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Procedia - Social and Behavioral Sciences 111 (2014) 559 – 566

Procedia
Social and Behavioral SciencesEWGT2013 – 16th Meeting of the EURO Working Group on Transportation

A modeling tool for measuring the performance of urban road networks

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Abstract

The aim of this paper is to develop an integrated performance indicator in urban road infrastructure for evaluating network functionality and the impact of transport system interventions. The complex indicator has been elaborated using a multicriteria algorithm, based on concordance analysis. We calibrate a synthetic performance indicator for an urban road network, containing all those elements required for characterizing urban network functionality. Specifically, a series of core indicators is identified, integrated and interlinked. The functionality of an urban road network can be determined by analyzing several aspects that commonly affect operating conditions such as traffic flow, safety, road maintenance conditions, accessibility and environmental impact. No methodology is currently available in the scientific literature for measuring urban road network performance, using indicators that combine information about various aspects: the indicators used in the analysis of transport systems assess performance separately from different perspectives. For example, the quality of traffic flow is measured through the Level of Service (HCM, 2010), accessibility performance is assessed through clustering measures (Jiang & Claramunt, 2004) and safety conditions are measured in terms of number of road accidents (Tingvall, Stigson, Eriksson, Johansson, Krafft & Lie, 2010). This paper proposes a unique modeling tool that incorporates the different indicators used separately to calculate network performance for each area.

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Selection and/or peer-review under responsibility of Scientific Committee

Keywords: key indicators; road functionality; multicriteria analysis.

1. Introduction

The analysis of urban transportation systems is an important research area as it concerns the daily activities of millions of people moving within a city. A variety of topics warrant investigation but assessing network performance is particularly important. Evaluation of transport network functionality has been widely studied. In

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general, the studies quantify urban road network performance by means of key performance indicators, that represent the functionality of the network from a specific aspect. Some investigations focus on the quality of traffic flow, i.e. the ability to keep traffic moving as smoothly as possible, using indicators that depend on the geometrical characteristics: travel time, delay at intersections, traffic flow) (TRB, 2010). Others address road safety, using indicators related to the number of accidents and deaths (Tingvall, Stigson, Eriksson, Johansson, Krafft & Lie, 2010). Still others measure performance as a function of the level of network accessibility, i.e. the ease with which it is possible to reach destinations (Cerdá, 2009). Finally, other assessments may concern the emissions of pollutants, the state of road maintenance, etc. This is due to the fact that functionality of the urban road network depends on numerous variables, but the studies carried out up to now, are oriented toward single-issue approaches and evaluate the different aspects one at a time. Instead no methodology is reported in the literature that is able to evaluate performance of different transport networks or different structure of one and the same network, analyzing them from a global perspective.

The aim of this paper is to develop a methodology for evaluating urban road network functionality. This methodology compares the global performance of an urban road network in different scenarios. It incorporates methodology core performance indicators related to the key areas affected by the road infrastructure. The model proves useful in transportation network planning for choosing among the different available options (traffic flow, accessibility, safety) on which to take action to improve road functionality. The technique adopted is the multicriteria analysis (MCA). This technique is used in decision-making processes to support the choice among different alternatives in complex problems (Fadda, 2002). Of the different multicriteria techniques available, concordance analysis will be used here. The aim of this analysis is to identify the best balanced solutions. These solutions perform well in multiple targets with respect to others that may provide excellent results for some targets but perform poorly for others (De Brucker, Verbeke & Macharis, 2004). The methodology is applied to a real case to assess the performance of the road network of Benevento, in Italy, in four different scenarios. The model identifies the best alternative, in accordance with the criteria established.

2. The Methodology

Concordance analysis is based on pairwise comparison of alternatives. A dimensionless matrix is constructed, using the indicator values. The preferability of one alternative over the others is measured by means of the concordance and discordance indexes (Hinloopen & Nijkamp, 1990) The model consists of 9 steps:

STEP 1) IDENTIFICATION OF THE ALTERNATIVE

Four different scenarios in an urban road network are considered for the comparison. The analysis was conducted in the “Ferrovía” district in Benevento, Italy,:

- scenario 1: actual road network in the “Ferrovía” district;
- scenario 2: road network having longer travel times, lower public transport frequency, higher level of pollutant emissions;
- scenario 3: road network having lower congestion, lesser degree of interference between vehicle and pedestrian traffic and higher public transport frequency;
- scenario 4: road network having higher public transport frequency, lower level of pollutant emissions and lesser degree of interference between vehicle and pedestrian flows.

STEP 2) SPECIFICATION OF TARGETS

The targets represent those parts of society that are affected by the impact generated by transport infrastructure. These components are: the users of transport infrastructure and road network managers. The users, in turn are divided into private transport users, public transport users and vulnerable road users (pedestrians, cyclists). Their interests naturally differ. Private transport users are more interested in easing traffic congestion,

public transport users in increasing public transport frequency and improving safety at public transport stops. Vulnerable road users are more interested in abating air pollution and improving traveling by bike or walking. Lastly, there are the administrators of the road transport network, which manage the infrastructure and whose objective is to minimize the costs of the transport system. The external users do not benefit from any direct effects generated by the implementation of interventions on the network. The class of external effects is not considered relevant for the purposes of the present analysis.

STEP 3) SPECIFICATION OF OPERATIONAL AREAS

Three operational areas are identified to measure the effects of the transport network and for which performance indicators are to be defined.

- traffic flow: characteristics related to the traffic flow;
- accessibility: ease of reaching destinations;
- safety: level of exposure of users to risk.

STEP 4) SPECIFICATION OF OBJECTIVE FUNCTIONS

Within each operational area described above, objective functions are defined. They are key indicators to quantify the performance of the road network in each operational area. The indicators used for the analysis multicriteria are briefly described below, specifying the target and operational area.

Indicator 1: Travel time and delay at intersections.

Target: private transport users

Operational Area: traffic flow

$$f = \sum_i \left(\frac{l_i}{v_i} \right) + \sum_j \delta_j \quad (1)$$

where l_i is the length of arc i ; v_i average speed of traffic flow along arc i ; δ_j average delay at junction j ;

Indicator 2: Average travel time between the external network and an internal attractor.

Target: private transport users

Operational Area: accessibility

$$f = \frac{\sum_{i,k} \left(\frac{l_{i,k}}{v_{i,k}} \right) + \sum_{j,k} \delta_{j,k}}{\sum_k n_k} \quad (2)$$

where $l_{i,k}$ is the length of arc i , which forms part of the path between external node k and the reference attractor, $v_{i,k}$ average speed of traffic flow along arc i , $\delta_{j,k}$ is the delay at intersection j along the path between external node k and the reference attractor, n is the number of shortest paths between the external nodes k and the reference attractor.

Indicator 3: number of points of conflict between vehicle flow at intersections.

Target: private transport users.

Operational Area: safety

$$f = \sum_j pc_j \quad (3)$$

where pc_j number of points of conflict between the vehicle flow at intersection j .

Indicator 4: length of public transport network multiplied by number of vehicles in one hour.

Target: public transport users

Operational Area: traffic flow

$$f = \sum_i l_i \cdot bus_i \quad (4)$$

where l_i is the length of arc i , bus_i the number of buses traveling along arc i .

Indicator 5: number of residents living within 300 meters from bus stops.

Target: public transport users

Operational Area: accessibility

$$f = \sum_i res_i \quad (5)$$

where res_i number of residents living within 300 meters from bus stop i ;

Indicator 6. number of bus stops with shelters.

Target: public transport users

Operational Area: security

$$f = \sum_i fer_i \quad (6)$$

where fer_i bus stops with shelters, in the arc i .

Indicator 7. level of pollutant emissions estimated using the CORINAIR model.

Target: vulnerable road users

Operational Area: traffic flow

$$f = \sum_a \sum_j \xi_j \cdot po_{j,a}^k \cdot f_{k,a} \quad (7)$$

where ξ_j the weight of polluting factors, $po_{j,a}^k$ factors pollutants emitted during time slot k as a function of the flow through the arc, $f_{k,a}$ is the flow through the arc during time slot k .

Indicator 8: average travel time between the walkways between each peripheral node

Target: vulnerable road users

Operational Area: accessibility

$$f = \frac{\sum_{i,k} l_{i,k}}{\sum_k n_k} \quad (8)$$

where $l_{i,k}$ is the length of arc i which forms part of the path between external node k and the reference attractor, n is the number of shortest paths between the external nodes k and the reference attractor.

Indicator 9. number of pedestrian crossings situated at a distance of less than 75 meters from the intersection

Target: vulnerable road users

Operational Area: safety

$$f = \sum_{i,j} ap_{i,j} \quad (9)$$

where $ap_{i,j}$ is the pedestrian crossing i situated at a distance of less than 75 meters from intersection j .

I10 Average degree of saturation

Target: Road Administrator

Operational Area: traffic flow

$$f = \frac{\sum_i \left(\frac{f_a}{c} \right)_i \cdot l_i}{\sum_i l_i} \tag{10}$$

where l_i is the length of arc i , f_a flow through arc i , c capacity of the arc i ;

I11 Degree of connectivity of arcs;

Target: Road Administrator

Operational Area: accessibility

$$f = \frac{\left(\frac{\sum_{i,j} l_{ij} + \sum_{j,i} l_{ji}}{n_j \cdot (n_j - 1)} \right)}{\sum_i n_i} \tag{11}$$

where n_i is a node in the urban network, n_j is a node connected with node n_i , l_{ij} is equal to 1 if node i is connected with node j , and equal to 0 otherwise; l_{ji} is equal to 1 if node j is connected with node i , equal to 0 otherwise.

I12. Number of left turns at intersections

Target: Road Administrator

Operational Area: safety

$$f = \sum_j ssx_j \tag{12}$$

where ssx_j is the number of left turns at intersections j which generate points of conflict at intersection j .

STEP 5) SPECIFICATION OF DECISION MATRIX

The decision matrix is a two dimensional array $n \times m$, where n rows are the criteria, the m columns are the alternatives, and the element p_{ij} is the value of the i -th criterion function for the alternative A_j .

The matrix must be normalized to obtain dimensionless data and to make data comparable.

STEP 6) ASSIGNING WEIGHTS TO THE CRITERIA

In this phase a hierarchy has been defined between the objective functions themselves. The weighting schemes are based on the recommendations put forward by the decision maker.

We defined five different weighting schemes:

Table 1. Set of weights

Targets	Set 1	Set 2	Set 3	Set 4	Set 5
private transport users	25%	40%	20%	20%	20%
public transport users	25%	20%	40%	20%	20%
vulnerable road users	25%	20%	20%	40%	20%
road administrators	25%	20%	20%	20%	40%

STEP 7) CONCORDANCE AND DISCORDANCE MATRICES

With the concordance – discordance method, two matrices need to be created by comparing the alternatives to define the system of final preferences. The basic starting information, obtained by pairwise comparing the alternatives, is quantified as $c(i, j)$ and $d(i, j)$ elements of the concordance C and discordance D matrices respectively, with m rows and m columns.

The elements c_{ij} of the concordance matrix are defined as:

$$c_{ij} = \sum_{k \in C_{ij}} w_k \quad (13)$$

where:

$$C_{ij} = k : p_{ki} \geq p_{kj} \quad (14)$$

w_k = weight assigned to the criteria

The elements d_{ij} of the discordance matrix are defined as:

$$d_{ij} = \frac{\sum_{k \in D_{ij}} \left(w_k \cdot |p_{kj} - p_{ki}| \right)}{m \cdot d_{\max}} \quad (15)$$

where:

$$D_{ij} = k : p_{ki} \leq p_{kj} \quad \forall i \neq j \quad (16)$$

$$d_{\max} = \max w_i |p_{kj} - p_{ki}| \quad (17)$$

w_k = weight assigned to the criteria

STEP 8) CONCORDANCE INDEX (I_c) AND DISCORDANCE INDEX (I_d)

The concordance index (I_c) symbolizes the total satisfaction of the decision-maker choosing the A_i alternative instead of the A_j alternative. I_c can take values from $1 - m$ (negative values) to $m - 1$ (positive values). Positive values indicate that the A_i alternative is totally preferred to others, while negative values indicate that the A_i alternative is not predominant over the others.

$$Ic_i = \sum_j c_{ij} - \sum_j c_{ji} \quad (18)$$

The discordance index (I_d) reflects the regret of the decision-maker in choosing the A_i alternative instead of the A_j alternative. The values of the I_d index fall within the same range as the previous index. In particular, when I_d has positive values, this index reflects how the A_i alternative is totally less predominant than the others: so if the I_d index is lower, the A_i alternative is preferred over alternative A_j .

$$Id_i = \sum_j d_{ij} - \sum_j d_{ji} \quad (19)$$

STEP 9) COMPARING THE ALTERNATIVES

The I_c and I_d indexes are structured successively according to two different vectors (the concordance and discordance vector) where each element represents the concordance and discordance assessment for each alternative in relation to all the others. The alternatives are structured by increasing the concordance index and decreasing the discordance index to obtain two lists which do not generally coincide. The best alternative has a maximum I_c and minimum I_d . When one of these conditions is not met, as often happens, we must evaluate the trade-off between the values of the two indexes to find a suitable alternative (De Luca, Dell'Acqua, & Lamberti, 2012).

3. Application to a case study

The application was conducted on a portion of the urban road network in Benevento, a medium-sized town (population 60,000) in Southern Italy. The "Ferrovia" district is analyzed and the four alternative scenarios described above, defined. Once the decision matrix has been constructed, the different objective functions are calculated for each scenario (Indicator 1-12). Note that the values shown in the decision matrix are merely indicative and do not reflect the real values in the urban context examined, as the local authorities were unable to provide certified data. Thus, the sole purpose the application was to illustrate the computation method of the model used here.

Table 2. Decision Matrix

Objective functions	"Scenario 1"	"Scenario 2"	"Scenario 3"	"Scenario 4"
I1	1,200	1,344	1,152	1,248
I2	90	100	86	94
I3	113	124	108	113
I4	30	27	32	35
I5	2,011	2,011	1,890	2,313
I6	1	1	2	4
I7	21	24	22	18
I8	310	310	310	248
I9	25	25	25	19
I10	0.75	0.82	0.71	0.79
I11	0.139	0.129	0.146	0.139
I12	22	24	21	21

The next step involved calculating the Concordance Index (Ic) and Discordance Index (Id) for the different scenarios. When an equal weight is assigned to all targets, Scenario 3 proves to be the best alternative. In this case, the concordance and discordance indexes take a positive and negative value respectively, equal to 1.667 and -0.116.

4. Sensitivity Analysis

Once this preliminary analysis has been completed, the calculation is repeated, from STEP 7 to STEP 10, analyzing the different sets of weights.

Table 3. Concordance and discordance

Set of weights	"Scenario 1"		"Scenario 2"		"Scenario 3"		"Scenario 4"	
	Ic	Id	Ic	Id	Ic	Id	Ic	Id
Set 1	-0.167	-0.971	-2.333	0.928	1.167	-0.116	1.333	0.158
Set 2	0	-0.775	-2.467	0.862	1.533	-0.199	0.933	0.112
Set 3	-0.333	-0.845	-2.200	0.545	0.867	-0.067	1.667	0.368
Set 4	-0.200	-0.764	-2.200	0.799	0.733	0.174	1.667	-0.208
Set 5	-0.133	-0.665	-2.467	0.953	1.533	-0.107	1.067	-0.181

In the sets of weights 2 and 3, the targets with the highest weight are private and public transport users respectively. In these sets, the preferred alternative is scenario 3. In set 4 where the vulnerable road users is the target with the highest weight, the preferred scenario is scenario 4. In the last set 5 of weights, for both scenarios 2 and 3 the concordance index is positive whereas the discordance index is negative. Scenario 3 has the highest concordance index, while scenario 4 has the lowest discordance index. This indicates that both scenarios 3 and 4 are good solutions, but no single solution has been identified that satisfies one target better than another.

In weight set 4, the trade-off analysis allows to establish a distance of 1.640 between the indexes. In weight set 5 the distance is equal to 1248. Therefore scenario 3 is the preferred one.

5. Conclusion

The method is effective because it provides support for strategic decision making, to identify the best alternative solution among different scenarios. According to the model, scenario 3 appears to be the best solution. When equal weight is assigned, scenario 3 is the only alternative that has a positive concordance index (I_c) and negative discordance index (I_d). Therefore, scenario 3 better meets the expectations of the targets than all the other scenarios. In the subsequent sensitivity analysis, the weights of the targets are varied. The weight of each target is doubled with respect to the others. When the greater weight is assigned to the private and public transport user targets, scenario 3 remains the only dominant alternative. In fact, when the greater weight is assigned to the vulnerable road users, scenario 4 becomes the only preferable alternative. When the greater weight is assigned to the road administrator, Scenarios 3 and 4 have a positive I_c index and negative I_d index. Scenario 3 has the highest value of I_c while scenario 4 has the lowest value of I_d . None of the alternatives have the highest concordance index and the lowest discordance index thus generating uncertainty that requires further analysis of the value of the trade-off between the two indexes. Further analysis of the trade-off always indicates scenario 3 as the preferable alternative. This research work is the first step towards defining a single computation procedure for evaluating the overall performance of an urban road network for different operational areas. Other targets or different kinds of indicators could also be examined, but here we limited our analysis to identifying indicators that were more readily computable in order to obtain an easy-to-use tool. Further developments of the model are currently under way to improve the representativity of the indicators, while maintaining computational simplicity.

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