A multicriteria environmental sensitivity evaluation of the urban road network: an Australian case study
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Abstract

Road traffic is a major contributor of amenity and environmental degradation in urban areas. Such degradation including both qualitative and quantitative aspects varies, ranging from direct health hazards to annoyance effects. The measurement and assessment of degradation are difficult and complex. A decision support tool has been developed to evaluate the multicriteria environmental sensitivity of urban road networks. It is an integration of management science and knowledge-based expert system (KBES) technology. This paper discusses the theoretical foundations and an application to an Australian case study. The findings from the case study matched the likely environmental sensitivity (ES) effects indicating by using other methods. Thus the tool can be used to assess the combined environmental impacts of road traffic at the local level, identify problem locations, and specify the possible causes and the factors contributing to such problems.

1 Introduction

Road traffic is a major cause of urban area degradation in terms of safety, environment and amenity. Estimation and assessment of such degradation is difficult. Although some can possibly be quantified (eg air pollution and noise level etc), others can only be qualitatively measured (eg difficulty of access and visual intrusion etc). In addition, both qualitative and quantitative environmental impacts vary, ranging from direct health hazards to annoyance effects. The impact assessment is therefore complicated. In practice, both qualitative and quantitative impacts need to be measured and compared. This is because the trade-offs of relative importance between them and the combined impacts are fundamental in the identification of problem locations, determination of the problems and their possible causes and recommendation of appropriate remedial treatments. The knowledge-based expert system (KBES) is a computer program
containing judgmental and other heuristic expertise that emulates some aspects of the human mind in solving problems of various types. A KBES has been developed for multicriteria environmental sensitivity evaluation of the urban road network and can be used to tackle such difficulties.

2 Methods for Assessing Traffic Environmental Impacts

Several methods have been developed to assess the safety, amenity and environmental consequences of road traffic in an urban road network. In Australia, Amenity Sensitivity (AS) (Loder & Bayley) 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.

A more rigorous method introduced by Buchanan was Environmental Capacity (EC). Holdsworth & Singleton 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 such criterion will be solved to yield the maximum traffic flow complying to the specified standard. Holdsworth & Singleton applied the EC in terms of noise pollution and pedestrian crossing delay to traffic management planning. Recently, Song et al expanded the Holdsworth-Singleton EC concept by including a pedestrian accident risk criterion. They also proposed the use of the geometric mean of different estimated ECs to calculate the combined EC.

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 & Singleton, Gilbert, Chadwick).

3 Environmental Sensitivity Method (ESM)

Singleton & Twiney 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 examine the ES of that road caused by 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.

![Figure 1: Environmental Sensitivity Method](source: Adapted from Singleton & Twiney, p. 179)

In practice, it is essential to combine the separate ES indices estimated for the different criteria on a given link in order to identify and compare the combined ES indices of the different links in a road network. Such 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 multicriteria decision making (MCDM) approach can be used to combine both tangible and intangible criteria and to recognise differences in the relative importance of each criterion.

4 Multicriteria Decision Making (MCDM) Process

The weighted summation method is used to integrate 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 1 (Nijkamp et al.). The Analytic Hierarchy Process (AHP) described below is utilised to estimate the relative weights \( w_{jk} \) for each criteria in different land use types. Then

\[
CESI_{ik} = \sum_{j=1}^{n} w_{jk} r_{ijk}
\]

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

where: \( CESI_{ik} \) is the Composite Environmental Sensitivity Index of link \( i \) in land use \( k, (i = 1, 2, ..., m \text{ and } k = 1, 2, ..., l) \); \( w_{jk} \) is the relative weight for criterion \( j \) in land use \( k, (j = 1, 2, ...,n) \); and \( r_{ijk} \) is the ES index of link \( i \) for criterion \( j \) in land use \( k \).
In this study, a similar ES scoring system to that used in Singleton & Twiney\(^8\) is applied to all selected criteria. An ordinal scale of 1, 2 and 3 is assigned to the ES scores of ‘low’, ‘medium’ and ‘high’ respectively, based on the assumption that the ES scores have a linear relationship.

### 5 Analytic Hierarchy Process (AHP)

AHP is a mathematical method for estimating relative weights among several decision elements. It 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. When the hierarchical structure of the decision elements is completely formulated, pairwise comparisons of the decision elements at the same hierarchy level are conducted corresponding to the scale of relative importance ranging from 1 (equal importance of both elements) to 9 (extreme importance of one element over another) (Saaty\(^10\)). 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 then inserted into a square matrix \(A = \{a_{ij}\}\) as shown in equation 2. The analytical solution of equation 3 then provides the relative weights for each element. According to the eigenvalue method, the normalised eigenvector \((W = \{w_1, w_2, ..., w_n\}^T)\) associated with the largest eigenvalue \((\lambda_{\text{max}})\) of the square matrix \(A\) provides the weighting values for all elements.

\[
A = \begin{bmatrix}
1 & \frac{w_1}{w_2} & ... & \frac{w_1}{w_n} \\
\frac{w_2}{w_1} & 1 & ... & \frac{w_2}{w_n} \\
: & : & ... & : \\
\frac{w_n}{w_1} & \frac{w_n}{w_2} & ... & 1
\end{bmatrix}
\]

(2)

\[
AW = \lambda_{\text{max}}W
\]

(3)

A Consistency Index (CI) is used to measure the degree of inconsistency in the matrix \(A\) (where, \(CI = (\lambda_{\text{max}} - n)/(n - 1)\)). Saaty\(^11\) compared CI with the Random Index (RI) as shown in Table 1. The ratio of CI to RI for the same order matrix is called the Consistency Ratio (CR). Generally, CR of 0.10 or less is considered acceptable, otherwise the matrix \(A\) should be revised to improve the judgmental consistency.

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.00</td>
<td>0.00</td>
<td>0.52</td>
<td>0.89</td>
<td>1.11</td>
<td>1.25</td>
<td>1.35</td>
<td>1.40</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Source: (Adapted from Saaty\(^11\), pp. 42)

Saaty\(^12\) also introduced the use of the geometric mean method (GMM) as shown in equation 6, to aggregate different judgments from different decision makers. In GMM,
the geometric mean \((a_{ij}^{gp})\) of the paired comparisons conducted by each decision maker \((a_{ij}^k)\) are inserted into the group pairwise comparison matrix and the normalised eigenvector associated with the \(\lambda_{max}\) of this matrix can provide the group relative weights of all decision makers.

\[
d_{ij}^{gp} = (a_{ij}^1, a_{ij}^2, a_{ij}^3, \ldots, a_{ij}^k)^{l/n} = (\prod_{k=1}^{n} a_{ij}^k)^{l/n}
\]

where, \(a_{ij}^k = (w_i / w_j)\) is an element of the matrix \(A\) of individual \(k\).

6 Development of A Prototype Knowledge-based Expert System

Knowledge-based expert systems (KBES) evolved as a branch of artificial intelligence and have been successfully applied mostly in the field of medicine, chemistry, engineering and the military (Han & Kim\(^\text{13}\)). 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 & Harris\(^\text{14}\)). The ESM approach involves and contains the judgment, experience 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 & Taylor\(^\text{15}\)).

The expert system shell, KnowledgePro for Windows was used to develop the prototype KBES. A rule-based structure is adopted as the knowledge representation and the control strategy used is backward chaining. The structure of the KBES is illustrated in Figure 2.

Figure 2: The Basic Structure of the Prototype KBES
In summary, the current KBES consists of four knowledge-based (KB) files. These are difficulty of access, noise sensitivity, pedestrian safety and multicriteria decision making (MCDM). While the knowledge contained in the first three KB files was derived from the ESM concept (Singleton & Twiney®) with some refinement, the knowledge stored in the last KB file was gleaned from direct interviews with three selected experts. The required data can be interactively entered by the user or directly imported from a data files stored in the Excel program. The operating procedures of KBES will be discussed in the next section.

7 The Case Study Area

The City of Unley, a suburb in 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 3.

The focus of the case study was to determine the ES of those main roads which serve both traffic mobility and access functions. Ten main roads in Unley were selected and these roads were divided into 23 links as indicated in Figure 3 according to: the uniformity of road physical characteristics; homogeneity of adjacent land uses; spacing and complexity of road junctions, and derived link lengths as suggested by Singleton & Twiney®. The physical and land use characteristics along each of these divided links were collected. These include: (i) road physical characteristics; (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.

The three environmental criteria considered for the City of Unley study were difficulty
of access, noise level and pedestrian safety. The established AHP hierarchical structure
is given in Figure 4. Three experts were asked to conduct pairwise comparisons of all
selected criteria for each land use category. All land use categories are classified as
given in Table 3. An example of the pairwise comparison matrix and the estimated
relative weights is shown in Table 2. Because the estimated CR values for all matrices
are less than 0.10, the conducted pairwise comparisons are considered consistent. The
GMM was applied to integrate different judgments of the three experts and the
estimated group relative weights were employed to combine the separate ES indices of
all criteria for each link in the MCDM calculation. The estimated group relative
weights of all criteria for each land use type are presented in Table 3.

![Figure 4: A Hierarchical Structure of Weight Estimation for Each Land Use Type](image)

**Table 2: Pairwise Comparisons of all Criteria for Land Use Type II by Expert 1**

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficulty of Access</td>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>0.3695</td>
</tr>
<tr>
<td>Noise Level</td>
<td>1/1.5</td>
<td>1</td>
<td>1/2</td>
<td>0.2238</td>
</tr>
<tr>
<td>Pedestrian Safety</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.4067</td>
</tr>
</tbody>
</table>

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

**Table 3: Group Relative Weights of All Criteria by Land Use Types**

<table>
<thead>
<tr>
<th>Land Use Types</th>
<th>Environmental Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difficulty of Access</td>
</tr>
<tr>
<td>(I) Residential/School/Hospital</td>
<td>0.3356</td>
</tr>
<tr>
<td>(II) Retail/Commercial/Office/Park</td>
<td>0.3535</td>
</tr>
<tr>
<td>(III) Industrial/Railway</td>
<td>0.4208</td>
</tr>
</tbody>
</table>

All information for each criterion of a specific link were interactively input to the KBES
which then identified the resultant ES indices. 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 shown in Figure 5.
Similar outputs were created for noise level and pedestrian safety. The estimated CESI values of all links are illustrated in Figure 6.

8 Interpretation

As geographically identified in Figure 5, all links with high ES indices are on the busy roads. These links indicate the needs for special attention or remedial treatment regarding the difficulty of access criterion. The possible contributing factors to such problems can be identified from information of each link’s road physical and land use characteristics.

CESIs can be used to assess the 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. The direct comparisons of the resultant CESI values are valid, because the influences of land use types on the separate ES indices have already been taken into account in the KBES. As illustrated in Figure 6, seven links with high CESI values (CESI is greater than 2.20) 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 = 2.840); links 6, 15 and 17 (2.647); link 16 (2.507); link 5 (2.354); and link 18 (2.329).

In addition, the 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 2.647. The descending rank of likely causes (criteria) of the environmental problem on this link are: pedestrian safety (1.4793 = (0.4931 x 3)); difficulty of access (0.7070 = (0.3535 x 2)); and noise level (0.4605 = (0.1535 x 3)). 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. The results of the interviews with three selected experts (as given in Table 3) interestingly showed that the relative weights among the three criteria are quite constant and barely vary with land use types. The likely contributing factors to each criterion can be determined in the same way as discussed previously.

9 Conclusion and Further Research Directions

This paper has presented the application of the decision support tool for assessing the multicriteria environmental sensitivity of urban road network. The decision support tool was developed as an integration of management sciences (MCDM and AHP) and a KBES. The findings from the case study matched the likely ES effects indicated by using other methods. Hence, this tool can be utilised to assess the combined environmental impacts of road traffic at a local level, identify problem locations, and specify the possible causes and the factors contributing to such problems. In addition, the tool can also be applied to road hierarchy classification and traffic management planning. This ongoing research at the Transport System Centre (TSC) is intended to
Figure 5 The Separate ES Indices for Difficulty of Access

Figure 6 The Estimated CESI Values of All Links
explicitly incorporate other related parameters such as road traffic conditions (e.g. volume, speed etc.), frontage land use activities (e.g. number of residents, pedestrians and visitors etc.) and so on. The current state of the decision support tool will be expanded and refined. It will be integrated with a geographical information system (GIS), to develop a Spatial Expert System (SES). The end result of this SES is expected to be a comprehensive and powerful decision tool for traffic engineers and urban planners.

References