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Comparison between trolley-bus and tram vehicles: performances and consequent environmental impact

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Abstract

The Public Transportation System is now rediscovering the use of trams due to ever increasing pollution problems. The entire system transports from 2000 to 15000 **p/hd**, and uses either the right of way (ROW) or the light rail transit (LRT). Nevertheless a new generation of articulated electric trolley buses (ETB) are becoming an attractive option. The ETB is "bimodal", or rather, it has a double traction energy supply. Its engine-electric generator unit allows it to disconnect from the Overhead Catenary System (OCS) and continue operating as before. This paper compares an ETB transportation system, which uses vehicles holding 155 **p**, with the currently tram system used in Rome, which uses vehicles holding 180 or 260 **p**. Based on the same passenger-flow, this comparison evaluates: which system, is more cost effective for a company, reduces waiting time at bus stops, provides less environmental impact (noise, vibrations, and visual one). These steps will be followed: data collection, energetic consumption simulation program, transportation costs definition, simulation model on tramway network. The Transport Costs Analysis develops a model based on overall total cost, including the complete construction of both the tram and ETB systems on the present network. Costs include personnel, traction materials, vehicles, infrastructures and plant maintenance and amortization. Costs are calculated per vehicle km, per place km, per km run by the whole fleet on a line.

1 Introduction

Today the selection of the best public transport system, to solve the mobility problem in the towns, becomes complicated by the variety of possible choices, even if this variety allows a more precise answer. Every possible system has its own utilisation range, function of necessary transport capacities and local conditions. We can assume [2] a range of 1000-4000 **p/hd** for buses and trams, 2000-6000 **p/hd** for trams sharing the roadway with private traffic, 6000-15000 **p/hd** for tram in ROW or LRT. These traditional classes are not so distinct anymore: you can find various options from vehicles on tyres with great capacities, thanks to 2 or 3 carbody articulated vehicles [3], from the possibility of bound driving with mechanical, optical or radio devices [4,5,6], from the level of lane protection. In this paper, a general design and evaluation model have been developed [7], which compare two urban public transportation systems, in the range of 1000-6000 **p/hd**. One of them uses different capacity trams, having 2 or 3 carbodies; the other uses 2 carbody bimodal articulated ETBs, which means they have a double traction energy supply, thanks to a Diesel engine-electric generator unit, that allows the same performances when vehicles disconnect themselves from the OCS.

Table 1. List of symbols.

symbol	meaning
p/hd	passengers per hour and direction
p	passengers
srlkm	simple rail linear kilometres
drlkm	double rail linear kilometres
kWh/vekm	kWh per vehicle and per km
€/vekm	euro per vehicle and per km
€/plkm	euro per place (standing or seated) and per km
€/lkmph	euro per km run by a line fleet at the highest point range of time

2 Evaluation methods

The present tramway network of Rome [8] has 6 lines equalling 68 **srlkm**. Some of them share part of the roadway. We assume the complete reconstruction of the whole net at the state of art in both cases (tram or ETB on the same net), that uses an antivibrating phonoabsorbing permanent way. About the vehicles, we consider in this paper the trams presently used by the Rome Transport Company:
- a new tram (body width: 2400 **mm**, total length: 30700 **mm**), consisting of three carbodies linked by two intercirculation modules. Total capacity: 260 **p** (we consider the European standard, that is 6 **p/m^2**)
- the usual tram, having two carbodies, whose total capacity is about 180 **p**
- the articulated trolley-bus considered has a body width of 2500 **mm**, a total length of 17985 **mm** and a total capacity: 155 **p**

The comparison evaluates, with the same capacity per hour:
- which system is more convenient for the company
- which one can offer better service, in terms of waiting time at the bus stops
- which one can cause less environmental impact, such as traffic problems during construction, vibration and noise pollution and visual impact.

The work has been divided in the following steps:
- data collection

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ng steps:

- use of an energetic consumption simulation program
- definition of transport costs
- transport costs calculus model
- application of the model to the Roman transport lines

We have simplified some of the calculations: first by considering the complete construction of the network at its present state of art, even if there may be some old parts that are still useful (which would be a disadvantage for the tram system). Then, by the hypothesis of a complete electrification of the network, even if ETB can travel without the OCS when it is requested (this would be a disadvantage instead for the ETB system). Regarding energetic consumption, we have preferred the use of a simulation program [9], instead of direct measurement. This way the study can be generalised for cases that are different from those considered here. Also because there aren't data on ETBs running in Rome. The above mentioned program has been realised and validated [10] at the University of Rome "La Sapienza". It needs a set of data available only for the tram running on line "8". Concerning the other trams and lines, we have extrapolated the obtained results, considering them proportional to the weight of the vehicle and the range of distance. This approximation doesn't greatly influence the simulation because, as we will see, consumption costs account for 5% of the transport costs. In addition, we have considered equidistant bus stops. Lastly, those stretches of roadway included between two consecutive bus stops, shared between two or more lines, are treated as fractions of the whole line. For instance: if a line has 30 stops and 8 of them are shared with another line, the pieces of roadways shared will be 7, so the 7/30 of the transport costs of the line in our analysis will be shared with the other line.

3 Data collection

For the data collection two things are important: the first is to give the input data to the consumption simulation program, which deals with lines, runs and vehicles. The results of the simulation are given at the end of the paragraph. The second need is to give the required items for the definition of infrastructures and plants costs, for the transport costs evaluation model, implemented in a calculus program.

3.1 Lines, runs and vehicles

The Roman tramway network has 11 **srlkm** and 29 **drlkm** in operation (tot: 69 **srlkm**). It also has an auxiliary net of 4 **srlkm** and 9 **srlkm** in the depots. The overhead support system for the conductor is a transversal suspension type, with use of plastic material tie-rods (Parafil), and the conductor is electrolytic copper of 100 **mm²**. There are three depots, one is used for extraordinary maintenance and parking. There are 11 electrical power substations of 2 and 3 **MW**: 6 of them feed 1 line, 3 feed 2 lines and 2 feed 3 lines. We'll contemplate fractions of substations in the calculus of costs: if a line is fed by 3 stations and one of them is shared with another line, the stations will be considered 2,5. The line used

[11] in the consumption simulation program is "8", which is about 5450 m long from one terminal to the other. It has 16 stops and 13 traffic lights that will be considered red (the other ones are pedestrian or immediately before stops, so they are assumed green). Altimetric and planimetric (with all sweep radii) sections are listed. About the runs, the peak period chosen is winter, during the working hours, when it is more intensive: in this period, the range of time between two runs, commercial speed and number of passengers getting on and off the vehicle at every stop are known. The tram [12] used in this line is bi-directional, and it has a lowered floor for 75% of the passenger area, with 350 **mm** ground clearance. Each of the two reduced wheel-base (1750 **mm**) motorbogies are equipped with two three-phase asynchronous motors. Overhead line voltage: 600 **Vdc**; max continuous power: 732 **kW**; max speed: 70 **km/h**; total seats: 54 (+2 for handicaps); dry weight: 40 **t**. The ETB has [13]: 360 **mm** ground clearance; overhead voltage: 450 **Vac**; max continuous power: 185 **kW**; max speed: 60 **km/h**; total seats: 30 (+1 for handicap); dry weight: 19 **t**; Diesel engine with 95 **kW** power, 3.749 cm^3 total displacement, 3000 **rpm** max; generator with 205-560 **V**, 80 **kVA** power, 36,6-100 **Hz** frequency. Final results on a complete run of line "8", from one terminal to the other and back, have given a tram consumption of 40,74 **kWh**. Introducing a 20% reduction due to deceleration recovered energy, it changes to 2,994 **kWh/vekm** (kWh/vehicle per km). About ETB: 32,74 **kWh** and 2,406 **kWh/vekm**.

3.2 Infrastructures and Plants

Infrastructures are made up of depot-workshop and line equipment. The first one has a workshop shed, washing-refuelling area, an ordinary and extraordinary maintenance line, a building with offices, locker rooms, mess and services. The second one includes OCS and the permanent way (this one is only for trams). And lastly, Plants are made up of the electric power substations.
References [7] and [11] have given data in Table 2. Line equipment costs depend on the suspension system adopted. For a simpler calculus we assume a complete electrification, even if bimodal ETBs can run by themselves when it is necessary. For the ETB system, we will consider a medium distribution between two-row per every direction on poles and on hooks. Similarly about tram system one-row. About permanent ways, the state of art are the ones on prefabricated antivibrating

Table 2. Elements forming infrastructures and plants costs.

	ETB	tram
depot	56.810 €/vehicle	216.912 €/vehicle
rows on poles (2 for ETB, 1 for tram)	482.887 €/km	414.715 €/km
rows on hooks (2 for ETB, 1 for tram)	198.836 €/km	113.620 €/km
medium (rows on poles and on hooks)	340.862 €/km	264.167 €/km
substations (one every 10÷11 srlkm)	723.040 €/km	723.040 €/km
permanent ways	0	1.859 €/srlm
permanent ways maintenance	0	238 €/srlm
additional elements	0	728 €/srlm
Points and special parts	0	795.344 €/line

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-phase asynchronous motors. Overhead
power: 732 kW; max speed: 70 km/h;
eight: 40 t. The ETB has [13]: 360 mm
) Vac; max continuous power: 185 kW;
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0	728 €/srlm
0	795.344 €/line

floating foundations, which are more expensive but cause less problems on laying, maintenance, noise and vibrations. Moreover, we have to add all those elements needed for the construction: powerlines, rail grinding, line protections, stop platforms, underground net, points remote controls, rail fastenings and antivibrating and phonoabsorbing profiles. Every line will also have points and special parts. Table 3 shows infrastructures and plants cost, put out by Villanti [1], having made use of Table 2, the number of vehicles in depot and the line length.

Table 3. Infrastructures and plants cost [M€].

line	infrastructures and plants cost [M€]	
	ETB	tram
8	7,752	38,347
30b	8,501	50,050
14	4,661	27,217
19	8,485	54,125
225	3,087	19,383
516	3,983	23,432

4 Transport costs definition and calculus model

Transport cost is sustained by the company to offer the public service. It can be formulated in different ways:
Ct1 [**€/vekm**], cost per km run by a vehicle;
Ct2 [[**€/plkm**], cost per km run by an offered place (**pl**: standing or seated);
Ct3 [**€/lkmph**], cost per km run by all vehicles at the same time on the line (**l**), during peak hours (**ph**).
This is useful for a correct comparison having the same passenger-flow.
In this model transport costs Ct1 will be defined by the sum of the elements listed in Table 4. About amortization costs, they have been reduced to Euro per vehicle and per km, considering infrastructures life, vehicles life and their annual medium run. Some of these elements (Ip, Im, Ia, Ge) need infrastructures and plant costs to be known: they available in Table 3.

Table 4. Elements forming transport costs Ct1 [**€/vekm**].

symbol	meaning
Dr	drivers
Co	collectors
Vp	vehicles maintenance personnel
Ip	infrastructures and plants maintenance personnel
Vm	vehicles maintenance materials
Im	infrastructures and plants maintenance materials
Es	traction materials (energy supply, lubricants, tyres)
Va	vehicles amortisation
Ia	infrastructures and plants amortization
Ge	general expenses (taxes, insurance, interests, fares collection, administration and organization)

The calculus model, applied to the roman tramway network, gives the values listed in the Table 6. The above mentioned values have been obtained by parameters that ATAC/COTRAL and BredaMenarinibus have kindly supplied (see Table 5), except energy specific consumption, that has been calculated with its simulation program. The whole transport costs formulation is shown in Table 7. The transport costs values, calculated for some of the Roman present tramway lines, are listed in Table 8.

Table 5. Data necessary to calculate values in Table 6.

line 8	ETB	tram
driving personnel annual standard cost [€/person year]	36.152	36.152
number of travelling personnel on a vehicle	1	1
number of driver annual service hours	1.625	1.625
number of driver annual driving hours	1.200	1.200
commercial speed [km/h]	17	17
number of vehicles used	*33*	20
number of collectors per vehicle	0,11	0,11
collector personnel annual standard cost [€/person year]	38.734	38.734
vehicle annual medium run [km]	46.000	46.000
mainten. personnel annual medium cost [€/person year]	36.152	36.152
number of persons employed per every vehicle	0,7	0,7
energy specific consumption [kWh/vekm] (calculated #)	*2,406 #*	2,994 #
energy supply cost [10^{-2} * €/vekm]	10,071	10,071
vehicle price [€/vehicle]	*650.736*	1.807.599
medium vehicle life [years]	*25*	30
medium infrastructures and plants life [years]	30	30

Table 6. Calculated values of the elements forming Ct1 [10^{-2} * €/vekm].

line 8	Dr	Co	Vp	Ip	Vm	Im	Es	Va	Ia	Ge
ETB	177	9,26	55,0	*20,4*	11,0	*4,1*	*24,2*	*56,6*	*17,0*	*37,5*
tram	177	9,26	55,0	167	11,0	33,3	30,1	131	138	75,3

Table 7. Transport costs formulation.

	formula	unit
Ct1	Dr + Co + Vp + Ip + Vm + Im + Es + Va + Ia + Ge + Ci + Ge	**[€/vekm]**
Ct2	Ct1 / vehicle capacity	**[€/plkm]**
Ct3	Ct1* number of vehicles at the highest point range of time	**[€/lkmph]**

Table 8. Transport costs values, calculated for some of the Roman tramway lines.

	line 8		line 30b		line 19		line 225	
	ETB	tram	ETB	tram	ETB	tram	ETB	tram
Ct1 **[€/vekm]**	4,12	8,28	5,23	10,26	5,24	11,16	4,53	8,48
Ct2 **[10^{-2}*€/plkm]**	2,63	3,20	3,36	5,68	3,51	6,20	2,89	4,70
Ct3 **[€/lkmph]**	119,6	140,7	99,37	164,1	92,21	167,4	40,74	67,88

5 Results and Remarks

Ct2 is a direct index of the expense for every offered place by the Transportation Company, and it is obtained by dividing Ct1 per vehicle capacity. Ct3 comes from Ct1 multiplied for the total number of vehicles present on the line (during peak hours). It provides a more correct comparison between the ETB system and the tram system, because ETBs have less capacity than trams, so more vehicles are necessary to have the same passenger-flow. The difference between Ct3 (tram) and Ct3 (ETB) is consequently smaller than that between Ct1 (tram) and Ct1 (ETB). If we calculate the per cent difference as related to the cheaper vehicle (ETB), we can see that, in regard to the Ct1, tram is 101% more expensive than ETB; about Ct2, it is 20% more expensive, and concerning Ct3 tram is 18% more expensive, in spite of the fact that ETB system uses more vehicles and therefore more personnel. This difference is greater if we consider a lower passenger-flow line: the model has given, on other lines of Rome, Ct3 per cent differences of 39%, 45%, 65%, 67%, 82% on lines "516", "14", "30b", "225", "19", respectively. Besides, waiting time at bus stops decreases with ETB from 2'30" to 1'29", which increases the quality of service. Moreover, smaller vehicles can be more filled during not peak hours. We can notice (see also Figures 1 e 2) that energy supply incidence on transport cost Ct1, on line "8", is marginal: 3,6% (tram) and 5,9% (ETB). The heavier items are personnel costs: 63,5% (ETB) and 49% (tram) on line"8". Then amortization costs come, with a stronger difference between the two systems: 17,8% (ETB) and 32,6% (tram). Here we find the penalty caused by the permanent way. The annual expense sustained by the company for line "8" is about 9,04 M€ making use of trams and 7,54 M€ making use of ETBs. Total expense for the whole net (6 lines) should be 40,54 M€ and 27,22 M€, with a potential saving of 13,32 M€ in case of ETB system adoption.

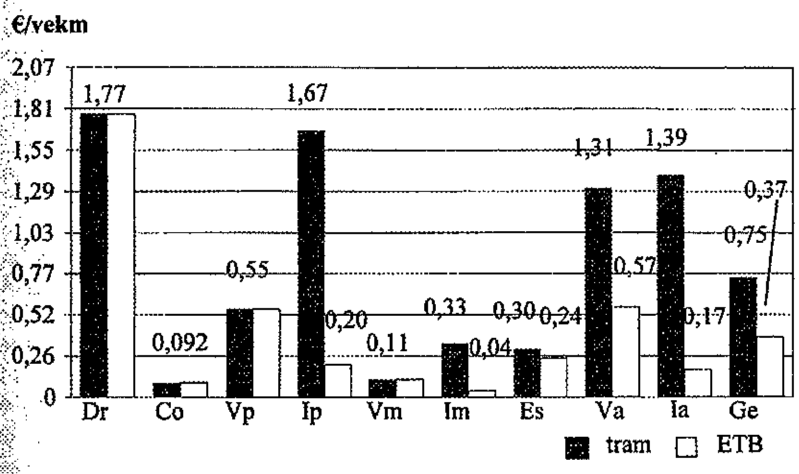

Figure 1: Ct1 transport cost components on line "8".

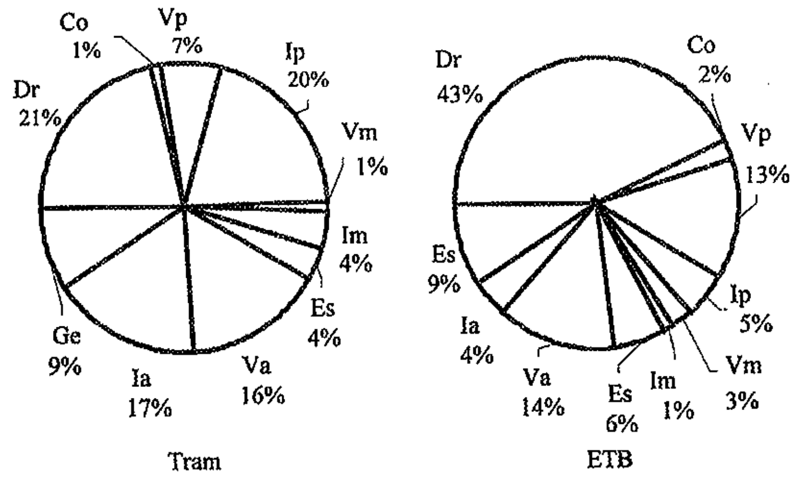

Figure 2: Ct1 transport cost components on line "8", for tram and ETB

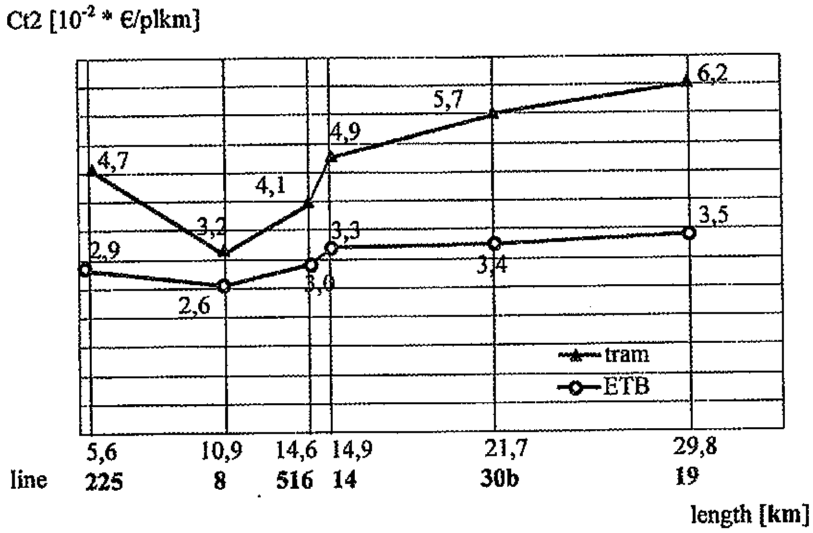

Figure 3: Ct2 transport cost [10^{-2} * **€/plkm**] as function of line length

The influence of line length and of passenger-flow on Ct2 can be seen in Figures 3 and 4. It's clear that infrastructures influence the costs: it's more expensive to transport one passenger through 100 **km** than through 20 **km**! That is caused by the fare criterion adopted in Rome, as a consequence of which the cost of the ticket is independent from the distance. On the contrary, passenger-flow causes a more intensive use of the system, and so more efficiency.

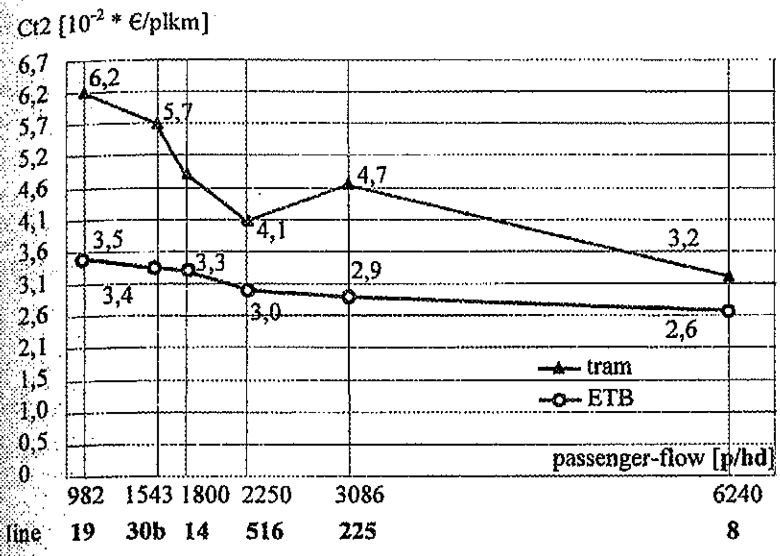

Figure 4: Ct2 transport cost [10^{-2} * **€/plkm**] as function of passenger-flow

6 Evaluation on environmental impact of tram and ETB's public transport systems

First of all, we have to say that the choice of antivibrating permanent ways on floating foundations for the tram system has been basic for the definition of costs, compared to traditional ballast permanent way (cost: 1085 **€/srlm** and maintenance: 516 **€/srlm**). But it has been a forced choice, in order to cause an environmental impact comparable to ETB's: the new system has the fundamental resonance frequency f_i= 12,6 **Hz** (not audible), while the old one has f_i= 43,5 **Hz** (audible). Moreover, the new system is prefabricated, so it is faster and it causes less discomfort during construction (not existing for ETBs), such as noise, dust production and road interruption. There is another kind of pollution to be considered: it is the OCS visual impact. Tram ways are very rigid in their design, but bimodal ETB can be adapted to a lot of needs. Rounds, inversions, roadways to depots, emergency roadways can be simplified, in order to appear lighter, without breaking streets. In these cases, OCS can be completely avoided, thanks to the vehicles' capability of double traction energy supply. Zones of particular interest also, that need to be free from the OCS, could be served by bimodal ETBs. A criterion of OCS visual impact evaluation has been studied [14], and can be concluded that radial nets are better, from this point of view, than grid nets, and also that a one-way on parallel streets is better than two-way streets. Besides, left turns should be obtained by turns around a block, instead of

crossing the main street OCS. All these conditions are better satisfied by a bimodal ETB rather than a tram.
In conclusion the authors suggest the use of ETB in spite of tram in towns where the underground is not possible for urbanistic and geomorphologic configuration, and if possible, it is too much expensive.

Acknowledgements

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