A SYSTEM SELECTION MODEL OF AN URBAN TRANSIT ROUTE

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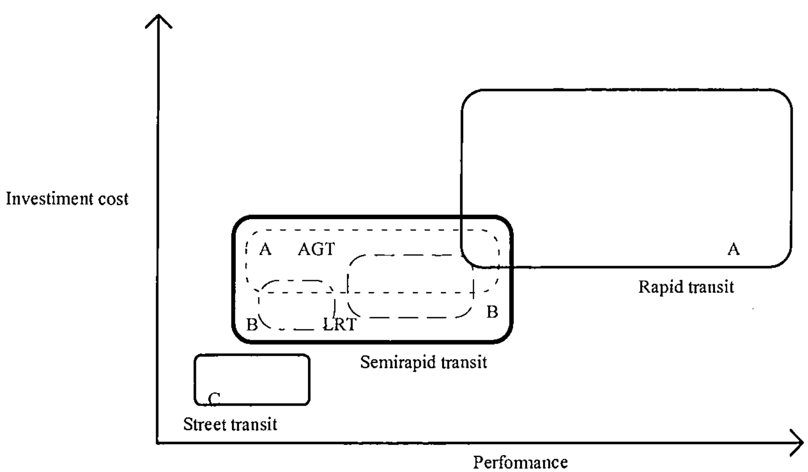
Abstract

For the selection of the urban transit system an analytical model has been developed in order to minimize different objective functions: Generalized User Cost (GUC), Transit Company Cost (TCC), Local Authority Cost (LAC), Central Government Cost (CGC).
Different expressions of the cost (user travel time, service cost, investment cost) will be considered depending on the selected objective function. Every kind of cost is an analytical function of relevant service variables as frequency, number of stops, vehicle size, route length, and travel length. An analytical model applied to main transit systems (bus, tram, LRT, AGT and subway) for one project variable (selected between the relevant ones) permits to define the minimum cost system for the input demand value.

INTRODUCTION

The design of a transportation system can be treated as an optimisation problem with an objective function to optimise and a set of constraints to satisfy. The objective function represents the point of view of the decision maker. The set of feasible solutions is represented by the technical and economical solutions for each one of the different objectives. Solving the mathematical model is the final step that measures the impact on different objectives of the feasible project solutions.
The model deals the system choice of a single transit line, stating that demand distribution and route characteristics are known and fixed. Problems related to network integration are explicitly not considered (Remak 1975). Mode selection depends on the level of service of the whole urban transit system. In fact a transport system, the more is composed by different modes, each one used in the demand interval in which is efficient, the better.
In this paper it will be assumed that every transport system (bus, tram, LRT, AGT, metro) will be used in the demand interval which permits the system to be more efficient. The transport designer must define a choice criterion which takes care of all the system requirements and conflict points. Comparisons and final assessment criteria can be defined in monetary, quantitative and qualitative units. Vuchic (1988) points out a set of rules to follow in the transit system selection. The output of this process is a graph in which the transportation systems are compared in function of costs and performances (Figure 1). Walbridge (1981) divides the process of selecting a technology for a transit system into two steps. The first is to identify from the wide variety of technology options those options that meet the demand and service requirements of the need being compared and do so at a cost which is reasonable in terms of the demand. The set of technology options thus identified consists of suitable alternatives for the need. The second step is a detailed study of the alternatives in the suitable set to determine the best (considering constraints) technology for implementation. The statement that a technology is suited to, or suitable for, a particular situation, means that the technology meets the demand and service requirements at reasonable cost. The cost of a technology here means the total (capital plus operating) cost per ride.



A-Rail rapid transit; B-Bus and LRT; C-Private car
AGT-Automated guided transit

Figure 1 Investment costs and performances of different urban transport systems.

The two examples described are exclusively methodological and they set in detail the steps which the planner has to follow selecting and designing a transit system. The most important step is the choice of a selecting criterion. Setting a selecting criterion is the same as formulating an objective function to optimise. The objective function can be defined as a Generalised Transit Cost Function (GTCF), that includes different components according to the role of the decision maker. Before formulating an objective function it's necessary to set the system relevant variables, that are the characteristics of the different transportation systems, and the relations between them.
The problem is that these parameters are linked by relations that form an undetermined system. The development of the study starts from the identification of these relations using simplified models (Carrese S. ,1995; Carrese et al, 1997). The main parameters which characterize different transit systems are the following : maximum speed, operational speed, transport unit capacity (Jansson J.O.,1980), line capacity, stop distance (accessibility) (Ling J. H. and Taylor M.A. P.,1988). Simplifying the problem to the four main parameters, literature supplies with different models which express one variable in function of the others.
De Luca (1989) determines the commercial speed on the base of the vehicle kinematics performances. Fleet characteristics can be calculated or with the Bly-Oldfield's model (1988), whose output is the vehicle optimum capacity obtained minimizing the users total cost plus the operational cost, or with the Kikuchi-Vuchic's (1982), which requires the frequency and the stops number to have the vehicles number necessary to the service. Kikuchi (1985) in other models determine the line frequency by the vehicle capacity and the optimum stops number in a calling stop regime. All the characteristic parameters of an urban transit line are linked, by a series of hypothesis, in a single function which represents the total transport cost for the community. This function is the set of the analytical relations existing between the system parameters.
Ticket revenues have not been considered in the development of the model because of the assumption of same fare for different transportation systems. This is a realistic hypothesis implemented in many Italian cities where the study takes references.

DEFINITION OF THE OBJECTIVE FUNCTION

The total cost (Figure 2), C_{tot}, is the sum of the investment cost for the infrastructure realization and vehicles acquisition, C_i, the operational cost including service and maintenance, C_o, and the expected value of the user cost, C_u. The user cost is the sum of three components: access cost, U, waiting cost, W, and travel time cost, R.

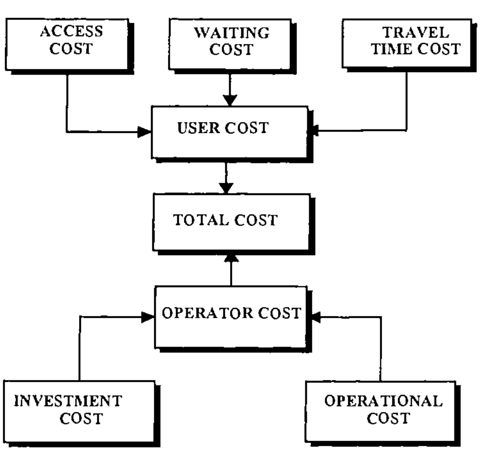


Figure 2 Components of GTCF

Then the total cost in aggregated form presents the following expression.

$$C_{tot}= C_u+C_{op}=C_i+ C_o+ U+W+R \quad (1)$$

Because of the time dependent value, every cost will be referred to a time unit. Further it will be assumed that the access area for every stop of every mode is a circle with a known radius (e.g. 300 m for the bus, 500 m for the metro).
The average demand rate per time unit, P, will be known and although it is implicitly dependent on the chosen time interval, it will be assumed that P does not influence the strategy. On the base of these hypothesis it has been developed the analysis of the total cost components.

User cost: access and exit cost

The access cost is the monetary equivalent of the time spent by the users to get to the stop. If the line access area is assumed as a following of circles whose diameter, equal to the average stop distance, D, tangential and with the center set in the stops, the average travel length, u, is equal to a fourth of the average stops distance

$$u = \frac{D}{4} = \frac{L}{4 \cdot n} \tag{2}$$

L is the route length and n is the stops number.
If it is assumed that users P don't have any information about the line schedule and they choose in any case the nearest stop, the access and exit cost is

$$U = \gamma_a P\left(\frac{L}{2nw'} + t_m\right) \tag{3}$$

in which $\frac{L}{2nw'}$ is the access plus the exit time, t_m is the time spent for the movements inside the stations (t_m=0, for bus and tram) ; γ_a is the access cost per passenger per time unit, w' the average passenger access speed.

User cost : waiting cost

The waiting cost is the monetary equivalent of the time spent by the users at the stop, waiting for the vehicle. If the vehicles frequency is constant and if the users have no information about the schedule, they arrive to the stops at an uniform rate and the average waiting time is equal to half the headway. The average waiting cost is

$$W = \gamma_w P \frac{h}{2} \tag{4}$$

in which γ_w is the waiting cost per passenger per time unit, h the headway.

User cost : travel time cost

The travel time cost is the monetary value of the time spent by the users on the vehicle. This cost is assumed to be proportional to the time spent on the route. Its math expression is

$$R=\gamma_t Pt \tag{5}$$

with γ_t travel time cost per passenger per time unit, t average weighted travel time. The average travel time t is got multiplying the ratio between the average length covered l and the total route length L by the total route time of the vehicle , T

$$t = \frac{l}{L} T \tag{6}$$

The route time can be divided in three components :
Travel time, T_c, at constant speed V, along the whole length L, between the headlines

$$T_c = \frac{L}{V} \tag{7}$$

Additional time due to acceleration and braking, at each stop, T_P. Braking time at average deceleration rate d from the speed V and acceleration time at a rate a to the speed V, is

$$t_{ad} = \left(\frac{V}{a} + \frac{V}{d}\right) \tag{8}$$

To formulate the additional time due to the vehicles stops, it has been considered a constant acceleration and deceleration rate and the trapezoidal speed-time diagram. The station to station travel time t_D, is the sum of t_{ad}, and the time necessary to cover at a constant speed V the distance between stations s_v:

$$t_D = t_{ad} + \frac{s_v}{V} = V\left(\frac{1}{a}+\frac{1}{d}\right) + \frac{D}{V} - \frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right) = \frac{D}{V} + \frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right) \quad (9)$$

The additional time due to the acceleration and deceleration per each stop, compared to the time spent to cover the same distance at the constant speed V is

$$t_p = \frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right) \quad (10)$$

The total route time due to the stops T_p is

$$T_p = n_{ef} t_p = \frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right) n_{ef} \quad (11)$$

in which n_{ef} is the average stop number. $n_{ef} = n\left(1-e^{-\frac{2Ph}{n}}\right)$ for a calling stop regime ; $n_{ef}=n$ for a fixed stop regime.

The total time spent at the stops along the route is the sum of the time spent at each stop

$$T_s = \frac{2Phb}{n_p} \quad (12)$$

where n_p is the number of doors per vehicle and b the boarding time per passenger.

Therefore the total travel time is

$$T = T_c + T_p + T_s = \frac{L}{V} + \frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right) n_{ef} + \frac{2Phb}{n_p} \quad (13)$$

Investment cost

The investment cost can be divided into two components, the vehicle cost x_v (Lit/vehicle) and the infrastructure cost x_l (Lit/Km). Investment costs have to be divided by the operative life time, t_{al} and t_{av} (years). The goal of the study is not a financial analysis of the investments but a comparison between all of the cost components on a common period of time; therefore, for an easy calculation the yearly investment depreciation is assumed uniformly shared during the infrastructure and vehicle operative life, without considering interest rate and inflation.

The infrastructure cost C_i is proportional to the cost per length unit γ_l

$$\gamma_l = \frac{x_l}{1000 \cdot t_{al}} \quad (14)$$

$$C_i = \gamma_l \cdot L \quad (15)$$

The single vehicle cost x in Lit/sec is

$$x = \frac{x_v}{t_{av}} \quad (16)$$

It hasn't to be forgotten that, for a transport system with a shared right of way, an increase in the vehicles number produces an increase of the congestion. If y is the coefficient relating congestion cost to a single vehicle (per time unit), the indirect cost due to congestion is calculated multiplying y by the number of vehicles, N.

The investment cost is

$$C_i = \gamma_l L + (y+x)N \quad (17)$$

Operative cost

If T_G is the run trip time per vehicle and $k>1$ is the coefficient needed to increase the number of vehicles, the fleet is composed by N number of vehicles

$$N = k\frac{T_G}{h} \tag{18}$$

The run trip time, T_G, is the double of the sum of the travel and stop time plus the time spent at the headlines (T_b).

$$T_G = T_c + T_p + T_s + T_b = 2\cdot\left\{\frac{L}{V}+\frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right)n_{ef}+\frac{2Phb}{n_p}\right\}+T_b \tag{19}$$

The line vehicles number is proportional to the frequency, f (number of vehicles per time unit), $N=fT_G$.

In order to calculate the minimum frequency the demand P_{max}, on the maximum loading section is divided by the transport unit capacity, C_v, multiplied for the load factor α.

$$f = \frac{P_{\max}}{C_v\alpha} \tag{20}$$

The maximum load, P_{max}, is proportional to the route demand, P, by the factor m which depends on the demand distribution $P_{max}=mP$.

The headway, h, is the inverse of the frequency, f,

$$h = \frac{C_v\alpha}{mP} \tag{21}$$

Therefore the operative cost , C_o, is

$$C_o = \gamma_o N = \gamma_o\frac{T_G}{h}k \tag{22}$$

where γ_o is the average operative cost per vehicle and per time unit.

In conclusion the expression of the total cost is:

$$\begin{aligned} C_{tot} &= \gamma_i L + (x+y+\gamma_o)\frac{k}{h}\left(2\cdot\left\{\frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right)n_{ef}+2Ph\frac{b}{n_p}+\frac{L}{V}\right\}+t_b\right)+ \\ &+P\left\{\gamma_t\frac{l}{L}\left(\frac{V}{2}\left(\frac{1}{a}+\frac{1}{d}\right)n_{ef}+2Ph\frac{b}{n_p}+\frac{L}{V}\right)+\gamma_w\frac{h}{2}+\gamma_a\left(\frac{L}{2nw'}+t_m\right)\right\} \end{aligned} \tag{23}$$

THE MODEL

The main criterion of system selection is the minimization of the total costs. If a first constraint on the satisfaction of the whole possible demand for the design route is introduced, the total cost function selects the appropriate transportation mode for different demand intervals. A capacity constraint must then be considered in the decision making process, so that every transportation mode presents a service upper bound which maximizes the system productivity.

The expression (23) of the total cost function refers to the most general point of view of the Central Government. In this case all the cost components are present in the general expression. It can be useful to consider the objective functions relative to other subjects involved in decision making and some term of the (23) will not be taken in account. In order to perform this sensitivity analysis, the following total cost function have been developed: Generalized User Cost (GUC), Transit Company Cost (TCC), Local Authority cost (LAC) and the Central Government Cost (CGC) which is right the expression (23).

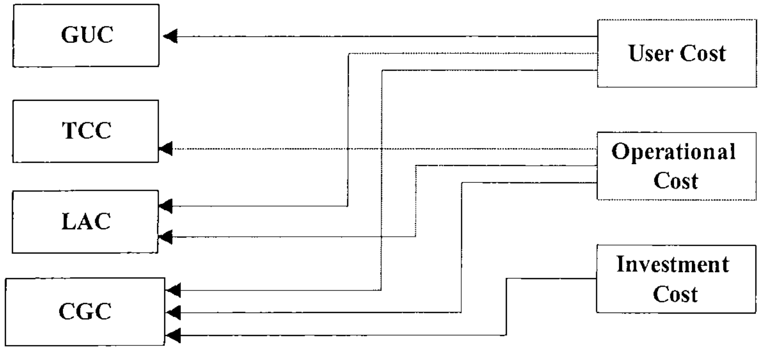


Figure 3 Relationship between total cost components and different decision makers

Depending on social, economical, political, or technological instances one of the subjects can became the decision maker and the relative total cost function will be minimized. For example the lack of capitals will help the use of low investment systems, so that the user will be penalized by a lower level of service.
Referring to the (1) which is relative to the CGC function, in Figure 3 it is shown how the expressions of GUC, TCC and LAC have been built.
The model must be able to determine for a given route the demand interval in which a transport system is more convenient, according to a selected objective function (GUC, TCC, LAC, CGC) and its system constraints. The proposed model is able to deal only one of the main variables as independent one, and all the others will be expressed as dependent. The main variables are the headway h, the number of stops n, the vehicle capacity C_v, the route length L, and the average travel length l.
The characteristic parameters of vehicle technology are considered fixed; e.g. acceleration a, deceleration d, number of doors n_p, etc. Other fixed parameters are demand characteristics (demand and space distribution), access speed, time cost per category, investments cost, operational costs per unit, congestion cost, etc.

The cost model for the system selection of an urban transit route can be summarized in the following steps (Figure 4).

1. Objective function. Determination of the objective function, GUC, TCC, LAC, CGC.
2. Relevant variables. Definition of the relevant variables between the ones present in the objective function, $X=x_1.....x_i......x_j$.
3. Project variable choice. Choice of the project variable, x_i between the relevant ones.
4. Existence range of the project variable. Determination of the existence constraints of the project variable, $x_i=x_{min},....x_{ik},....x_{Max}$.
5. Demand. Definition of the demand, P, characteristics : spatial distribution along the route, time distribution (week, day, hour), user characteristics (time cost, access speed).
6. Analytical cost function. Choice of the cost function that represents the objective function, $C(P,X)$.
7. Transport systems. Setting of the transport systems to compare and the values of their parameters, $M_1.......M_n$.
8. Capacity constraint. Determination of the maximum capacity of the chosen systems. If the maximum speed for a stated level of service is fixed, the system characteristics determine the minimum headway between the vehicles, $h_{min1}.......h_{minn}$. The maximum capacity of each system, $P_{M1}, P_{M2},......P_{Mn}$, is calculated with the equation $P_{Mn}=C_{vn}\alpha/h_{min}$
9. Comparison order. Numbering of the systems on the base of their increasing capacity $P_{M1}<P_{M2}<......<P_{Mn}$. They are compared in demand range progressively increasing. Consequently their number decreases.

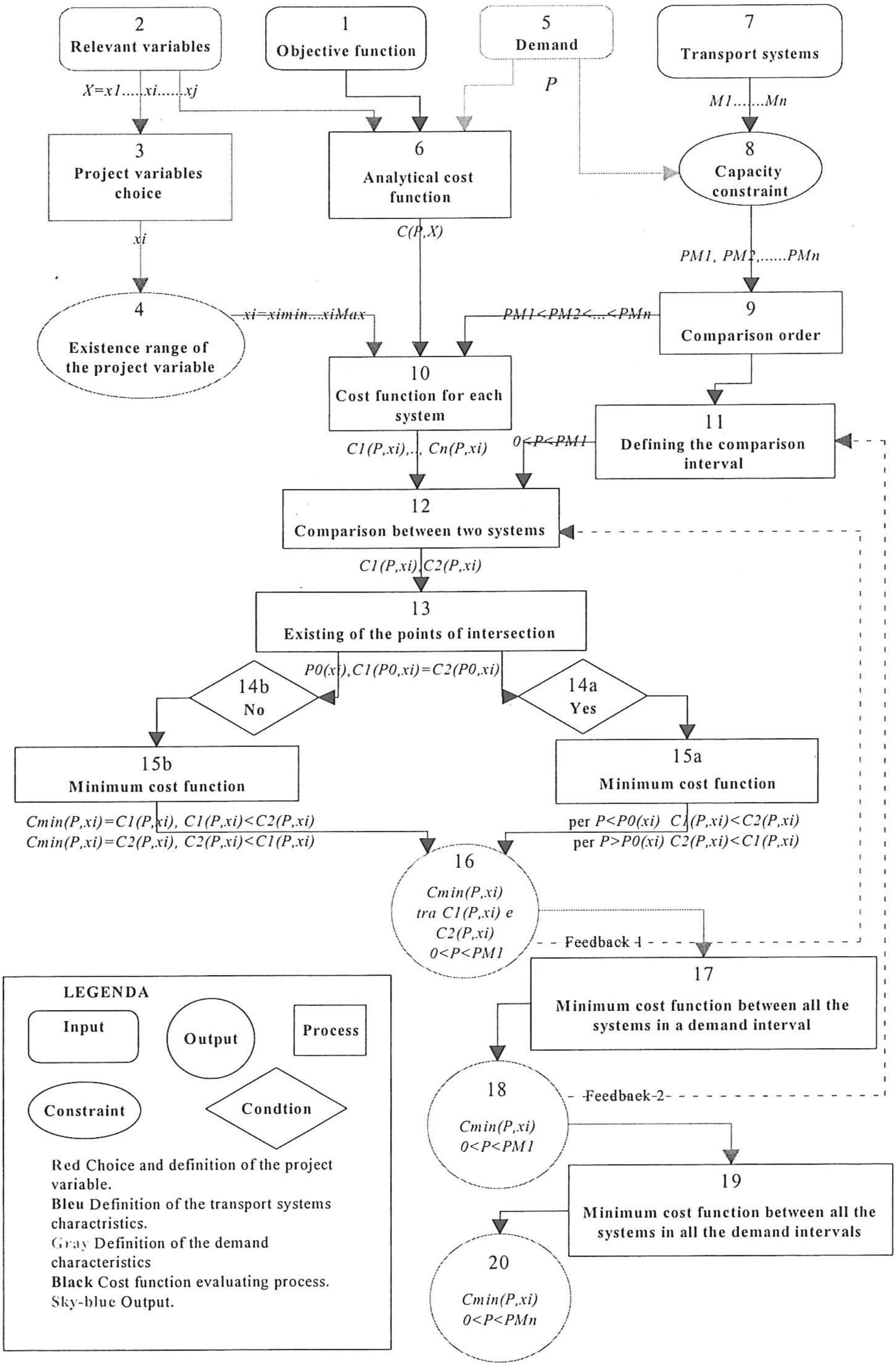


Figure 4 Model for the system selection of an urban transit route

E.g. For $0<P\leq P_{M1}$ it can compare systems $M_1, M_2..........M_n$,
for $P_{M1}<P\leq P_{M2}$ systems $M_2, M_3........M_n$, and so on.

10. Cost function for each system. Determining the cost function of all the modes, for the fixed decision making goal, as a function of the project variable $C_1(P,x_i),........, C_n(P,x_i)$, with P varying in the system capacity interval, (for example $M_1 \Rightarrow P=0.......P_{M1}$) and x_i assuming the values for which is defined, $x=x_{imin}.......x_{iMax}$.
11. Defining the comparison interval. Demand and existence intervals of every modes are compared starting with the smallest. If, for example, $P_{M1}<P_{M2}$, it doesn't make sense to compare the two systems, M_1 and M_2 in the interval $0\leq P\leq P_{M2}$ because for $P>P_{M1}$, M_1 can't satisfy the required capacity. On the contrary it is important the comparison in the interval $0\leq P\leq P_{M1}$ because in this one it is possible to find some values of P over which M_2 can be more advantageous than M_1.
12. Comparison between two systems. Starting with the smallest demand interval, systems are compared, two by two, in conformity with the fixed order.
13. Existing of the points of intersection. Finding out of the demand values $P_0(x_i)$, for which a system become more advantageous than another one, varying $x_i=x_{imin}.........x_{iMax}$. Considering modes M_1 and M_2 with the respective cost functions $C_1(P,x_i)$ e $C_2(P,x_i)$ in the capacity interval $0<P\leq P_{M1}$, for each value of x_i there is a demand value, $P_0(x_i)$, such that $C_1(P_0,x_i)=C_2(P_0,x_i)$.

14a. Exist.

15a. Minimum cost function. Given a value of the project variable $x_i= x_{ik}$ it emerges that
for $P<P_0(x_{ik})$ $C_1(P,x_{ik})<C_2(P,x_{ik})$
for $P>P_0(x_{ik})$ $C_2(P,x_{ik})<C_1(P,x_{ik})$
It is carried on a graph the function $P_0(x_i)$ which represents the points x_i and $P_0(x_i)$ over which $C_2(P,x_i)<C_1(P,x_i)$

14b. Don't exist

15b. Minimum cost function. If the equality $C_1(P,x_{ik})=C_2(P,x_{ik})$ is not verified for any value of P, it is carried out the equality in the range in which is defined x_i, $x_i=x_{imin}.......x_{iMax}$; if there aren't convergence values of the cost functions C_1 and C_2, the system, which has the minor cost function, is the optimum in the whole demand interval $0<P\leq P_{M1}$.

16. Output 1 : $C_{min}(P,x_i)$ between $C_1(P,x_i)$ and $C_2(P,x_i)$ for $0<P\leq P_{M1}$
Feedback 1. Coming back to step 12 and proceeding with the comparison between all the different pair of modes in the interval $0<P\leq P_{M1}$.
17. Minimum cost function between all the systems in a demand interval. After having compared the modes $M_1,......,M_n$ it is determined the minimum cost function in the interval $0<P\leq P_{M1}$.
18. Output 2 : $C_{min}(P,x_i)$ between $C_1(P,x_i)$ and $C_n(P,x_i)$ for $0<P\leq P_{M1}$.
Feedback 2. All the systems are compared in every demand interval.
19. Minimum cost function between all the systems in all the demand intervals. All the systems $M_1,......,M_n$ are compared in every demand interval. It is determined the minimum cost function in the interval $0<P\leq P_M$.
20. Output 3 : $C_{min}(P,x_i)$ between $C_1(P,x_i)$ and $C_n(P,x_i)$ for $0<P\leq P_M$.

MODEL APPLICATIONS

The model has been applied to different cost functions and project variables comparing the four most common urban transport systems, bus, tram, LRT and metro. In Table 1 the values of the systems parameters are shown as they are used in the applications, including the values of the relevant variables when they aren't chosen as the project one. These values are referred to real operation data gathered from Rome's main public transport companies

Table 1 Transport systems parameters (1 euro = 1936 Lit)

PARAMETERS	BUS	TRAM	LRT	METRO
γ_i [Lit/pass-sec]		1.5		
γ_a[Lit/pass-sec]		4.5		
γ_w[Lit/pass-sec]		4.5		
w' [m/sec]		1		
α		0.9		
k		1.2		
L [m]		15,000		
l [m]		5,000		
b [m/sec]	1.2	1	1	0.8
n_p	2	4	4	15
a [m/sec^2]	0.5	0.8	1	1.2
d [m/sec^2]	0.5	0.8	1	1.2
V [m/sec]	40	50	60	80
t_m [sec]	/	/	/	150
T_b [sec]	300	300	300	300
D [m]	300	300	500	800
C_v [pass]	100	180	332	1000
h_{min} [sec]	60	60	90	90
y [Lit/sec]	0.96	0.96	/	/
x_{bv}[10^{6}Lit/vehicle]	300	3,000	3,000	18,000
x_l [10^{6}Lit/Km]	1,600	8,000	16,000	144,000
T_{av} [years]	8	10	25	25
T_{al} [years]	32	18	62	62
γ_o [Lit/sec]	29	27	48	134

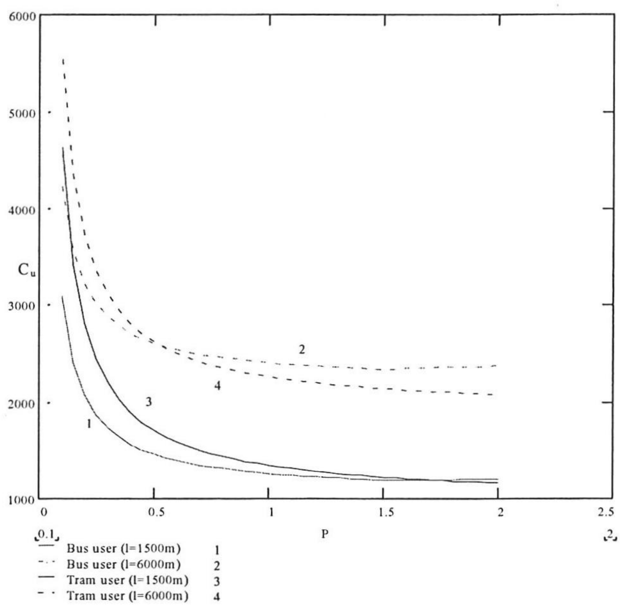


Figure 5 User cost (Lire) in function of the demand (0<P<1.5 pass/sec) and the average user travel length (meters), for bus and tram.

Figure 5 represents the trend of the single user cost varying in function of the demand and the average travel length. The demand interval in abscissa is from 0 to 5400 pass/hour. The chosen values of the average travel length have been the extremes of the l definition range, *1500* and *6000 meters*. It can be pointed out how, increasing the user travel length, the demand value, P_0, for which the tram cost is lower than the bus one, decreases. In Figure 6 is shown the line of the points $P_0(l)$ such that $C_{BUS}(P,l)=C_{TRAM}(P,l)$ The figure can be read as follows. If it is chosen as project variable the average user travel length, l_k, on the abscissa axis, the straight line $l=l_k$ intersects curve

$P_0(l)$ at point $U_0(l_k,P_0)$ whose respective ordinate P_0 quantifies the route demand value over which tram has user costs lower than bus ones. Point $U_1(l_k,P_1)$ is such that $C_{BUS}(P,l)>C_{TRAM}(P,l)$. The area under curve $P_0(l)$ is the points $U(P,l)$ set for which the minimum user cost function is obtained choosing a busway. The area over curve $P_0(l)$ represents the points $U(P,l)$ set for which the minimum user cost function is obtained choosing a tramway. It can happen that the equality of costs doesn't exist for any value of P and l. This happens, for example, for the other systems analysed in greater demand interval.

Figure 7 shows how, with demand varying between $5400<P\leq 9700$, tram has lower cost than LRT and metro for any value of the project variable. Increasing the demand, the minimum unitary cost is that of the mode with the lowest capacity and it is to the limit fixed by the capacity of each system compared.

Applications can be extended to other objective functions. In Figure 8 is represented the demand threshold for which total cost (CGC) is equal for bus and tram, tram and LRT. Figure 9 represents points $P_0(l)$ such that $C_{BUS}(P,l)=C_{TRAM}(P,l)$ for three different cost functions, GUC, LAC and CGC. The curves trend proves that, according to the fixed criteria, system choice is more or less sensible to the project variable value. If the objective function is the central government's one, the choice between bus and tram doesn't depend much on the user travel length. In this case the most important variable in the system choice is the route demand, P.

Interesting results can be obtained applying the model to other project variables. Figure 10 represents the threshold demand over which the minimum cost is the tram's one compared with bus for three different criteria of system selection with the route length as project variable.

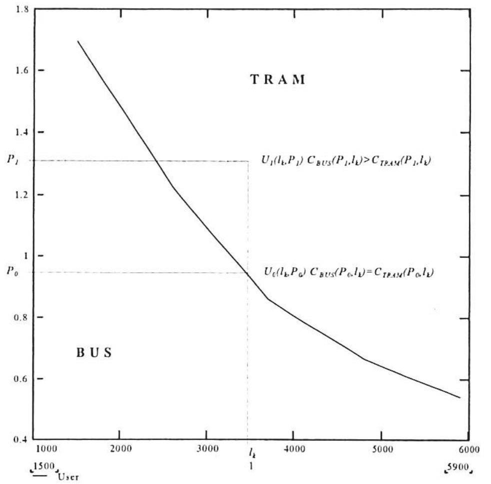


Figure 6 Trend of the threshold demand values $P_0(l)$ for which the user cost is equal selecting bus or tram

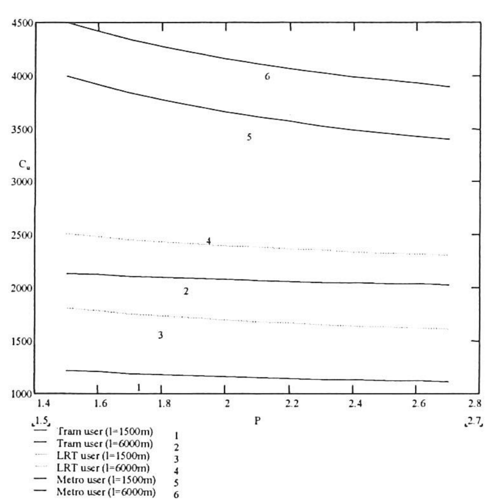


Figure 7 User cost (Lire) in function of the demand ($1.5\leq P\leq 2$ pass/sec) and the average user travel length (meters), or tram, LRT and metro.

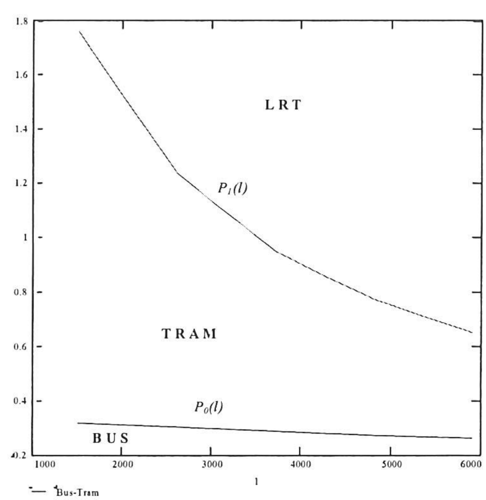


Figure 8 Trend of the threshold demand values $P_0(l)$ and $P_1(l)$ for which GUC is equal selecting bus, tram and LRT

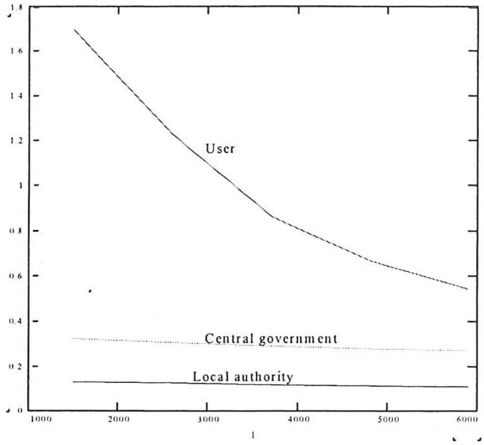


Figure 9 Trend of the threshold demand $P_0(l)$ for which the objective function values are equal selecting a bus or a tram way for three different criteria

For all the three criteria, the system selection is not much influenced by changes in the project variable. For the local authority, more sensible to operative costs, tram is convenient at low demand values. Central government, whose cost includes also the investments, profits by selecting a tramway for higher values of *P*.

Instead, if the demand is assumed as an increasing function of the route length, the model output is different. Figure 11 represents equality cost function between bus and tram for three different criteria. If the route length increases, the equality demand value decreases for all the selecting criteria. Because demand is function of the route length, a short route collects less passengers ; therefore user profits by using systems with a lower capacity and a higher frequency. Increasing the route length, the demand and the benefits in the investments and in the management of systems characterised by low capacity, low frequency and good performances increase proportionally.

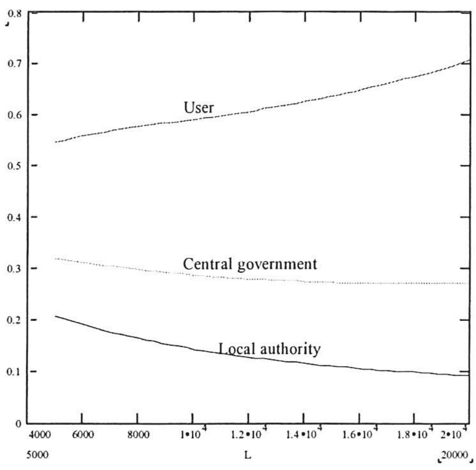


Figure 10 Trend of the threshold demand $P_0(L)$ for which the objective function values are equal selecting a bus or a tram way for three different criteria

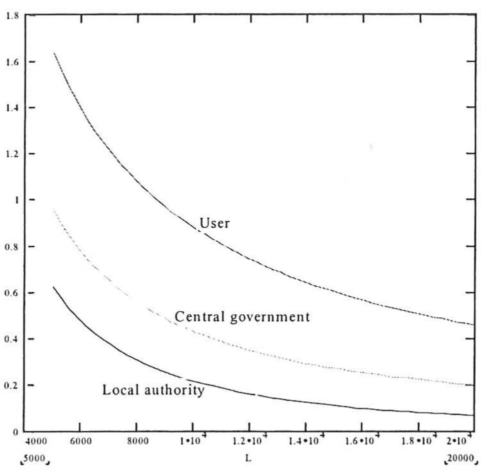


Figure 11 Trend of the threshold demand $P_0(L)$ for which the objective function values are equal selecting a bus or a tram way for three different criteria, P=P(L).

RESULTS

The model application demonstrates that different objective functions provide different model outputs. The transit company has been assumed to be sensitive only to operational costs. With this assumption the goal of the transit company is to use transportation systems at low service cost, without taking care of demand satisfaction. The application of this criterion is not feasible in real cases, because it will provide as a paradoxical result the use of a metro even for low volume.
The system selection according to the user brings to high cost solutions.

The user prefers a transport service with small vehicles, frequent and close stops (bus or AGT). For increasing demand it means many vehicles with high operational cost and, if the bus is selected, high external impact on traffic flows and environment (air and noise pollution).
The Local Authority (region, province or municipality) is assumed to receive financing from the Central Government for vehicles and infrastructure investments, in order to check system management. The Local Authority is sensible to operational and user costs. This criterion usually leads to short period solutions. Further the comparison between the Central Government and the other criteria shows the weight of the social-political role in transit system investment. Finally this analytical model makes it possible to apply the system classification proposed by Vuchic.
The results of the selection model, applied to the most common systems (bus, tram, LRT and metro), show, a part from the selection criterion, which are the profit ranges of the urban systems. The heavier factor in the system choice is the route demand. As expected, considering different route demand values, model applications have brought to the following conclusions.
Bus is the profitable system for low demand volume (700 pass/hour) because of the close stops, relative high frequency and small vehicles. It exist a medium-low level of demand, between 700 and 9000 passengers per hour, in which three different systems can be chosen, bus, tram or LRT. This choice depends on several factors like relevant variables, demand, selection criterion.
For high demand values (over 9000 pass/hour) the system selection doesn't depend any more on the project variable or the objective function. Because of the investment costs, stop distance and vehicles capacity, metro can't be compared with the others (except for the operative costs). A rapid transit line is indispensable only for demand volumes so high that they can't be satisfied by the other systems for their lower capacity limits.

CONCLUSIONS

The study object has been the formulation of an analytical model for the urban transport system selection. The model deals with the analysis of the objective function, relevant variables, demand characteristics and transport systems. The determination of the analytical cost function has been the basic step of the study. The synthesis of the mathematical links between all the parameters of the public transport in a single cost function, considering together investments, management and users, has been possible thank to a set of work hypothesis. Different conclusions can be achieved modifying the hypothesis done, stating the validity of the procedure. The study can be extended to the urban transport network building a sum of cost function, each one characteristic of a different mode. This summation is the cost of the integrated system. The model output is the best set of transport systems. In this case the cost function has to be calibrated considering that the user travel time must consider the transfer time and the demand has to be split in an origin-destination matrix.
The demand values used in the model refer to the peak hour of the average working day. Analysis can be extended to the whole day. Known the time demand distribution during the day, the daily cost function is the summation of the hourly cost functions. With this approach the model outputs are different, the more demand peaks are high compared with the average. Selecting a system on the base of the peak hour, the less is profitable the more the demand volume varies during the day.
Operative costs, evaluated on the basis of real data and in function of the number of vehicles forecast for the line, can be developed with models considering other factors like the vehicle and personnel scheduling. Not necessarily the transport system can be optimised through a choice of different modes but also through the development of different managerial strategies. For example the capacity of a bus line can be increased using vehicle platoons or express services with a lower number of stops and with controlled intersections.
The constraints fixed on the system capacity can be modified with technical-managerial instruments like, a better control system, an increasing of the length and number of station platform, an extension of the headlines. The fare can be decisive in the user choice if it is related to the travel length and time, and differentiated depending on the mode. The cost function could consider also the indirect costs (for example air and noise pollution) if their real monetary evaluation is developed.

Finally the main observation on the system selection procedure regards the importance of the decisional framework in terms of technical, political and environmental choices. In this case the proposed device, after having defined objectives and constraints, admits to address the choice toward the optimal system in a contest of technical rationality.

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