ANALYSIS AND EVALUATION OF RAPID TRANSIT SYSTEMS

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1. INTRODUCTION

Operational instruments and procedures capable of analyzing and evaluating a transit system became more and more necessary in view of the technical and economical recovery process of these systems which is under way in many countries. However the development of the above procedures has been considerably hampered by the subjectivity of the methodologies used, as the empirical character of the evaluation criteria implied.

Moreover these methods of analysis lack instruments aimed at collecting systematic, homogeneous and essential elements which are, essentially, needed to measure the relationships existing between the transit system and the city where it operates.

This paper presents the results of a research whose purpose is to offer a methodology of analysis and evaluation of the efficiency of a specific transit system (rapid transit) and which expresses the adequacy of the system to meet the city's needs. It is based on the use a systematic set of quantitative elements (measures and indicators) which define the physical, productive and economic characteristics of the system and its relationship with the city.

An application of the proposed methodology on metro systems in selected cities is presented; it can be used either for evaluating the reliability of the system, or it can represent a fundamental experimental tool for designers of lines and networks to perform comparative analyses or to utilize experiences from transit systems operations in other cities.

2. GUIDELINES

As already mentioned, the aim of the study is to offer a methodology for the analysis and evaluation of an urban transit system based on its adequacy to meet the city's needs.

For this purpose a procedure, which has already been partially experimented in previous studies by the author (see Musso and Vuchic (1), Corazza and Musso (2) and Musso(3)), has been carried out and can best be illustrated by the following logical phases as well as the flow chart in Table 1:

- Division of the transit system into three subsystems:
    - Physical subsystem (geometric characteristics);
    - Productive subsystem (technical performances and productivity);
    - Economic subsystem (economic and financial performances);

- Identification of the components to be analysed in each subsystem (Table 2);

- Selection and definition of functions (indicators) capable of analyzing and measuring each component (Tables 4,6 and 8), on the basis of the type of analysis to be carried out and of the characteristics of the system to be evaluated;

- Measurement of the average values of each indicator, on the basis of available data (statistics on current transit systems) (4);

- Measurement of the values of the indicators of the system under examination;

- Calculation of the deviations between the average values and the values of the system;

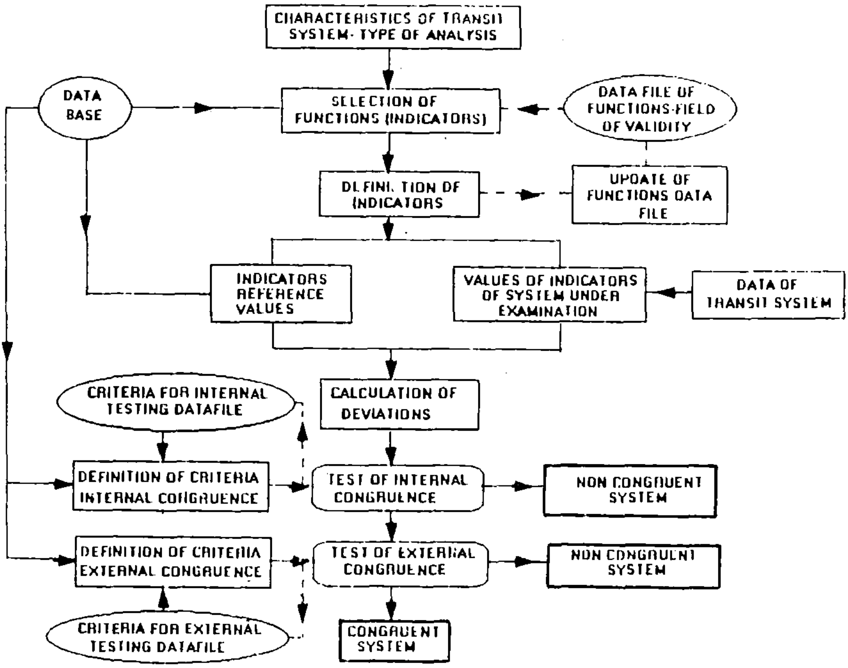

Table 1 - Flowchart of transit system evaluation procedure.

- Analysis of the internal congruence of the system;

- Analysis of the external congruence of the system.

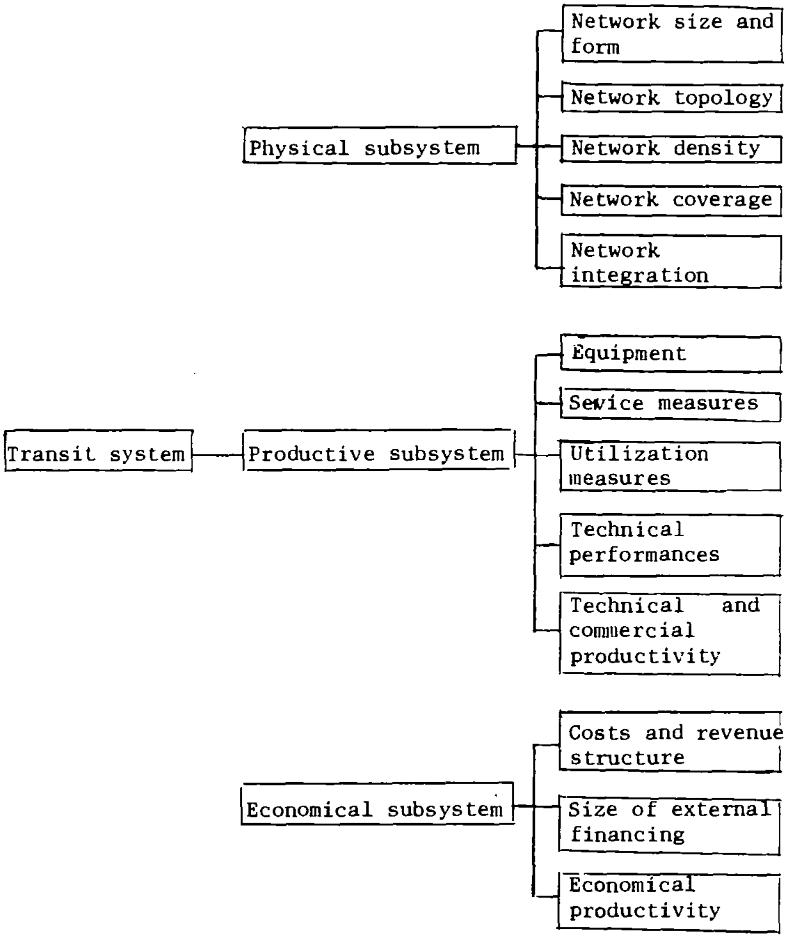

Table 2 - Analytical disaggregation of transit system.

The criteria underpinning this procedure can be summarized as follows:

- the division into subsystems and components enables the different characteristics of the system and its relationship to the external environment to be analysed separately and to utilize the procedure, for very specific aims (e.g., the analysis of the topology of the network for the evaluation of the impact of a new line or the analysis of economical indicators for evaluation of the impact of the fares increase);

- the utilization of a systematic set of quantitative elements (measures and indicators) , enables the anomalies of the system and their causes to be evaluated, albeit only in outline; these elements are chosen on the basis of the type and purpose of analysis to be performed and of the characteristics of the system to be evaluated. They are stored on a data file of functions which contains indicators of general nature taken from previous research of the author and from extensive literature available (see Botzow(5), Tomazinis (6), Vuchic (7) and Lehner (8)) and specific indicators tailor-made to fulfill the requirements of selected objectives;

- the existence of constantly updated functions (indicators), in addition to proving to be a fundamental tool for the correctness of the procedure , also increases its capacity and allows its utilization for analysing and evaluating specific characteristics of new systems (e.g. AGT systems); expert systems could help to develop a comprehensive package for the automation of this part of the procedure;

- the analysis of internal congruence makes it possible to check that every subsystem tends to reach, within the different strategic vision, not only its own optimal level but also a global target at a general level;

- the analysis of external congruence makes it possible to weigh up the impact of the various local constraints (structure of the urban area, political, social, economical and environmental characteristics etc.) on the system. Both criteria for testing must be defined for the specific purpose and selected from existing datafiles, which will also be constantly updated.

3. SELECTION AND DEFINITION OF INDICATORS FOR THE EVALUATION OF RAPID TRANSIT SYSTEMS

The following measures and indicators which will be defined have been selected because particularly useful in metro network planning and efficiency analyses and also because they most accurately reflect the relationship between the metro system and the city it serves.

3.1 Physical subsystem (geometric characteristics)

The utilization of theoretical concepts, particularly from graph theory (9), have lead to the definition of quantitative elements expressing a geometric representetion of metro network. They are grouped in table 3 (measures of size and form) together with the measures describing the city in which the system operates (population, area served) and those describing the size and quantity of the other transport infrastructures (length of other transit networks, number of transfer stations, etc.). They constitute the input for physical subsystem indicators.

N.	ITEM	SYMBOL
	<u>City features</u>	
1	Population of the served area	P
2	Size of the served area (km)	S
3	Number of metro transfer stations with other transit systems	N_t
4	Length of other transit networks (km)	L_s
5	Schematic map of network with stations	
	<u>Measures of network size and form</u>	
6	Number of lines in metro network	n
7	Number of stations in metro network (nodes)	N
8	Number of station spacings in metro network (arcs)	A
9	Length of metro network (km)	L
10	Metro average interstation spacing (km)	s
11	Number of circles in metro network	C_l

Table 3 - Items for analysis of physical subsystem

The indicators of network topology, network density, network coverage and network integration, which are grouped together and defined in Table 4, will be briefly described here.

a-1 <u>Circle availability - α</u> - represents the ratio of the number of circles (sections of lines comprising closed loops in the network) to the maximum number of circles which the network with the given number of nodes theoretically could have :

$$\alpha = \frac{C_l}{2N - 5} = \frac{A - N + 1}{2N - 5} \qquad (1)$$

This ratio varies from zero to unity: The greater the ratio the larger the number of actual circuits that a network has, and the larger the extent of interconnections the network has built into the layout of its arcs. Open networks with lines radiating from the central trunk lines (Atlanta, Rome, i.e.) have $\alpha = 0$.
The greater is, the more options passengers have to travel through the metro network : the complex Paris metro network has the largest α indicator of all cities, 0.11.

a-2 <u>Network complexity indicator - β</u> - is the ratio of the number of spacings (arcs) and stations (nodes) :

$$\beta = A / N ; \qquad \beta > 0.5 \qquad (2)$$

This indicator reflects complexity, in terms of the number of interstation spacings (arcs) as related to stations (nodes), of the network. Its minimum value of 0.5 is obtained on an elementary line with two stations; as the line is extended, adding more stations and spacings, β asymptotically approaches 1. On closed networks with cross-connections β can exceed the value of 1.

N.	INDICATOR	SYMBOL
	Network topology	
a-1	Circle availability	α
a-2	Network complexity	β
a-3	Network connectivity	γ
	Network density	
b-1	Density of metro network (km/km²)	L_m
b-2	Network extensiveness per population (km/P)	L_p
	Network coverage	
c-1	Area coverage	N_a
c-2	Density of access (km²)	D
	Network integration	
d-1	Street transit integration ratio	η_t
d-2	Metro extensiveness per total transit extensiveness	η_s

Table 4 - Indicators for analysis of physical subsystem.

a-3 Network connectivity γ - represents the ratio of the number of arcs existing in a network and the maximum number which could exist for the available number of nodes :

$$\gamma = \frac{A}{3\ (N - 2)} \ ; \ 0.33 \leq \gamma \leq 1, \text{ for } N > 2 \qquad (3)$$

Similarly to the indicator α, the more connections among nodes in the network there are, the greater is the value of γ. The network connectivity indicator γ is a little more comprehensible, because it focuses directly on nodes and avoids the concept of circuit.

b-1 Density of Metro Network - L_m - is the ratio of the network length to the area of the city. This indicator reflects the extensiveness of a network with respect to the area it serves, primarily center city; for regional networks this indicator is sometimes imprecise because of the difficulty in delineating the "served area" of the region. The indicator is defined as:

$$L_m = \frac{L}{S} \quad (\mathrm{km/km^2}) \qquad (4)$$

S is the area of the city or of the served area, as applicable.

b-2 Network extensiveness per population - L_p- expresses the ratio of network length to the population of the served area:

$$L_p = \frac{L}{P} \quad (\mathrm{km/P}) \qquad (5)$$

For cities with similar populations, greater value of L_p indicates a more extensive network and, usually, more utilized by the population (P).

c-1 Area coverage - N_a- is the percent of the served area (S) which is within walking distance of metro stations:

$$N_a = \frac{N\ S_l}{S} \times 100 \quad (\%) \qquad (6)$$

S_l being an area around metro station with a radius of 400m. (sometimes 500 m. of radius, is used as a standard). Equation (6) produces a number that varies between zero and unity. Where the sum of the area served equals that of the city, the network, obviously, covers the entire area (i.e. Paris) and its area coverage rating is 1, the maximum possible rating, and the desired rating for maximum efficiency for this network objective. Area coverage is the most important measure of the availability of metro services within the entire served area; this indicator is therefore used extensively in the planning of metro lines and networks.

c-2 Density of access to the network- D is the ratio of the served area (S) to the number of stations (N) of network :

$$D = \frac{S}{N} \quad (\mathrm{km^2}) \qquad (7)$$

This indicator evaluate an average amount of area for each access point of the system. The greater the number of access points in a network for a given area the smaller the system's density of access and thus the more satisfactory its area coverage.

d-1 Street transit integration ratio - η_t - is the percent of metro stations which have transfers to street transit lines (N_t as percent of N):

$$\eta_t = \frac{N_t}{N} \times 100 \quad (\%) \qquad (8)$$

This indicator shows the relative geometric and functional role the metro network has within the total public transport network in the city.

d-2 Metro extensiveness per total transit extensiveness η_s
This indicator expresses the importance of metro network in the larger context of the city's total transit system; it is represented by :

$$\eta_s = \frac{L}{L_s + L} \qquad (9)$$

Its value varies between 0 (when there is no metro in the city) and 1 (when the overall network consists of metro).

3.2 Productive subsystem (Technical performances and productivity)

This subsystem deals with indicators reflecting the efficiency with which resources are employed in order to provide a given service level and its attractiveness for the users.
Basic equipment measures, the typical measures of quantity and quality of offered service (speed, frequency, etc) and the characteristics of satisfied demand are presented in Table 5.
They constitute the input for the indicators of technical performances and productivity which are illustrated below in Table 6.

e-1 Maximum theoretical flow - φ is obtained as the number of places in a train of maximum composition multiplied the maximum freqency passing through a section of a line in one hour :

$$\varphi = f\, n_{tu} C_v \qquad (10)$$

The maximum theoretical flow of the various systems appear variable; its value is between 15.000 and 70.000 places/h.

e-2 Maximum hourly performance on network - K_m
If the same flow were produced throughout all the network (in both directions), the performance obtained would be :

$$K_m = 2\, L \varphi \qquad (11)$$

If each line in the network has a different flow, K_m is equal to the sum of the products of the flow on the single lines and the length of these lines (in both directions), or:

N.	ITEM	SYMBOL
	Equipment	
1	Units	U
2	Vehicle capacity	C_v
3	Staff	Ag
	Service measures	
4	Vehicle-km per year	V_k
5	Number of vehicles per train (TU)	n_{tu}
6	Commercial speed (km/h)	V
7	Frequency of service (trains/h)	f
8	Daily duration of service	H
	Utilization measures	
9	Passengers per year on metro	P_m
10	Average passenger journey (km)	l_m

Table 5 - Items for analysis of productive subsystem.

$$K_m = 2\ \Sigma_l l_l \varphi_l \tag{12}$$

K_m represents the maximum number of places-km ($PK = VK \times C_v$) that the system can produce in one hour.

Indicators e-1 and e-2 define the potential performance or the upper limits that the systems can reach when working at maximum capacity ; the following three indicators represent the actual performances or how these systems actually operate.

N.	INDICATOR	SYMBOL
	Technical performances	
e-1	Maximum theoretical flow	φ
e-2	Maximum hourly performance on network	K_m
e-3	Transport power on a line	W
e-4	Flow coefficient	Q
e-5	Load factor	F_l
	Productivity	
f-1	Technical productivity	P_t
f-2	Commercial productivity	P_c
f-3	Commercial performance	G

Table 6 - Indicators for analysis of productive subsystem.

e-3 Transport power on a line - W is expressed by :

$$W = \frac{n_{tu} C_v N_l V}{l_m} \quad (13)$$

where N_l is the number of trains operating on the line. Whith this indicator, expressed in places/h it is possible to evaluate how the system really works. In fact the flow (φ) does not highlight importance of the speed of the system on the user.
An example can better explain it (10) : "...an army parading on foot at a speed of 4 km/h in ranks of 20 men with each row 2 meters behind the other one, would have a flow of soldiers equal to a metro with trains each carrying 1,000 passengers at a commercial speed of 30 km/h with each convoy 1 km behind the other. The flow is of 40,000 passengers per hour and, considering that both systems operate continously, journeys over a given distance (i.e. 1 km) will have the same number of 40,000 passengers km/h. In this context both systems are equivalent. However, every soldier marches at a speed of only 4 km/h while each metro passenger moves at 30 km/h; consequently, each journey of 1 km will be completed in 15 minutes by each soldier and in 2 minutes by each metro passenger...".
Whith the same power, higher speed obviously means a smaller number of total places on the line.

e-4 Flow coefficient - Q indicates the percent of maximum potential passengers on a line who make their required journey in one hour.

$$Q = (1 - l_m / V) \quad (\%) \quad (14)$$

This measure is an index of evaluation of the total time loss for all passengers during one hour of operation.
The various networks in service provide a type of service that enable 75-90 % of maximum potential passengers to make their required journey in one hour.

e-5 Load factor - F_l expressesthe ratio between the average hourly performance ($\bar{K}$) and the maximum hourly performance on network K_m

$$F = \frac{K}{K_m} \quad (15)$$

where the average hourly performance K is obtained as a ratio of the places-km produced annually (PK) and the conventional annual duration of the service (365 x daily duration). The pattern of this indicator in systems currently operating reveals a substantial difference between groups of systems which tend to bunch together in two bands with average values of about 0.6 and 0.2.

f-1 Technical productivity - P_t is expressed by the relationship between the physical service produced (PK) and the manpower resources used (Ag):

$$P_t = \frac{PK}{Ag} \qquad (16)$$

f-2 Commercial productivity - P_c is expressed by the relationship between phisical service sold (P_m)and manpower resources used (Ag).

$$P_c = \frac{P_m}{Ag} \qquad (17)$$

f-3 Commercial performance - G is expressed by the relationship between the physical service sold (Passengers times average length of the journey) and the service produced (PK), both calculated on a year basis :

$$G = \frac{P_m l_m}{PK} \qquad (18)$$

This indicator is subject to marked effects of scale depending of the size of the system. Metro systems with network length of over 100 km present extremely low G values, ranging from 0.05 to 0.15 (the maximum value of G may not generally exceed 0.50 owing to the frequency of empty runs). This clearly results from the rigidity of a rail system of this size, and from the difficulty for it to adapt to the demand pattern in time and space terms (peak traffic, night traffic, etc.). Against this, networks of less 100 km are characterised by a clearly homogeneus behaviour pattern, with a G value between 0.15 and 0.25 for European and North American metro systems and of between 0.25 and 0.35 for Japanese metro systems.

3.3 Economical subsystem (econonic and financial performances)

The purpose of this subsystem is to supply general indications on profitability, economic management and financial policy of the transit firm. Table 7 contains the main items for economic analysis which make up the input for the indicators concerning the structure of the costs and revenue, the financial structure and economic productivity (Table 8).

g-1 Global performance indicator - R is expressed by the ratio between traffic revenues (T) and operating costs :

$$R = \frac{T}{C} \qquad (19)$$

N.	ITEM	SYMBOL
1	Total operating costs	C
2	Traffic revenue	T
3	Size of external grants	F

Table 7 - Items for analysis of economic subsystem.

h-1 Degree of financial dependance - Z is expressed by the relationship between the size of external grants (F) and traffic revenues (T):

$$Z = \frac{F}{T} \qquad (20)$$

This indicator shows the percentage of external funding of company activities and it reflects the power of the enterprise.

N.	INDICATOR	SYMBOL
	Costs and revenue structure	
g-1	Global performance indicator	R
	Financial structure	
h-1	Degree of financial dependance	Z
	Economical productivity	
i-1	Economic performance indicator	P_e

Table 8 - Indicators for analysis of economical subsystem.

i-1 Economic performance indicator - P_e is expressed by the ratio of the total costs (C) to the manpower resources (AG) used :

$$P_e = \frac{C}{Ag} \qquad (21)$$

4. OVERALL EVALUATION OF RAPID TRANSIT SYSTEMS

To illustrate the practical application of the procedure presented for evaluation of an existing rapid transit system, indicators described above have been computed in 3 cities (Milan, Nagoya and Oslo). The length of the network in the three cities is similar, while the topological structure, as can be seen from the network sketch in Table 9, is quite different. The Table also shows the deviations between the values of the indicators (normalized where necessary) computed in the three cities and the average values based on calculations from a representative sample of metro networks with dimensions similar to those under examination, which represent the average standards of service.

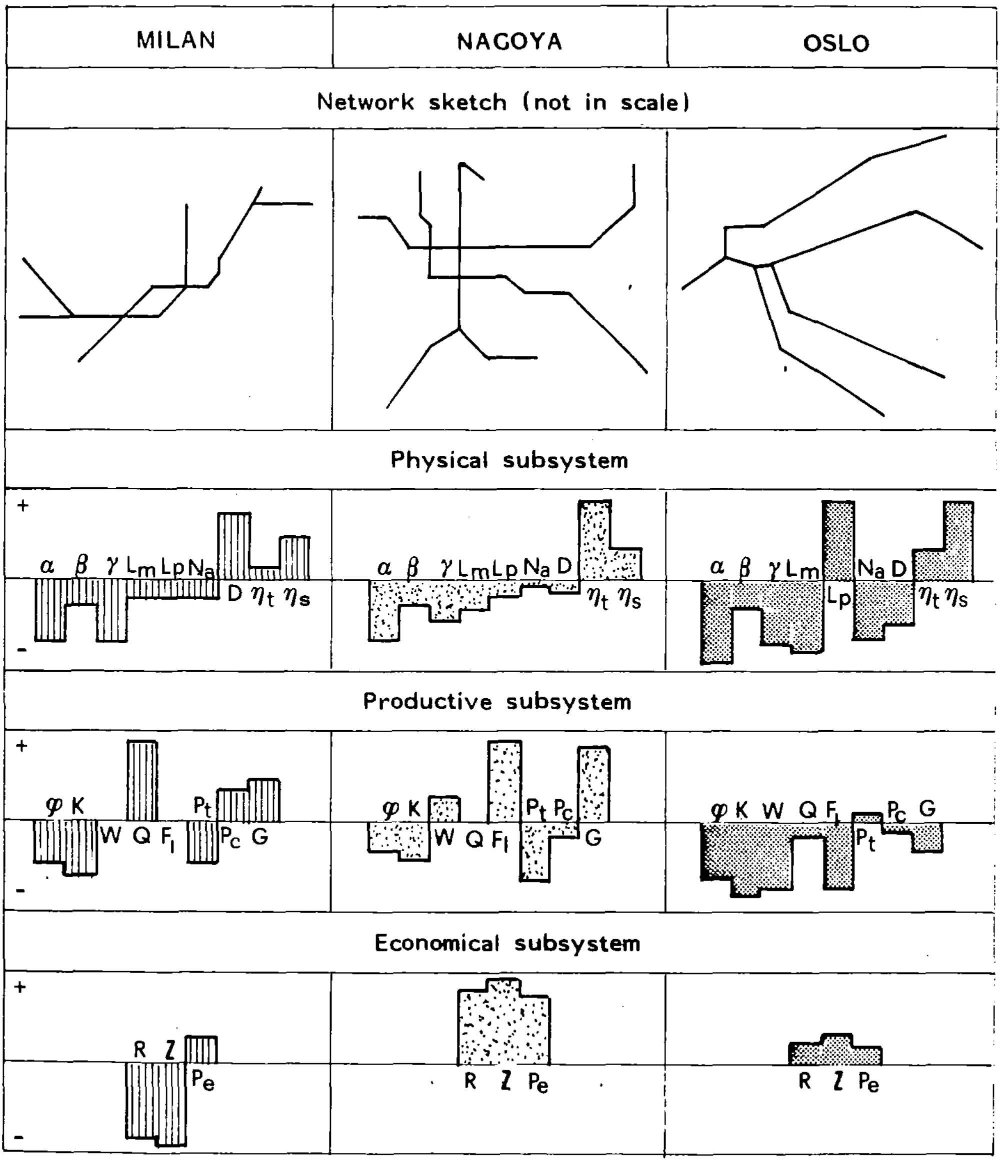

Table 9 - Example of evaluation of transit systems.

The measures presented in the table must be considered with caution since they are linked to a number of relevant local conditions and to external constraints within which the systems operate. For example, Oslo's "Metro extensiveness per population" indicator (L_p) is higher than the average as a result of a decrease in the population in recent years. Milan's economic-financial indicators are very low as a result of the government's policy concerning public transport and low fares in particular.
The final evaluation can only be reached after the overall sistem's congruence has been tested

To further illustrate the potential use of the procedure for planning and design of rapid transit systems, several typical applications are defined here and the most useful quantitative items for each type of analyses are summarized as follows:

- adding a new line to network: evaluation of its impact (α, β, γ, L_m, L_p N_a, D, η_t, η_s);
- selection among several alternative network extensions (N_a , D, η_t, η_s);
- planning a new metro network (all physical indicators presented).

5. CONCLUSIONS

A methodology for the analysis and evaluation of a transit system based on the utilization of a systematic set of functions (indicators) has been presented.

The disaggregrate approach offers the possibility to analyse the main features of the system, to evaluate the individual anomalies and briefly outline the causes which have given rise to them.

Moreover, the possibility of continuously updating the datafile of functions and the databases gives the procedure great potential and possibilities of generalized use.

Quantitative analyses capable of quick and easy measurements can assist in selecting a mode for a new service, in planning networks and appear desirable to facilitate both the daily management and the uniform improvement of public transport.

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