Analysis of Guided Public Transport Systems in Urban Zones

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ABSTRACT

In recent years, there has been great progress in the public transportation sector with regards to innovative alternatives, providing great advantages to several traditional public transport systems. Within these alternatives, more focus has been placed on transport systems that have an unconventional guidance which may benefit the public transport sector, since, for low average demand, these alternatives may be more economically viable than the conventional rail transport system, maintaining a good operational performance.

This master thesis intends to evaluate the potential of implementing unconventional public transport systems. In a first step, information about conventional and unconventional public transport systems were collected. Then, a multicriteria analysis method was used, more specifically the ELECTRE method, to analyse nine alternatives of conventional and unconventional transport systems through thirteen evaluation criteria associated with the system's performance, associated costs and environmental and urban aspects, for a total of four scenarios created with different hourly demand values (between 1000 and 4000 passengers per hour and direction). For the data adopted in the model, the results highlight the interest of: implementing the Irisbus system for an hourly search equal to or less than 3000 passengers per direction and to implement the conventional tram system for an hourly search equal to or greater than 4000 passengers per direction. Additionally, the feasibility of implementing Autonomous Rail Rapid Transit (ART), an unconventional transport system that could have great potential, was tested, that may have an interesting potential for an hourly demand equal to or greater than 4000 passengers per direction.

Keywords: Public transport system, Flexibility, Guided systems, Costs, Multicriteria analysis, ELECTRE

1. Introduction

A good public transport network reflects a good image of a city, and the more efficient, pleasant and faster citizens travel, the more seamless their mobility will be, consequently with greater benefits for society as a whole. In addition, the quality of the public transport offer increases its attractiveness to the population, reducing the use of individual transport. This action induces not only a greater balance in transport modal share, but it also helps to reduce car congestions and the carbon footprint [1].

The public transport systems most used in metropolitan areas include suburban heavy rail, metro, tram or bus transport. In recent decades, some technological innovations have emerged that combine the advantages of some of these systems, taking advantage of some type of less conventional guidance [2].

In areas of medium and low demand, where the implementation of heavy transport systems is not economically viable, it is important to evaluate the feasibility of implementing unconventional transport systems and establish which are actually best suited to a particular demand. Thus, the present study intends to evaluate the potential interest of some of these systems when compared to traditional ones.

2. Conventional and unconventional transport systems

2.1. Conventional transport systems

Conventional and economically viable systems, for medium low demand, comprise the bus and trams transport systems. The main difference between a bus system and a tram system is the existence of a guidance. A conventional bus has no guidance, providing a great flexibility as it can easily change its route. However, this transport has a low commercial speed, thus reducing the efficiency of the system [3]. On the other hand, trams constitute a continuously guided system, with the following advantages: greater autonomy, greater attractiveness, greater capacities in the system and greater easiness in approaching the stations. However, the drawbacks of this system include the inflexibility that the railway vehicle has in its path, being always dependent on the infrastructure that enables its circulation [4].

The type of infrastructure to be implemented directly influences the operation of the transport system, more specifically, the commercial speed. Thus, Institute for Mobility and Land Transport (IMTT) in Portugal, defined standard commercial speed values depending on the type of track/lane (**Table 1**).

Table 1 – Standard commercial speed values of transport systems depending on the type of track/lane

Type of track/lane	Standard commercial speed [km/h]
On-street running	15.5
Semi-reserved track/BUS lane	17.5
Reserved track/lane	21.5

Source: [5]

Another important parameter in the evaluation of transport systems is the directional capacity. This depends on the frequency of services and the capacity of each vehicle. **Table 2** shows the values of the average capacity of the most common vehicles in urban areas, together with the respective acquisition costs.

Table 2 – Average rolling stock capacity and acquisition costs

Type of vehicle	Average vehicle capacity [4p/m^2]	Vehicle cost in M€
Standard bus	80	0.305
Articulated bus	120	0.499
Biarticulated bus	150	0.832
Articulated Trolleybus	120	1.109
Tram - 3 carriages	200	2.33

Source: [6];

Construction costs are highly dependent on the type of infrastructure. Thus, these were branched according to the type of lane/track, as shown in **Table 3**.

Table 3 – Construction costs for conventional transport systems

Type o lane/track	Construction costs in M€/km
Bus in on-street lane	1.62
Bus in reserved lane	6.6
Trolleybus in reserved lane	10.18
Tram in reserved track	17.66

Source: [6];

2.2. Unconventional transport systems

In recent years, major technological advances have been carried out in order to ensure convergence in terms of the advantages of both conventional transport systems (bus and tram), with four groups of unconventional transport systems having emerged: a mechanical guided system (MecGS), a guided system with an intermediate rail (GSIR), an optical guided system (OGS) and a magnetic guided system (MagnGS).

<u>Mechanical guided system (MecGS)</u>

The MecGS consists of guiding a bus or trolleybus through small horizontal rubber wheels that are in contact with the curbs of the track, as shown in **Figure 1**. This guidance has a great impact in terms of driving since the driver only has to control the speed of the bus, not needing to guide it. In addition, the driver can take full control of the bus, which behaves like a traditional bus outside the corridors specifically designed for this system [7].

Figure 1 - MecGS [8]

To implement this type of guidance, it is necessary to have a base platform for buses to be able to circulate. In summary, there are three basic elements for this system's infrastructure design: the circulation path, the curb and the transition pieces. The circulation path is formed by two reinforced concrete slabs, each being 0.7 meters wide. The guide curb must be 18 cm high in order to ensure appropriate guidance of the bus through the horizontal wheel. The distance between the internal faces of the curbs on the same road must be of 2.6 meters, considering that a valid bus for this system must be at least 2.45 meters wide [9]. At each interruption of the guided mechanism, it is necessary to implement a transition piece.

Table 4 summarises the essential parameters of this guided system.

Table 4 – Essential features of the MecGS

Mechanical Guided System (MecGS)		
Maximum gradient	13%	
Two-way width [m]	6.00	
Vehicle width [m]	2.45	
Minimum turning radius [m]	25	
Commercial speed [km/h]	38	
Construction cost [M€/km]	7.26	
Rolling stock cost [M€/km]	Standard	0.309
	Articulated	0.503

Source: [6];

Guided system with an intermediate rail (GSIR)

The GSIR has the functionality of using the traction of the tires to move, together with steel wheels, in the centre of the axle, to guide the vehicle (**Figure 2**).

Figure 2 – GSIR in the city of Caen [10]

There are currently two types of GSIR: *Transport sur voie réservée* (TVR) and Translohr. The TVR runs in guided and unguided modes, showing a great flexibility as the vehicle can travel guided on a rail and can operate similarly to a bus, in an unguided mode. In contrast, the Translohr system only circulates according to the guide rail [11]. Due to several problems, the TVR system is no longer being developed [12].

Table 5 presents the characteristics related to the Translohr and TVR systems.

Table 5 – Characteristics of GSIR

	Translohr	TVR
Maximum gradient	13%	13%
Two-way width [m]	5.40	6.20
Minimum turning radius [m]	10.5	12
Commercial speed [km/h]	20.33	17.25
Average capacity $[4p/m^2]$	170	131
Construction cost [M€/km]	17.91	18.33
Rolling stock cost [M€/km]	2.43 (for STE4 models)	2.02

Source: [6];

Optical guided system (OGS)

The OGS aims to shorten the space between the vehicle and the platform, allowing passengers to more easily hop on and off, enabling drivers to stop near the stations, always ensuring the safety and comfort of passengers.

In functional terms, the OGS was developed to detect dashed lines, present in the centre of the lane and thus proceed to its optical guidance, through a camera that is attached to the top of the bus [13] (**Figure 3**).

Figure 3 – OGS in Rouen [14]

Table 6 summarises the most important characteristics of an OGS.

Table 6 – Essential features of OGS - Irisbus

Optical guided system (OGS) - Irisbus		
Maximum gradient	13%	
Two-way width [m]	6.80	
Minimum turning radius [m]	12	
Commercial speed [km/h]	21.2	
Construction cost [M€/km]	8.35	
Rolling stock cost [M€/km]	Standard Trolleybus	1.14
	Articulated Bus	0.52

Source: [6];

In the city of Zhuzhou, in China, a public transport system is being created that consists of incorporating a vehicle that resembles an electric vehicle with tires that is optically guided (**Figure 4**). This system is called: Autonomous Rail Rapid Transit or simply ART.

Figure 4 – ART in Zhuzhou, China [15]

The carriages of an ART are made up of sensors that capture the dashed lines, in order to follow the implemented trajectory. In addition to this software, vehicles are also supported by other types of technology, which ensures greater vehicle accuracy, detection of dashes and vehicle stabilisation [16].

Table 7 shows some characteristics of this new autonomous system.

Table 7 – Essential features of OGS - ART

Optical guided system (OGS) - ART	
Capacity of 3 carriages [4p/m^2]	200
Two-way width [m]	7.66
Minimum turning radius [m]	15
Construction cost [M€/km]	10.01
Rolling stock cost [M€/km]	2.00

Source: [6];

Magnetic guided system (MagnGS)

The goal of a MagnGS is to implement transport that is flexible, viable, comfortable and environmentally friendly [17].

In functional terms, the system incorporates a bus with an intelligent system that recognises the route through magnetic markers installed on the track, within the pavement and spaced between 4 to 5 meters [18] (**Figure 5**).

Figure 5 – MagnGS [19]

Table 8 summarises the characteristics of MagnGS.

Table 8 – General features of MagnGS

Magnetic guided system (MagnGS)		
Commercial speed [km/h]		26.4
Two-way width [m]		6.6
Minimum turning radius [m]		12
Maximum gradient		13%
Construction cost [M€/km]		4.66
Average capacity [4p/m^2]	Articulated bus - 18.5m	103
	Biarticulated bus - 24.5m	129
Rolling stock cost [M€]	Articulated bus – 18.5m	1.25
	Biarticulated bus – 24.5m	1.53

Source: [6];

3. Application of multicriteria analysis to assess the potential interest of unconventional systems

3.1. Methodology

This analysis aims to compare conventional and unconventional transport systems, in order to obtain the most viable transport system to implement, in relation to a given induced demand.

As there are several transport systems to compare, a multicriteria analysis (AMC) was carried out, using the ELECTRE III and ELECTRE IV methods. These are non-compensatory methods widely used in the analysis of transport systems [20].

The following analysis was based on the study by An [21].

3.2. Case study

To elaborate this analysis, it was necessary to create a theoretical study case, which enshrines a line extension per direction of 15km, with a maximum slope of 5%. Other variables were also defined, in order to calculate some other parameters, as the calculation of the economic analysis regarding the operating costs of the transport systems [6].

The alternatives (ai) to be analysed are shown in **Table 9**.

Table 9 – Alternatives to analyse

Alternative (ai)	Transport system	Type of vehicle
a1	Bus in on-street lane	Articulated bus
a2	Bus in reserved lane	Biarticulated bus
a3	Trolleybus in reserved lane	Articulated trolleybus
a4	Tram	Tram 32m
a5	MecGS	Articulated bus
a6	GSIR – TVR	TVR
a7	GSIR – Translohr	STE4
a8	OGS – Irisbus	Articulated bus
a9	MagnGS - Phileas	Biarticulated bus – 24,5m
a10	OGS - ART	ART

Although ART system is indicated in **Table 9**, its analysis will be only performed in Chapter 4,

In order to enrich this analysis, four scenarios were created with different hourly demand values per direction (**Table 10**), in order to analyse the different scenarios influence on the alternatives classification.

Table 10 – Scenarios created for the analysis of transport systems

Scenarios	1	2	3	4
Hourly demand per direction (Passengers/h)	1,000	2,000	3,000	4,000

The criteria (gj) that will evaluate each alternative are available in **Table 11**, according to the type of category.

Table 11 – Criteria to be assessed in the ELECTRE method

Category	Criteria to be assessed	Nomenclature (gj)
System performance	Accessibility	g1
	Frequency	g2
	Reliability	g3
	Flexibility	g4
	Punctuality	g5
	Safety	g6
Associated costs	Rolling stock cost	g7
	Construction cost	g8
	Operating cost	g9
Environmental and urban aspects	Attractiveness	g10
	Gas emissions	g11
	Insertion in the urban space	g12
	Noise	g13

3.3. Establishment of the criteria to be assessed

Before executing the ELECTRE method, it is necessary to establish all the criteria to be addressed, through at an evaluation scale. Thus, for each alternative, a score will be given in relation to each criterion. The justification for the score system was based on the collection of information from each transport system presented in Chapter 2, which is detailed in the master thesis [6].

Table 12 contains the system performance's criteria, with the exception of the criterion related to frequency. **Table 13** presents the criteria for construction cost and environmental aspects.

Table 12 – Criteria related to system performance, except the criterion related to frequency (g2)

ai	g1	g3	g4	g5	g6
	0 or 1	1 to 9	0 or 1	0 or 1	1 to 5
a1	0	9	1	0	5
a2	0	9	1	1	5
a3	0	9	1	1	5
a4	1	9	0	1	5
a5	1	8	1	1	3
a6	1	5	1	1	2
a7	1	8	0	1	4
a8	1	8	1	1	4
a9	1	5	1	1	4
a10	1	8	1	1	4

Table 13 – Criteria related to the construction cost (g8) and the environmental and urban aspects (remaining)

ai	g8	g10	g11	g12	g13
	M€/km	1 to 5	1 to 5	1 to 5	dB
a1	1.62	1	2	4.0	68
a2	6.61	2	3	4.0	68
a3	10.18	2	5	4.0	60
a4	17.66	5	5	2.5	60
a5	7.26	3	2	4.0	68
a6	18.33	4	5	5.0	60
a7	17.91	5	5	3.5	60
a8	8.35	3	2	3.5	68
a9	4.66	3	4	3.5	64
a10	10.01	4	5	2.5	60

The criteria linked to the frequency (**Table 14**), the costs of purchasing rolling stock (**Table 15**) and operating costs (**Table 16**) are the only that vary according to the demand imposed, through the scenarios.

Table 14 – Criterion regarding the frequency (g2), scored with a 0 or a 1

ai	Scenario1	Scenario 2	Scenario 3	Scenario 4
a1	1	0	0	0
a2	0	1	1	0
a3	1	1	1	0
a4	0	1	1	1
a5	1	1	1	0
a6	0	1	1	0
a7	0	1	1	1
a8	1	1	1	0
a9	0	1	1	0
a10	0	1	1	1

Table 15 – Criteria related to the cost of rolling stock (g7), in M€

ai	Scenario1	Scenario 2	Scenario 3	Scenario 4
a1	12.48	24.95	37.43	49.90
a2	13.31	27.46	38.27	64.06
a3	22.18	43.25	64.32	85.39
a4	27.96	53.59	90.87	107.18
a5	10.06	19.62	29.17	38.73
a6	36.36	78.78	117.16	155.54
a7	34.02	70.47	111.78	140.94
a8	10.40	20.28	30.16	40.04
a9	27.54	59.67	88.74	117.81
a10	24.00	46.00	78.00	92.00

Table 16 – Criterion related to the operating cost (g9), in M€/year

ai	Scenario1	Scenario 2	Scenario 3	Scenario 4
a1	7.56	12.42	17.38	22.20
a2	6.50	10.93	14.31	22.04
a3	7.35	11.30	15.20	19.22
a4	6.86	9.48	13.07	14.85
a5	6.96	11.17	15.32	19.60
a6	7.78	12.80	17.27	21.90
a7	7.34	10.75	14.93	17.58
a8	6.97	11.15	15.27	19.53
a9	6.00	9.99	13.53	17.20
a10	5.69	8.22	11.69	13.40

3.4. Calibration of thresholds and weights for the ELECTRE method

The ELECTRE III method considers the weighting between criteria where one criterion can have a greater importance than another. Thus, similar to the study by An [21], four different weight groups were created to assess the sensitivity of the ELECTRE III method. The first (W_{REF}) concerns the reference group, with the second group (W_{I}) focusing on the criteria related to the performance of the system, the third (W_{II}) highlights the criteria related to the associated costs and the last group (W_{III}) highlights the criteria referring to the environmental and urban aspects. The stipulated weight values are defined in **Table 17**.

The ELECTRE IV method does not consecrate the weighting between criteria. Therefore, the question of different weights between criteria is not applicable.

Table 17 – Stipulated weights for the sensitivity analysis

gj	W_{REF}	W_{I}	W_{II}	W_{III}
g1	25	30	20	15
g2	30	40	25	25
g3	30	40	25	25
g4	20	20	15	15
g5	20	20	15	10
g6	25	30	20	20
g7	25	20	35	20
g8	25	20	35	20
g9	50	40	70	40
g10	5	10	10	20
g11	15	10	10	30
g12	15	10	10	30
g13	15	10	10	30

In another aspect, both ELECTRE methods consider thresholds of preference to evaluate the different alternatives. These thresholds are shown in **Table 18**. All thresholds established were based on the study by An [21].

Table 18 – Defined thresholds for analysis

gj	Q	P	V
g1	0	1	2
g2	0	1	1
g3	1	2	5
g4	0	1	2
g5	0	1	2
g6	1	2	5
g7	10%	20%	100%
g8	10%	20%	100%
g9	10%	30%	50%
g10	1	2	5
g11	1	2	5
g12	1	2	5
g13	10%	20%	50%

The unit used in each threshold is in accordance with the scale of units used in each criterion, except for criteria g7, g8, g9 and g13, whose thresholds are a percentage compared to the highest value presented by the alternatives, for each criterion.

3.5. Results analysis

Analysing the results obtained according to the ELECTRE III method, it can be seen that the Irisbus system (a8) is the system that, globally, has the best classification in relation to scenarios 1, 2 and 3. In other words, the Irisbus system is the most viable to implement for an hourly search equal to or less than 3,000 passengers per direction.

The tram system (a4) is preferable in scenario 4. Therefore, for an hourly search equal to or greater than 4,000 passengers per direction, the tram system is the most viable to implement.

On the other hand, the TVR system (a6) is, globally, the transportation system with the lowest rating due to its poor performance in terms of safety and reliability and, additionally, due to its high cost associated with the construction of the infrastructure, the material and the operating cost of the system.

Regarding the results obtained according to the ELECTRE IV method, in all scenarios the electric (a4) is the system with the best classification and Irisbus (a8) is the system with the worst classification. Based on these results obtained, the theory that the ELECTRE IV method has a very different approach from the ELECTRE III method is corroborated, providing completely different results.

By analysing the credibility matrices of the ELECTRE IV method, it is possible to identify that, globally, there is a weak credibility that one alternative over-classifies another, and it can be concluded that the ELECTRE IV method does not perform well in this analysis.

In comparison with the results obtained by An [21], the author also identified that the ELECTRE IV method is not a good evaluation method for its analysis. Moreover, in relation to the solutions obtained according to the ELECTRE III method, although the author has stipulated scenarios with different parameters, he concludes that the tram system is more suitable for medium and bigger demands and the Irisbus and trolleybus systems are preferable for smaller demands. However, in the present analysis, it is possible to observe the hourly demand transition value that influences the preference in the choice of transport systems.

4. Feasibility analysis of the Autonomous Rail Rapid Transit (ART)

4.1. Methodology

The ART system is one of the future innovations in OGS, which combines the advantages of an optical guided system with the attractiveness of a vehicle model similar to a tram. Thus, it becomes attractive to investigate the feasibility of implementing a transport system with this technology and to compare it with the other alternatives already analysed.

To carry out this analysis, the ELECTRE III method was used, based on the criteria stipulated in the previous chapter. Within these criteria, those that are related to costs are the criteria with less rigour, since there is still no official data on the costs of construction, rolling stock or operating. Only estimates are available for the first two costs listed, while there is no estimate for the cost of operating the ART system. Therefore, annual operating cost was considered as a dependent variable, being constantly changed, through several iterations, until the limit value that makes the ART system preferable in relation to the other alternatives is established.

4.2. Results analysis

Table 19 shows the maximum operating cost values that make the ART system more viable to implement.

Table 19 – Summary of the maximum operating costs that make the ART system feasible, in M€/year

	W_{REF}	W_{I}	W_{II}	W_{III}
Scenario 1	3.15	3.05	0	2.40
Scenario 2	10.75	12.85	7.40	8.25
Scenario 3	14.95	17.85	8.80	10.75
Scenario 4	23.80	25.45	24.45	25.20

In order to validate the values obtained in **Table 19**, the minimum and maximum values of operating costs which the remaining alternatives present, were compiled in **Table 20**. Thus, the greater the difference between the iterated cost of the ART system and the minimum cost presented by the other alternatives, the higher the feasibility of implementing ART.

Table 20 – Minimum and maximum operating costs of the remaining alternatives, for each scenario, in M€/year

	Minimum	Maximum
Scenario 1	6.00 – a9	7.78 – a6
Scenario 2	9.48 – a4	12.80 – a6
Scenario 3	13.07 – a4	17.38 – a1
Scenario 4	14.85 – a4	22.20 – a1

By analysing **Tables 19** and **20**, it appears that, only in scenario 4, all iterated values are higher than the minimum operating cost presented by the other alternatives, increasing the feasibility of implementing the ART system. It is important to note that all ART operating costs whose values are higher than the minimum costs of the other alternatives are coloured in green. Otherwise, the cells are coloured red.

Moreover, an estimate of the costs of operating the ART system was carried out, via economic analysis, taking into account the guidance system of Irisbus and the system for capturing energy from the tram, since, there is still not enough information for the concrete calculation of these costs. In addition, in order to guarantee a greater safety margin in relation to the real value, a safety factor of 1.1 will be applied to the result obtained from this economic analysis. The values obtained from this economic analysis, performed for each scenario, are shown in **Table 21**.

Table 21 – Estimated operating costs of the ART system via economic analysis, in M€/year

	a10
Scenario 1	6.26
Scenario 2	9.04
Scenario 3	12.85
Scenario 4	14.74

By comparing the results of the table in question with the iterated values (**Table 19**), it appears that, similarly to what had been previously concluded, only taking into account scenario 4, the ART system is the most viable to implement, for all groups of weights.

In summary, it can be pointed out that full viability for the implementation of the ART system is only ensured in scenario 4 (4,000 passengers per hour-direction), since all values obtained according to the ELECTRE III method are higher than the minimum and the maximum values of the operating cost of the remaining alternatives. Moreover, they are even higher than the estimated values of operating costs of the ART system via economic analysis.

5. Conclusions

The existing conventional public transport systems of bus and rail have unique features, many of which are distinct from each other. Accordingly, new unconventional transport systems have emerged which establish the flexibility of the bus system with the efficiency of the rail system. Through the analysis of these unconventional transport systems, it was observed that these are not yet properly improved, and there are still several problems in relation to the type of guidance. In addition, several studies are still being carried out aimed at developing these transport systems, with emphasis on the Autonomous Rail Rapid Transit (ART) system with optical guidance.

With the purpose of comparing the feasibility of implementing unconventional public transport systems, a multicriteria analysis was carried out, more specifically through the ELECTRE III and IV methods, comparing these systems with the conventional public transport systems. This type of analysis is essential to establish which transport systems are the most prominent. Subsequently, a cost-benefit analysis could be performed on the systems with the best performance.

Through an analysis of the ELECTRE method, it was found that this method is very flexible, allowing the analyst to insert: the criteria to be stipulated, together with the scores for each alternative; the weights to be assigned, in the case of ELECTRE III; and set preference thresholds. However, this advantage can also be a drawback, since each person can take a different approach to the same project.

The results obtained according to the ELECTRE III method indicate that the Irisbus system is chosen for an hourly demand of 3,000 passengers or less per direction. On the other hand, the tram system is preferable for an hourly value search of 4,000 passengers or more per direction.

Finally, a feasibility analysis of introducing the ART system to the market was carried out, using the ELECTRE III method. In the applied methodology, operating costs became a dependent variable, as they are unknown. However, both construction costs and rolling stock costs are still being estimated. Thus, it is necessary to update these values or carry out an economic analysis of these types of costs. The results obtained from the application of this methodology, point out that, similar to the tram system, the ART system has a great feasibility of being introduced in the market for an hourly demand equal to or greater than 4,000 passengers per direction.

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