A COMPARATIVE ANALYSIS OF URBAN PUBLIC TRANSPORTATION SYSTEMS AND SERVICE QUALITY LEVELS

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1. INTRODUCTION

The ever increasing mobility requirements in urban and metropolitan areas, mainly with regard to operating speed and transportation capacity, makes it necessary to develop and set up technical-economic analyses based on new and more complete methods aimed at identifying the solution more suitable to the specificity of the situation under study.

To this end, several analytical methods were developed in the past. They were exclusively referred to supply and productivity parameters and did not take into consideration the degree of satisfaction of the users' needs, *desiderata*, and expectations. Because of this, such methods turned out to be rather limited, poorly reliable, and of little use when choosing and designing the system. Therefore, it is necessary to analyze in details the importance and the meaning of the parameters which do affect the choice of the transportation system and the user's satisfaction, not forgetting the implications that they may cause to the operator of the service.

In this paper a comparative analysis of the most widespread transportation systems and a methodological scheme for the assessment of the service quality are proposed. The first is based on a set of performance indexes (supply parameters), the latter is representative of users' behaviours and provides a tool to foresee the system choices.

The considered systems cover the variety of urban public transportation but the remarks developed therefrom go behond the particular system, maintaining completely their methodological validity and also allowing to evaluate *a priori* the impact of a hypothetical transportation system on the supply/demand binomial and, subsequently, to define its advantageous applicability field. In this way, the achieved results provide a supporting tool for the choice that local policy-makers and designers have to make in different urban configurations.

2. PRINCIPLES OF THE ANALYSIS

Each transportation system is characterized by three classes of parameters (or indexes), which represent:

- the **supply**, in terms of physical (structural and geometric characteristics) and operating parameters (mainly, transportation capacity and frequency) of the lines ;
- the **productivity**, through the economical and financial characteristics (e. g., cost and income per passenger and/or per passenger-Km);
- the **user's satisfaction**, expressed by all the parameters measuring the correspondence degree between the service quality level and the user's expectations. Such parameters can be synthesized by a mix where the relative weight of each of them is "subjectively" evaluated by the various segments of users in terms of perception/satisfaction of the quality offered by the transportation system.

It is appropriate to observe that the same indicator can be suitably used to characterize supply and user's satisfaction as well. Let us consider, as a symbolic example, headway which, besides characterizing the supply (with considerable economical implications for the operator), affects the user's opinion about the quality of the service enjoyed. Similarly, within the three macroclasses defined above, the same indicator can have a different, and even opposite, influence according to the subject which is referred to. For instance, the ratio "passengers carried/spaces offered" represents the productivity index of the system/service for the operator while, from the point of view of the user (travelling in strong overcrowded conditions), such a ratio affects in a highly negative manner the quality perceived and, therefore, the evaluation of the system.

2.1 Indicators of supply throughout the territory

Such indicators are representative of both the supply and the qualitative evaluation made by the passenger-customer. The ones mostly used in practice are related to the geometric characteristics of the system and, in particular, to its pervasiveness, i. e., the ability to cover adequately the served territory. In fact, the following quantities are usually considered:

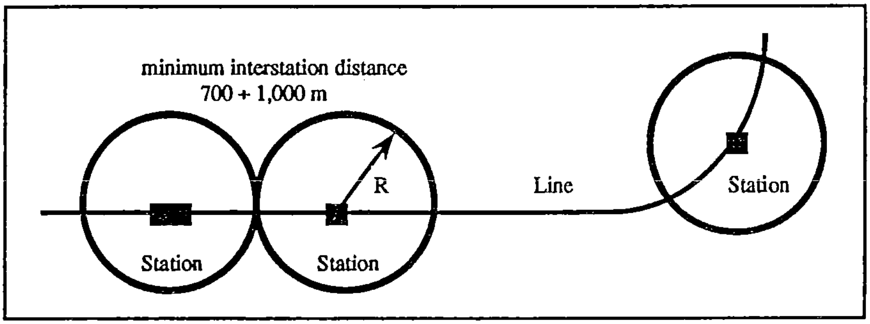
a)	served population	P
b)	size of the served area	A
c)	network length	L
d)	network density	
	- with respect to population	L/P
	- with respect to the area	L/A
e)	number of stations (stops)	S
f)	density of stations (stops)	
	- with respect to population	S/P
	- with respect to the area	S/A
g)	average interstation (stop) distance	S_a

"Population" means the served population, i. e., the one who fall within a predefined walking distance from the nearest station (stop), while the "served area" by a station (stop) is the one delimited by a circumference, the radius of which is not any longer than the fixed distance the user has to walk to reach the system. Such specifications are fundamental since the user is on the whole willing to walk a distance proportional to the total travel length (Origin/Destination distance), which usually ranges from 300 to 500 meters. Therefore, it is necessary to analyze the service areas of each station (stop), which is generally delimited by a circumference with variable radius and centre in the access point to the system. Figure 1 represents the spatial distribution of the service areas of the stations of a subway line. On the basis of such a simple consideration, the spatial distribution of the access points on demographically isotropic territories must have a minimum interstation distance of 700+1,000 meters in the case of subways, Light Rail Rapid Transit (LRRT) systems, and urban railways. Such values diminish to 400+600 meters for buses and tramways (in mixed traffic or in separated right-of-way), since the average length of the travel is shorter. On the other hand, longer interstation (stop) distances[1] can be preferred in the case of dishomogeneous distribution of the population on the urban territory, whereas shorter distances are not advisable since they would imply more or less extensive overlaps among different service areas.

Data in the literature [3; 5] show interstation subway distances between 580 meters (Buenos Aires, Argentine) and 1,800 meters (Cleveland, USA) and interstop tramway distances between 380 meters (Berna, Switzerland) and 680 meters (Hannover, Germany). Analogous comparative data for road public transportation are not available as yet. Moreover, it has to be considered that the average stations (stops) spacement is one of the factors which mostly affect the operating speed of the transportation system [2] and that the maximum speed and acceleration performances, apt to increase the operating speed by themselves, are faced by intrinsic restrictions due to the propulsion unit costs and the severe regulations about carried passengers' safety.

Figure 1

Spatial distribution of the service areas of the stations of a subway line



From the above, it becomes immediately evident how choice and design of urban public transportation must be strictly related to the characteristics of the served territory, in order to minimize the number of entrance/exit points and, subsequently, to increase the operating speed with respect to mobility demand and users' expectations.

2.2 Total door-to-door time

For the user, the variable which mainly represents the quality of an urban transportation system is the door-to-door time of the travel. In fact, since such a variable is the one mostly felt by the user, it affects her/his qualitative evaluation more than the speed itself (the speed of the mean and the total one), the rather complex quantification of which being task for the network designers and traffic control and regulation experts. The developed analysis has taken into account three categories of transportation systems, the door-to-door time of which being reasonably reckoned to have the same structure: 1) subways, LRRT systems, and urban railways; 2) tramways (in mixed traffic and in separated right-of-way); 3) buses (in mixed traffic and in separated right-of-way).

Moreover, the total travel time from Origin to Destination was articulated in the following components, corresponding to the various segments of the travel:

a) **access time**, i.e., the walking time from the Origin of the travel to the entrance to the transportation system;

b) **time of approach** (on foot and/or on hectometric systems) **to boarding platform at the entrance station;**

c) **waiting time;**

d) **boarding time;**
e) **on board time;**
f) **alighting time;**
g) **time of approach** (on foot and/or on hectometric systems) to **the exit of the system from the alighting platform;**
h) **exit time**, i.e., the walking time from the exit point of the transportation system to Destination.

Times related to possible intra-intermodal transfer were not taken into account, but they can be easily extrapolated by procedures similar to the described one. Observed data on the average walking speed give values equal to 1 m/sec. Such a value can appear reductionist [3], but it represents in a realistically precautionary way the standard capability/possibility for a person to walk. For the boarding/alighting times, an average total time of 30 seconds was established for the three categories, such a value being acceptable from experience. By hypothesizing uniform distribution conditions of the frequencies, the average waiting time at departure stations (stops) was evaluated equal to half of the headway. Therefore, once established the fixed components (boarding and alighting times, times to approach to platform - and viceversa - in case of subways), the variances of the total travel time have to be analyzed as functions of four characteristic parameters, which vary from a system to another: average length of the trip on board; operating speed; walking distance, at the entrance (exit) to (from) the system; headway. From the mathematical point of view, the probable presence of separated right-of-way (buses and tramways) and the differences between subways, LRRT systems, and urban railways are expressed as variations of the operating speed, thus proving the effectiveness of the aggregation of different systems with reference to the structure of travel times.

2.2.1 Subways, LRRT systems, and urban railways

For these systems, the walking times within the station play a fundamental role. Though they are extremely variable as a consequence of the specific design and organization of each station, they strongly depend on the distances "entrance-boarding platform" and "alighting platform-exit", on the height of stations with respect to the street level, and, in case of tunnel subway, on the depth of the underground stations as well. Therefore, the walking times within the stations range from 60 to 200 seconds, according with the plant design and the configuration of the system. In the present study, by adding the walking times in the entrance station to those in the exit one, a total time of 240 seconds was hypothesized, the latter being an average value which matches well with the variety of the existing plants. As far as the average travel length by subway is concerned, the data provided by the International Union of Public Transport (UITP) were used [5]. They show an average length varying between 4 and 9 Km for the 38 networks taken into consideration. In order to include in the same category subways, LRRT systems, and urban railways, average travels ranging from 5 and 15 Km were considered, since these distances cover almost the whole range of possible urban people movements. Because of the strong dishomogeneity recorded in different situations, for the operating speed a variability field from 18 to 56 Km/h was fixed, which, due to its extent, comprehends all possible solutions. Headways were made to range between 2' (minimum value corresponding to very high frequencies obtained in some cases) and 20' (value representative of the service during off-peak hours and/or in low population density areas).

2.2.2 Tramways

As far as trams are concerned, their operating speeds and average travel lengths are lower than those of subways, due to mixed traffic and/or to interferences of at-grade crossings. Consequently, values from 6 to 20 Km/h and from 1 to 6 Km, respectively, were assumed for such quantities. Headways were made vary from 3' to 20' in order to include also very low values recorded is some particular situations.

2.2.3 Buses

Because of the acceleration performances yielded by their propulsion units, buses usually present operating speeds higher than those of trams. Therefore, to consider all possible situations, speed values ranging from 6 to 40 Km/h were taken into account.

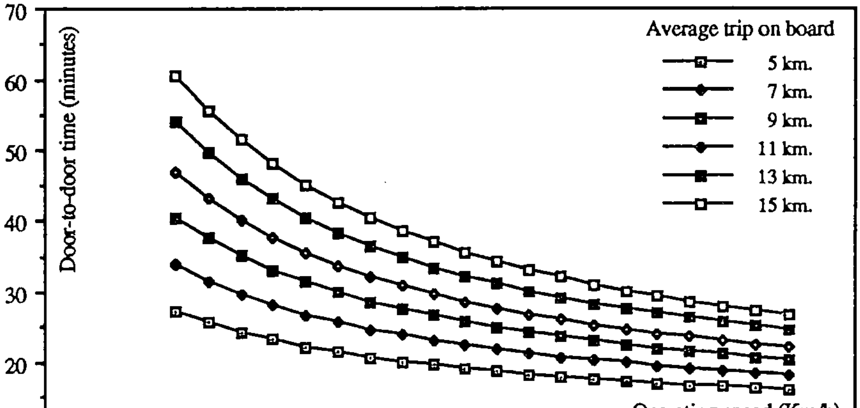
The average trip on board was considered equal to the one on tram, while for headway, which in some cases can be extremely reduced, the 1'+20' field was chosen.

2.2.4 Graphs analysis

"Door-to-door time/operating speed" graphs for subways were drawn with reference to an average walking distance to reach the entrance to the system of 300 meters (corresponding to 5 minutes). The analysis of the curves thus obtained (see Graphs 1 and 2, reported as an example) allows to establish that the total travel time is substantially independent of the average trip on board at high operating speed, while it is highly influenced at low operating speeds. Such a fact finds a logical explanation in the considerable influence of walking times (including those within the station, which cannot be avoided).

Graph 1

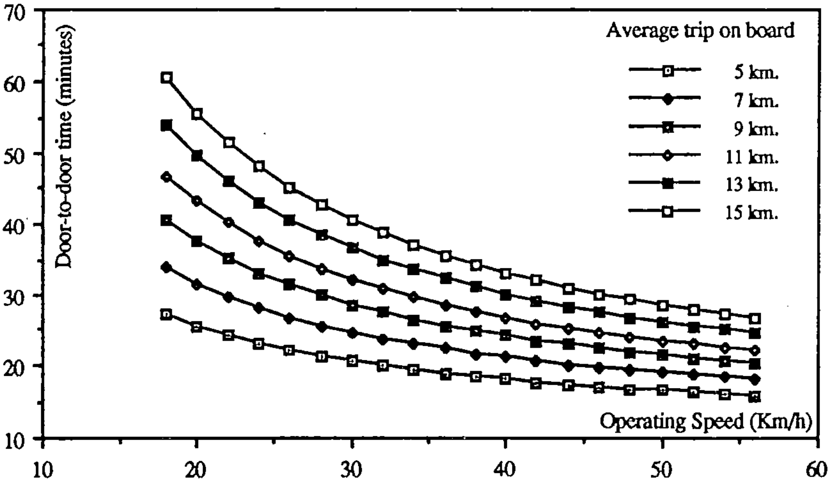
Subways, LRRT systems, and urban railways: door-to-door time as operating speed function (headway = 2'; average walking distance = 300 m



For the same reasons, the sensitivity of the service frequency to the total door-to-door time is reduced. In fact, by increasing headway from 2' to 20' (1 to 10 rate), the total travel time shows an average increase of only 20%. Nevertheless, it is necessary to point out that, although frequency increase has little influence on the total travel time, it corresponds to a proportional increase in transportation capacity, the latter being a parameter of both supply and user's satisfaction since it is linked with the probability of finding a seat. The average trip on board being the same, it is interesting to analyze also the sensitivity of the walking distances to reach the system access to the total door-to-door time. The distance to walk can affect remarkably (even up to 50%) the total travel time in the case of high frequency services (see Graph 3). By diminishing the frequency and increasing the average trip on board, such effect decreases (- 30% at the most), even if the total walking distance is increased (see Graph 4).

Graph 2

Subways, LRRT systems, and urban railways: door-to-door time as operating speed function (headway = 20'; average walking distance = 300 m



This fact suggests a network design focussed on placing the stations as near as possible to traffic attractors/generators centers and, at the same time, it plays a role in favour of the hectometric systems, which help to improve the plant look and the user's satisfaction, besides reducing the walking times. Under the same hypotheses, graphs similar to the above-described ones were obtained also for tramways and buses. In the case of tramways, with an average walking distance of only 300 meters, Graph 5 indicates for the door-to-door time that:

- operating speed has a remarkably higher effect than that of headway;
- average trip on board has a less influence than the operating speed one, i. e., speed increases are much more affecting than the increased length of the trips on board;

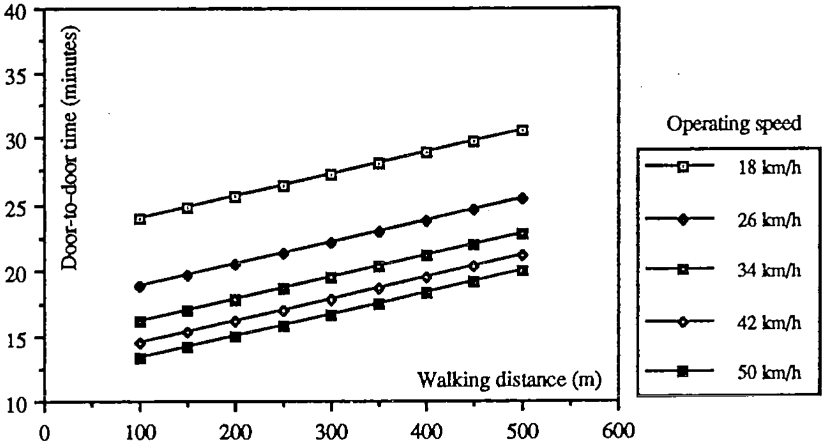
and, eventually, as far as the time is concerned, that it is more convenient to walk for distances of 1+2 Km even if the frequency of the service is very high (10+20 trams/h). Therefore, medium/long distances makes tramways advantageous in comparison with other urban transportation systems, even when service frequency is low.

For buses, Graph 6 shows that:

- in high traffic attractors/generators areas, buses services at high operating speeds and very high frequencies (60 buses/h) are to be always preferred;
- the sensitivity of the average length of the trip on board to the on board total time, little in itself, is inversely proportional to the operating speed.

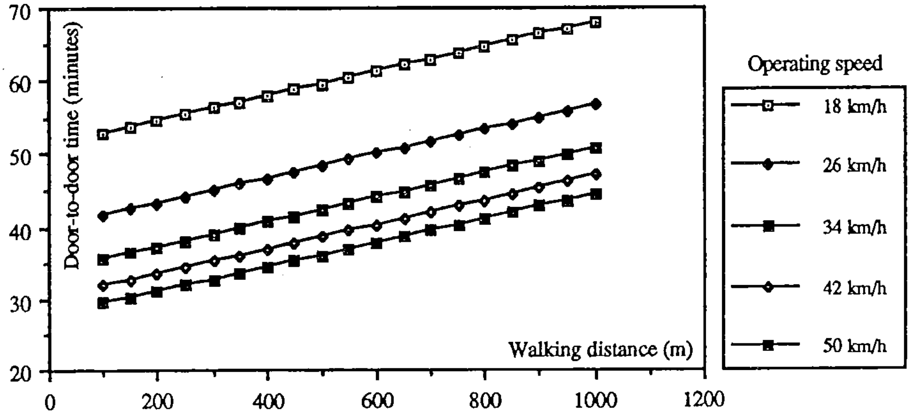
Graph 3

Subways, LRRT, and urban railways: door-to-door time as walking distance function (headway = 2'; average trip on board = 5 Km



Graph 4

Subways, LRRT systems, and urban railways: door-to-door time as walking distance function (headway = 20'; average trip on board = 11 Km)

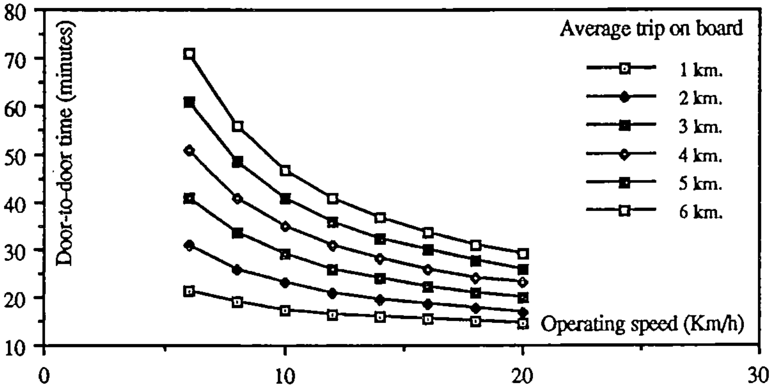


In order to increase operating speed and consequently to reduce the door-to-door time, it is appropriate to adopt separated right-of-ways, given for granted the convenience of walking in case of short distances (1÷2 Km) and low operating speeds. Service frequency, average trip on board, and walking distance being fixed, a comparison among the examined systems with respect to the offered door-to-door time was carried out.

Graph 7 represents, still as a demonstration, the comparison between buses and subways/LRRT systems/urban railways in the case of average trip on board = 5 Km, average walking distance = 300 m, and headway = 10' and 20'. At equal operating speed, subways, LRRT systems, and urban railways are disadvantaged by considerable time losses related to the distances "entrance-boarding platform" and "alighting platform-exit", thus presenting a total door-to-door time noticeably longer than buses.

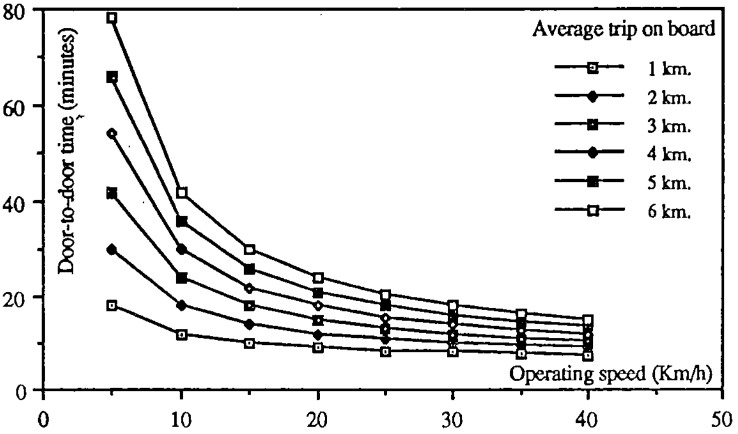
Graph 5

Tramways: door-to-door time as operating speed function
(headway = 12'; average walking distance = 300 m)



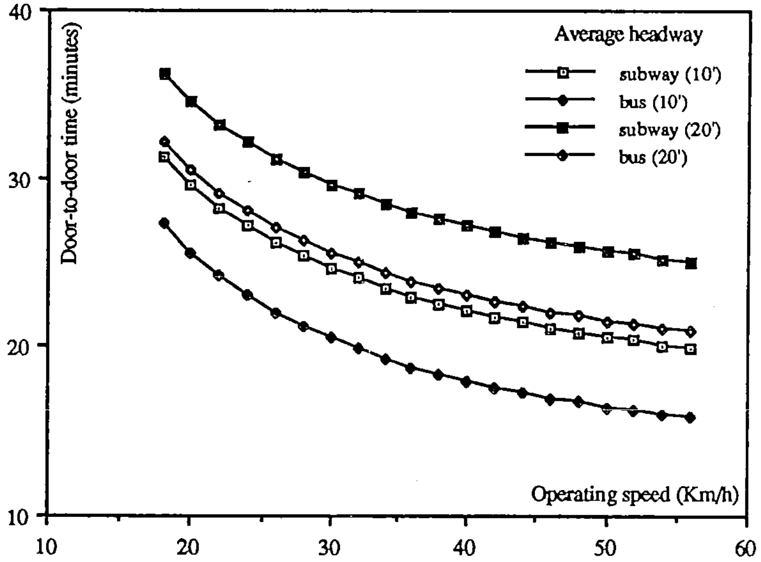
Graph 6

Buses: door-to-door time as operating speed function
(headway = 1'; average walking distance = 300 m)



Graph 7

Buses- subways/LRRT systems/urban railways comparison: door-to-door time as operating speed function (headway = 10' and 20'; average trip on board = 5 Km; average walking distance = 300 m)



From the graphs, which correspond to the range of urban transportation systems, it can be concluded that:

- subways, LRRT systems, and urban railways are not competitive on short and medium distances because of the long walking times within stations. They find their best field of application on long distances which other systems are not able to cover or when traffic conditions do not allow surface steel-on-wheel systems (in separated right-of-way) to run at full operating speed;
- subways, LRRT systems, and urban railways present transportation capacities clearly higher than that of the other two categories of systems;
- for trams and buses, the adoption of such solutions as separated right-of-ways or considerable stops spacements give rise to increases in operating speed and to decreases in total door-to-door time, which are quantifiable on the basis of diagrams and/or law of locomotion mechanics;
- psychological and subjective factors push forward one system or another, since the user's evaluation cannot be only related to the door-to-door time (or to the fare). Under this aspect, innovative systems meet with the ever-growing favour of the users, who appreciate their qualitative characteristics in terms of both service and technical solutions.

2.3 Productivity indicators

Productivity evaluation is usually referred to both technical and economical items and it can be expressed by absolute and relative quantities [1; 4; 6]. Table 1 reports a set of representative quantities concerning technical productivity. Such quantities, both theoretical and real ones, allow to characterize transportation systems within a time interval (T), the width of which varies according to the phenomenon under analysis (one or more peak-hours, standard day, week, month, year).

Table 1

Quantity	**Symbol**	$\dfrac{\textbf{Real value}}{\textbf{Theoretical value}}$
Flow on arc j	Φ_j	η_j
Flow on station i	Φ_i	η_i
Flow by network km	Φ/L	η_L
Transport power	ΦV	η_V
Specific transport power	$\Phi V/S_S$	η_S
Passengers-km	Φl_a	η_a

where:

- Φ_j = passengers carried in time interval T on any arc j;
- Φ_i = passengers carried in time interval T, whose travel has Origin or Destination at station (stop) i (i. e., arrivals and departures);
- ΦV = flow per operating speed;
- $\Phi V/S_S$ = transport power by section unit (S_S);
- Φl_a = passengers carried in time interval T per average length of the trip on the system (l_a).

The ratios between real and theoretical values are necessarily ≤ 1 also due to the fact that for any transportation system the Origin/Destination matrices of passengers travels coincide exactly with the offer only in exceptional cases. Such ratios provide information on the real exploitation level of the offered system and are inversely proportional to the degree of satisfaction of the users.

3. QUALITY SERVICE INDICATORS

The quality of a transportation system is measured by the ratio between the quality functions realized by the supply and the quality functions expected by the users, weighted by appropriate factors which take into account the users' perception degree [2; 4].

In case of additive functions, the quality of the transportation service can be expressed by:

$$Q_g = \sum_{i=1}^{n} \frac{F_{ri}}{a_i F_{ei}} \tag{1}$$

where:

- Q_g = global quality of the transportation service;
- a_i = weight of quality function i in the user's expectation/evaluation;
- F_{ri} = quality function i realized by the transportation service;
- F_{ei} = quality function i expected by the user-customer.

Expression (1) can be substituted by (2), in order to consider the overall combined effect of the variables representative of users' evaluation of the system/service:

$$Q_g = \prod_{i=1}^{n} \frac{F_{ri}(a_i)}{F_{ei}(a_i)} \tag{2}$$

The following three cases may occur:

- $Q_g > 1$ the quality of the offer is lower than expected by the user;
- $Q_g > 1$ the quality of the offer is better than expected by the user, but it is charged by extra costs for useless performances not required by the user;
- $Q_g = 1$ the offer meets, on the whole, the users' *desiderata*.

Situations in which $Q_g = 1$ may occur when realized and expected quality functions are indifferently higher and lower than 1 but their addition (or product) is equal to 1. Therefore, it is appropriate to consider equal to 1 also the ratios between functions which, in strictly algebraic terms, show a qualitative surplus of the offer with respect to the demand ($Q_g > 1$). In fact, only in the presence of such a condition, the values obtained by (1) or by (2) are fully representative of the subjective evaluations made by the user-customer on the quality of the transportation system/service. For some quantities, measures of the "user evaluation functions" do exist (e. g., delay probability for punctuality or failure probability for reliability), while for other quantities the evaluation is utterly subjective and difficult to be quantified, though the ratio of expression (3), which provides a measure of relative quality, can be always calculated:

$$\frac{\text{number of unsatisfied customers}}{\text{number of customers}} \tag{3}$$

Table 2 reports schematically the main quantities, which must be taken into account in formulating the above-mentioned quality functions F_{ri} and F_{ei}, which must be mediated with respect to the universe of subjects-customers, possibly divided by classes.

4. CONCLUSIONS

In order to assess, to choose, and to design urban public transportation systems it is necessary to consider, besides the ordinary parameters, other quantities which are fundamental for the demand/supply matching in quality. For example:

- the "total door-to-door time", which allows to differentiate systems according to their operating speeds, frequencies, and walking distances outside and inside stations (the latter in the case of subways);
- the "transport power" and the "specific transport power", which lead to a more accurate and complete evaluation of the technical productivity;
- the "system/service quality", which synthesize the subjective evaluations leading to the users-customers' choice and behaviours and which allow to characterize transportation systems behond their effectiveness and theoretical productivity.

In this view, it looks worthwhile setting up and validating, through *ad hoc* surveys for different space-time configurations, mathematic formulations apt to represent, in a more complete and reliable way, the quality functions realized by the transportation system/service and the quality functions expected and/or perceived by the user-customer.

Table 2

QUANTITY	INDICATOR
Time	Door-to-door time
Punctuality	Probability of delay
Reliability	Failure probability
Comfort	Density on board (prs/sq. m) - probability to find a seat Expression (3): e. g., for air-conditioning, acoustical treatment, and weather protection
Cleanliness	Expression (3)
Safety	Accident probability
Accessibily	Average time (or distance) from the Origin of the travel to the entrance station (stop) and viceversa
Modal integration	Number of transfer - waiting time at inter/intramodal transfers
Service availability	Number of daily working hours - frequency Expression (3): e. g., for distribution of working hours during the day
Treatment (station/on board)	Expression (3): e. g., for courtesy and professionalism of the staff

5. ENDNOTES

1. The arc width is a function of the number of residents and/or activities set up in the service area of the single station (stop).
2. In fact, the operating speed is related to the stations (stops) spacements through the time diagram of mean movement.
3. In the case of flat path, without obstacles and with one way flow, it can be generally assumed an average walking speed of 1.25 m/sec.

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