A DECISION SUPPORT TOOL FOR THE FUZZY MULTICRITERIA ENVIRONMENTAL SENSITIVITY EVALUATION OF URBAN ROAD NETWORKS

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abstract: Road traffic is a major source to degradation of safety, amenity and environment in urban areas. The measurement and assessment of such degradation is difficult and complex. A decision support tool has been developed to evaluate the fuzzy multicriteria environmental sensitivity of urban road networks. It involves an integration of a fuzzy multiattribute decision making (FMADM) approach and knowledge-based expert systems (KBES) technology. This paper discusses the theoretical foundations of the tool and the application to the Australian case study area. The results indicate the potential use of this tool to assess the composite environmental impacts of road traffic at the local level, identify problem locations, and specify the possible causes of those problems.

1. INTRODUCTION

Road traffic is a major source of degradation in urban areas in terms of safety, the environment and amenity. This degradation includes air pollution, difficulty of access, noise and vibration, pedestrian crossing delays, pedestrian safety, severance, visual intrusion, fear and intimidation (Singleton and Twiney, 1985; May, 1988). The estimation and assessment of such degradation is difficult. Although some impacts can possibly be quantified (eg air pollution and noise level), others can only be qualitatively measured (eg difficulty of access and visual intrusion). In addition, both qualitative and quantitative environmental impacts vary, ranging from direct health hazards to annoyance effects. The impact assessment is therefore complicated. A decision support tool has been developed to evaluate the fuzzy multicriteria environmental sensitivity of urban road networks. It is an integration of a fuzzy multiattribute decision making (FMADM) approach and knowledge-based expert system (KBES) technology based on the environmental sensitivity methodology (ESM) concept introduced by Singleton and Twiney (1985).

This paper is organised to present the following elements: (i) brief literature reviews of the environmental sensitivity methodology (ESM) and other traffic environmental impact evaluation methods; (ii) the theoretical foundations and all key components of this decision support tool; (iii) the application of the tool to the City of Unley road network in Adelaide, Australia; (iv) the possible limitations of the tool; and lastly (v) conclusions and future research directions.

2. METHODS FOR EVALUATING TRAFFIC ENVIRONMENTAL IMPACTS

Several methods have been developed to evaluate the safety, amenity and environmental consequences of road traffic in an urban road network. In Australia, Amenity Sensitivity (AS) (Loder and Bayly, 1980) was developed to specify the environmental and amenity impacts of road traffic on its adjacent environment. The method assigns a subjective score ranging from 1 (less sensitive) to 5 (highly sensitive) for each of the selected criteria and then sums the scores up to obtain a 'Composite Sensitivity Index' for a specific road section. This index is mainly relied on the experiences and judgement of traffic engineers or urban planners and may not lead to the comprehension of the actual interaction of road traffic and adjacent environment (Singleton and Twiney, 1985).

A more rigorous method introduced by Buchanan (1963) was Environmental Capacity (EC). Holdsworth and Singleton (1979) defined EC of a road as *"the maximum number of vehicles that should be permitted to pass along that road during a certain period of time and under fixed physical conditions without causing environmental detriment"*. Initially, the environmental standard for a given criterion is specified and then the numerical equation available for the criterion will be solved to yield the maximum traffic flow complying with the specified standard. Holdsworth and Singleton (1979) applied the EC in terms of noise pollution and pedestrian crossing delay to traffic management planning. Recently, Song *et al* (1993) expanded the Holdsworth-Singleton EC concept by including a pedestrian accident risk criterion. They also proposed the use of the geometric mean method to calculate the combined EC of various ECs estimated for different criteria.

In practice, EC suffers from several limitations including: (i) the EC value can only be estimated for quantifiable criteria from a numerical equation; (ii) the inappropriate use of a single environmental standard as a specific criterion for all road sections regardless of road hierarchy classes and land use types; (iii) derived EC values are sometimes inappropriate or misleading; (iv) the use of only the minimum EC estimated for any single criterion among all others is unrealistic; (v) considerable time, effort and resources are needed for EC data collection and numerical computation (Holdsworth and Singleton, 1980; Gilbert, 1988; Chadwick, 1990).

3. ENVIRONMENTAL SENSITIVITY METHODOLOGY (ESM)

Singleton and Twiney (1985) proposed the Environmental Sensitivity Method (ESM) as a means to evaluate the Environmental Sensitivity (ES) of road sections caused by road traffic. The ESM assumed that the physical and land use characteristics of a particular road section can be utilised to determine the ES of that road due to road traffic. The methodology falls between the simple and judgmental nature of the AS concept and the robust and objective nature of the EC approach. The ESM concept can be used to overcome some of EC's limitations. For example, ESM can handle both qualitative and quantitative criteria, take the effects of different land use types into consideration, tackle the high degree of numerical accuracy of estimated EC values, and reduce time, effort and resources required in EC estimation. The methodology is shown in Figure 1 and described below.

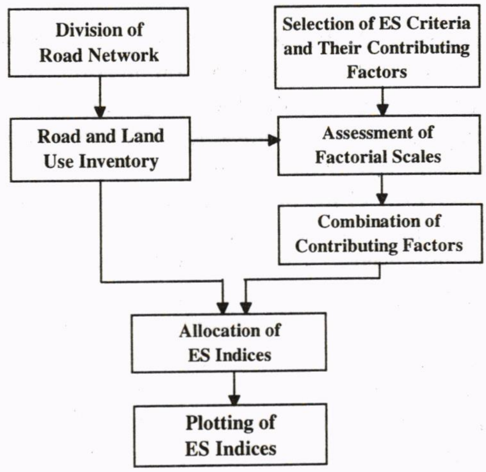

Figure 1: Environmental Sensitivity Method
Source: (Adapted from Singleton and Twiney (1985), p. 179)

The Singleton-Twiney method was adapted as follows. A number of appropriate environmental criteria were selected and key factors contributing to each criterion were identified. Experiences with the EC concept were used to choose appropriate criteria, identify major contributing factors and establish the scales of measurement for various factors for each criterion. Table 1 shows the different measuring scales of several factors contributing to the noise level criterion. The road network in the study area was divided into a number of homogenous links according to the uniformity of physical characteristics; homogeneity of abutting land uses; spacing and complexity of road junctions, and derived link lengths. Then the road physical and land use data relevant to the contributing factors for each criterion of both sides of each link were collected.

Table 1: The Measuring Scales of Contributing Factors for Noise Level

Contributing Factors	Measuring Scales	Descriptions
Opposite facade	Yes	Existence of opposite facade generally assumed
	No	If park or open space opposite etc.
Road gradient	Low	Slight or flat (road gradient less than 5 %)
	High	Medium or steep (road gradient equal to or greater than 5%)
Building setback	Small	Building setback less than 2 m.
	Medium	Building setback equal to or greater than 2 m and less than 6 m.
	Large	Building setback equal to or greater than 6 m.
Land use type	1	Residential/School/Hospital
	2	Retail/Commercial/Office/Park
	3	Industrial (light or heavy)/Railway

Source: (Adapted from Singleton and Twiney (1985), pp. 174)

The measured value of each contributing factor for each criterion will then be compared with the corresponding measuring scales (see Table 1) and a score of each factor assigned accordingly. For each criterion, all derived scores of each factor were used to determine the ES index by using an established system for combination. As an illustration, Table 2 presents the decision table containing the knowledge extracted from the combination system for all contributing factors for the noise level criterion presented in Singleton and Twiney (1985). All decision rules given in Table 2 were encoded and stored in the noise level knowledge-based (KB) file of the prototype KBES, which is discussed later. Finally, the ES indices of different links for each criterion were then plotted separately. It should be noted that ESM is mainly used to assess the likely environmental sensitivity of urban road network to traffic effects, but not directly evaluate the actual environmental impacts of the road network. It can be used as a preliminary indicator of environmental impact assessment or screening approach for more detailed study to be undertaken. ESM has been widely used as an important input for various road hierarchy classification studies and an indication of environmental conflict locations and their possible causes in Australia (Ove Arup Transportation Planning, 1983 and 1989; Singleton and Twiney, 1985).

Table 2: Decision Table for Combining the Factorial Scores of Noise Level

Rule Number	Opposite Facade	Land Use Type	Road Gradient	Building Setback	Sensitivity Rates
1	-	1	Low	Large	Medium
2	-	1	-	-	High
3	Yes	2	High	Medium	High
4	No	2	Low	Large	Low
5	-	2	-	Small	High
6	-	2	-	-	Medium
7	Yes	3	-	Small	Medium
8	-	3	-	-	Low

Remark: '-' sign means that the factorial scores in that cell can be any defined ones, except the one which will produce the identical rule previously established.

The obtained ES indices of all links for each criterion can be used to indicate the locations of links that need special attention or remedial treatments for each particular criterion. In practice, it is essential to combine the separate ES indices estimated for different criteria of a given link in order to assess and compare the combined ES indices of all different links in a road network. Such combined indices can be utilised to uncover the ranking order among different road links according to the degree of the combined ES of each link. The resultant ranking order is of particular importance in prioritising the special investigation on different links in a road network. The multiattribute decision making (MADM) approach can be used to combine both tangible and intangible criteria and to recognise differences in the relative importance of these criteria. However, the final ES indices for each criterion derived from the ESM concept is indicated as low, medium or high. This information clearly contains imprecise, ambiguous and uncertain meanings. Fuzzy set theory is primarily suitable to deal with these difficulties. Therefore, a fuzzy multiattribute decision making (FMADM) approach is used to handle the decision problem.

4. A FUZZY MULTIATTRIBUTE DECISION MAKING APPROACH

After completing the systematic and critical reviews of various FMADM approaches, Chen and Hwang (1992) introduced a new FMADM approach to overcome several difficulties experienced in several earlier FMADM methods. Some of these difficulties were: the requirements of unnecessarily considerable numerical computations; the needs of all elements of decision evaluation matrix to be presented in a fuzzy format; the impracticality of some assumptions used; and so on. Chen and Hwang assumed that the MADM problem may consist of both fuzzy and crisp (clearly defined boundary) information and the fuzzy information can be presented as linguistic terms or as fuzzy numbers. The two fundamental phases of the new FMADM approach are: (i) transformation of fuzzy information into crisp scores; and (ii) application of traditional MADM methods to estimate the ranking order of alternatives. Chen and Hwang also pointed out that the new approach is relatively easy to apply and understand.

In this paper, a new FMADM approach proposed by Chen and Hwang (1992) is adopted. Initially, the fuzzy set theory is applied to transform each linguistic term of each separate ES index (in terms of low, medium or high) for each environmental criterion to the appropriate fuzzy number. Then, Chen and Hwang's fuzzy scoring method is used to convert those fuzzy numbers to the corresponding crisp (numerical) scores. A simple additive weighting (SAW) method is employed as traditional MADM method to determine the composite ES indices for each link in the concerned road network. The analytic hierarchy process (AHP) is also used to estimate the relative weights of all decision criteria for each land use type. This FMADM procedures is shown in Figure 2 and discussed in detailed later.

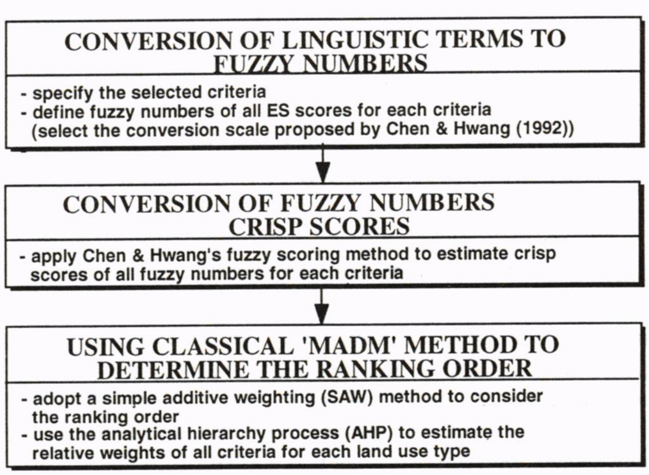

Figure 2: The Fuzzy Multiattribute Decision-Making Procedures

4.1 Fuzzy Set Theory

Zadeh (1965) introduced the fuzzy set concept as a collection of elements and its degree of belonging, called grade of membership. This can be done by adopting the concept of a membership function to assign a number ranging from zero (absolutely not belonging) to unit (fully belonging) according to the degree (grade) of belonging to each element of a universe of discourse. Suppose that $X = \{x\}$ is a universe of discourse. Then a fuzzy set (subset) A in X is defined as a set of ordered pairs $\{(x, \mu_A(x))\}$, where $x \in X$ and $\mu_A : X \rightarrow [0, 1]$ is the membership function of A; $\mu_A(x) \in [0, 1]$ is the grade of membership of x in A. It should be noted that if a real number in the interval [0, 1] is replaced by a discrete integer number {0, 1}, this definition will be exactly the same as the characteristic function of a traditional set theory. Therefore, the fuzzy set theory is considered to be an extension of the traditional set theory (Fedrizzi and Kacprzyk, 1995). The fuzzy subset A of X is expressed in equation (1) and (2) for a finite and an infinite universe of discourse, respectively.

$$A = \sum_{i=1}^{n} \mu_A(x_i) / x_i \tag{1}$$

$$A = \int_X \mu_A(x) / x \tag{2}$$

where $\mu_A(x)/x$, called a singleton, is a pair of grade of membership and element of a fuzzy set A and 'Σ' and '$\int$' signs mean a union operation in the ordinary set theory. In this study, the trapezoidal fuzzy number (M_{tpz}), as shown in Figure 3, is adopted, because it has been widely used and the cumbersome numerical computations are decreased dramatically (Zimmermann, 1991). It should also be noted that the triangular fuzzy number could be determined as a special case of the trapezoidal fuzzy number.

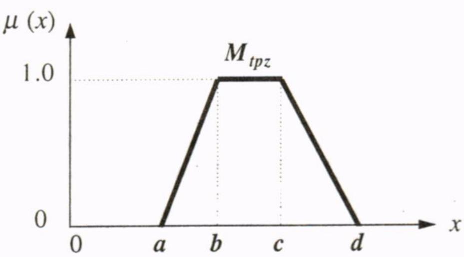

Figure 3: A Trapezoidal Fuzzy Number

4.2 Transforming Linguistic Terms to Fuzzy Numbers

Chen and Hwang (1992) suggested a numerical approximation system to systematically transform linguistic terms (eg low, medium or high) to their corresponding fuzzy numbers. A fuzzy number is defined as a convex and normalised fuzzy set of the real line (**R**) whose membership function is piecewise continuous (Zimmermann, 1991). The system contains eight transforming scales. One of these scales as shown in Figure 4 is well matched to all linguistic terms used in this study and therefore adopted. It should be noted that these transforming scales were derived from the synthesis and modification of the several research works previously conducted (Chen and Hwang, 1992). Consequently, the transforming scale used in this study is considered to be the knowledge contained in the knowledge base component of the prototype KBES. Chen and Hwang claimed that this scaling system is capable of transforming linguistic terms into fuzzy numbers in a systematic, intuitive and consistent manner.

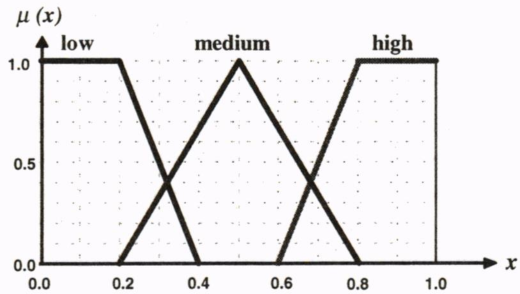

Figure 4: A Transforming Scale for Three Linguistic Terms (low, medium and high)
Source: (Chen and Hwang (1992), p. 467)

4.3 Chen & Hwang's Fuzzy Scoring Method

Chen and Hwang (1992) also proposed a fuzzy scoring method to convert fuzzy numbers to corresponding crisp (numerical) scores and defined a fuzzy *max* and a fuzzy *min* as:

$$\mu_{\max}(x) = \begin{cases} x, & 0 \le x \le 1, \\ 0, & otherwise, \end{cases} \tag{3}$$

$$\mu_{\min}(x) = \begin{cases} 1-x, & 0 \le x \le 1, \\ 0, & otherwise, \end{cases} \tag{4}$$

The left and right utility scores of each fuzzy number M_i are defined as:

$$\mu_L(i) = \sup_x \, [\mu_{\min}(x) \wedge \mu_{M_i}(x)], \tag{5}$$

$$\mu_R(i) = \sup_x \, [\mu_{\max}(x) \wedge \mu_{M_i}(x)] \tag{6}$$

In equation 5, the left utility score ($\mu_L(i)$) can be interpreted as the maximum membership value of the intersection of fuzzy number M_i and the fuzzy *min*. Similarly, the right utility score ($\mu_R(i)$) is a maximum membership value of the intersection of fuzzy number M_i and the fuzzy *max*. These definitions are illustrated in Figure 5 below.

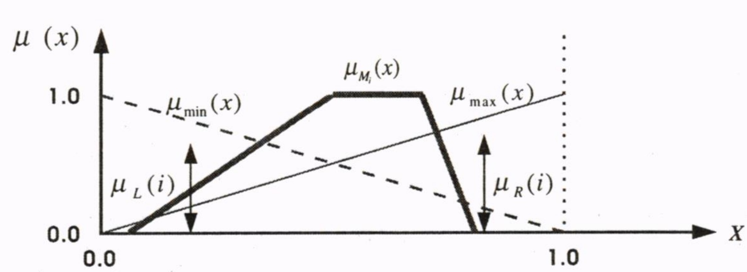

Figure 5: Chen and Hwang's Fuzzy Scoring Method

Given the left and right utility scores, the total utility score of a fuzzy number M_i is defined as:

$$\mu_T(i) = [\mu_R(i) + 1 - \mu_L(i)]/2 \tag{7}$$

Given three fuzzy numbers: M_{low}, M_{medium} and M_{high} as shown in Figure 4, the crisp scores and their normalised values (divided by the maximum estimated crisp score) for each of these fuzzy numbers are presented in Table 3. The normalised total utility scores ($\mu_{NORM(T)}(i)$) are used in this study. The total utility score is used to rank different fuzzy numbers. In general, the higher the total utility score, the better the ranking order. However, a 'high' ES score of any road link means that such link will experience greater detrimental environmental impacts with respect to a specific criterion than a link having 'low' score. Therefore, the links having greater normalised total utility scores present the higher degree of environmental adverse effects.

Table 3: Crisp Scores of Low, Medium and High Fuzzy Numbers

i	low	medium	high
$\mu_L(i)$	1.000	0.615	0.333
$\mu_R(i)$	0.333	0.615	1.000
$\mu_T(i)$	0.167	0.500	0.833
$\mu_{NORM(T)}(i)$	0.200	0.600	1.000

4.4 Simple Additive Weighting Method

Several techniques were established to handle MADM problems. These techniques include simple additive weight (SAW), concordance analysis, ideal point analysis and others (Hwang and Yoon, 1981). The most popular, widely used and simplest one is SAW. The use of the SAW method is justified because of: (i) it is easily and clearly understandable for non-specialists; (ii) it is easy to calibrate; and (iii) it is capable of producing the empirical results which frequently well matched to a range of real multicriteria problems (Bonsall *et al*, 1992). The SAW method is therefore used to combine all separate ES indices for different environmental criteria to derive the Composite Environmental Sensitivity Index (CESI) for each link of the road network as shown in equation 8.

$$CESI_i = \sum_{j=1}^{n} w_{jk} r_{ijk} \tag{8}$$

$$\sum_{j=1}^{n} w_{jk} = 1, \quad w_{jk} > 0$$

where: $CESI_i$ is the Composite Environmental Sensitivity Index of link i (i = 1, 2, ..., m); w_{jk} is the relative weight for criterion j in land use k, (j = 1, 2, ..., n and k = 1, 2, ..., l); and r_{ijk} is the ES index of link i for criterion j in land use k. The Analytic Hierarchy Process (AHP) described below is utilised to estimate the relative weights (w_{jk}) for all criteria in different land use types and the Chen and Hwang's fuzzy scoring method mentioned previously is used to determine the numerical values of each ES index for all criteria. It should be noted that the same ES scoring system was applied for all criteria in the ESM. Therefore, the identical fuzzy numbers (as shown in Figure 4) for each ES index are used for all criteria accordingly.

5. ANALYTIC HIERARCHY PROCESS

Several mathematical techniques such as the trade-off method, rating method, ranking method and pairwise comparisons (Nijkamp *et al*, 1990) were developed to compute the relative weights among various decision elements. Pairwise comparison, known as the Analytic Hierarchy Process (AHP) has gradually become more popular than the other methods because of its simplicity, its theoretical robustness, its ability to handle both intangible and tangible criteria and its capability to directly determine the judgment consistency (Saaty, 1980; Vargas, 1990). Therefore, AHP was used to estimate the relative weights of different criteria for each land use type.

AHP mainly comprises a three-step process: (i) identifying and organising the decision elements into a hierarchical structure; (ii) estimating the relative importance of each decision element at each hierarchy level and determining the consistency of judgment; and (iii) synthesising the results of the pairwise comparisons over all the levels. In this paper, the AHP procedures, as shown in Figure 6, are slightly different from the typical AHP steps (Saaty, 1980) and briefly discussed below.

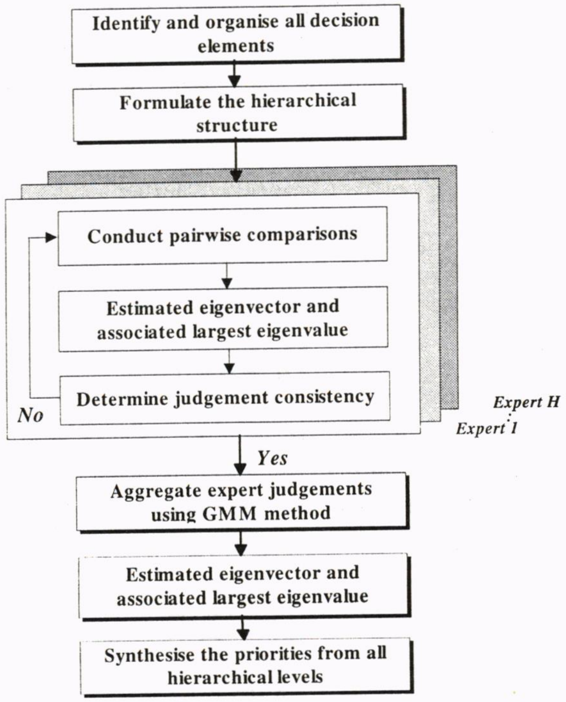

Figure 6: The AHP Flowchart Diagram

All important decision elements (environmental criteria) of the problem are identified and the relationship among them is formed as the hierarchical structure. Then, six experts (including one local government officer, two urban planners, two traffic engineers, and one university professor) were asked to conduct pairwise comparisons of these decision elements at the same hierarchical level corresponding to the scale of relative importance ranging from 1 to 9 as shown in Table 4.

Table 4: Scales of Relative Importance

Intensity of Importance	Definition
1	Equal importance
3	Weak importance of one over the other
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements

Source: (Adapted from Saaty (1994), pp. 26)

For each expert, the derived pairwise comparisons of relative importance, $a_{ij} = w_i/w_j$, for all decision elements and their reciprocals, $a_{ji} = 1/a_{ij}$, are inserted into a reciprocal square matrix $\boldsymbol{A} = \{a_{ij}\}$ as shown in equation 9. The analytical solution of equation 10 then provides the relative weights for each decision element. According to the eigenvalue method (Saaty (1980)), the normalised right eigenvector $(\boldsymbol{W} = \{w_1, w_2, \ldots, w_n\}^T)$ associated with the largest eigenvalue (λ_{max}) of the square matrix $\boldsymbol{A}$ provides the weighting values for all elements.

$$\boldsymbol{A} = \begin{bmatrix} 1 & w_1/w_2 & \ldots & w_1/w_n \\ w_2/w_1 & 1 & \ldots & w_2/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & \ldots & 1 \end{bmatrix} \tag{9}$$

$$\boldsymbol{AW} = \lambda_{max}\boldsymbol{W} \tag{10}$$

For the ease of numerical computations, one of Saaty's approximation methods (Saaty, 1980), namely 'Normalisation of the Geometric Mean (NGM)' of the rows was used to estimate the normalised right eigenvector associated with the largest eigenvalue (λ_{max}) and the largest eigenvalue (λ_{max}) as shown in equation 11 and 12, respectively.

$$w_i = (\prod_{j=1}^{n} a_{ij})^{1/n} \Big/ \sum_{k=1}^{n}(\prod_{j=1}^{n} a_{kj})^{1/n} \tag{11}$$

$$\lambda_{\max} = \sum_{i=1}^{n}[(\sum_{j=1}^{n} a_{ij}) * w_i] \tag{12}$$

A Consistency Index (CI) is used to measure the degree of inconsistency in the square matrix $\boldsymbol{A}$ (where, $CI = (\lambda_{max} - n)/(n - 1)$). Saaty (1980) compared the estimated CI with the same index derived from a randomly generated square matrix, called the Random Consistency Index (RCI) as shown in Table 5. The ratio of CI to RCI for the same order matrix is called the Consistency Ratio (CR). The judgmental consistency of each expert will be determined. Generally, CR of 0.10 or less is considered acceptable, otherwise the matrix ***A*** will be revised to improve the judgmental consistency.

Table 5: The Random Consistency Index (RCI)

n	1	2	3	4	5	6	7	8	9
RCI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45

Source: (Adapted from Saaty (1994), pp. 42)

The Geometric Mean Method (GMM) (Saaty, 1989), as shown in equation 13, was employed to aggregate different judgments from several experts. It should be noted that only consistent expert judgements would be included in this step. According to a GMM method, the geometric means (a_{ij}^{gp}) of the paired comparisons conducted by each expert (a_{ij}^{h}) are inserted into the group pairwise comparison matrix which is similar to the reciprocal square matrix ***A*** previously mentioned and then the traditional eigenvalue method is used to estimate the group relative weights of all experts.

$$a_{ij}^{gp} = (a_{ij}^{1} \cdot a_{ij}^{2} \cdot \ldots \cdot a_{ij}^{h} \cdot \ldots \cdot a_{ij}^{H})^{1/H} = (\prod_{h=1}^{H} a_{ij}^{h})^{1/H} \tag{13}$$

where, $a_{ij}^{h} = (w_i / w_j)$ is an element of the square matrix ***A*** of a decision maker *h*. *H* is the total number of human experts. Saaty (1989) proposed an approach similar to the typical AHP to determine group consistency. The Group Consistency Index (GCI) was defined as $GCI = (\lambda_{max} - n)/n$ (where: λ_{max} is the largest right eigenvalue estimated from the group pairwise comparison matrix). The group consistency ratio (GCR) is calculated in the identical way as the typical CR value (GCR = GCI/RCI). The group judgment is considered to be consistent, if GCR is less than 0.10. In this study, it is assumed that the consensus among different individuals can be mathematically achieved by applying the GMM approach. The global relative weights for each decision element in the lowest hierarchical level can be obtained by multiplying its local weights by each of the global weights of their parent elements in the immediate higher level. Then the obtained results are summed over those parent elements.

6. BASIC STRUCTURE OF A KNOWLEDGE-BASED EXPERT SYSTEM

Knowledge-based expert system (KBES) have evolved as a branch of artificial intelligence and have been successfully applied mostly in the field of medicine, chemistry, engineering and the military (Han and Kim, 1990). The KBES is defined as *"a computer program that emulates human behaviour in solving problems. It includes a separate reasoning mechanism that performs the same function as a human expert's brain"* (Cohn and Harris, 1992). The ESM approach involves and contains the judgments, experiences and other heuristic expertise of human experts and is consequently well-matched to the KBES concept. Hence a prototype KBES was developed for the evaluation of the multicriteria ES of urban road networks (Klungboonkrong and Taylor, 1995 and 1996). In this study, the expert system shell KnowledgePro for Windows (KPWin) is used to develop the prototype KBES for the fuzzy multicriteria ES evaluation of urban road networks. The selection of expert system shell and the KBES development procedures used in this paper were discussed elsewhere (Klungboonkrong and Taylor, 1995). In addition, the prototype KBES will also be linked with the GIS (MapInfo) package, which has been used to integrate, store, manage and retrieve all spatial information and its attributes of the concerned road network, to geographically display the analysed results. The fundamental structure of the KBES is illustrated in Figure 7 and briefly described below.

Knowledge base: the knowledge base contains the knowledge derived from human experts (ie people recognised as having special expertise and knowledge in the particular field) and research papers, study reports and other related publications. This includes judgments, facts or belief, rules of thumb, professional experiences, and other heuristic expertise. The knowledge base is the strength of the KBES.

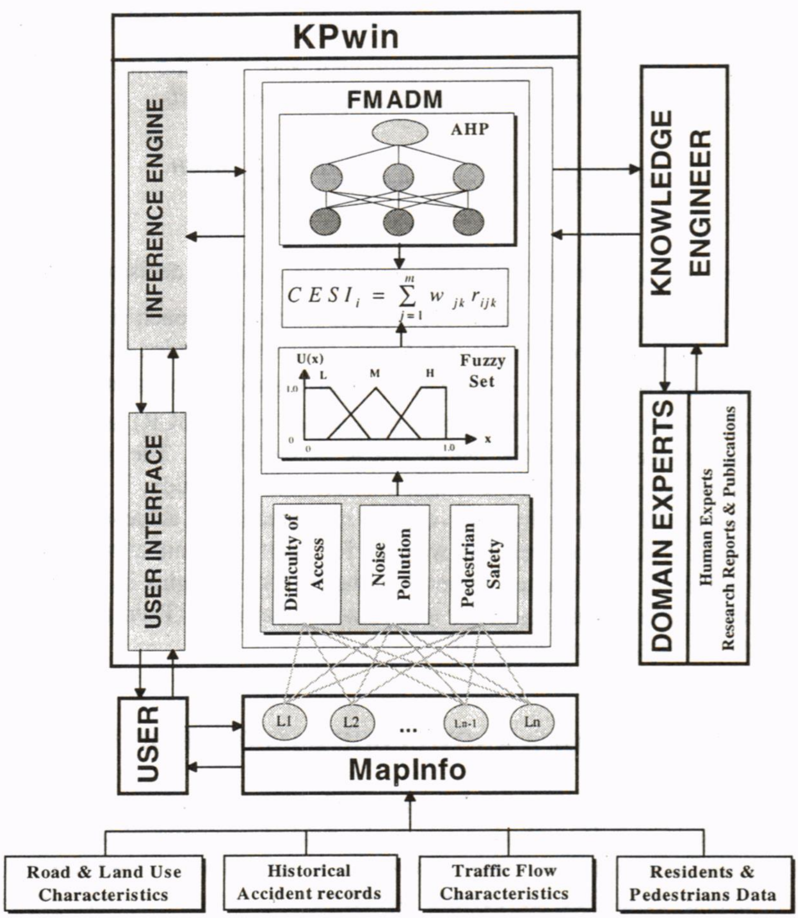

Figure 7: The Basic Structure of the Prototype KBES

The current KBES consists of four main knowledge-based (KB) files. These are difficulty of access, noise level, pedestrian safety and fuzzy multiattribute decision-making (FMADM). The knowledge contained in the first three KB files was mainly derived from the ESM concept (Singleton and Twiney, 1985) and the structured interview with one expert who developed the ESM concept. The decision table concept (Seagle and Duchessi, 1995) was used to extract and reformulate the relevant knowledge from Singleton-Twiney factorial combination system for each corresponding criterion. In addition, the interview with this expert provided the significant explanation for each derived decision rule. For the FMADM file, the knowledge regarding the relative importance (weighting values) of all environmental criteria for each land use type was gleaned from additional structured interviews with six other experts. The AHP approach was used to transfer and aggregate this knowledge from these experts. In addition, the knowledge concerning the numerical scores of each ES index (low, medium and high) for all criteria was achieved by using Chen and Hwang's conversion scale system and fuzzy scoring method. Lastly, the SAW computing procedures was also established in the FMADM file. All of the knowledge described previously was encoded and stored in the prototype KBES under a KPWin environment. A rule-based structure is adopted as a knowledge representation. Therefore, the knowledge base consists of a set of rules and is represented in the form of IF *(premises or conditions)* THEN *(actions or conclusions)* ELSE *(actions or conclusions).*

Inference mechanism: the inference mechanism is the control level of the KBES. This component will manipulate the relevant knowledge stored in the knowledge base to resolve the concerned problem. A control strategy used is backward chaining. **User interface:** the user interface efficiently provides interactive two-way communication among user, the prototype KBES and other packages.

In this study, the required information (the physical and land use characteristics of each link in the road network) for each of difficulty of access, noise level and pedestrian safety KB files was interactively entered to the prototype KBES. The backward chaining strategy is used to resolve for ES indices of any road links for each criterion. Subsequently, the derived ES indices will then be automatically input to the FMADM file. These ES indices will be converted to the corresponding numerical scores and then according to the SAW procedures, these converted scores will be multiplied with the appropriate relative weights depending on their corresponding criteria and land use types. Finally, the CESIs for each link will be achieved.

7. THE CASE STUDY

The City of Unley, a suburb of Adelaide, Australia was adopted as a case study area. It is an inner suburban area immediately adjacent to the Adelaide Central Business District (CBD). Its road network is basically a grid system as illustrated in Figure 8. The focus of the case study was to determine the ES of all roads which reflects the perspective of the residents and pedestrians living in abutting land uses. The geographical boundary of environmental impacts concerned is within the roadway area and immediate adjacent environment falling between the first row of the buildings located on both sides of the roads. The main roads, which serve both traffic mobility and frontage, related activity functions (eg access, shopping, etc) were the main subject of this study. Ten main roads in Unley were selected and these roads were divided into 23 homogeneous links as indicated in Figure 8, according to the criteria suggested by Singleton and Twiney (1985).

The physical and land use characteristics along each of these divided links were gathered from existing data and field surveys. These include: (i) physical characteristics of the roads; (ii) pedestrian facilities; (iii) nature of parking restrictions; (iv) type and practicality of land use access; (v) adjacent land use categories; (vi) typical building setback from the property line; and (vii) building facade orientation. These data were refined and verified by using on-road video recordings, aerial photographs and other relevant documents. The database has been established within a geographical information system (GIS) environment, namely MapInfo.

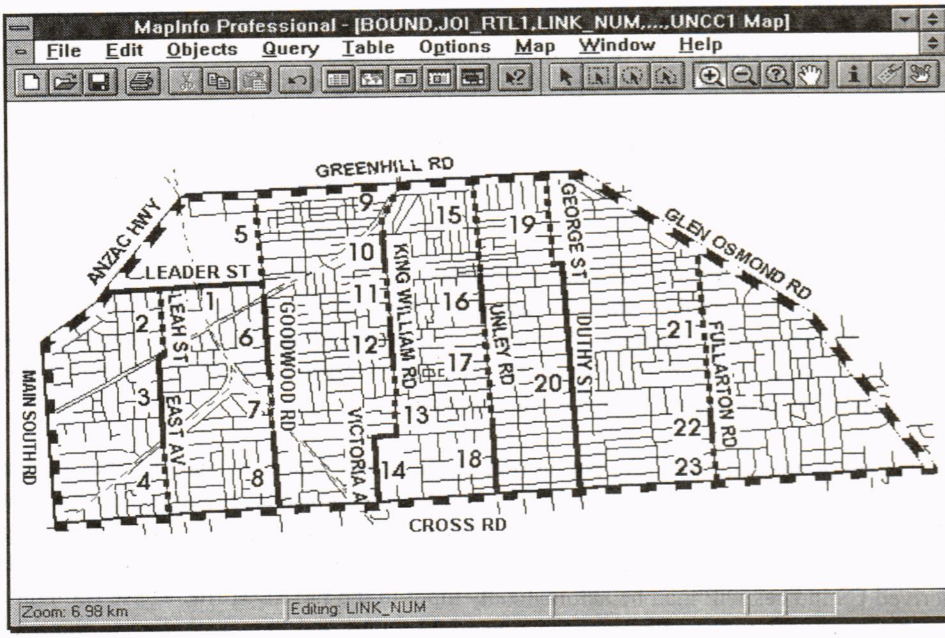

Figure 8: The City of Unley Road Network

Previous research indicated that residents living along busy roads were most concerned about four aspects, namely air pollution, noise, pedestrian crossing delay and pedestrian safety (Holdsworth and Singleton, 1979; Hollingworth, 1982; May, 1988). Three criteria selected for the City of Unley case study were difficulty of access, noise level and pedestrian safety. It has been known that the relative importance of different criteria varies with land use types and road hierarchy classes. Consequently, only the main roads serving both traffic mobility and frontage related activity functions were considered and the relative weights of different criteria for each land use type were separately determined. This means that the influences of both road hierarchy classification and land use type are fully taken into account. Six selected experts (eg local government officer, urban planner, etc) were directly interviewed. Based on their professional experiences and judgements, these experts served the community as the 'measuring instrument' in determining the relative weights of these criteria for each land use type. All land use types were classified as suggested by Singleton and Twiney (1985) and indicated in Table 7.

The AHP hierarchical structure was established and shown in Figure 9. An example of the pairwise comparison matrices and the estimated relative weights is shown in Table 6. All of the estimated CR values for all matrices were less than 0.10, the resulting pairwise comparisons were therefore considered consistent. The GMM was then applied to aggregate different judgments of the six experts and the estimated group relative weights were then employed to combine the separate ES indices of all criteria for each link in the FMADM process. The estimated group relative weights of all criteria for each land use type are presented in Table 7. It was found that all GCR values estimated for each group pairwise comparison matrix were less than 0.10, group judgements were therefore consistent. However, it was found that the relative weights (derived from each human expert) of the three criteria for land use type I expressed the greatest dispersion, while those for land use type II and III illustrated the less and compatible dispersion.

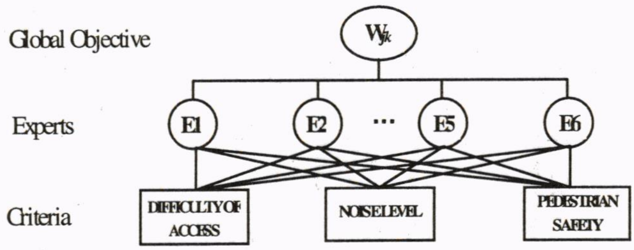

Figure 9: A Hierarchical Structure of Weight Estimation for Each Land Use Type

Table 6: Pairwise Comparisons of all Criteria for Land Use Type II by Expert 1

Criteria	(1)	(2)	(3)	Weights
(1) Difficulty of Access	1	1.5	1	0.3695
(2) Noise Level	1/1.5	1	1/2	0.2238
(3) Pedestrian Safety	1	2	1	0.4067

$\lambda_{max} = 3.009$, $CI = 0.005$, and $CR = 0.009$

Table 7: Group Relative Weights of All Criteria by Land Use Types

Land Use Types	**Environmental Criteria**		
	Difficulty of Access	**Noise Level**	**Pedestrian Safety**
(I) Residential/School/Hospital	0.2658	0.2059	0.5284
(II) Retail/Commercial/Office/Park	0.3603	0.1237	0.5160
(III) Industrial/Railway	0.4918	0.1062	0.4019

All required information for a specific link for each criterion was directly entered into the KBES that then identified the resultant ES index. Finally, the KBES estimated the CESI of all criteria for that link. As an illustration of this technique the ES indices for the difficulty of access criterion of all links in the City of Unley are indicated in Figure 10. Similar outputs were created for noise level and pedestrian safety. The estimated CESI values of all links are illustrated in Figure 11 and these values were grouped into five equal intervals and illustrated in Figure 12.

8. INTERPRETATION

As geographically identified in Figure 10, all links with high ES indices occur on the busy roads. These links indicate the need for special attention regarding the difficulty of access criterion. A similar interpretation can be drawn for the noise level and pedestrian safety criteria. The key factors contributing to such problems for each criterion can be identified from information of each link's road physical and land use characteristics contained in both the prototype KBES and the GIS (MapInfo) database.

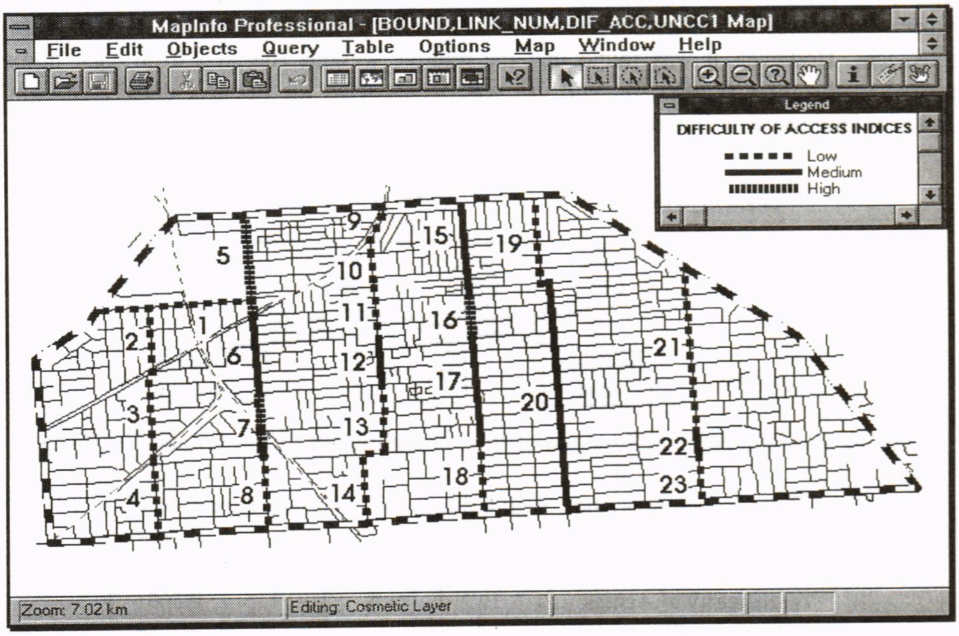

Figure 10: The Separate ES Scores for Difficulty of Access

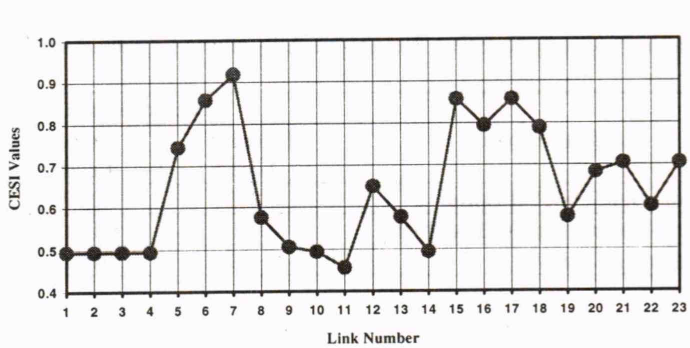

Figure 11: The Estimated CESI Values for All Links

It should be noted that each Figure showing the ES indices of different links for each specific criterion (like Figure 10) can be considered as a separate GIS layer for that criterion. Given different contributions of each separate GIS layer to the CESI estimation, the different relative weights associated with different criteria for each land use type can be applied (via SAW method) to aggregate those separate ES indices of each link in each layer to derive the CESI layer as shown in Figure 12. In this way, the GIS technology can play a vital role in FMADM process and also produce the excellent graphical map displays of the analysed results. The estimated CESIs were used to assess the likely combined ES effects of different criteria for each link. Such indices can be utilised to identify problem locations and reveal the ranking order corresponding to the degree of the combined environmental impacts of each link. As illustrated in Figure 11, six links with high CESI values (CESI is greater than 0.75) lie along the busy roads. The rank for those links according to the magnitudes of their CESI values in descending order are: link 7 (CESI = 0.918); links 6, 15 and 17 (0.856); link 16 (0.794); and link 18 (0.787).

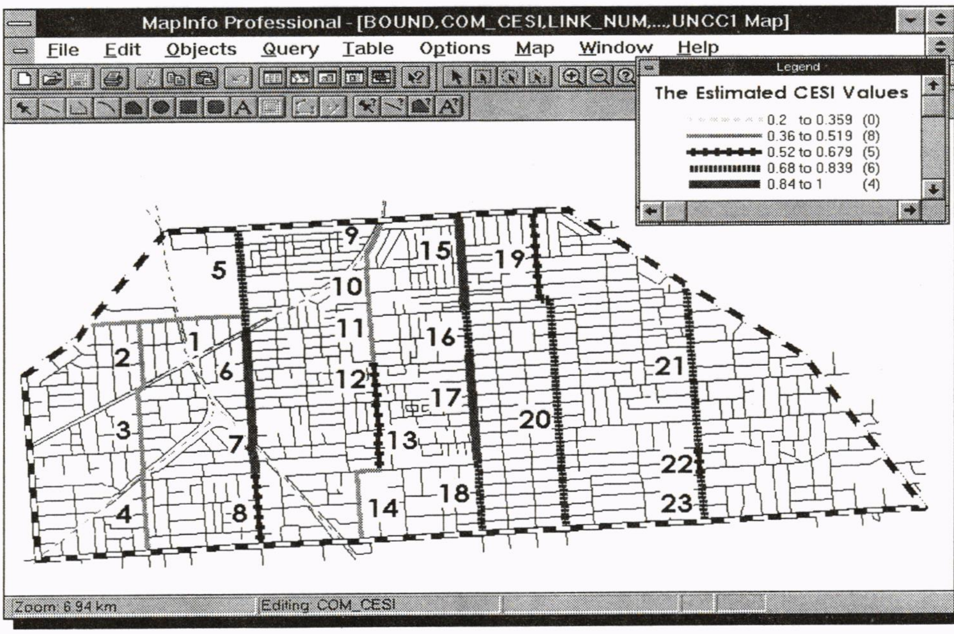

Figure 12: Five Divided Groups of the Estimated CESI Values for All Links

In addition, the numerical composition of CESI values can also be used to indicate the possible causes of the problem for each link. For example, link 17 lying in land use type II along Unley Road has an estimated CESI value of 0.856. The descending rank of likely causes (criteria) of the environmental problem on this link are: pedestrian safety (0.516 = (0.516 x 1.0)); difficulty of access (0.216 = (0.360 x 0.6)); and noise level (0.124 = (0.124 x 1.0)). It should be noted that although noise level scored a high degree of ES, it is considered to have less problem-generating potential than difficulty of access. This is because the relative importance of difficulty of access is much greater than noise level for the predominant land use type II and this condition can override the influence of a high degree of ES for the noise level criterion.

When the thematic map layer (see Figure 12) indicating the estimated CESI values of all links is superimposed on top of raster image layer showing the aerial photograph of the City of Unley area, a useful graphical presentation of the likely problem locations and the pattern of affected land use adjacent to those problem links are explicitly revealed. Figure 13 illustrates this zoomed in map layer and focuses only on link 17. As shown in Figure 13, the key contributing factors for each problem criterion of link 17 can be easily achieved from road physical and land use information contained in the GIS (MapInfo) database.

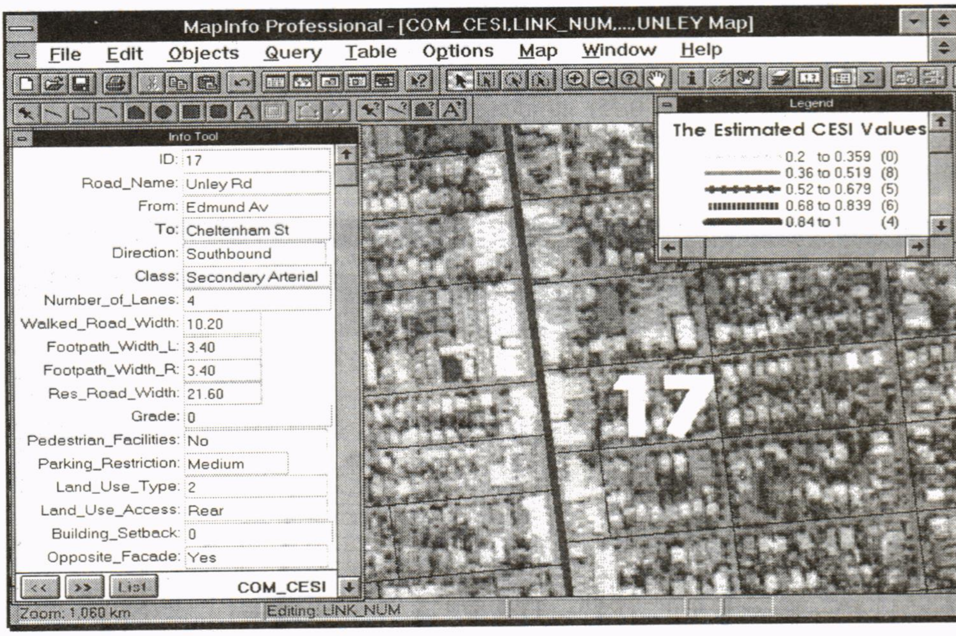

Figure 13: The Estimated CESI of Link 17, Its Attributes and Adjacent Land Use Pattern

9. LIMITATIONS

The separate ES indices derived from the KBES have been based solely on the physical and land use characteristics of road concerned, but neglected other important factors such as the influences of traffic conditions (eg volumes, speed, heavy vehicle composition, etc) and others. This may lead to the misinterpretation of the obtained results. Therefore, on-going research at TSC has been conducted to include the effects of traffic characteristics (eg traffic volumes, speeds, heavy vehicle composition, etc) in the KB file (called "decision rules") developed for noise level as reported in Woolley *et al* (1996). Decision rules for the pedestrian risk criterion that accounts for traffic conditions has also been under establishment. In addition, the relative weights used in the SAW method are based on a linear utility function, which has been applied for trade-off interpretation (Nijkamp *et al,* 1990). This implies that the method allows for a high degree of compensatory justification among different criteria. For example, a high ES index for a lower relative weight criterion can possibly be compensated by a low ES index for a higher relative weight criterion. Therefore, the results derived from this method must be carefully interpreted. Further research is needed to study the influences of the compensatory justification.

10. CONCLUSION

This paper described the theoretical foundation and the application of a decision support tool for evaluating the fuzzy multicriteria ES of the City of Unley road network in Adelaide, Australia. The tool was developed as an integration of a fuzzy multiattribute decision making (FMADM) approach and a knowledge-based expert system (KBES) technology. The results of the case study indicate the potential utility of the tool for assessing the both separate and composite environmental sensitivity of urban road network at a local level, identify problem locations, and specify the possible causes and the key factors contributing to such problems. In addition, the tool can also be used as the key input to the road hierarchy classification and as a prioritising instrument for road links that require special investigation or budget allocation for remedial treatments. The tool is expected to explicitly incorporate other significant influencing factors such as road traffic characteristics into consideration. The current state of the tool will be expanded and refined and it will be integrated with a GIS (MapInfo), to form a powerful microcomputer-based system, called "Spatial Intelligent Multicriteria Environmental Sensitivity Evaluation Planning Tool" (SIMESEPT).

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