COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING

Computer-Aided Civil and Infrastructure Engineering **28** (2013) 344–358

Quantifying the Contextual Influences on Road Design

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Abstract: *This article describes the COSMA (COntext Sensitive Multimodal Assessment) method that uses contextual information to develop road infrastructure recommendations for the purpose of improved road design. The method uses a GIS-based Spatial Multi-criteria Analysis (SMCA) that is combined with statistical clustering techniques to identify contextually similar areas along arterials. The context is defined in terms of a range of land use, socioeconomic, environmental, and transportation information, presented spatially, which are used as inputs to the SMCA. The results of this analysis describe the relative suitability of different modes of transport to locations along an arterial route. Clustering the output of this analysis allows for sections of the route with similar contexts to be identified. The attributes of these clusters are then used to derive descriptive statements of contextually appropriate operational conditions for each mode in a particular section of the route in terms of access, right of way, and independence of movement. These can be used by road designers to develop proposals for road infrastructure design. We demonstrate the workings of the method for an arterial road in Cape Town, South Africa. The method described is explicitly multimodal and sensitive to the variations in local context. It can be used by planners and roads authorities to provide additional perspective on road user needs and facility provision, and introduces quantification, and the concomitant benefits thereof, to the largely qualitative field of Context Sensitive Design.*

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DOI: 10.1111/j.1467-8667.2012.00804.x

1 INTRODUCTION

Transportation planning, increasingly, relies on the use of computer-aided techniques to conduct analyses and make recommendations (Xie and Waller, 2012; Putha et al., 2012; Mouskos and Greenfeld, 1999; Tillema et al., 2006). Improvements in the performance and the availability of computers, from the 1960s onward, have fueled a revolution in the use of quantitative approaches, based on statistical and mathematical techniques, to model the operations and performances of transportation networks (Szeto and Sumalee, 2011; Jiang and Adeli, 2004; Samant and Adeli, 2001). This analytical approach to transport planning and modeling is epitomized by a number of landmark planning studies conducted between the 1960s and the 1980s, most notably those conducted in Chicago and Detroit in the United States (Black, 1990), that has, to a large extent, also come to form the standard approach to analyzing transport problems, which is still ubiquitous in practice today.

Naturally, road design cannot be divorced from transportation planning; transportation models are used to determine the operational parameters and requirements for infrastructure. Objections raised against the use of transportation models often relate to how the findings of these models are translated into infrastructure requirements (see Vigar, 2001). Because transportation models are typically used to predict the demand for travel along routes, infrastructure proposals have tended to focus on meeting this demand through capacity improvements, often having unintended consequences for the social, environmental, and economic systems that interface with the transport system (see Cervero, 2001; Cervero and Hansen, 2002; Fröhlich, 2003; Vuchic, 1999).

As a result, integrated land use and transport planning, and demand side transport management approaches, have since come to be seen as the most sustainable way forward for transport planning (see Aarhus, 2000; Akinyemi and Zuidgeest, 2002; Banister et al., 1999; Newman, 1996; Walton and Shaw, 2003). Increasingly, the importance of other modes of transport, such as walking, cycling (referred to as nonmotorized transport or NMT), and public transport (PT), to the overall transport system is also being recognized in areas where they were previously neglected (see also Guttenplan et al., 2001; Kenworthy, 1999; Van Exel and Rietveld, 2009; Wang, 2008). Concerns around the sensitivity of infrastructure to the local context have also become more important (Caltrans, 2005; Stamatiadis et al., 2009; Venner et al., 2007). The Context Sensitive Solutions/Context Sensitive Design (CSS/CSD) movement, which espouses the importance of contextual factors in infrastructure planning in the United States, has gained significant traction in recent years (De Cerreño and Pierson, 2004; D'lgnazio and Hunkins, 2005; Mok et al., 2006; Rauch, 2005).

However, despite these efforts and the emergence of a general consensus that these developments are necessary and important (Goodwin and Lyons, 2010), practice still tends to produce infrastructure that prioritizes the needs of the private automobile, and discourages mode shifts (Tennøy, 2010). There is, still, substantial debate around what the reasons for this may be, and how to reverse this trend, but increasingly the role of these analytical methods and the system of guidelines and manuals that inform road design practice is being called into question (Laplante and McCann, 2008; Osman et al., 2007; Paiewonsky et al., 2007).

Road design and transport planning are, generally, linked through traffic volumes. Typically, traffic volumes, either measured directly or estimated from a set of land use and socioeconomic data sources, are used to determine a range of parameters that are used for the majority of road design considerations, such as capacity requirements and levels of service (Dowling et al., 2008). Contextual information, such as the distinction between urban and rural roads, the functional classification of the route in the larger network and, to a limited extent, factors such as adjacent land uses and socioeconomic conditions, is then used to supplement these inputs and finalize designs. Two problems are immediately apparent here; first, the definition and scope of the contextual information used to supplement the primary design variables is not well defined, and is certainly not in line with the land use planning conceptualization of context (or for that matter the CSS/CSD view of context), and second, whereas rigorous methods for estimating traffic volumes are well established, methods for quantifying these contextual factors are poorly developed. The influence of the local context on the final design is, often, mostly left up to the discretion of the designer and, because opinions vary, so does the extent to which these factors influence designs.

The combination of capacity focused infrastructure design and a limited appreciation for, and integration of, a holistic view of the local context in design, can lead to contextually inappropriate road infrastructure that has negative effects on safety, mobility, the local economy, and livability. Additionally, the local context may change over time and, unless the road changes to suit, or other interventions are taken, the effects can be severe. However, without a systematic method to estimate the impacts of the local context, planners are often left without the justification to take preventative action.

The COSMA (COntext Sensitive Multimodal Assessment) method, outlined in this article, aims to address these problems by providing transport planners with a set of tools that can assist with identifying facility design priorities for all modes of transport and for any stretch of road. The COSMA method quantifies the contextual influences on road operations and incorporates them into the road design process. The method uses spatial analysis techniques, because the context varies spatially. Decision analysis methods, including Multi Attribute Value Theory (MAVT) (Keeney and Raiffa, 1993), were used to analyze the contextual data and the solutions were clustered using K-means clustering. This approach, although computationally intensive, is able to combine disparate qualitative and quantitative information into spatially distinct context types. The local context is presented as an m-dimensional vector, the components of which are the relative contextual suitability of each mode of transport, defined by the cluster means. The cluster means are then used to develop descriptive interpretations of the road infrastructure that is best suited to that particular context. These interpretations are derived from statements describing the level of access provided to each mode of transport, the priority of movement or right of way of each mode of transport in relation to the others on the facility, and the level of independence of operation afforded to each mode of transport using the facility.

The method can be used to guide the preliminary planning of roads projects by highlighting the modal priorities in various stretches along the route, and by allowing planners to investigate, in detail, the factors that influence the context in various locations.

The method was case-tested using data from roads in Cape Town, South Africa. Case studies were selected from routes that displayed a wide variety of land use, social, economic, and environmental characteristics along their length, and that were known to have high accident rates. Three roads were selected, of which the results from one, Voortrekker Road, are presented in this article. The Vootrekker Road case study route is a 16 km long arterial road linking the western suburbs to the eastern suburbs in Cape Town.

2 METHODOLOGY

2.1 Criteria selection and standardization

The combination of GIS and MCDA, termed Spatial Multi-criteria Analysis (SMCA), has already been successfully used in a range of fields including environmental impact assessment (Blaser et al., 2004; Brown and Affum, 2002), public transport and land use development planning (Sharifi et al., 2006), and routing problems for pipelines and roads (Keshkamat et al., 2009; Rescia et al., 2006).

The method lends itself well to, for example, assessing the spatial variation in sustainability impacts of infrastructure proposals. López and Monzón (2010) used a GIS-based multi-criteria model to integrate sustainability issues into transport planning. They tested their methodology using a case study looking at the extension of the high speed rail network in Spain. Their study assessed the effects of the proposed project on transport sustainability and, thus, also assumed a planning scenario. In the COSMA method, however, the decision problem is stated as: "*Given a set of information regarding a particular location and information regarding the various modes of transport, which mode is best suited to that location?*" To evaluate the suitability of one mode over another, the SMCA is conducted using the five main road based modes (private vehicles, freight, pedestrian, public transport, and bicycle) as the alternatives (see Beukes et al., 2011a). Whereas Farkas (2009), Keshkamat et al. (2009), and Sharifi et al. (2006) used SMCA to identify routing alternatives for one or more modes of transport given a set of assessment criteria, in this research, as with that of López and Monzón (2010), the routes are predefined. Instead, it is the suitability of the various modes that use the route that is determined.

MCDA methods rely on the construction of a performance table containing the scores of the alternatives for each criterion. Criteria were selected from four categories of contextual information: land use, socioeconomic, environmental, and transportation, to describe the context of each location along the route. The criteria that were considered relate specifically to what the characteristics that define the locality are (referring to the criteria in the land use and environmental categories), who the people using the locality are (referring to the criteria in the socioeconomic category), and how these people are using the locality (referring to the criteria in the transportation category). The criteria used in this study to demonstrate the COSMA method are shown in Table 1.

In general, each criterion is defined as being either a cost or a benefit in relation to an overarching assessment goal, and each criterion is standardized to reflect this interpretation. However, this approach is too simplistic when modes of transport are the alternatives, because the criteria can have differing implications for each mode.

Using the example of household density, as the household density increases, public transport becomes more important because higher densities can support greater levels of public transport. Higher densities are also more amenable for NMT modes. Higher household densities, therefore, represent a benefit for these modes of transport. Conversely, in higher density areas, private vehicles and freight vehicles are not as desirable as the other modes. Higher densities are, therefore, a cost for these modes. Table 2 shows the standardization approach used in this study for each criteria.

The alternatives used in the assessment are measured using different scales (ordinal, interval, and ratio). However, multi-criteria methods require that all of the criteria are expressed in the same scale. Standardizing the criteria permits the rescaling of all the criteria dimensions to between 0 and 1. This permits algebraic operations to be carried out on the criteria.

Although there are a number of standardization methods, a simple linear transformation was used in this study. It associates with each score x the percentage of the maximum over all alternatives. Different approaches are used depending on whether the criterion expresses a cost or a benefit.

For a benefit criterion:

$$x' = \frac{x}{(x_{\max})} \tag{1}$$

and for a cost criterion:

$$x' = 1 - \frac{x}{x_{\max}} + \frac{x_{\min}}{x_{\max}} \tag{2}$$

In (1) and (2), the input score, x describes the performance at any given location on the map of criterion C_i (where i is the total number of criteria used in the assessment). In the case of household densities, x would be the density value at that location. The transformed score, x', then represents the standardized score for that location.

Table 1
Criteria, aggregation level, number of features, year, and source of data used for the study

Category	*Criteria (year)*	*Aggregation level*	*No. of features*	*Data source*
Land use	Land use (2009)	Individual plot	67, 198	City of Cape Town Corporate GIS Department
	Household density (2001)	Small Area Level	3, 451	2001 National Census
Socioeconomic	Proportion of vulnerable road users (2001)	Small Area Level	3, 451	2001 National Census
	Income* (2001)	Small Area Level	3, 451	2001 National Census
	Employment (2005)	Sub-Place Level†	318	Regional Services Council
Environmental	Proximity to heritage sites (2009)	Exact Extent	N/A‡	City of Cape Town Environmental Resource Management Department
	Proximity to wetlands (2009)	Exact Extent	N/A	City of Cape Town Environmental Resource Management Department
	Proximity to ecologically sensitive areas (2009)	Exact Extent	N/A	City of Cape Town Environmental Resource Management Department
Transport	Public transport demand (2007)	Travel Analysis Zone§	842	City of Cape Town Transport, Roads & Major Projects Department
	Private car demand (2007)	Travel Analysis Zone	842	City of Cape Town Transport, Roads & Major Projects Department
	Proximity to public transport stop (2009)	Exact Location	N/A	City of Cape Town Transport, Roads & Major Projects Department

*Education level data were used as a proxy for income data since education level data were available at a higher level of disaggregation, and the two data sets were found to have a positive correlation ($r = 0.491$, $p < 0.001$).
†In the 2001 National Census data, the Sub-Place is defined as the next spatial level up from the enumeration area in the place name hierarchy. In metropolitan Cape Town, Sub-Place boundaries roughly coincide with the planning suburb boundaries.
‡Because the exact extents of these features are available, the number of features does not affect the analysis.
§The travel analysis zones were generated by the city municipal authorities for traffic modeling purposes, and are less aggregated than the census Sub-Place level, but more aggregated than the census Small Area Level (which was designed to comprise no more than 500 households).

Table 2
SMCA performance table

Category	*Criteria*	*Car*	*Public transport*	*Pedestrian*	*Bicycle*	*Freight*
Land use	Land use	Varies	Varies	Varies	Varies	Varies
	Household density	−	+	+	+	−
	Employment	−	+	+	+	−
Socioeconomic	Proportion of vulnerable road users	−	+	+	+	−
	Income	+	−	−	−	+
Environmental	Proximity to heritage sites	−	+	+	+	−
	Proximity to wetlands	−	−	−	−	−
	Proximity to ecologically sensitive areas	−	−	−	−	−
Transportation	Public transport demand	−	+	+	+	−
	Private car demand	+	−	−	−	+
	Proximity to public transport stops	−	+	+	+	−

+ denotes a benefit criterion for the mode.
− denotes a cost criterion for the mode.

Table 3
Value statements, indicators, and standardizations for land uses

Land use	*Value*	*Indicator*	*Car*	*Public transport*	*Pedestrian*	*Bicycle*	*Freight*
Residential	Safety for NMT	Lowest speed	0.25	0.50	1.00	0.75	0.00
Commercial	Access for patrons	Highest volume	0.50	0.75	1.00	0.25	0.00
Industrial	Mobility for vehicles	Highest speed	0.75	0.25	0.50	0.00	1.00
Education	Safety for learners	Lowest speed	0.25	0.50	1.00	0.75	0.00
Sports and recreation	Access for spectators	Highest volume	0.25	0.50	1.00	0.75	0.00
Vacant land	Mobility for passersby	Highest speed	1.00	0.75	0.00	0.25	0.50
Medical	Access for patients	Highest volume	0.25	0.75	1.00	0.50	0.00
Office	Access for workers	Highest volume	0.50	0.75	1.00	0.25	0.00

Categorical variables, such as land use, require a slightly different standardization approach, because for every land use type the modal relationship varies. Land uses have different characteristics in the types and volumes 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. 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 performance table, these differences, and the costs or benefits of prioritizing a particular mode as a result of them, can be captured.

The costs and benefits assigned to any land use for any mode can vary according to the point of view taken in the analysis. For example, in an industrial area it is reasonable to expect high volumes of freight vehicles. In fact, the businesses in these areas depend upon the ease of access afforded to these vehicles. From this point of view, maximizing the mobility of freight vehicles (and, in fact, all motorized vehicles) is an important consideration. However, industrial areas, especially in South Africa, also have high volumes of pedestrian traffic in the form of workers walking to and from work. The conflicts between pedestrian road users and vehicles factor as a significant cost from this perspective.

The question centers around the values that are imposed on the evaluation. These values can be translated into impacts through value statements. Value statements identify a goal or objective and an indicator that ranks the performance of the mode of transport in relation to the goal. For example, a value such as safety can be translated into a performance rank by relating it to operating speeds. These ranks can then be scored and mapped, and finally be applied in the SMCA.

It is apparent that, for any land use, multiple value positions could be taken that would each yield different qualitative rankings. Furthermore, because the concerns around traffic vary between land uses, it is not sensible to assume one value position for all land uses. Instead, the qualitative ranking 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 chosen as being best suited to it. This yields an ordinal scale of benefits as seen in Table 3.

In Table 3, different value statements (to be read as: "*We want to maximize [value] by conferring the highest rank to the mode with the [indicator]*") are used to express value priorities varying between safety, access, and mobility. In this study, only two indicators, the speed of the mode and the volumes by mode, were used to distinguish between the alternatives in terms of the value statement, but others are, conceivably, possible as well. An ordinal scale was used for scoring the qualitative rankings used to interpret the value statement. The disadvantage of an ordinal scale is that the extent of preference is lost. Also, it is not possible to confer the same rank to different alternatives (in this case, modes of transport).

2.2 Spatial multi-criteria assessment

The performance of mode j under criterion i, a_{ij}, is given by the product of $x\prime$ and the weighting selected for criterion C_i, w_i, as in Equation (3).

$$a_{ij} = w_i \times x' \tag{3}$$

The nature of the MCDA method means that the introduction of weights will have an impact on the results produced. A range of weighting techniques can be used, but for this study, all of the criteria were equally weighted.

A sensitivity analysis was conducted to investigate the effects of weighting, and the results (not included in this article) indicate that weights do have a significant effect on the final scores. The selection of weights should, therefore, be carefully considered if they are to be applied.

The final suitability score for mode j at any location on the route is then given by

$$A_j = \sum_{i=1}^{n} a_{ij}; \quad i = 1, \ldots, n; \quad j = 1, \ldots, m \tag{4}$$

where A_j, thus, represents the composite weighted suitability of mode j to that particular location. Because the suitability of each mode of transport is evaluated separately, the COSMA method produces an m-dimensional vector describing the modal suitability characteristics of that location, where m is the number of modes considered in the assessment.

A SMCA involves conducting many (possibly tens of thousands) individual sub-analyses over a raster grid for each alternative (mode of transport). The output of the analysis is a new raster grid, where the value of each cell in the grid is given by the score, A_j, calculated in Equation (4). Because there are m alternatives, there are also m raster grids produced. In this study $m = 5$ (five modes of transport were included), and so five separate suitability rasters were produced.

Spatial data sets were compiled in the software ArcMap by ESRI Inc. (Redlands, CA, USA), which was also used to carry out the image processing and raster algebra required to conduct the analysis.

For each suitability map, neighborhood averaging was then used to aggregate the results in a 150 m radius from the route centerline. It was found that as the influence area is increased, the variation in context along the route decreases. A 150 m radius influence area (approximately one and a half blocks away from the road) was found to provide the best balance between detail and coverage. Because 10 m×10 m raster cells were used (this cell size was found to provide the best balance between data resolution and processing time), this equates to a circular area 30 cells wide. Each cell in the averaged raster is, therefore, assigned the average value of the cells with a 15 cell radius of it. The score of each cell in the averaged suitability raster is, therefore, given by

$$\overline{A_j} = \frac{d^2 \times \sum_{i \in P} A_j}{\pi r^2} \tag{5}$$

where $\overline{A_j}$ is the averaged suitability value for the cell, P is the set of all cells in the influence area, d is the cell length (10 m), and r is the influence area radius (150 m). The values for $\overline{A_j}$ along the road centerline of every case study route for each suitability map were then extracted and exported to a spreadsheet program for further analysis.

The methods described above are illustrated using the example of Voortrekker Road in Cape Town, South Africa, one of the roads that were case tested in the research. Figure 1 shows the extracted average suitability scores for this case study road, Voortrekker Road.

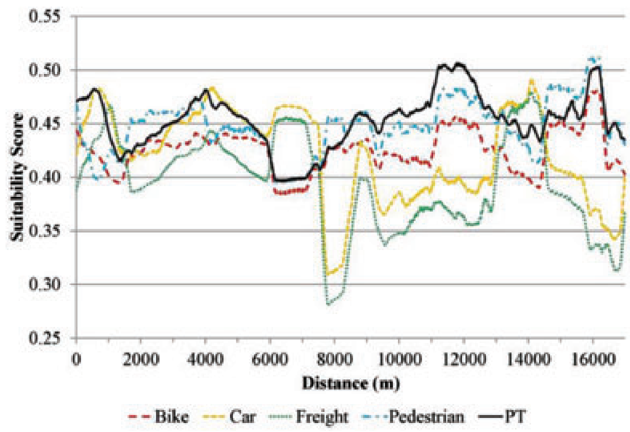

Fig. 1. Suitability scores along Voortrekker Road.

In Figure 1, the values of $\overline{A_j}$ along the centerline of Voortrekker Road for each mode of transport are plotted by distance. The chart represents the effects of contextual factors on modal suitability along the route, and it can be seen that there is significant variation along the route. Descriptive statistics of the SMCA results are provided in Table 4.

These statistics provide some interesting insights into the performance of the various modes of transport along the route. On average, public transport is the highest scoring mode along the route, followed by pedestrian. Freight is, on average, the lowest scoring mode. The car and freight modes have the largest amount of variation in their data sets; on average double that of the other modes. This is an indication of the highly location-specific suitability for these modes; they tend to only receive preference in areas where they are very highly suited, and everywhere else they score comparatively poorly.

Car and freight have heavily skewed score distributions, whereas bicycle and pedestrian are close to evenly distributed about their mean scores. Therefore,

Table 4
Descriptive statistics for Voortrekker Road suitability scores

	Bike	*Car*	*Freight*	*Pedestrian*	*Public transport*
N	1,699	1,699	1,699	1,699	1,699
Mean	0.425	0.421	0.394	0.447	0.453
Std. deviation	0.020	0.043	0.045	0.025	0.026
Skewness	0.032	−0.514	−0.291	−0.094	−0.180
Kurtosis	0.061	−0.499	−0.437	−0.070	−0.028
Minimum	0.384	0.309	0.281	0.395	0.396
Maximum	0.481	0.492	0.480	0.513	0.506
Range	0.097	0.183	0.199	0.117	0.110

the most frequently occurring scores for car and freight tend to be higher than the mean.

This indicates that there are only a small number of values having a negative influence on the mean, and that the mean itself may not be a reliable representation of the performance of these modes along the route. Referring back to Figure 1, the localized low scores around kilometer 8.0 and kilometer 16.5 explains the low mean scores for these modes. The range of scores for each mode is also revealing, with car and freight having a much larger range of scores than the other modes. The kurtosis and range values for these modes all highlight the high levels of variation in the suitability of these modes along the route.

2.3 Clustering contextual suitability data sets

The SMCA provides a means of quantifying the context and describing the implications thereof in terms of the relative suitabilities of the different modes of transport to various locations along the route. Although the analysis of these data can provide useful information for the road planner, additional insights can be gained by clustering similar sections into groups that can then be analyzed further and used as proxies for the actual scores. These proxy results can be thought of as modal suitability types, for which road design proposals can be developed that would be sensitive to the locational context.

Everitt (1994) notes that clustering is, typically, used to ascertain the underlying structure of a set of data to gain insight into data, generate hypotheses, detect anomalies, and identify salient features; to establish a natural classification by establishing the degree of similarity among forms in a data set; or to simplify data through compression where clustering is employed as a method for organizing the data and summarizing it through cluster prototypes.

Han and Kamber (2006) identify two main clustering techniques, partitional and hierarchical. A partitional clustering algorithm constructs partitions in the data, such that each cluster optimizes a pre-stated clustering criterion, such as the minimization of the sum of the squared distances from the mean within each cluster. The popular K-means algorithm is an example of a partitional algorithm, and was selected for use in this research primarily for its flexibility and its ability to manage large data sets.

Deciding on the correct number of clusters, that accurately reflects the structure of a data set, is a subject that has been the focus of a significant amount of study in the field of data mining (see Fraley, 1998; Kothari, 1999; Milligan and Cooper, 1985). The approach used in this research is an adaptation of the Silhouette Validation technique (Rousseeuw, 1987). This technique uses a measure of how close each point in one cluster is to points in the neighboring clusters to ascertain the coherence of the clusters produced for a given k clusters. These data are represented as a silhouette value, which is calculated using Equation (6).

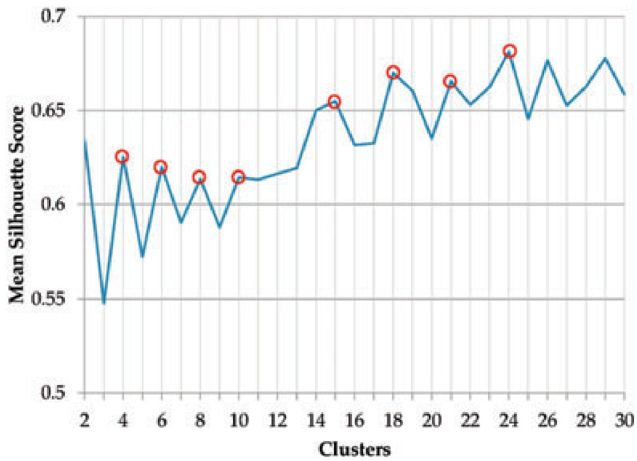

Fig. 2. Mean silhouette score versus number of clusters (first 30 clusters shown).

$$S_i = \frac{(b_i - a_i)}{\max(a_i, b_i)} \tag{6}$$

In Equation (6) we define a_i as being the average dissimilarity of a point i to all other points within the same cluster. Any measure of dissimilarity can be used but distance measures are the most common, and this is what was used in this research as well. The smaller the value of a_i, the better i is matched to its cluster. We can then find the average dissimilarity of i to the data of another single cluster, and repeat this for every cluster of which i is not a member. We can define the lowest average dissimilarity of i to any such cluster as b_i. This value defines the cluster that is the next best match for point i, other than the cluster that i is already a member of. The mean silhouette value for all the clusters is an indication of the overall strength of the clustering.

Equation (6) is only valid for $-1 \leq S_i \leq 1$, and when $a_i \ll b_i$, $S_i \rightarrow 1$, the clusters are badly matched, implying that they are quite distinct from each other, which suggests the value selected for k is appropriate. Using Equation (6), the average silhouette value for each cluster and average silhouette value for the total data set are calculated for each k between 1 and 100, and the silhouette means plotted against the number of clusters k (Figure 2). Peak mean silhouette values occur at 4, 6, 8, 10, 15, 18, and 21 clusters (highlighted with rings). Peak mean silhouette values for k values higher than this are ignored because cluster sizes become too small,

Table 5
Cluster centroid details for the Voortrekker Road case study

Cluster	*Bike*	*Car*	*Freight*	*Pedestrian*	*Public transport*
1	0.429	0.431	0.399	0.444	0.451
2	0.429	0.465	0.430	0.464	0.444
3	0.418	0.382	0.357	0.456	0.443
4	0.421	0.330	0.303	0.435	0.448
5	0.395	0.461	0.450	0.418	0.411
6	0.453	0.394	0.365	0.482	0.482

and the difference between clusters becomes immaterial. The choice of which of these to select was made by defining a threshold range for the distance between adjacent cluster centers (or the least acceptable difference between adjacent clusters). This range was defined in terms of the range of scores along the road, and was taken as being between 15% and 20%. Any k that had a peak mean silhouette value that was within this threshold range would have clusters that were a good representation of the natural pattern within the data set.

Using this methodology, a value for k is selected and cluster centroids calculated (see Table 5). The cluster means (the components of the cluster centroids) for each cluster within the data set describes the contextual characteristics of each section of the route in a much more compact form than can be achieved by simply analyzing the raw SMCA data. Plotting the cluster means along the route (Figure 3) allows for the identification of areas along the route with similar contexts. These areas should, in terms of the decision problem, receive similar road treatments along the arterial being assessed (see also Beukes et al., 2011b).

3 INFRASTRUCTURE AND CONTEXT

Using the cluster means in Table 5, it is possible to develop descriptive statements regarding the priority of each mode at each point along the route. The approach used the mode rank and the mode score range to identify priority. If one mode is ranked higher than another then, by definition, it should receive higher priority, because it is better suited to that location. Also, where one mode scores much higher than another, it should receive much higher priority than if it only scored slightly better than the other mode.

To effect such a comparison, a standardized scale is required against which cluster means can be ranked. Because cluster means are already scored on a scale between 1 and 0, a ratio scale between these values is naturally suited to compare the cluster means. However, because the range of scores is limited, it is necessary to rescale the cluster means to amplify their differences.

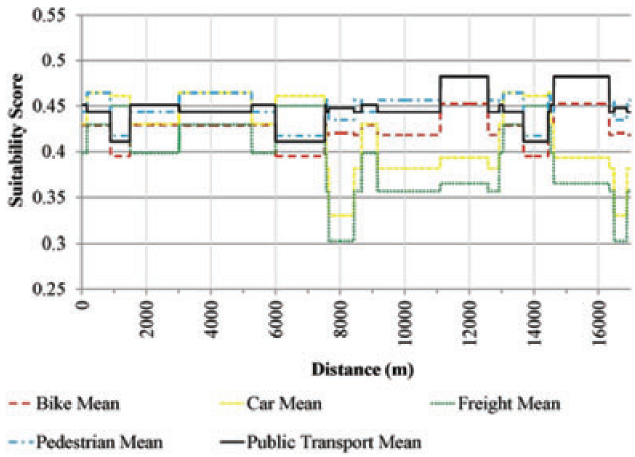

Fig. 3. Comparison of cluster means and cluster location on Voortrekker Road.

To this end, a route maximum and minimum score was defined as being the highest and lowest score obtained by any mode, in any cluster along the route. The cluster means were re-mapped, with the route maximum and minimum being rescaled to 1 and 0, respectively, using the transformation in Equation (7):

$$m'_j = \frac{m_j - \min(m_j)}{\max(m_j) - \min(m_j)} \quad (7)$$

In Equation (7) m_j is the cluster mean for mode j, m'_j is the rescaled cluster mean value for mode j, $\max(m_j)$ is the route maximum score for mode j, and $\min(m_j)$ is the route minimum score for mode j.

The approach adopted to describe the operational conditions for a mode in terms of its suitability ranking was to reinterpret mode suitability in terms of three parameters: access to the segment, right of way or ease of movement within the segment, and the level of independence afforded to the mode within the segment. This interpretation of mode priority develops a description of the level of operation for each mode, at all sections of the route.

In terms of the operational characteristics of a mode in a particular section of the route, the defining characteristic of that section is to what extent a particular mode is afforded access to it. In certain circumstances, it may be undesirable or unsafe for a mode to operate in an area at all or at specific times. Modes that, in terms of the analysis, are poorly suited to the context at a location should most probably be excluded from accessing that location. Conversely, modes that are well suited to the context at a location should be afforded unencumbered access. Infrastructure should be planned so as to facilitate and enforce these various levels of restriction.

Table 6
Mode suitability in terms of modal operations

Rescaled score	*Suitability*	*Access*	*Priority*	*Independence*
0.00–0.25	Unsuitable	Restricted—physically prevented from accessing the road	Not applicable	None provided
0.25–0.50	Low	Access allowed, but movements physically restricted	Lowest priority afforded	Shared infrastructure, with minimal dedicated mode specific features
0.50–0.75	Medium	Partial access levels provided	Priority given according to need and in subservience to highest scoring mode	All needs catered for, mixture of shared and dedicated infrastructure
0.75–1.00	Highest	Highest access allowed	Priority of movement given in all circumstances	Dedicated infrastructure wherever practical, minimal interaction with other modes

Table 7
Mode priorities and ranks for the Voortrekker Road case study

Cluster	*Bike*	*Car*	*Freight*	*Pedestrian*	*Public transport*
1	Medium (4)	Medium (3)	Medium (5)	Highest (2)	Highest (1)
2	Medium (5)	Highest (1)	Medium (4)	Highest (2)	Highest (3)
3	Medium (3)	Low (4)	Low (5)	Highest (1)	Highest (2)
4	Medium (3)	Unsuitable (4)	Unsuitable (5)	Medium (2)	Highest (1)
5	Medium (5)	Highest (1)	Highest (2)	Medium (3)	Medium (4)
6	Highest (3)	Medium (4)	Low (5)	Highest (1)	Highest (1)

Another defining characteristic of a route is the right of way, or priority of movement, allowed for the mode. Right of way is an aspect of traffic control that can have dramatic implications for the operations of a section of road. The determination of the right of way is important at conflict points along the route, because practice generally dictates that modes should be kept separate from each other. As such, at these conflict points, time needs to be allocated for each mode to use the space, in as efficient a manner as possible. If, in terms of the contextual analysis, a mode is better suited to a location, this implies that it should be given priority of movement, or the right of way in that location, wherever possible. This dictate should, naturally, be tempered by safety considerations.

One of the guiding principles of multimodal road planning is that, as far as possible, it is best to keep modes separate from each other. To achieve this, separate infrastructure must be provided for all modes operating in the corridor. Although this is ideal, given constraints of space and cost, it is not always possible in practice, and may not always be desirable, given the operational aspects of that section of the route. Allowing a mode to operate independently from the others in the corridor affords that mode significant benefits that cannot be realized if the mode shares space. Space allocation which, in essence, translates to independence of operations is, therefore, the third way in which to afford one mode priority over another.

Table 6 summarizes the approach to relating the cluster means to mode operations and infrastructure requirements. Applying the information in Table 6 to the Voortrekker Road case study SMCA results yields the set of priorities shown in Table 7, where the mode priority is given in each cluster and the mode rank in parentheses beside it.

4 INTERPRETING MODAL SUITABILITY

Defining modal suitability in terms of operational parameters provides the planner with some guidance as to what combination of infrastructural interventions or components would be appropriate in that particular context, while still allowing for innovation and flexibility in planning choices. This is important for two reasons, contexts are spatially and temporally fluid, and design circumstances may vary from place to place, even in areas with similar contexts. There are, thus, many possible design solutions for any given context that could

Fig. 4. Voortrekker Road in a cluster 1 area.
Source: Image sourced from Google Maps, accessed 15/04/2011.

Fig. 5. Damrakstraat, Amsterdam.
Source: Image sourced from Google Earth, accessed 15/04/2011.

function equally well, and only a careful analysis of each option, preceded by a thorough investigation into the reasons for the cluster mean values in any area, would produce contextually appropriate infrastructure.

The adjusted cluster mean values for the Voortrekker Road data set, redistributed into the four categories described earlier in Table 3, are used to demonstrate the application of the method (see Table 7).

Considering cluster number 1, all the modes are relatively well suited, but the pedestrian and PT modes are the best suited to the context. Accordingly, in terms of the operational descriptions in Table 3, these modes should receive unrestrained access to the area, priority of movement over the other modes, and should have infrastructure dedicated for their exclusive use.

This has a number of immediate important implications. First, the pedestrian mode should receive full access to the area, implying that pedestrians should be expected to cross the road anywhere in the area. This would necessitate very low vehicle speeds. Second, there should also be dedicated PT infrastructure, which implies the provision of a dedicated lane for buses and taxis.

The other modes, car, bicycle, and freight, all fall within the medium access range. This implies that these modes should be allowed access to the area, but with some restrictions on their operations. It may be appropriate to limit freight access to delivery vehicles only, and to not allow parking for private cars. Cyclists may be required to stay within a designated cycling lane, or may be required to dismount during certain times of day.

Figure 4 shows a typical street scene along Voortrekker Road in a cluster 1 area. The area is characterized by mixed land uses, including small retail stores, offices, and apartments along the road, and residential suburbs further away from the road. The road itself consists of two undivided lanes with on-street parallel parking and sidewalks on either side of the road.

To more closely comply with the requirements of Table 3, this section of the route might be reconfigured to more closely resemble the example in Figure 5. The allocation of space in Figure 5, as well as the priority and independence of movement, quite closely matches what is suggested by the description of an ideal cluster 1 area. There is dedicated infrastructure for PT, and a large amount of space is given over to the pedestrian, who is free to cross wherever required. Private Motorized Transport (PMT) movement is restricted to one lane, which, in this instance is one way only, and parking is not provided. Cyclists and cars share the same road surface, with bicycles not being allowed to cycle on the pedestrian only areas.

An immediate problem with this solution is that this section of Voortrekker Road is much narrower than the example shown in Figure 5. Compromises will, therefore, have to be made, but these should be made in deference to the mode ranking and road safety concerns.

For example, it may not be possible to provide a dedicated bicycle lane. However, because vehicle speeds are likely to be low, and bicycles and motorized modes have almost identical suitability scores, they could be made to share a lane. This demonstrates the need for flexibility in the approach since, often, compromise solutions will call for design innovation. Figure 6 shows the existing cross-section for this section of the route, and two proposals for context sensitive cross-sections, given the cluster mean scores for each mode, and the discussion above.

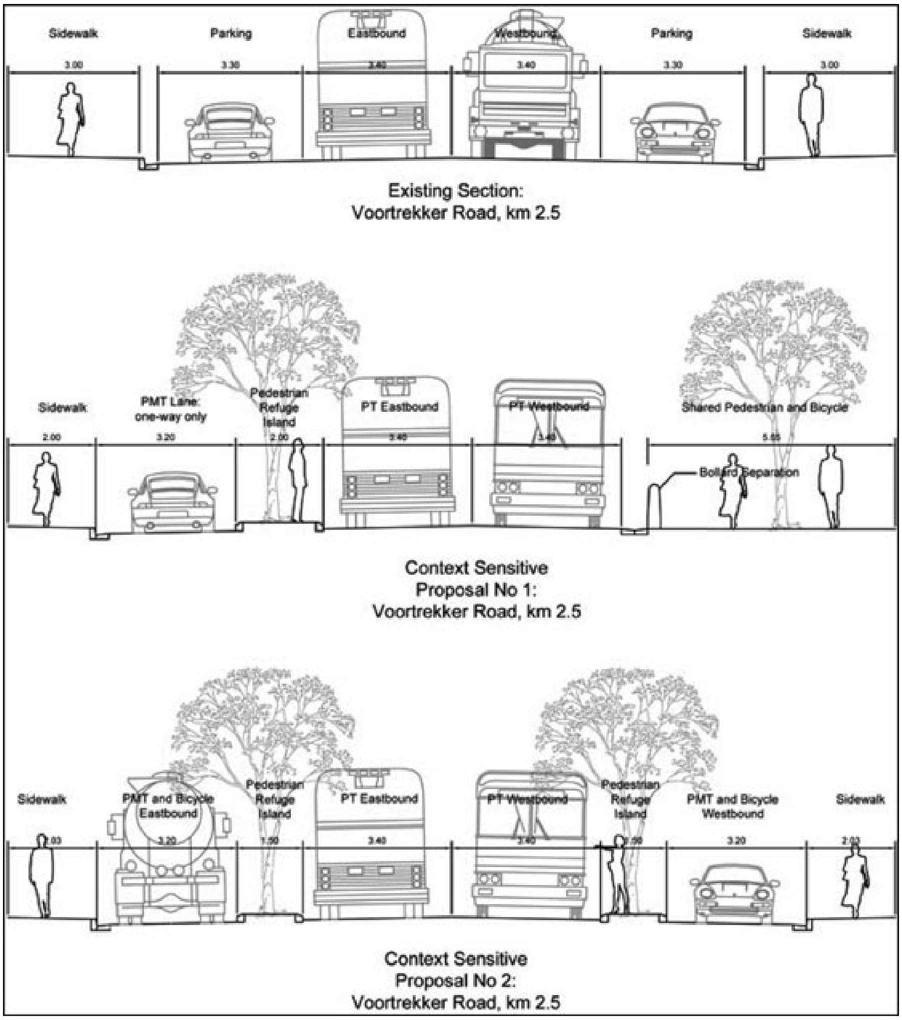

Fig. 6. Existing layout and proposal for context sensitive upgrade in a cluster 1 area on Voortrekker Road.

The two proposals highlight the roadspace allocation compromises that are required as a result of the road reserve constraints. In the existing section, approximately 70% of the roadspace is allocated to motorized modes (including PT). In both of the proposals presented, parking has been eliminated, and in Proposal 1, only one direction of flow has been allocated to PMT modes. This frees up significant amounts of space for the other modes, but could be argued to be impractical, and not truly representative of the suitability scores, because the Car mode does score comparatively well overall. Nonetheless, the space allocation has been changed to: 34% to PT, 16% to PMT, and 46% to NMT. The remainder is made up by drainage and street furniture.

In Proposal 2, both directions of flow have been accommodated for all modes. To accommodate the extra vehicular lane, some of the space for NMT had to be reassigned. However, the remaining NMT space is also now more fragmented, because refuge islands must be provided between PT and PMT lanes to assist with the unregulated crossing required by the context. The narrow PMT lanes can also be interspersed with raised humps to keep speeds down.

Another interesting example is that of cluster 4 (see Figure 7), which is found only in two, relatively short, stretches of the route. The cluster means suggest that PMT modes should be restricted from accessing these areas, which should only allow for PT and NMT modes. Of these modes PT is the preferred mode, with the NMT modes categorized as being of medium suitability. The implication is that provision should be made for dedicated PT facilities, possibly aligned along the median and shared pedestrian and bicycle facilities. Cluster 4 occurs along the section of Voortrekker Road between kilometer 16.5 and kilometer 17.0 (as can be seen in Figure 3). This area has already been subject to

Fig. 7. Voortrekker Road in a cluster 4 area.
Source: Image sourced from Google Maps, accessed 15/04/2011.

Fig. 8. Industrial area along Voortrekker Road designated as cluster 5.
Source: Image sourced from Google Maps, accessed 15/04/2011.

significant infrastructure improvements to improve its pedestrian friendliness, with frequent pedestrian crossings and pedestrian friendly street furniture and lighting having been installed in the past. This shows that there is already an awareness of the special context in the area, although this analysis indicates that the interventions did not go far enough to address the problems.

Cluster 5 is unique in that it is the only cluster of the six generated for Voortrekker Road that has the PMT modes as being the most suitable to the context. Both PMT modes are highly suited to the context, whereas the remaining modes fall in the medium suitability category (with the bicycle mode being on the boundary of medium and poorly suited). In terms of the definitions outlined in Table 6, this means that the PMT modes must be afforded full access and priority of movement, and should have dedicated infrastructure. The remaining modes should receive partial access, with their movements or operations somewhat restricted, and can be made to share infrastructure. Cluster 5 is found in three locations along the route. These are typically areas with either primarily industrial activities that attract lots of freight and delivery vehicles (Figure 8), or large undeveloped areas with very little activity of any kind (Figure 9).

The infrastructure in these areas could be said to already be quite appropriate given the context. The PMT modes are well catered for, there being two lanes in each direction, separated by a median.

The addition of on-street parking could improve conditions in the industrial area, with space for parking taken from the very large sidewalks along the route. Dedicated turning lanes at intersections are not necessary, because there are already two lanes in each direction (although this would also depend upon turning movement volumes). PT stops should be provided here as well, given that it scores as medium suitability. However, this should be provided in embayments only, so as not to interfere with the operations of the PMT modes. Bulbouts could be provided at intersections to improve pedestrian crossing level of service. Cycling facilities could be shared with pedestrian facilities beyond the on-street parking.

Fig. 9. Undeveloped area along Voortrekker Road designated as cluster 5. To the left is a large cemetery, and to the right is an undeveloped strip of marshland.
Source: Image sourced from Google Maps, accessed 15/04/2011.

5 DISCUSSION

The basis of the COSMA method is that there are a range of factors that can be used to describe the characteristics of the local road users, and the activities they are involved in along it. This information should play a more direct role in the design of these roads. The factors, collectively termed the context, have tended to be overshadowed by concerns around efficiency and cost, and there has not been a comprehensive framework within which the context could be evaluated, and its implications investigated. The way in which infrastructure interfaced with, or suited the context has, thus, always been left to the discretion or judgment of the engineer or planner of the facility.

The research identified which factors could be used to describe the context of a location, and demonstrated that it is possible to quantify the context in terms of its effects on the suitability of the various modes of transport. Quantification has a number of advantages for planning and designing infrastructure. Being able to quantify the suitability of a mode of transport to a particular location, given the context, allows for the prioritization of modes in terms of infrastructure provision, which can then be used as the basis for planning and design. Case study applications in Cape Town have demonstrated the possibilities of the method. However, further testing in other locations will verify the robustness of the method.

Quantification also has the benefit of facilitating accurate comparisons between different locations along the route. This is useful for planning and design, in that the subtleties in the variation of the context along the route are retained during the analysis, allowing for a fine grained tailoring of the required infrastructure. It is also possible to show that context varies spatially, that it is not static, and that for infrastructure to be contextually sensitive it must, therefore, vary accordingly.

The COSMA method employs a novel application of the principles of multi-criteria assessment to conduct the evaluation. Whereas SMCA had previously been used to compare the suitability of a number of sites for a development, or to identify routing alternatives in an analysis space, the application developed here assesses suitability of a number of alternatives in a constrained space. Uniquely, no alternative is necessarily taken as being the one correct solution. Instead, it may only be the highest scoring at that specific location. None of the other alternatives are abandoned if they do not rank highest.

Instead, their relative suitability is used to determine their priority in terms of the operational aspects of the road being planned.

The context, being an amalgam of a range of disparate factors, does not have any intrinsic meaning by itself. Instead, it is the implications of the context that has meaning and, therefore, context can only be understood in terms of its implications for other aspects of the facility. In this research, context is defined in terms of its implications for the suitability of the various modes of transport. The translation of contextual suitability into infrastructure recommendations, therefore, relied on defining the operations of the modes of transport on the road.

The COSMA method develops a quantified definition of the context, demonstrates its importance, explores its characteristics and implications, and translates these into descriptives that can be used to inform infrastructure provision. The method is also intrinsically multimodal in nature. Because all modes receive equal treatment, the method is able to highlight any existing disparities in the provision of infrastructure for the various modes (see Beukes and Zuidgeest, 2010).

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