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IMPROVING PUBLIC TRANSPORT MANAGEMENT THROUGH OPTIMIZING USE OF RESOURCES: A CASE STUDY

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ABSTRACT

High-performing public transport shall be effective to meet user's mobility and accessibility needs and, at the same time, use resources efficiently. This paper presents the optimisation of an urban transport network as part of a study implemented within the municipality of Pombal, located in the Centre Region of Portugal. The study aimed to answer effectively local demand through satisfying quality management criteria such as comfort and safety, origin-destination travel times compatible with user's daily mobility needs and to contribute to social inclusion and economic development. The strategic objectives of the study can be described as follows: a) to promote sustainable mobility within the municipality and the region; to improve the efficiency of the bus network (Pombus); b) to adjust bus timetables in accordance to user needs; c) to increase the number of daily passengers served; d) to use the existing vehicles fleet in a more efficient way by addressing actual and potential demand needs; e) to adopt a multimodal perspective by integrating bus services with other transport modes such as rail; f) to improve energy efficiency; g) to value the social dimension of the bus network by assuring access to public service with quality for all. The optimisation algorithms developed accounted for the demand profiles obtained through the mobility surveys implemented, the location of the set of obligatory stops, the quickest routes taking into account congestion, demand

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distribution along the day, bus occupancy rates and existing supply and energy consumption. An experimental period of five months was set to test the optimised bus network solution. Results from bus operation showed that it was possible with the same resources to enlarge the bus catchment area to cover a higher number of users and to adjust timetables to meet user daily mobility needs (trips to school of the youngsters, trips to other daily services of the elderly, etc.). The follow-up surveys to the population, as part of the public participation process, showed that the solution implemented contributed to reinforce the role of the bus network (Pombus) as a key element for achieving sustainable mobility in the municipality of Pombal: it accounted for social equity issues in accessibility, met expectations and needs of the local population, minimised energy consumption and improved the financial sustainability of the bus operation.

Keywords: Management, Public resources, Optimization, Public transport, Efficiency

Introduction

In Europe, approximately 75% of the population lives in urban areas where exceedances of air quality standards frequently occur, instigating serious health risks and costs to society representing approximately 2% of the Gross Domestic Product (GDP) [1]. In addition to air pollutants, noise emissions from road traffic are associated with various health outcomes. In this context, the technological improvements in the automobile industry are not sufficient per se to minimize the aforementioned problems. Therefore, road networks must be operated more efficiently in order to maximize the economic growth and to minimize negative impacts on the population and the environment. Adequate public transport is key to the quality of life of the population. However, public transport enterprises often face the challenge of meeting user needs while assuring efficient management and the financial sustainability of their operations.

Efforts to optimize use of resources need a holistic approach able to consider system performance, social equity, and a comprehensive assessment of environmental impacts and other external costs. Besides traffic congestion, multiple transport-related negative externalities are known to cause market inefficiencies and social welfare losses [2]. Nowadays, the fuel supply to the road sector is dominated by oil which has proven reserves that are expected to last around 40 years. Despite the fact the fuel efficiency of new vehicles has been improving (thus reducing also CO_2), total CO_2 emissions from transport have increased by 24% from 1990 to 2008, representing 19.5% of total European Union (EU) greenhouse gas emissions [3]. Concerning pollutants with effect at local scale, despite the legal restrictions on emissions factors, in recent decades, pollutant emissions from road vehicles are still a main source of air pollution significant for human exposure. As stated in the European White paper for transport [4], a higher share of travel by collective transport in relation to individual transport, combined with minimum service obligations will allow increasing the density and frequency of services, thereby generating a virtuous circle for public transport modes.

This paper presents the optimization of an urban transport network which was a component of a study developed for the municipality of Pombal, located in the Centre Region of Portugal. The study aimed to answer effectively local demand through satisfying quality management criteria such as optimized energy consumption, comfort and security, origin-destination travel times compatible with user's daily mobility needs and to contribute to social inclusion and economic development.

Optimization of Public Transport Networks

Service Quality and Critical Variables

Service quality of public transport networks is critical to assure moving towards sustainable mobility.

The geometric configuration of routes is often determined by the conditions of road infrastructure and safety concerns. Frequently, the definition of internal regulations specifies the type of streets where vehicles can operate safely, namely by considering steep slopes, uncontrolled intersections, deteriorated road conditions or recurrent problems with illegal parking. Another key issue involves the determination of the extent to which a route operating in a given corridor should take a detour to service a population center away this corridor. In addition to the economic and financial point, it is necessary to take into account the gain in convenience for passengers embarking and the degree of discomfort to other passengers. Some requirements are usually considered to consider this effect [5]:

- For a specific deviation from the existing route, the total additional travel time for all passengers should not exceed three minutes for each passenger embarking or disembarking along the route detour.
- The shift can be achieved with the existing resources if for every two minutes of increased travel time, the passengers increase is not less than 25 percent of passengers affected by the detour.

The location of stops and their spacing is another factor influencing the efficiency of service. The location of bus stops has always been one of the most controversial issues in the public transport industry due to lack of consensus on the best solution. Nevertheless, there is some unanimity that point out that stops away from intersections are underused although it may be the best option in certain circumstances, particularly to serve specific services and equipment with high demand [6].

"Attractive frequencies, comfort, easy access, reliability of services, and intermodal integration are the main characteristics of service quality" defined in the European White paper for transport [4]. The availability of information over travelling time and routing alternatives is equally relevant to ensure seamless door-to-door mobility for passengers.

Ibarra-Rojas et al. [7] already reviewed the literature on public transport network planning problems (e.g. transit network design problem, frequency setting problem, transit network timetabling problem, vehicle scheduling problem and driver scheduling problem) and real-time control strategies suitable for bus transport operations.

Given the above, the study developed at the municipality of Pombal aimed to answer the following questions:

1. How to promote sustainable mobility within the municipality and the region?
2. How to adjust bus timelines in accordance to user needs (i.e. to answer effectively local demand)?
3. How to increase the number of daily passengers served?
4. How to use the existing vehicles fleet in a more efficient way by addressing actual and potential demand needs?
5. How to adopt a multimodal perspective by integrating bus services with other transport modes such as rail?
6. How to improve energy efficiency in bus operations (using resources efficiently)?
7. How to value the social dimension of the bus network if the network assures access to public services with quality for all?

Case Study Development

Methodology and Data Collection

The study phases can be described as follows: a) Diagnosis and data collection (user needs and expectations, most valued service attributes, actual constraints of the bus services provided, analysis of energy consumption by route/service and related CO2 emissions, etc.); 2) Development of the optimization algorithms; 3a) Experimental period by testing in situ the optimization algorithms, including the implementation of user satisfaction surveys and other spontaneous citizens' suggestions; 3b) Public consultation: population and other stakeholders; 4) Implementing adjustments to bus routes/services; 5) Running buses along optimized routes/services.

The Diagnosis phase used a participatory methodology that comprised the implementation of more than 3000 mobility surveys targeting four type of users (2098 validated); i) students who actually use bus services and other transport modes; ii) adult passengers (more than 18 years old and non-student); iii) resident population in other areas that are not actually served by bus services; iv) active population working in industrial areas. These mobility surveys were complemented by personal interviews to confirm users' perceptions of specific service attributes of the bus network and, also, interviews to bus drivers. The diagnosis of the actual public transport services included the following aspects: a) analysis of existing and potential demand; b) analysis of actual and future supply; c) characterization of road infrastructures, bus stops and equipment. The mobility survey collected data on the socioeconomic characteristics of the different bus users (age, gender, education level, household monthly income, etc.), mobility patterns (origin-destination) and daily activity data, perceptions of services along actual routes, user mobility and accessibility needs (actual and in the future), constraints of the actual public transport system, most valued bus attributes for choosing bus, user satisfaction regarding actual bus routes/services and bus drivers opinions, inbound/outbound passengers at each bus stop, bus tariffs for each type of user, daily vehicle occupancy rates for each bus route, bus frequency/waiting time at each bus stop. The diagnosis also included the analysis of operational costs, including energy consumption and CO2 related emissions for each running bus service/route.

The data collection was gathered during 2014 for three months, from March to May. The validated sample size, statistically representative of the population, comprises 2098 surveys (99% confidence level and maximum error of 1,6%). The statistical analysis of data was done through the SPSS® - Statistical Package for the Social Sciences.

To estimate the average consumption per route and to identify the most critical areas, in terms of fuel consumption (resulting either from the features of each route or from driving behavior), a fuel/consumption emission model based on Vehicle Specific Power [8] has been applied. The VSP concept is used in the evaluation of vehicle emissions. VSP is determined based on the following equation (eq.1):

$$VSP=v[1.1a+9.81\times\sin(arctang(\text{grade\%}))+0.132+0.000302v^3] \quad (1)$$

Where:
VSP: (kW/Ton); v: velocity (m.s.-1); a: acceleration (m.s.-2).

A major advantage of this method is its easy physical interpretation, the concept of vehicle-specific power (VSP) is a formalism used in the evaluation of vehicle emissions. VSP reflects the sum of the loads resulting from aerodynamic drag, acceleration, rolling resistance, and slope, all divided by the mass of the vehicle [9]. Conventionally, it is reported in kilowatts per tonnage VSP. Thus for different levels of specific power requirement there is correlations determining the instantaneous consumption of the vehicle (g /s). In order to gather the necessary data for the application of this methodology second-by second measurements of speed, acceleration and road grade were performed equipping buses with a GPS data logger device. A detailed analysis of the environmental performance of the bus fleet is not part of the scope of this study. However, the results of this environmental monitoring will be used for three distinct purposes: 1) to inform drivers about the importance of eco-driving highlighting the positive impacts on fuel consumption and emissions minimization and increase of passengers' comfort; 2) to avoid whenever possible routes whose characteristics imply high levels of fuel consumption; 3) to identify possible improvements in the operation of infrastructure (e.g. optimization of traffic signals).

Optimization Algorithms

One important issue for the optimization study was to avoid disruptive solutions to the existing bus network services. This would minimize negative impacts on users that are actually satisfied by the current level of services and avoid breaking mobility user routines. As such, we could concentrate our efforts on improving overall service performance, optimizing demand and supply and increase bus coverage as much as possible, considering population needs, energy and environmental constraints. The optimization of the network had several constraints discouraging the direct application of a common optimization model. On the one hand, a key objective was to keep the nature of a social network service, namely by ensuring the accessibility of elderly population to the main city facilities. On the other hand, it was intended to ensure a regular bus service to the remaining users (e.g. commuting trips and home-school trips) with reasonable levels of frequency and travel time. In addition to these principles, it was intended to increase the coverage of the network without decreasing the levels of efficiency.

Several alternatives of route and schedules were analyzed with the primary objective of increasing the effectiveness and efficiency of the bus network. Three different scenarios were analyzed: A1 and A2 scenarios consider a fleet increase with an extra minibus and scenarios B1 e B2 scenarios consider a fleet increase with a 60 seats bus. The scenario B1 was dismissed because the results obtained do not answer to the fixed goals. The fleet reinforce in all scenarios was considered just to assure that the stop-time for maintenance do not affect the baseline number of vehicles on service. For each scenario considered, the network optimization process consisted of four main steps (Figure 1): 1) Route assignment, 2) Route optimization, 3) Network expansion, 4) Schedule optimization.

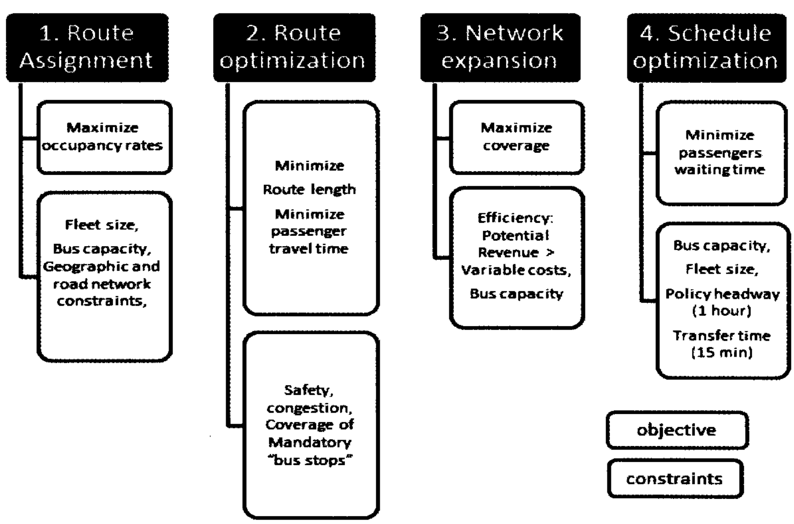

Figure 1. Layout of first page and subsequent pages.

As Figure 2 shows, the first optimization step (route assignment) consists of assigning the available fleet resources to the main influences zones of the network. Taking into account the results of the observed average occupancy rates (AOR) per vehicle in the baseline scenario, the primary objective was to reassign the number of buses (i.e. services per hour) in each zone of influence with the aim of achieving more balanced occupancy rates and also to foster demand in areas with greatest potential for growth in the number of paying users.

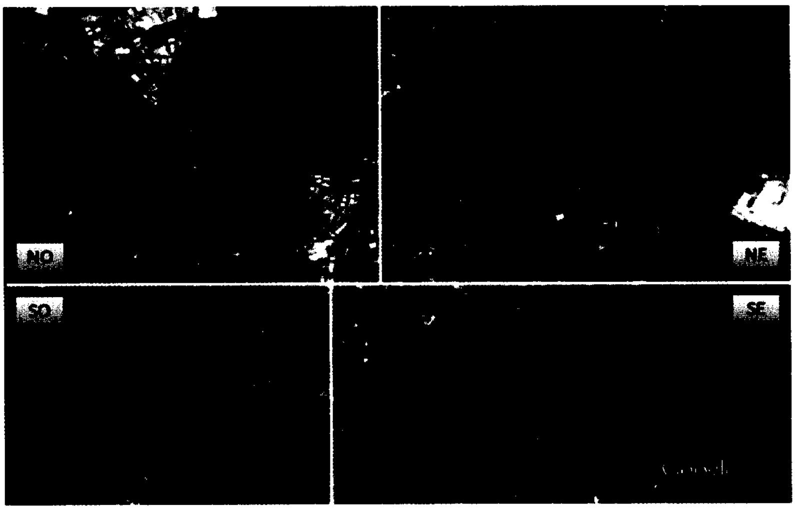

Figure 2. Segmentation of the bus network into four quadrants: ex ante bus routes (before optimization).

The second step (route optimization) consists in optimizing the design of the routes. The studied network is a special case of bus route optimization where the traveling salesman problem (TSP) may be applied. In the TSP a single vehicle has to visit a set of nodes (mandatory or fixed stops) exactly once before returning to its starting position (e.g. the focus of the network in the city center). Such problems implicitly assume that the sum of the total demand for services at the nodes is less than the capacity of the bus. These conditions are met in this case study assuming that available vehicles are already allocated to each zone of influence and with the exception of school peak periods no critical capacity problems were observed.

In the third step (network expansion), a simplified sensitivity analysis for each potential expansion area was performed. More precisely, it was assessed the number of users required to generate the necessary revenue related to the increase of variable costs due to each detour. Since the expansion of the network implies changes in travel time and frequency, the elasticity of demand was estimated based on [10].

The main objective of the fourth step (schedule optimization) was to minimize the waiting time of passengers while taking into account the resources (bus fleet) and service related constraints (e.g. frequency of services). The total waiting time of passengers includes both the total initial waiting time (before bus arriving) and the final waiting time (e.g. travel time until reaching school) and the total transfer time.

Key Performance Indicators

Nine Key Performance Indicators (KPI) were considered to analyze different possible scenarios as follows:

- KPI_01 - Average daily users during the school period. This indicator reflects the daily demand as "passengers/day".
- KPI_02 - Offered capacity in the 45 minutes′ period before the beginning of classes. This indicator reflects the total supply of the bus network as " available seats " to the main schools of the city during morning rush.
- KPI_03 - Number of daily runs. This indicator reflects the number of runs covering a certain bus stop of the network.
- KPI_04 – Headway. This indicator refers to the time interval between successive bus passages at a given point of the network measured in "minutes".
- KPI_05 - Operating profitability ratio. This indicator represents the ratio between the estimated total revenue and total operational costs (expressed as %).
- KPI_06 - Equivalent cost per passenger. This indicator reflects the ratio between the total cost and the number of daily passengers and is measured in "€/passenger".
- KPI_07 - Equivalent average revenue per passenger. This indicator represents the ratio of the estimated total daily income and the daily number of passengers and is measured in "€/ passenger".
- KPI_08 - Daily Operational Deficit. This indicator reflects the difference between the estimated total revenue and total operating costs per day and is measured in "€/day".
- KPI_09 - Ratio Total Demand Average vs. Capacity Offered. This indicator reflects the ratio between demand (number of passenger per day) and the number of places (seats runs) offered in a given period of operation.

Table 1 shows a synthesis of critical parameters and key performance indicators (KPI) for some examples of the modelled scenarios: A1, A2 and B2.

Table 1. Examples of KPIs for the modelled scenarios.

	Daily distance traveled) (km/day	Demand (KPI_01) (pass/day)	Operational Cost (€/day)	Revenue (€/day)	Operating profitability ratio KPI_05) (%)	Cost (KPI_06) (€/pass)	Revenue per passenger (KPI 07) (€/pass)
Base	642	981	916	211	23.1%	0.93	0.22
A1	614	1060	871	228	26.1%	0.82	0.22
A2	702	1204	993	261	26.3%	0.82	0.22
B2	736	1210	1106	275	24.8%	0.91	0.23

The operating profitability ratio (KPI_05) of the network takes into account the income of a typical day during the school period and the total costs of operation. It is also presented the average cost per passenger (KPI_06) (ratio of the total daily costs and the number of passengers per day) and the average equivalent revenue per passenger (KPI_07) (ratio of the total daily estimated revenue and the daily number of passengers). Bus services are critical to provide the daily access of students to schools located within the municipality of Pombal. As such, this social dimension of the bus service was considered as a key objective. Figure 3 shows examples of KPI_09 (Ratio of average demand vs. capacity supplied) for the various modelled bus route scenarios.

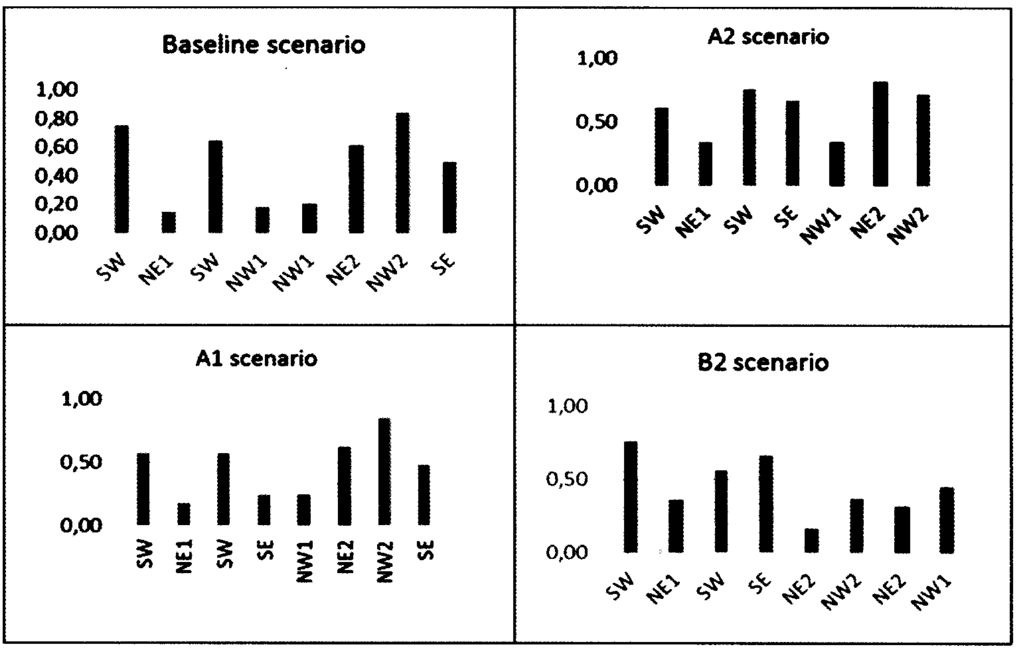

Figure 3. KPI_09 - Estimation of Average demand *vs*. Average capacity per influence zone for A1, A2 and B2 scenarios (4pm – 7:30pm)

Results

Taking as reference the base scenario (current situation) all the proposed scenarios allow a reduction in costs per passenger as well as an increase in operational profitability. Scenarios A1 and A2 scenarios are the ones presetting better results from the point of view of network efficiency, namely in terms of operational profitability (KPI5). In the case of A1 scenario, the increase in the daily number of passengers (KPI1) is related to the increase in the frequency in some routes which predictably may generate higher demand. By contrast, in A2 scenario it is estimated an increase of the indicator KP1 in 18%. However, in this case this increase is mainly related to passengers from the new expansion areas considered in this scenario. The B2 scenario presents a higher equivalent cost per passenger (KPI6) and a slightly lower operating profitability ratio. The analysis shows that scenario A2 represents the best optimization solution, for the KPIs considered (b. in Figure 4).

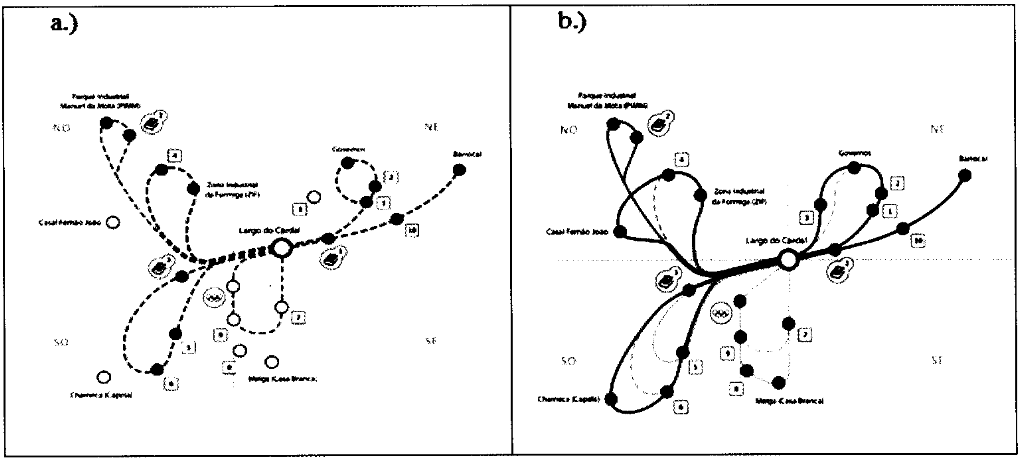

Figure 4. Bus network routes: a.) before optimization and b.) after optimization.

Conclusions

The optimization study showed that it was possible to increase performance of the bus services without adding more resources (e.g. vehicles in operation and bus drivers). Considering the main KPI described in section 3.3, the study findings are as follows:

a) The average daily users of the bus network (KPI_01, passengers/day) considering all the bus routes increased 27%;
b) The available bus fleet within a 45 minutes' period (KPI_02, available seats) increased 25%, as bus frequency increased in some critical routes and periods;
c) The distance covered (KPI_03, number of trips per day) increased 11%, which included a 61% increase in the number of bus stops and 24% in bus coverage;
d) The operating profitability ratio (KPI_05, %), increased 5%;
e) The equivalent cost per passenger (KPI_06, €/ passenger) decreased 8,6%;
f) The ratio total demand average vs. capacity offered (KPI_09, %), increased 21,4%.

The optimization study showed that a more efficient and effective management of existing resources can yield significant social and environmental benefits to society and improve the financial sustainability of transport operations. Modelling results led to the identification of critical dimensions for value creation by public transport system and demonstrated that the shareholder value depends on the creation of value for the various stakeholders [11].

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