COMPARISON BETWEEN BUS RAPID TRANSIT AND LIGHT-RAIL TRANSIT SYSTEMS: A MULTI-CRITERIA DECISION ANALYSIS APPROACH

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ABSTRACT

The construction choice between two different transport systems in urban areas, as in the case of Light-Rail Transit (LRT) and Bus Rapid Transit (BRT) solutions, is often performed on the basis of cost-benefit analysis and geometrical constraints due to the available space for the infrastructure. Classical economic analysis techniques are often unable to take into account some of the non-monetary parameters which have a huge impact on the final result of the choice, since they often include social acceptance and sustainability aspects. The application of Multi-Criteria Decision Analysis (MCDA) techniques can aid decision makers in the selection process, with the possibility to compare non-homogeneous criteria, both qualitative and quantitative, and allowing the generation of an objective ranking of the different alternatives. The coupling of MCDA and Geographic Information System (GIS) environments also permits an easier and faster analysis of spatial parameters, and a clearer representation of indicator comparisons. Based on these assumptions, a LRT and BRT system will be analysed according to their own transportation, economic, social and environmental impacts as a hypothetical exercise; moreover, through the use of MCDA techniques a global score for both systems will be determined, in order to allow for a fully comprehensive comparison.
Keywords: BHLS, urban transport, transit systems, TOPSIS.

1 INTRODUCTION

In recent years a large quantity of funds has been invested in the realization of Bus with a High Quality Level of Service (BHLS) systems, which can be defined as a system that "offers to the passenger a very good performance and comfort level, as a rail-based system, from terminus to terminus at station, into vehicle and during the trip" [1].

Yet from this definition it is possible to understand why a great interest has been shown in the comparison between this type of system and the Light-Rail Transit (LRT) system; moreover, when comparing it to the Bus Rapid Transit (BRT) system, which, at its peak performance, can reach up to one million passengers per day [1]. Supporters of the BRT system highlight how rubber tires allow for operation flexibility, which is impossible for a tram system; while those decrying BRT say that such flexibility does not ensure a high quality of service. In the United States, the debate concerning BRT and LRT systems is very tight and supporters of LRT have accused the US Federal Transit Administration of excessively sponsoring systems like BRT only with the purpose to facilitate road transport and oil industry lobbying [2].

The main differences between the two systems are essentially due to the following characteristics:

- BHLS systems allow for more track flexibility;
- LRT vehicles have a longer life than BHLS systems;
- Initial funding for the realization of BHLS systems is generally less than for LRT systems;

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- LRT systems can operate safely on rails, in tunnels and on overpasses;
- Access time to LRT stops is generally longer than to BHLS stops;
- LRT vehicles need less space both in stations and on tracks.

The characteristics of a BHLS system that make it more similar to a tramway are to be found in the improvements compared to a classic road for public transport:

- A reduced number of stops;
- Reserved lanes in which it is possible for the bus to achieve a higher speed, without excluding the possibility of operation in a mixed zone; reserved lanes introduction is not dependent "from means of transport riding but from political support which allows to deduct space for cars, offering alternative solutions to car drivers" [3];
- Priority systems at intersections and turn prohibitions for motorized vehicles on the reserved lane;
- High frequency;
- Increased comfort due to the absence of continuous acceleration and braking;
- Information about the real-time position of the vehicle;
- Ticketing outside the vehicle;
- Road-level access through low-floor bus and stations equipped with facilities for passengers.

Marc Le Tourneur, a member of the *Direction de l'Innovation et du Développement of Veolia/Transdev*, argues that the choice between a BRT system and a tramway is mainly related to the number of passengers: a number of less than 3000 passengers/h should lead to opting for the BRT system; a larger number for the tram system [4]. Actually, it is not possible to consider a system absolutely more suitable than the other; both the solutions could be ideal on the basis of a particular scenario. Choice criteria should include each system's available funds, its operation costs, environmental improvements and possible economic developments. Conventional cost-benefit analysis is not always able to take into account all of the wide range of impacts deriving from the competing projects, since it generally provides the decision maker with an economic assessment expressed in a monetary scale. Multi-Criteria Decision Analysis (MCDA) techniques are indeed able to incorporate multiple parameters related to both economic and strategic aspects and they are a good aid for decision makers in identifying priorities.

In this study, MCDA will be used to evaluate the choice between the application of a BHLS system and a LRT one; a spatial analysis via a Geographical Information System (GIS) environment will be used for designing some parameters of the analysis.

2 METHODOLOGY

2.1 Literature review

Through an analysis of recent literature on the evaluation of transport projects, it can be seen that there are several articles reporting growing attention to the use of MCDA techniques; this is due to the fact that MCDA is able to cope with several criteria besides the economic aspects and can also deal with different, often contrasting, decision makers [6], [8], [9].

In particular, the use of compensatory approaches (based on the assumption that a high performance achieved on a criterion can compensate bad performance of another one) is widespread in mobility management, infrastructure and public transport analysis; it is used in the comparison of different road or rail projects [10], [11], the construction of public transportation models [12], integrated planning for public transport and land use development [13], and in the creation of personalized route planning systems [14].

Decision-making problems, as transport system evaluations, require taking into account some spatial parameters of each alternative; integration with GIS can be useful in this perspective. Jankowski [6] distinguishes between two strategies for integrating GIS with MCDA: the first strategy suggests linking them by using a file exchange mechanism (*loose coupling strategy*); the second strategy suggests the full integration of multiple criteria evaluation functions into GIS with a shared database and a common user interface. In Gonçalves Gomes and Estellita Lins [15], a multi-objective linear programming technique integrated in a GIS environment is used to select the best municipal district of Rio de Janeiro State in Brazil, in relation to the quality of urban life. A good example of integration between MCDA and GIS in the transport field is the evaluation of alternatives in transportation planning made by Piantanakulchai and Saengkhao [16] in which a case study of alternative motorway alignments in Thailand was conducted through the application of a compensatory approach.

In our study, a loose coupling strategy will be adopted and compensatory MCDA methods will be applied to evaluate the global score of both LRT and BRT systems.

2.2 Fundamental objectives and related criteria

MCDA techniques allow the evaluation of different project solutions on the basis of a limited number of criteria, through a unique global judgement, giving the decision makers the chance to tend to the most satisfactory opportunity.

In its basic application, any MCDA technique pursues the following steps:

- Identification of the alternatives, which may consist of different project solutions or different elements of a whole project;
- Identification of the objectives;
- Identification of criteria, which are performance indicators related to each objective; they can be both quantitative and qualitative.

In our study, the two different transport systems BRT and LRT will be compared through the application of a MCDA technique, illustrated in sections 2.3 and 2.4. Here we present the objectives to be satisfied, divided into three categories according to their corresponding impacts: transportation impact, economic impact, social and environmental impact.

The main objectives and their associated criteria in the transportation impact category are:

1. Improve safety: the number of interaction points with other road users such as road junctions, roundabouts, pedestrian crossings and right of way;
2. Improve security;
3. Improve accessibility: two different types of accessibility can be taken into account. A a passive accessibility, i.e. the difficulty of access by communities to the transport system, which can be represented by:

$$A_i = \frac{1}{\sum_{i=1}^{n}(P_i * d_i^c)}, \tag{1}$$

where Ai is the difficulty of access by community in the Traffic Analysis Zone (TAZ) of the transport system; Pi is the population in the TAZ i; dic is the distance of TAZ i to the nearest transport system station; c is a parameter reflecting the willingness to use the system; an active accessibility, measuring the easiness of reaching opportunities for people leaving the transport system, which can be measured by Hansen’s accessibility index:

$$A_i = \sum_j \left(\frac{B_j}{d_{ij}^a}\right), \quad (2)$$

where A_i is the difficulty of access by users getting off the transport system at the station i; B_j is the opportunities in the TAZ j; d_{ij} is the distance from i to j; a is a deterrence parameter. Nine different types of activities have been taken into consideration to evaluate active accessibility, according to the following categories: parking locations, health places, administrative offices, worship places, food shops and courts, entertainment, education, culture/tourism, tourists' accommodation. The results have been classified into 10 different levels of passive and active accessibility.

4. Minimize travel cost. Generally, the public transport systems, on rail or road, are represented with not-congested network models, which means that they neglect speed reductions due to the phases of boarding and alighting of the passengers at the stops, and also the cost perceived by users in relation to the degree of crowding on board. For systems on totally or partially mixed ways (e.g. tramways, buses, etc.), it is preferred to estimate the commercial speed of the line, which depends not only on the characteristics of the vehicles (maximum speed, acceleration, etc.), but also on road traffic on the mixed way.
5. Guarantee integration with other transport systems. The integration criterion is used to judge how well the structure is integrated with other transport systems and other city structures. Separate underground and aboveground systems are an example of disintegrated structures. Transfer nodes, shared stops, common information for passengers, common tariff, coordinated timetables, shared road sections.
6. Guarantee flexibility. This criterion is related to the potential of renewing elements of the system, such as including other itineraries, displacing the track, moving the stops' locations.
7. Maximize capacity, in order to achieve a higher number of passengers carried at peak hour.
8. Optimize reliability. This criterion is used to guarantee the highest punctuality being in the interest of the operator, public transport management, and passengers.

The main objectives and their associated criteria in the economic impact category are:

1. Minimize infrastructure cost;
2. Minimize operating and maintenance costs;
3. Minimize vehicle purchasing costs;
4. Maximize urban public transport system profitability.

The main objectives and their associated criteria in the social and environmental impact category are:

1. Avoid community severance: community severance, or the barrier effect, happens when the transport system limits people's mobility, instead of facilitating it. Railways, motorways, and roads with high traffic levels or speeds, create physical and psychological barriers that separate communities, with effects on walking and cycling mobility and possible negative effects on individual health and social cohesion.
2. Minimize land use: the land use criterion should be considered in order to assess whether an element of the infrastructure is likely to require more or less space.
3. Improve comfort. This takes into account the social requirements of urban public transport passengers by guaranteeing the optimum travel conditions. It determines the percentage share of the travel performed in good and very good conditions during an

entire urban public transport journey. This criterion also takes into account the share of seated travel, i.e. the number of passengers able to occupy seats on the urban public transport vehicles.

4. Minimize energy consumption, basing on kWh produced by both transport systems.
5. Noise pollution. Roadway noise is the prevalent environmental noise in the cities; emissions from vehicles are influenced mainly by traction mechanisms, and by the contact between the wheel and the sliding surface. The noise level N_i to the TAZ i if a transport system would be constructed can be evaluated as:

$$N_i = N_0 - \alpha \log \frac{D_i}{D_0}, \qquad (3)$$

where N_0 is the noise level at a standard distance from the centre of the line; D_0 is the standard distance from the centre of the line; D_i is the shortest distance between the line and the TAZ centroid; α is a parameter reflecting type of ground and obstruction from roadside; total weighted noise impact N to neighbouring communities could be represented by [16]:

$$N = \sum_{i=1}^{n} \frac{(\frac{P_i}{\bar{P}})(\frac{N_i}{N_0})}{L_{i,noise}}, \qquad (4)$$

where P_i is the population within the community i; $\bar{P}$ is the mean population; $L_{i,noise}$ is the Land use factor related to the noise impact on the community i (equal to 1 in this study).

6. Air pollution, expressed in kg/m^3 using the Gaussian Air Dispersion Model [18].

2.3 TOPSIS

TOPSIS, which stands for 'Technique of Order Preference Similarity to the Ideal Solution', is a goal reference technique that requires a minimal number of subjective inputs (just the weights associated to the criteria; the fundamental idea is that the best solution is the one which has the shortest distance to the ideal solution and the furthest distance from the anti-ideal solution [5].

The TOPSIS method is based on five computation steps [17]:

1. The first step is the gathering of the attribute values of each alternative on the different criteria.
2. Attribute values need to be normalized in order to allow the comparison of different units. Normalization has been made through the application of two different methods. The distributive normalization, which requires that the performances are divided by the square root of the sum of each squared element in a column, according to the following equation:

$$r_{ia} = \frac{x_{ia}}{\sqrt{\sum_{a=1}^{n} x_{ia}^2}} \text{ for } a = 1, \ldots, \text{n and } i = 1, \ldots, \text{m}. \qquad (5)$$

The ideal normalization, which requires dividing each performance by the highest value in each column if the criterion has to be maximized. If the criterion has to be minimized, each performance is divided by the lowest score in each column, according to the following equations:

$$r_{ai} = \frac{x_{ai}}{u_a^+} \text{ for } a = 1, \ldots, n \text{ and } i = 1, \ldots, m, \qquad (6)$$

where $u_a^+ = \max(x_{ai})\ for\ all\ a = 1, \ldots, n$;

$$r_{ai} = \frac{x_{ai}}{u_a^-} \text{ for } a = 1, \ldots, n \text{ and } i = 1, \ldots, m, \qquad (7)$$

where $u_a^- = \max(x_{ai})\ for\ all\ a = 1, \dots, n.$

3. Normalized scores are then weighted. A weighted normalized decision matrix is constructed by multiplying the normalized scores r_{ai} by their corresponding weights w_i.
4. The distances to an ideal and anti-ideal point are calculated. The decision has been made to assume an absolute ideal and anti-ideal point, defined without considering the actions of the decision problem, A+ = (1, ..., 1) and A− = (0, ..., 0). The distance for each action to the ideal action is calculated using the following equation:
$$d_a^+ = \sqrt{\sum_i (v_i^+ - v_{ai})^2\ with\ i = 1, \dots, m}. \tag{8}$$
The distance for each action to the anti-ideal action is calculated using the following equation:
$$d_a^- = \sqrt{\sum_i (v_i^- - v_{ai})^2\ with\ i = 1, \dots, m}. \tag{9}$$
5. Finally, the closeness, whose value is always between 0 and 1, is given by the ratio of the calculated distances:
$$C_a = \frac{d_a^-}{d_a^+ + d_a^-}\,. \tag{10}$$

3 CASE STUDY

3.1 Cities involved

For the application of the methodology, as a hypothetical exercise, the tramway of Santa Cruz de Tenerife in Spain and the BRT system of Prato in Italy have been chosen for comparison. These two cities were chosen because of their similar characteristics with regard to geographic and demographic data, and because of the similarities noticed between the two respective transport systems, as it can be seen from the data reported in Table 1. Data used for this study, as well as information regarding the transport system, refer to the year 2013 (see http://www.comune.prato.it/ and http://www.santacruzdetenerife.es/).

The public transport system in Prato includes a railway system and urban and sub-urban bus lines. This road network is based on different bus lines operating in the whole Prato area managed by CAP (Cooperativa Auto-trasporti Pratese). Five BHLS lines – LAM (*Linee ad Alta Mobilità*) – operate in the city: the Blue line (Fig. 1, analysed in this study), Red line, Orange line, Light blue line, and Purple line. The first three serve the urban area, whereas the Light blue line and Purple line link the city centre with the sub-urban area.

The main urban transport systems of Santa Cruz de Tenerife consist of collective *guaguas* (bus lines managed by the operator TITSA), and the tramway of Tenerife is managed by *Metropolitano de Tenerife Sociedad Anónima* (MTSA). The Tramway of Tenerife covers a total of 15.1 km and includes two lines, the Línea 1 and 2. The Línea 1, analysed in this study (Fig. 2), opened in 2007, is the main line with 21 stops and a length of about 12.6 km, and links the *Intercambiador de Transportes* of Santa Cruz de Tenerife at the Trinidad station.

Cities	Area (km^2)	Population (inhab.)	Density (inhab./km^2)	System	Line	Length (km)
Tenerife	150.56	214,477	1363.44	Tram	1	12.6
Prato	97.35	191,070	1962.01	BHLS	Blue	9.61

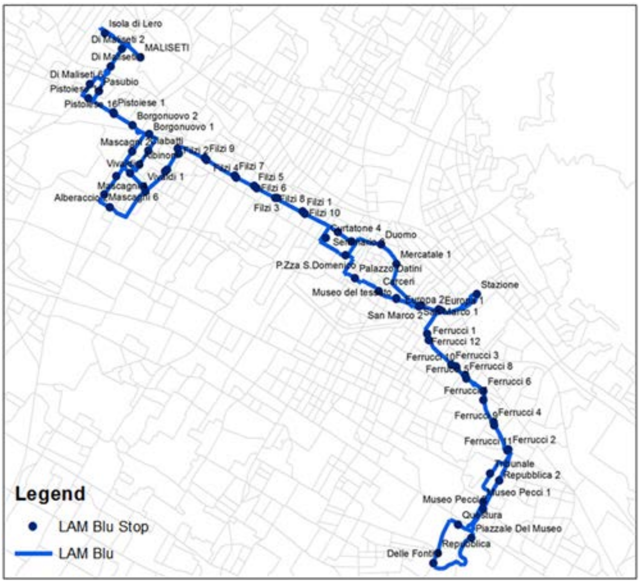


Figure 1: Prato BRT study area.

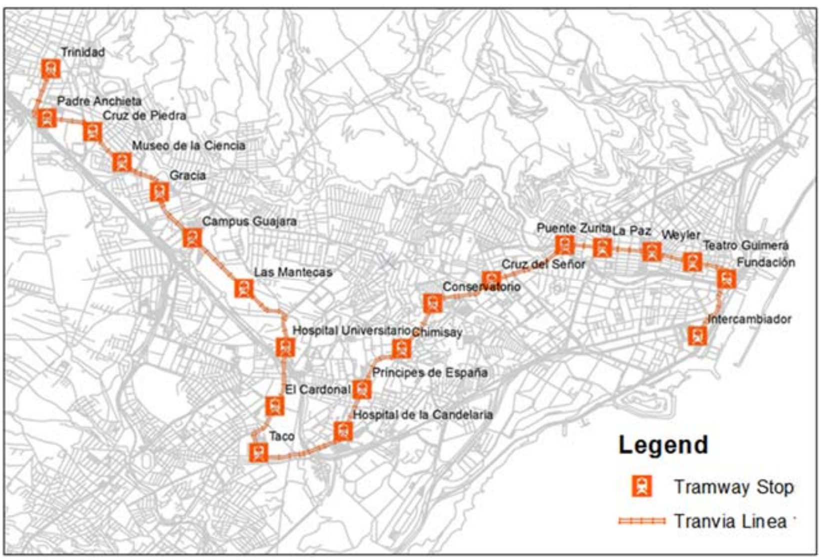


Figure 2: Tenerife LRT study area.

3.2 Weight assignments

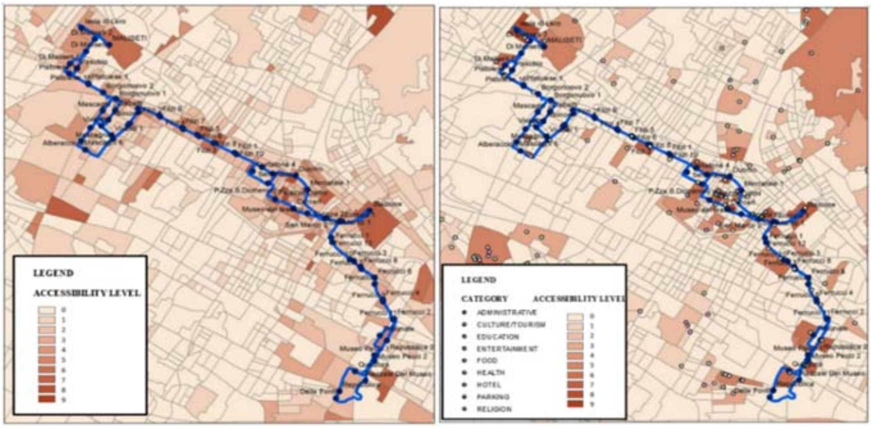
Since it is not possible to involve, at this stage of the study, decision makers and stakeholders of the two communities, it has been decided to assign the same weight to all criteria, making sure that the total sum of the weights would be equivalent to 1.

3.3 Evaluation of indicators

Data on vehicle purchasing costs, profitability and seated travel are not included in this case study; all the other indicators have been evaluated from COST Actions TU0603 and TU1103 [1], [19], and from information given by the operation companies in their websites; the indicators used for analysis are shown in Table 2. The estimation of spatial indicators has been realized through the use of the software ArcMap10.1 in the ArcGIS environment. The final outputs of indicator evaluation are the criterion maps which, with regard to accessibility indicators, are shown in Figs 3 and 4. In order to interpret what is represented in the maps, the values of accessibility indices have been normalized and grouped into 10 different levels (from 0 to 9, with 0 being the lowest accessibility level to 9 being the highest accessibility level). In both cities, it is possible to see how the zones surrounding the transit line always show high levels of accessibility.

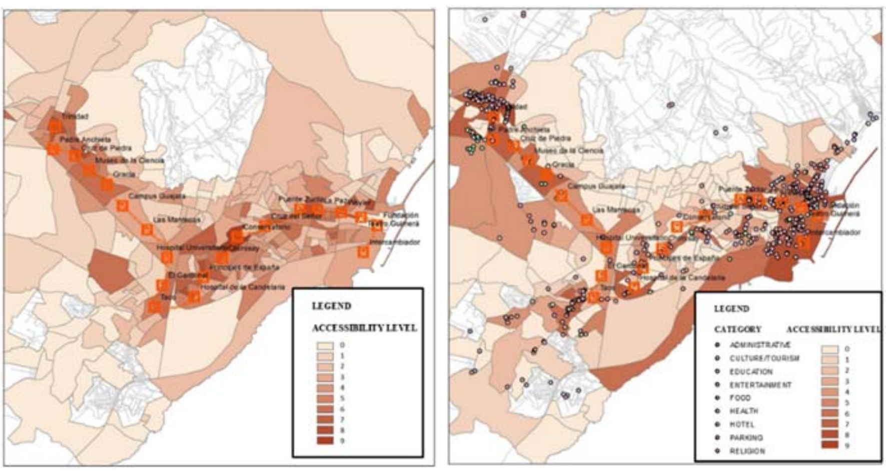
Table 2: Indicators used for TOPSIS method.

City		Tenerife	Prato
Transport system		Tram	BHLS
Criteria	*Unit*	*Attribute*	
Area	km^2	150.56	97.35
Population	Inhab.	205279	190777
Density	Inhab./km^2	1363.44	1959.70
Length	km	12.62	15.10
Interaction points	Number/length	38.00	283.00
RoW	length mixed/length	0.00	0.30
Accidents	Acc./km	1.73	4.37
Criminality	Number/year/inhab.	0.00	
Passive accessibility	INDEX (medium)	0.58	110.50
Active accessibility	INDEX (medium)	1288.59	856.95
Cost	h	0.59	0.80
Speed	Km/h	21.30	18.90
integration nodes	percentage	1.00	4.00
shared stops	percentage	0.44	0.46
information for passengers	yes/no	0.00	1.00
common fare	yes/no	1.00	1.00
coordinated timetables	yes/no	0.00	1.00
shared intermodal sections	Length/tot length	0.00	0.00
Flexibility	yes/no	0.00	1.00
Capacity provided	Pass/h	5400.00	282.86
punctuality	percentage	0.995	0.74
Infrastructure cost	€/km	€ 22,821,638.06	€ 589,400.00
Operating and maintenance costs	€/km	€ 812,500.00	€ 1,300,000.00
Community severance	m/km	0.18	0.00
Energy	kWh/km	6.53	7.72
Noise level	INDEX	42.91	215.40
Air pollution N_{ox}	kg/m^2	0.000001	0.000033
Air pollution PM_{10}	kg/m^2	0.000000	0.000000
Air pollution CO_2	kg/m^2	0.000086	0.000002
Air pollution CO	kg/m^2	0.000000	0.000003



(a) (b)

Figure 3: (a) Passive; and (b) Active accessibility levels in Prato.

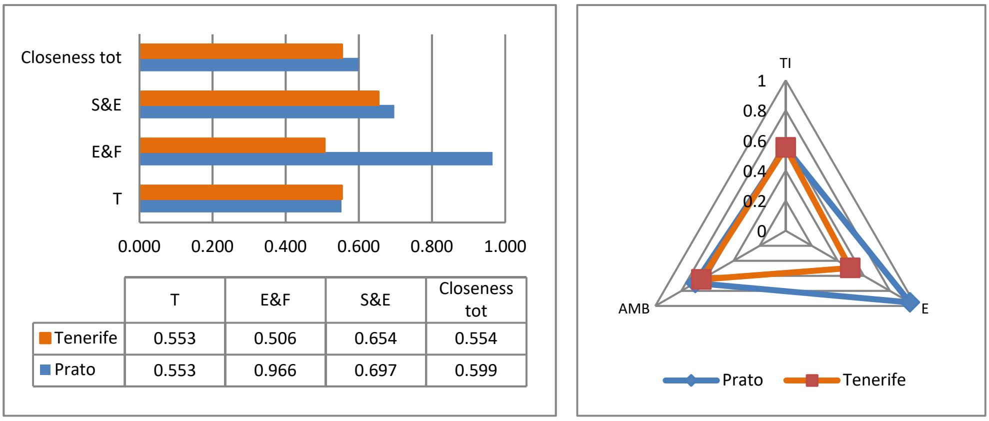


(a) (b)

Figure 4: (a) Passive; and (b) Active accessibility levels in Tenerife.

3.4 MCDA through TOPSIS approach

The ideal normalization approach has been applied; the technique ranked the two alternatives assigning a better global score to the BRT solution, indicated through the total closeness in Fig. 5(a). Analyzing partial scores, BRT obtained a better score for Social and Environmental impact score (S&E; Fig. 5), a high partial score for the Economic and Financial impact score (E&F; Fig. 5), while in the Transportation impact score, LRT just overpasses BRT. In the radar chart of Fig. 5(b), it is possible to appreciate the closeness of each partial indicator to the ideal solution, with the Economic impact score of BRT standing out among the others, almost reaching the value of 1.



(a) (b)

Figure 5: Ideal normalization TOPSIS. (a) Results; and (b) Radar chart.

3.5 Sensitivity analysis

A sensitivity analysis has been conducted in order to identify whether the outputs coming from the method are influenced by the weights assigned to the input factors. Most of the time, in fact, data in multi-criteria decision-making problems are changeable and unstable, and a sensitivity analysis after problem solving can effectively contribute to the choice of the appropriate method to obtain more accurate decisions.

Three more possible weight scenarios of analysis have been assumed: a scenario in which all the impacts have the same weight; a hierarchical scenario in which social impact criteria have the biggest weights and economic impact criteria the smallest ones; a scenario with random weights assigned. Partial scores, global score and their variances (Tables 3 and 4) within the four analysis scenarios have been calculated. Sensitive analysis shows that the solution is robust.

Table 3: Partial and global score comparison within the four different weight scenarios.

Method	Scenario	City	T	E&F	S&E	TOT
TOPSIS ideal	Base	Prato	0.552	0.952	0.694	0.599
		Tenerife	0.553	0.495	0.648	0.554
	Impacts	Prato	0.553	0.927	0.691	0.599
		Tenerife	0.554	0.414	0.641	0.519
	Hierarchy	Prato	0.552	0.9524	0.694	0.600
		Tenerife	0.553	0.4956	0.648	0.554
	Random	Prato	0.552	0.940	0.678	0.598
		Tenerife	0.553	0.489	0.598	0.545

Table 4: Variances of the four analysis scenarios.

	Transportation impact	Economic impact	Social and environmental impact	Total score
Prato	3.72E-06	1.39E-06	6.54E-08	3.16E-06
Tenerife	2.37E-05	1.58E-05	9.29E-08	1.88E-05

4 CONCLUSIONS

After some years of the disposal of tramway lines, we are currently witnessing their great renaissance and a consequent modernization of vehicles and operations that are leading to the increased use of LRT systems. At the same time, a new bus system concept providing high quality service is developing and the competition between the two types of systems is becoming more frequent. In this paper, a comparison between LRT and BRT systems has been conducted with the use of the TOPSIS technique. A case study involving the cities of Prato and Santa Cruz the Tenerife has been presented. The results of the application to a medium-sized city with similar characteristics gave comparable results concerning partial and global scores, indicating that the BRT system is the best solution.

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