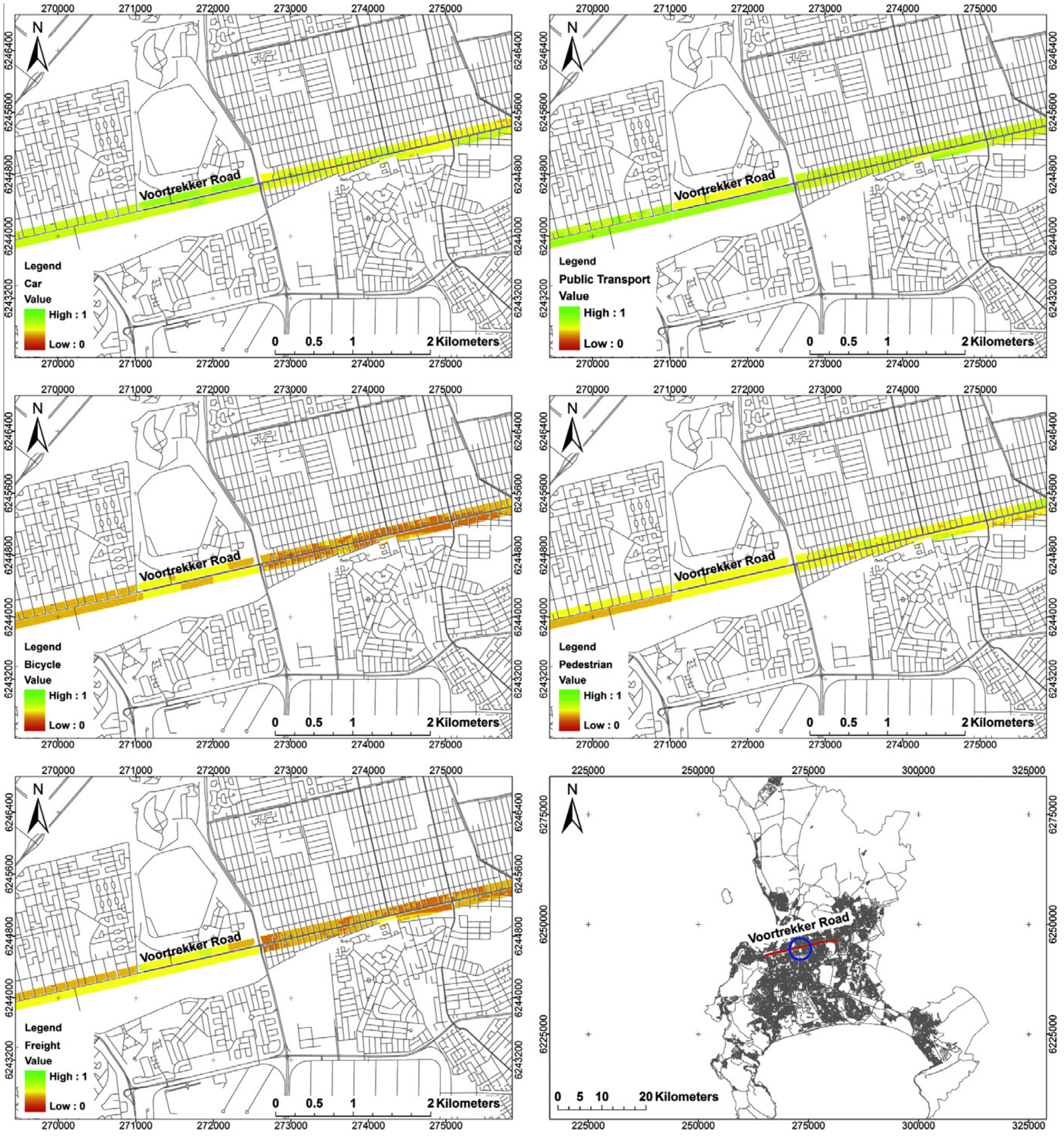

Fig. 2. Extracts from modal preference rasters for car, public transport, bicycle, pedestrian and freight and location of voortrekker road (left to right, top to bottom).

apparent. The method allows for a large range of inputs and their various effects on the different modes to be assessed coherently. It is also 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.

An initial conclusion from this case study is that overall, public transport, the car and pedestrians are the most important modes along this corridor, with freight being an important consideration near industrial areas. Furthermore, since there are clearly differing priority regimes for different sections of the route, the planning and design of these sections should reflect these varying priorities.

6. Sensitivity analysis

The nature of SMCE is that weighting schemes play an important role in determining the final results. Since a uniform weighting scheme was used to highlight the importance of contextual differences on mode preference, it was important to test the robustness and flexibility of the results to alternative weighting

Table 4
Criteria, value statements, indicators and standardisations.

Criteria	Option	Value	Indicator	Car	Public transport	Bicycle	Pedestrian	Freight
Density	Low	Mobility of majority	Highest volume	0.25	0.25	0.15	0.1	0.25
	Medium			0.2	0.3	0.2	0.2	0.1
	High			0.1	0.35	0.25	0.3	0
Property value	Low	Mobility of majority	Highest volume	0.1	0.3	0.15	0.4	0.05
	Medium			0.2	0.3	0.15	0.3	0.05
	High			0.3	0.3	0.15	0.05	0.2
Vulnerable road users	Low	Safety of vulnerable road users	Lowest speed	0.25	0.25	0.1	0.1	0.3
	Medium			0.2	0.2	0.15	0.3	0.15
	High			0.05	0.1	0.25	0.55	0.05
Education level	Low	Mobility of majority	Highest volume	0.05	0.25	0.3	0.4	0
	Medium			0.15	0.25	0.25	0.3	0.05
	High			0.5	0.1	0.15	0.15	0.1
Heritage	No	Access	Lowest speed	0.5	0.2	0.05	0.05	0.2
	Yes			0.05	0.35	0.15	0.45	0
Wetland	No	Minimise impact	Lowest speed	0.5	0.2	0.05	0.05	0.2
	Yes			0.05	0.35	0.15	0.45	0
Eco sensitive areas	No	Minimise impact	Lowest speed	0.5	0.2	0.05	0.05	0.2
	Yes			0.05	0.35	0.15	0.45	0
Public transport demand	Low	Minimise impact	Highest volume	0.3	0.1	0.15	0.15	0.3
	Medium			0.2	0.3	0.2	0.2	0.1
	High			0.1	0.4	0.2	0.25	0.05
Private car demand	Low	Mobility of majority	Highest speed	0.1	0.4	0.2	0.25	0.05
	Medium			0.2	0.2	0.2	0.2	0.2
	High			0.3	0.1	0.15	0.15	0.3
Proximity to public transport stop	Low	Minimise impact	Lowest speed	0.3	0.1	0.15	0.15	0.3
	Medium			0.2	0.3	0.2	0.2	0.1
	High			0.1	0.4	0.2	0.25	0.05

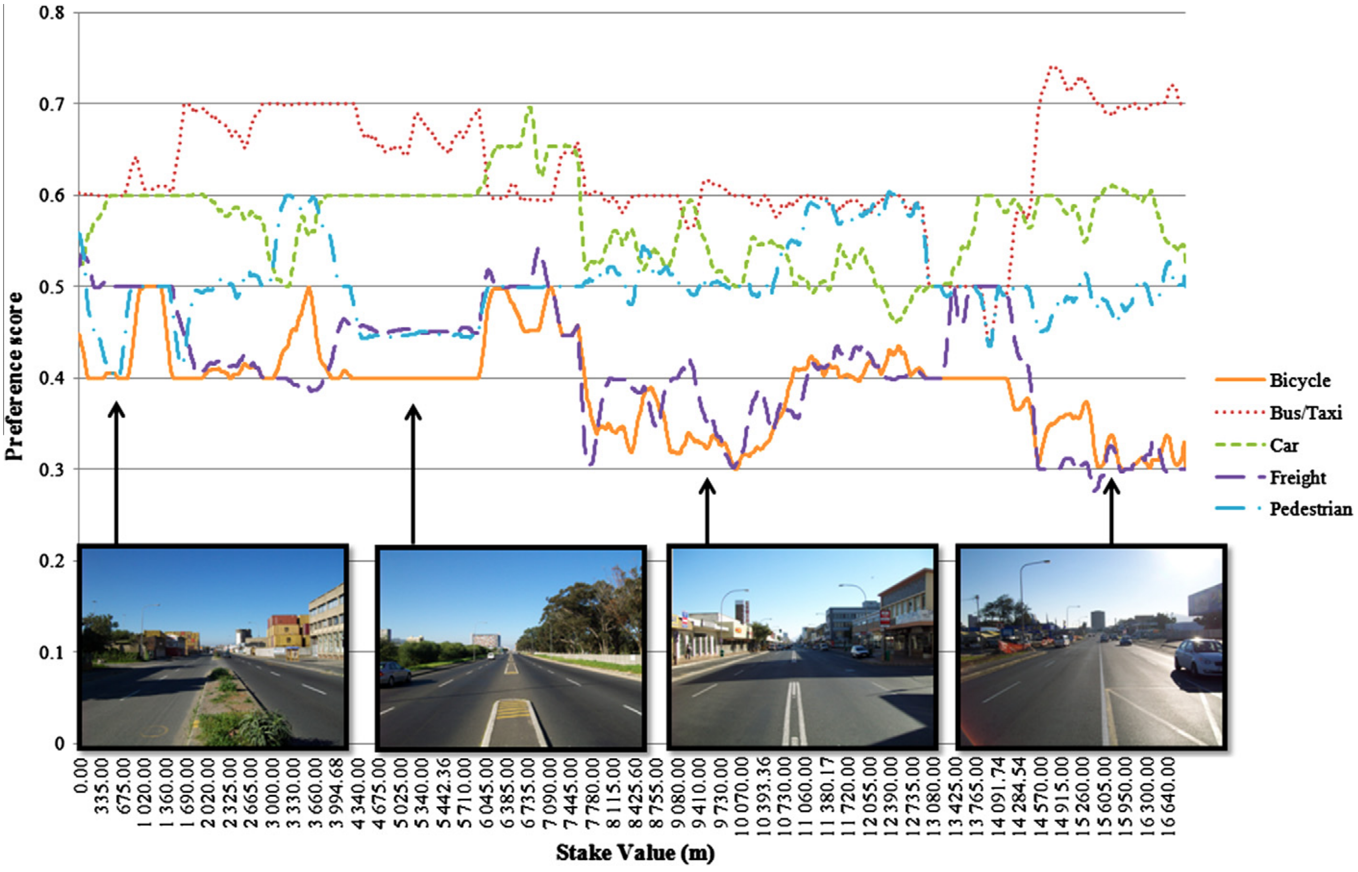

Fig. 3. Relative rankings of modes.

Table 5
Sensitivity analysis results ($n = 3734$, $df = 3733$).

Mode	Altered factor category ($w_i = 1.2$)	Correlations		Paired samples test						
		r	Sig.	Paired differences					t	Sig. (2-tailed)
				Mean	Std. deviation	Std. error mean	95% Confidence interval of the difference			
							Lower	Upper		
Bus	Environmental	0.946	0	−0.01575	0.02061	0.00034	−0.01641	−0.01509	−46.702	0
	Land use	0.99	0	0.00274	0.00945	0.00015	0.00244	0.00304	17.714	0
	Socio-economic	0.98	0	0.00172	0.01478	0.00024	0.00124	0.00219	7.097	0
	Transport	0.924	0	0.0135	0.02418	0.0004	0.01272	0.01427	34.114	0
Car	Environmental	0.887	0	−0.01881	0.02087	0.00034	−0.01948	−0.01814	−55.093	0
	Land use	0.961	0	0.00694	0.01256	0.00021	0.00653	0.00734	33.753	0
	Socio-economic	0.947	0	0.00758	0.01555	0.00025	0.00708	0.00808	29.797	0
	Transport	0.975	0	0.00401	0.01074	0.00018	0.00367	0.00436	22.839	0
Freight	Environmental	0.933	0	0.01306	0.02373	0.00039	0.01229	0.01382	33.614	0
	Land use	0.987	0	−0.00555	0.01037	0.00017	−0.00589	−0.00522	−32.741	0
	Socio-economic	0.998	0	−0.00093	0.00454	0.00007	−0.00108	−0.00078	−12.508	0
	Transport	0.99	0	−0.00273	0.00915	0.00015	−0.00302	−0.00243	−18.223	0
Pedestrian	Environmental	0.995	0	0.00081	0.00425	0.00007	0.00068	0.00095	11.702	0
	Land use	0.979	0	−0.00263	0.00942	0.00015	−0.00293	−0.00233	−17.085	0
	Socio-economic	0.962	0	0.00038	0.01196	0.0002	0	0.00076	1.946	0.052
	Transport	0.938	0	0.00268	0.01646	0.00027	0.00216	0.00321	9.966	0
Bicycle	Environmental	0.888	0	0.01297	0.02262	0.00037	0.01225	0.0137	35.048	0
	Land use	0.982	0	−0.00516	0.00949	0.00016	−0.00546	−0.00485	−33.207	0
	Socio-economic	0.995	0	−0.00153	0.00528	0.00009	−0.0017	−0.00136	−17.662	0
	Transport	0.979	0	−0.00395	0.01178	0.00019	−0.00433	−0.00358	−20.518	0

schemes. The results presented in Section 5 were subjected to a sensitivity analysis in order to investigate the robustness of the evaluation to changes in the weighting scheme. The method used was to increase the weighting of each category of criteria (land use, socio-economic, environmental and transportation) by 20% in turn, and compare the results to the base case. A correlation test and a dependent *t*-test were selected as the testing mechanisms. The results are shown in Table 5.

The Pearson product-moment correlation coefficient, *r*, is a measure of the linear dependence between two variables. Here, the main interest was to determine the influence of the change in the weighting scheme on the results. Since each category of criteria was altered in turn for each mode, the analysis also gives insight into which category of criteria accounts for the highest change for each mode. Since both samples used the same case data (the input rasters remained the same), with only one category of weighting changed in each test case, it could be expected that the results would be strongly correlated. Therefore, to improve the understanding of the extent of change, a dependent *t*-test was conducted to compare the difference between the means of the base case and the weighted case to the difference that could be expected between the sample means when the null hypothesis (that there is no difference between the base case and the weighted case) is true.

The analysis found that as expected, for each mode, the adjusted results were very strongly correlated to the base case result. For all modes, the environmental category of factors proved to have the strongest effect on the results. This was especially true for the car and the bicycle. The difference between the means shows that the impact was negative for the car, and positive for the bicycle. The coefficient of determination, R^2 (not included in Table 5), is a measure of the variability in one variable that is shared by the other. For these two modes, in both cases R^2 was calculated as 79%. This implies that 21% of the variation between the base case and the case where the environmental category weight was increased can be accounted for by the change in weight, meaning that the change in weight produced a meaningful (one fifth) difference from the base case.

Although the differences in the means was very low overall (<2% in all cases, also supported by the small confidence intervals), the change in weight had a significant effect (since *t* is always so large) on the results, and this effect is almost certainly not due to chance ($p < 0.05$). This result is expected since the inputs are identical. However, although the effect is statistically significant, it is scientifically small since the means are so similar. It can be expected that the cumulative effects of changing more than one category's weighting simultaneously would be greater, however, since there are only four criteria categories and the summation method is linear, it is unlikely that this will exceed a 10–15% difference from the mean base scores.

It can be 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 show that the method is able to produce results that are flexible to variations in weighting schemes without inducing radically altered outcomes.

7. Conclusions

There is a need for road planning and design to be sensitive to the contextual aspects related to a roads location, in addition to the roads traffic and transport function. Furthermore, there is a need to recognise the importance and needs of all modes that may be expected or desired along a route when planning roads. To respond to these needs, this paper presents a GIS based method to derive a contextually appropriate mix of service levels for the various modes along a road. A SMCE is conducted along an arterial road in Cape Town, South Africa. The case study road was selected because of the heterogeneity of the contextual circumstances along the route, which is typical for many arterials in cities across the world.

In the research, context is defined as including aspects related to the adjacent land use, the socio-economic profile along the route, the environmental aspects of the route and the traffic and transport needs along the route. The analysis for the road in Cape

Town shows that there are clear differences in locational context along the route and that it is possible to discern clear sections of the route where definite priority regimes exist. These differences underline the importance of understanding these contextual factors and the role they play in who uses the road and how it is used. Since such contextual differences exist along the route, it is imperative that these factors are quantified and included from the outset when planning the facilities that are provided along the route.

The research develops an easy to understand method based on SMCE theory and techniques that can be used with readily available data and technologies to analyse complex and multifaceted urban routes. The planning recommendations that can be derived from the method are driven by values outlined by policies and regulations, but the method remains flexible enough to examine the implications of alternate perspectives. The sensitivity analysis indicates that the method is able to produce results that reflect the variations of weighting priorities without completely distorting or radically altering the unweighted results.

Methodologies and planning tools such as described in this paper are becoming increasingly important as city and municipal authorities attempt to implement modern policy directives in the absence of established best practice and comprehensive guidelines around planning for multiple modes, as is the case in South Africa. The method described here can provide planners with additional insights into the complexities of urban environments and the needs of the multiple modes that traverse them.

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