ENERGY, ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF MULTIMODAL URBAN TRIPS IN DIFFERENT DISTANCE RANGES

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Abstract

In a context of change associated with urban mobility, such as the emergence of new services and technologies, it is imperative to rethink the modes used. The objective of this work was to obtain multimodal energy consumption and emission factors as a function of the distance of each trip, in an urban context. In addition, an analysis of the total cost of different modes for the user was carried out, according to the modal split, for different ranges of distance, in the current scenario and considering an alternative scenario promoting micromobility solutions.

The methodology used includes the use of COPERT and the processing of IMob data to obtain energy consumption and pollutant emission functions for different ranges of distance, for different modes of transport. The average energy consumption and CO_2 emission for the fleet over the distance ranges was 1.42 MJ/(pass.km) and 56 g/(pass.km), respectively. The study of mobility patterns in the AML reveals that, trips with origin and/or destination in Lisbon are the most efficient, justified by the favorable modal split compared to trips in other municipalities. The TCO method is used to estimate the total cost of owning private cars. The total cost of using other modes of transport was also estimated in the AML. Revealing a reduction (€/km) compared to gasoline vehicles of 28% (BEV) and -1% (PHEV). The promotion of micromobility in the modal split led to savings of 85€/month and 1365 tons of CO_2/day.

Keywords: Energy efficiency; Decarbonization; Multimodal emission factors; TCO; Urban mobility; AML

1. Introduction

The rapid growth of the world population has been accompanied by a fast technological and industrial evolution, specifically concerning the utilization of private vehicles.

The high or low pollutants emissions can have a big environmental impact and, thus, it's necessary to be analyzed and regulated. For this reason, the Euro norms are imposed, responsible for the limitation of the emission factors of vehicles by exhaustion for the following pollutants: NOx, CO, PM, HC e HC+NOx.

Paving the way for the electrification of transportation, it's important to consider the electricity generation mix. In Portugal (2021), renewable energy sources contribute to 74.2% of the total electricity generated, leading to a future of green mobility. [1]

In this context, it's important to evaluate alternative solutions, such as electric vehicles, hybrids, plug-in hybrids and alternative energy sources such as electricity, hydrogen, ethanol, biodiesel, propane and natural gas.

The cost of transportation is an important factor when choosing a way to move. Also, it is estimated that 58.9% of an inquired population uses a private car due to speed, comfort and an absence of public transports that suppress their needs. [2] Therefore, the need to quantify the economic and environmental impacts of certain transports is clear, also in order to reach the consumer and feeling the lack of information.

There are some tools on the market to calculate the costs of cars, including the respective externalities. The app AYR developed by CEIIA, works as a digital wallet and allows to quantify the saved CO_2 emissions by choosing eco-friendly means of transportation instead of traditional vehicles. These emissions are converted into tokens and stored in the wallet, later exchanged for goods and services. In this app, it's not considered the ponderation of the kilometers driven by each mode, for each range of distance.[3]

Another resource available is the online calculator, Autocustos.pt, that allows the users to estimate the total cost of ownership of a private car. It's very rigorous with 12 parcels integrated in the calculation, such as, depreciation, insurance, inspection, maintenance, fuel, parking, among others. Requires a lot of data about the user and therefore is very detailed and came to fill the lack of depth of the tools available in Portugal, however it is very time and knowledge demanding. Also, the default values available are statistical data for each country and the precision of the costs can vary a lot by region, even within one country.[4]

The objective of this work is to obtain multimodal emission and consumption factors as a function of distance, in an urban context. As well as an analysis of the total cost of utilization of different transports and the average cost, according to the modal split, for different ranges of distance.

In regards to costs, Geng Wu et al. (2015) uses the approach of TCO to analyze and compare the costs per distance for different categories of vehicles. The projection for 2020 for a mean distance range, reveals that the vehicles in a crescent order of the TCO (€/km) is interna combustion, hybrids, plug-in hybrids and electrics. [5]

2. Methodology

2.1. Characterization of the energy consumption and vehicle emissions

In order to obtain the energy consumption and pollutants emissions for the average national fleet, the software COPERT 5.0 was used. The total estimated emission represents the sum of the following: non-exhaust, cold start and hot emissions.[6] All emissions and consumption values are related to the utilization of the vehicles and not the life cycle.

Firstly, the software was used to calculate the emission factors, considering the fleet in the Portuguese national inventory (NIR) for atmospheric pollutants.[7] COPERT requires some input parameters, that whenever available for the Portuguese reality were used and otherwise the default values from the program were kept.

The fleet in NIR has a diversity of 149 types of vehicles with different technologies. Certain categories available in COPERT are not present in NIR because they represent recent Euro classes and more advanced technologies. Since light passenger cars represent 71.4% of the fleet, only light passenger cars, buses and motorcycles were included in the present study.

Finally, something to consider is that the driving modes in NIR (and previous versions of COPERT) are urban, rural and highway. Additionally, the most recent version of COPERT distinguishes these modes as peak and off-peak. Peak (8am to 10am and 5pm to 7pm) being the mode with higher traffic and lower average speeds and off-peak the period of time outside of the previous one. [7], [8]

Thus, obtaining values for the energy consumption and emission factors of CO_2, PM, NMVOC, VOC, CO and NOx, which will then be compared to the literature. In order to assess the effect of the driving shares and speeds for each mode, the procedure is repeated 20 times for trips with speeds of 10, 15, 20, 25, 30, 35, 40, 45 and 50 km/h, for a 100% urban peak mode and 100% urban off-peak mode. Obtaining functions of the emission factors and consumptions with the velocity for each transportation and after, functions with the distance range.

2.2. Characterization of the total costs of transportation

In this chapter, it's defined the method to calculate the total cost associated with different transportations necessary to obtain the total cost for different classes of private cars and for public and shared mobility. All the costs are utilization only.

2.2.1. Private car

TCO is a method aimed at consumers and business managers, a method of financial estimation that allows the cost of purchasing a product or service to be evaluated as completely as possible throughout its lifecycle.

The first steps for this analysis include estimating the lifetime of the vehicle and the distance traveled over the period of time, 12 years and 200,000 km, respectively. [9], [10]

The defined costs are divided into fixed and variable costs, and the fixed costs include the following: purchase price, mandatory periodic inspection, circulation tax (IUC), vehicle tax (ISV), vehicle depreciation, car insurance and incentives. Variable costs taken into account are maintenance, parking, tolls and fuel.

According to the correspondence between an anonymous database and the NIR, the profile of a standard car was created, comprising 39% utility vehicle, 37% minivan and 24% of an average of the remaining segments. This database revealed average values of depreciation (after 12 years), consumption and purchase price for each category and fuel. [7]

For hybrid and electric vehicles, there is a lack of sampling for depreciation, the recent penetration of these technologies in the market and the consequent lack of confidence on the part of the same, lead to the assumption of depreciation values equal to those of petrol vehicles.[11]

Regarding consumption for hybrid vehicles, the average value was taken from COPERT. The NIR fleet does not include plug-in hybrids or 100% electric cars, so the consumption of these classes corresponds to the average consumption values of the best-selling PHEV and BEV in Portugal in 2017: BMW 330e BERLINA and Renault Zoe, respectively. [11]

For simplification purposes, it is assumed that around 78% of the kilometers driven by plug-in hybrid vehicles use electric motor and that these are petrol/electric hybrids, as they represent 92% of the total of conventional hybrids. [11] The assumptions for the estimated costs are shown in Table 1.

*Table 1 - Assumptions for the calculation of fixed and variable costs for private cars: petrol, diesel, plug-in hybrid, hybrid e electric. *Values based on confidential data.*

	Petrol	Diesel	Plug-in hybrid	Hybrid	Electric
Fixed costs					
Acquisiton price (€) *	36 190	38 970	73 090	47 170	53 860
Depreciation (%) (t=12y) *	31	28	31	31	31
Incentives (€) [21]	0	0	0	0	-3 000
ISV (€) [18], [22]	1 423.00	4 054.00	355.75	853.80	0.00
IUC (€/year) [17], [18], [23]	122.64	132.88	122.64	122.64	0.00
Periodic inspection (€/inspection) [24]	25.61	25.61	25.61	25.61	25.61
Insurance (€/year) [18], [25]-[28]	266.94	266.94	266.94	266.94	266.94
Variable costs					
Parking (€/year) [2]	125.40	125.40	125.40	125.40	125.40
Toll (€/year) [2]	184.50	184.50	184.50	184.50	184.50
Fuel (€/km) *, [30]-[32]	0.130	0.080	0.058	0.078	0.033
Maintenance (€/km) [33]	0.082	0.082	0.041	0.041	0.042

2.2.2. Public and shared transport

The cost in €/km obtained for the different categories of vehicles will also be compared with the cost of alternative transport, such as: public transport (train, underground and bus), car sharing (taxi and TVDE), electric bicycles, electric motorcycle and electric scooters. The prices of alternative transport mentioned are related to the AML.

As for public transport, the cost (€/km) was obtained by dividing the annual revenue by the number of passengers*km. The revenues considered are only those related to the public service (sale of occasional tickets, passes and co-payments) and all the necessary data are taken from the respective company's report and accounts for each transport. [24]–[26]

The tariff system of a taxi, within the AML, is assumed for simplification, as tariff 1 of the urban service. This is divided into day fare (6am-9pm) and night fare (9pm-6pm). In order to calculate the price per distance of a taxi, it is necessary to calculate a weighted average, taking into account the range of distances the vehicle travels, the percentage distribution of trips for each distance and the percentage distribution between the two times (daytime and night). These data are obtained according to the information calculated in the analysis of the mobility survey, in trips within the AML made by a taxi. [27]

Currently the TVDE platforms operating in Lisbon are Free Now, Uber and Bolt. It is assumed that a TVDE vehicle behaves similarly to a taxi, in relation to the journeys it makes. In order to calculate the price per distance of a TVDE, it is necessary to calculate a weighted average, taking into account the range of distances the vehicle travels and the speed and percentage travel distribution for each distance. The vehicle data necessary is assumed the same for the taxi.

The companies with e-scooters operating in Lisbon are currently Lime (associated with the Uber platform), Bird, Bolt and Frog. It's assumed that an e-scooter has a similar behavior to that of a bicycle and serves similar routes. [2]

The next shared micro mobility service, electric bicycles, began with the launch of the Gira – Bicycles de Lisboa system. [28] Currently, only Bolt and Gira offer this service in Lisbon. Following the methodology for calculating the cost of scooters, the data necessary is assumed the same for bicycles within the municipality of Lisbon. [2]

Currently, the companies providing the shared service of e-mopeds in Lisbon are eCooltra and Wyze Moblitiy. The behavior of these transport is similar to conventional motorcycles within the municipality of Lisbon. [2] Operators only operate in the municipality of Lisbon, so the data taken from the Mobility Survey are only for the municipality of Lisbon.

2.3. Characterization of mobility patterns

The National Institute of Statistics (INE) carried out the Mobility Survey in the Metropolitan Areas of Porto and Lisbon (IMob) in the 4th quarter of 2017. This survey covered close to 100 thousand residents in the two areas, with the aim of characterizing movements carried out by the resident population in each of the regions.

The data was analyzed and all answers with no real meaning were disregarded. Non-road transport modes are not relevant for the study of movements in the Metropolitan Area. The transports were grouped so that there were only cars, motorcycles, buses, bicycles, taxis, undergrounds, trains and walking. In order to differentiate the underground from the urban train, it is assumed that the underground has a lower average speed within the AML. While consumption is obtained from COPERT equations, for these two, consumption is constant and emissions are zero in their use, as they are electric. The average consumptions assumed for the underground and for the urban train are 21.6 MJ/km and 36.0 MJ/km, respectively. [29], [30]

It is important to note that the survey responses are given for one day and that each response has a weighting factor (pesofin), which represents how many people are associated with each response. Vehicles in different categories have different occupations, so that, in order to carry out a comparative analysis, it is necessary to take into account the occupancy rate (*Table 2*) and the pesofin factor.

Table 2 - Occupation rates.

Transport	Occupation rate (pass/vehicle)	Source
Car (peak)	1.23	-
Car (off-peak)	1.26	-
Bus	14.55	[26]
Motorcycle	1.00	-
Bike	1.00	-
Walking	1.00	-
Train	22.20	[25]
Underground	31.00	[24]

In this work, the data is treated according to variables such motive and period of time. A departure time between 8 a.m. and 10 a.m. and between 17 a.m. and 19 a.m. are peak hours, otherwise off-peak.

From the maintained 80% of AML trips, the average speed, travel time and modal split are obtained as a function of distance. As well as equations for speed as a function of distance for each mode of transportation.

2.4. Impact assessment associated to mobility patterns

It is very interesting to carry out an assessment of all these impacts (environmental, consumption-related and economic) in the AML. Through IMob data, it's possible to obtain carbonic intensity and consumption matrices among all municipalities. In order not to interpret trips with little representation, only intra-municipal trips and 80% of inter-municipal trips are included.

The modal split of the AML is integrated with the cost per kilometer (€/km and €/month) of each transport. The monthly cost requires data from IMob and it's assumed that the

Table 3 - Functions obtained from COPERT for pollutants emissions (g/km) (CO, CO_2, NO_x, VOC, NMVOC e PM) with speed (km/h) for different transports and traffic modes.

Transports	Traffic mode	Variable	Speed range (km/h)	Equation
Passenger cars (PC)	Urban – Peak (P)	CO_2	10-50	$FE(CO_2) = 0.12 * V^2 - 10.92 * V + 425.22$
		EC	10-50	$CE = 0.0016 * V^2 - 0.15 * V + 5.79$
		CO	10-50	$FE(CO) = 0.00010 * V^2 - 0.040 * V + 2.26$
		NOx	10-50	$FE(NOx) = 0.00020 * V^2 - 0.019 * V + 0.97$
		NMVOC	10-50	$FE(COVNM) = -0.10 \ln V + 0.56$
		VOC	10-50	$FE(COV) = -0.0040 * V + 0.35$
		P	10-50	$FE(PM\ TSP) = 9.00 * 10^{-7} * V^2 - 0.00040 * V + 0.079$
	Urban – Off Peak (OP)	CO_2	10-50	$FE(CO2) = 0.14 * V^2 - 12.09 * V + 426.41$
		EC	10-50	$CE = 0.0018 * V^2 - 0.16 * V + 5.77$
		CO	10-50	$FE(CO) = -0.015 * V + 1.08$
		NOx	10-50	$FE(NOx) = 0.00040 * V^2 - 0.036 * V + 1.21$
		NMVOC	10-50	$FE(COVNM) = -4.00 * 10^{-5} * V^2 + 0.0019 * V + 0.13$
		VOC	10-50	$FE(COV) = -5.00 * 10^{-5} * V^2 + 0.0022 * V + 0.13$
		PM	10-50	$FE(PM\ TSP) = -5.00 * 10^{-5} * V^2 + 0.0032 * V + 0.012$
Motorcycle (M)	Urban – Peak (P)	CO_2	10-50	$FE(CO_2) = 0.15 * V^2 - 12.23 * V + 347.46$
		EC	10-50	$CE = 0.0021 * V^2 - 0.17 * V + 4.82$
		CO	10-50	$FE(CO) = 0.0020 * V^2 - 0.18 * V + 8.24$
		NOx	10-50	$FE(NOx) = -0.013 lnV + 0.77$
		NMVOC	10-50	$FE(COVNM) = -0.52 lnV + 3.66$
		VOC	10-50	$FE(COV) = -0.52 lnV + 3.75$
		PM	10-50	$FE(PM\ TSP) = -2.00 * 10^{-6} * V^2 + 9.00 * 10^{-5} * V + 0.048$
	Urban - Off Peak (OP)	CO_2	10-50	$FE(CO_2) = 0.026 * V^2 - 3.57 * V + 206.45$
		EC	10-50	$CE = 0.00030 * V^2 - 0.048 * V + 2.85$
		CO	10-50	$FE(CO) = 0.0017 * V^2 - 0.16 * V + 7.94$
		NOx	10-50	$FE(NOx) = 3.00 * 10^{-5} * V^2 - 0.0021 * V + 0.14$
		NMVOC	10-50	$FE(COVNM) = 0.00050 * V^2 - 0.045 * V + 2.79$
		VOC	10-50	$FE(COVNM) = 0.00050 * V^2 - 0.045 * V + 2.88$
		PM	10-50	$FE(PM\ TSP) = -3.00 * 10^{-6} * V^2 + 0.00010 * V + 0.048$
Taxi (T)	Urban – Peak (P)	CO_2	10-50	$FE(CO_2) = 0.11 * V^2 - 10.16 * V + 412.54$
		EC	10-50	$CE = 0.0015 * V^2 - 0.14 * V + 5.56$
		CO	10-50	$FE(CO) = 8.00 * 10^{-5} * V^2 - 0.010 * V + 0.42$
		NOx	10-50	$FE(NOx) = 0.00030 * V^2 - 0.030 * V + 1.32$
		NMVOC	10-50	$FE(COVNM) = -0.0011 * V + 0.068$
		VOC	10-50	$FE(COV) = -0.0011 * V + 0.071$
		PM	10-50	$FE(PM\ TSP) = -0.014 lnV + 0.12$
	Urban - Off Peak (OP)	CO_2	10-50	$FE(CO_2) = 0.21 * V^2 - 17.35 * V + 514.00$
		EC	10-50	$CE = 0.0029 * V^2 - 0.23 * V + 6.92$
		CO	10-50	$FE(CO) = 0.00020 * V^2 - 0.016 * V + 0.49$
		NOx	10-50	$FE(NOx) = 0.00070 * V^2 - 0.055 * V + 1.71$
		NMVOC	10-50	$FE(COVNM) = -0.0011 * V + 0.064$
		VOC	10-50	$FE(COV) = -0.0011 * V + 0.066$
		PM	10-50	$FE(PM\ TSP) = 6.00 * 10^{-7} * V^2 - 0.00050 * V + 0.085$
Bus (B)	Urban – Peak (P)	CO_2	10-50	$FE(CO_2) = 0.45 * V^2 - 41.32 * V + 1601.40$
		EC	10-50	$CE = 0.0064 * V^2 - 0.59 * V + 22.88$
		CO	10-50	$FE(CO) = -1.30 lnV + 5.90$
		NOx	10-50	$FE(NOx) = -4.26 lnV + 21.76$
		NMVOC	10-50	$FE(COVNM) = -0.31 lnV + 1.29$
		VOC	10-50	$FE(COV) = -0.34 lnV + 1.63$
		PM	10-50	$FE(PM\ TSP) = 1.00 * 10^{-4} * V^2 - 0.0095 * V + 0.47$
	Urban - Off Peak (OP)	CO_2	10-50	$FE(CO_2) = 0.45 * V^2 - 41.32 * V + 1601.40$
		EC	10-50	$CE = 0.0064 * V^2 - 0.59 * V + 22.88$
		CO	10-50	$FE(CO) = -1.30 lnV + 5.90$
		NOx	10-50	$FE(NOx) = -4.26 lnV + 20.76$
		NMVOC	10-50	$EF(COVNM) = -0.31 lnV + 1.28$
		VOC	10-50	$FE(COV) = 0.00040 * V^2 - 0.038 * V + 1.19$
		PM	10-50	$FE(PM\ TSP) = 1.00 * 10^{-4} * V^2 - 0.0095 * V + 0.47$

monthly mileage is 30 times the daily mileage. Average costs for motorcycles, mopeds and bikes of 0.122 €/km and 0.019 €/km, respectively, are obtained. [7], [31] Obtaining a graph that represents the average cost of travel in AML per kilometer and per month.

Finally, it is possible to obtain a hypothetical scenario by changing the modal split, in order to assess the impacts this would have. Modal variations are in the sense of testing a greater use of eco-friendly transport and the impacts are in terms of cost, consumption and emission.

Lisbon municipality defines a strategic vision for 2030 mobility, involving a 12% reduction in the use of own car (compared to 2017). [32] The new (hypothetical) modal scenario is based on the same 12 p.p. reduction of trips by private cars to other transports. This reduction is total (total distance ranges) and it is assumed that the use of public transport remains constant. Transport available for the redistribution are: bicycle, shared electric mobility (e-bike and e-scooter) and on foot. The replacement of car journeys is from 0 to 20 km. Based on the modal split and making some assumptions it is decided between what distance ranges and how much alternative transport substitute car trips.

It is assumed that the number of car trips to be replaced range from 30% (0 km) to 0% (20 km), so that in the final modal split for the total distance, there is a 12 p.p. reduction. From 0 to 5 km, car journeys are replaced by walking, conventional bicycle, e-scooter and e-bike. From 5 to 20 km, the replacement is made only by electric bicycles, as for higher distance ranges the journeys are mostly carried out by motorized modes.

Alternative 2 consists in the reduction of 30 p.p. of trips by conventional private cars to electric (additional to alternative scenario 1). This is achieved by replacing 45% (0 to 20 km) of the number of trips by convention cars.

3. Results and discussion

3.1. *Characterization of the energy consumption and vehicle emission*

It's concluded by the emission and consumption results, that petrol vehicles emit more CO, VOC, NMVOC, while diesel vehicles emit more CO_2, PM and NOx.

Results are compared to reference values for calibration purposes. The CO_2 emissions obtained are compared with the values present in the NIR [7] It is concluded that the factors by categories obtained are lower than the values present in the NIR, except for light diesel vehicles, however they are of the same order of magnitude. [7] This difference may be due to differences in the information considered in COPERT and NIR, such as: average speed, fuel specifications (diesel in this case) and other assumptions. The results have a total average error of 13%: 6.5% for cars, 8.4% for buses and 30.8% for motorcycles.

In the case of cars, the average CO_2 emission factor obtained by COPERT and the factor present in the NIR is 206 g/km and 192 g/km, respectively. [7]

The absolute energy consumption (TJ) obtained is lower for almost all vehicle categories than the reference values, as expected, as the fleet entered in COPERT is smaller than the total fleet present in the NIR. [7] The 48% higher error for diesel vehicles is mainly due to the fact that heavy goods vehicles are not included. This category corresponds to the majority of the fleet's fuel consumption and all vehicles in the category are diesel, which results in a lower energy consumption than present in the NIR.

In relation to the emission factors of the remaining pollutants, the results are of the same order of magnitude with the values present in the Euro standards. As expected, the values obtained by COPERT are typically higher, as the tests for the Euro standards are carried out in controlled laboratory environments, which do not represent 100% real driving conditions.

3.2. Characterization of mobility patterns

In the first analysis, after filtering only the coherent results of the survey, the modal split, average speed and travel time over the distance were calculated. A histogram is made for each transport medium to obtain the maximum velocity corresponding to 80% of the sample, in order to eliminate results without real meaning. The exclusion of non-land trips and subsequent elimination of about 20% of the sample leads to a reduction in the sample, with 92241 responses included. The average speed of the bus is much lower than that of the bicycle, which can be justified with the perception of respondents, i.e., the travel time that respondents report.

Walking shows not only the lowest average speed and the smallest variation with the distance range, but there is also a large sampling reduction from higher distance ranges (>23 km, approximately). Conversely, the car is the mode with the highest average speed and where a gradual increase is observed with increasing distance. Unlike the car and other transports whose speed curve undergoes large oscillations, the train and the underground, despite having high average speeds and which also increase with increasing distance, have a behavior closer to polynomial equations and, therefore, more predictable, with fewer variations.

Regarding the average duration of journeys, up to a range of 25 km, walking is the mode that takes longer to travel, followed by the bus. The fastest modes are car, taxi and motorcycle. With increasing distance, the duration of trips naturally increases and there is also less transport available, as not all are accessible for long distances (mostly walking and motorcycles). For longer distances, there is less variation in the time of a car journey and a more irregular behavior in the cases of the train and the underground.

Looking at the modal split of urban travel, the car is the mode of transport that most represents mobility, almost regardless of distance (80% of travel, on average). Only being surpassed by walking for very short journeys (<1 km). Unlike walking, the train has a more constant representation over the distance and the bus (with a similar behavior to the underground) has more significant values between 1.5 and 13 km, approximately. Finally, taxis, motorcycles and bicycles are the least used transports in general, for all ranges of distance. Since 76% of road trips are made on weekdays, 99% of which are within the AML, it is based on these assumptions that the effect of time and reason for travel on speed was studied.

The functions of speed as a function of distance were obtained for all modes of transport, if the sample was greater than 5 and the coefficient of variation was less than 75%.

The integration of equations of speed vs distance and emissions/consumption vs speed, result in the emission of pollutants and consumption in g/(pass.km) and MJ/(pass.km), respectively. The functions obtained for emissions and consumption are for distance ranges up to 20 km, a value that represents 94% of the answers. Results reveal that the car represents a large share of overall consumption across all distance ranges. The car and bus are the transports with the highest absolute energy consumption (MJ), followed by metro (constant consumption with speed, but not with distance), for low and intermediate distance ranges. With the increase in distance (intermediate ranges), the underground gains more and more representation, unlike the bus.

Car and taxi consumption are residual, bicycle and walking are null. The average consumption (1.42 MJ/(pass.km)) is relatively constant (standard deviation: 0.15 MJ/(pass.km)), while the consumption per kilometer (7.04 MJ/km) has quite large variations. Consumption per kilometer, irregularly, increases with increasing distance. The relatively constant behavior of consumption per passenger*kilometer is largely due to the train. Although the consumption (and use) of the train increases a lot with distance, the train has a very high occupancy rate (22.20 passengers), which means that the average consumption remains constant for longer distances. In conclusion, the assumption of using an average for consumption (MJ/km) constant for any distance range is unreliable. Conversely, using an average for consumption (MJ/(pass.km)) constant as a function of distance will not result in very large errors.

While the average CO_2 emission factor increases with the distance to a peak, 4 km (367 g/km), from which it decreases. Also, the emission factor per passenger x km decreases with distance (average of 56 g/(pass.km)).

Table 4 - Matrix of CO_2 emissions in trips between municipalities of AML (gCO_2/(pass.km)). The values are color coded: red for higher values and green for lower.

Municípios	Alcochete	Almada	Amadora	Barreiro	Cascais	Lisboa	Loures	Mafra	Moita	Montijo	Odivelas	Oeiras	Palmela	Seixal	Sesimbra	Setúbal	Sintra	V.F.Xira	Total
Alcochete	167	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	167
Almada	-	77	-	-	-	34	-	-	-	-	-	-	-	65	-	-	-	-	64
Amadora	-	-	136	-	-	24	-	-	-	-	67	117	-	-	-	-	58	-	66
Barreiro	-	-	-	137	-	-	-	-	76	-	-	-	-	-	-	-	-	-	124
Cascais	-	-	-	-	129	28	-	-	-	-	-	62	-	-	-	-	124	-	93
Lisboa	-	30	25	-	18	52	46	-	-	-	29	52	-	11	-	-	13	32	39
Loures	-	-	-	-	-	49	131	-	-	-	130	-	-	-	-	-	-	80	91
Mafra	-	-	-	-	-	-	-	151	-	-	-	-	-	-	-	-	-	-	151
Moita	-	-	-	87	-	-	-	-	133	-	-	-	-	-	-	-	-	-	128
Montijo	-	-	-	-	-	-	-	-	-	165	-	-	-	-	-	-	-	-	165
Odivelas	-	-	-	-	-	22	72	-	-	-	141	-	-	-	-	-	-	-	63
Oeiras	-	-	91	-	55	58	-	-	-	-	-	135	-	-	-	-	74	-	93
Palmela	-	-	-	-	-	-	-	-	-	-	-	-	143	-	-	40	-	-	105
Seixal	-	63	-	-	-	10	-	-	-	-	-	-	-	122	-	-	-	-	75
Sesimbra	-	-	-	-	-	-	-	-	-	-	-	-	-	-	157	-	-	-	157
Setúbal	-	-	-	-	-	-	-	-	-	-	-	-	87	-	-	148	-	-	142
Sintra	-	-	54	-	130	14	-	-	-	-	-	88	-	-	-	-	112	-	71
V.F.Xira	-	-	-	-	-	24	88	-	-	-	-	-	-	-	-	-	-	132	94
Total	167	64	65	127	85	39	84	151	124	165	76	95	129	77	157	126	66	101	63

Regarding pollutant emissions, for non-motorized modes (on foot and bicycle) and for train and metro, the factors are null. With increasing distance, the total emission (g) decreases (efficiency gains with distance), as for greater distance ranges certain modes of transport are no longer used. In general, over the distance, all emissions (g) are maximum for the bus and car. In the 3 to 5 km range, the fleet is inefficient and it is precisely in this range that the transfer to active modes is most important. For CO, VOC and NMVOC emissions, the motorcycle is a little more representative than for other pollutants.

Regarding trips in Lisbon, for trips within the same municipality, the most used transports are car and walking. Lisbon is the municipality where a low percentage of journeys are made by car (41%) (compared to the other municipalities) and where travel is more evenly distributed among the different modes: on foot (34%), bus (12%) and metro (11%).

The largest number of total trips in the AML takes place between Lisbon and the other municipalities with a maximum number of trips within the municipality of Lisbon and the municipality (origin or destination) where fewer trips take place is Alcochete.

Since the survey responses refer to an entire day, it would be expected that symmetry could be observed in the matrices, both for emission factors (). It would be expected that the outward journeys would be similar to the return journeys, although they may vary if different transports are used, if the return is not on the same day or due to external factors such as traffic, for example.

The trips that consume the most energy are the intra-municipal ones in Mafra (2.63 MJ/(pass.km)). Within this municipality, 77% of trips are made by car (high consumption) and 17% by foot. Intercity trips in Mafra have the highest percentage of car trips and the lowest percentage of walking. The route with less consumption originates in Odivelas and goes to Lisbon (0.83 MJ/(pass.km), with 56% of journeys made by car and 15% by bus.

Lisbon has a diversified and efficient public transport network: metro (Metropolitano de Lisboa), bus (Carris) and train (CP) and an equally diversified modal split: 10%, 11% and 4%, respectively. It is actually the municipality (origin or destination) of the AML with a more balanced modal split among all transports. In addition, the fact that 72% of trips are intra-municipal means that active mobility (therefore with zero emissions) has a much greater representation (24%). These factors lead to lower consumption per passenger*km (as well as a CO_2 emission) compared to a car-led breakdown.

The municipality of Sintra also has some trips included and relatively low consumption (average 1.71 MJ/(pass.km)), with a maximum consumption for intra-municipal trips. The total journeys are made mostly by car and train. Sintra is served by a railway network (CP), with three main lines, connecting Lisbon, Alverca and Azambuja, which can also intersect with the Fertagus line.

Finally, the average of intra-municipal and inter-municipal consumption is 2.07 and 1.51 MJ/(pass.km), respectively. As for CO_2 emissions, the trips that emit more and less are Alchochete-Alchochete (167 g/(pass.km)) and Seixal-Lisbon (10 g/(pass.km)), respectively (origin-destination). With 67% carried out by car and 29% on foot, these data do not necessarily indicate a higher CO_2 emission. Thus, this may be due to the fact that, within intra-municipal trips, Alcochete-Alcochete is the route with the lowest total number of journeys and, therefore, it is not so representative of real mobility. From Seixal to Lisbon, 49% of trips are made by car and 44% by train. The Fertagus network links Lisbon to Setúbal and the Sulfertagus network links certain locations (Seixal) close to the Fertagus network. Thus, through the two networks, the train connection from Seixal to Lisbon is made. Due to the high level of the train (zero emission), it was expected that this route would have a very low CO_2 emission. The average of intra-municipal and inter-municipal consumption is 131 and 57 g/(pass.km), respectively.

In conclusion, a very large use of the car, generally associated with the absence or deficit of the public transport network, results in very high CO_2 emissions. However, a homogeneous modal split of travel between municipalities not only benefits from a lower carbon footprint, but also leads to a reduction in energy consumption. Additionally, a greater use of transports with zero or reduced emissions (e.g., train or underground), accompanied by a reduction in car use, results in a reduced average CO_2 emission factor.

3.3. Characterization of the total costs of transportation

3.3.1. Private car

It is possible to observe, in Figure 1, that the total cost of vehicles grows in ascending order for: electric (BEV), hybrid (HEV), diesel, petrol and plug-in hybrid (PHEV).

It is also possible to observe the weight of each variable or fixed cost in the total cost of ownership, and for all categories of cars, the cost of acquisition and depreciation (acquisition and sale) corresponds to the highest percentage. However, for electric cars, the cost of purchase and sale (discounting incentives) represents a large part of the total cost (61%), followed by maintenance (15%), energy source (12%) and the remaining costs residuals. The maintenance cost has a minimal representation for hybrid (and plug-in) vehicles. It is concluded that in terms of total cost of ownership, the most economical vehicle is the electric one and the least economical ones are the internal combustion ones (petrol and diesel), and the biggest obstacle for the electric one is the acquisition and sale cost (which is minimal for conventional ones).

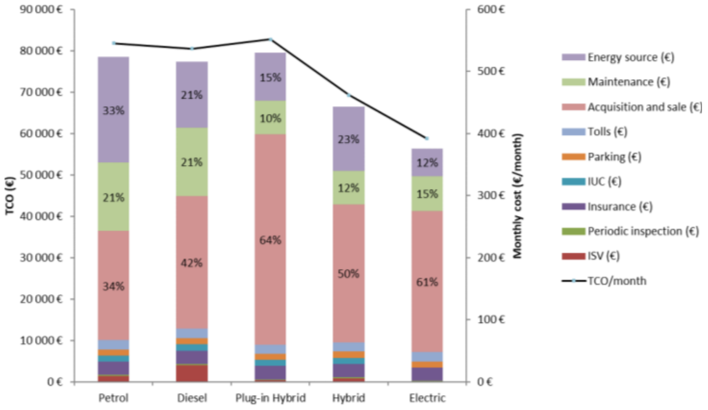

Figure 1 - Results obtained for TCO and monthly cost of vehicles: petrol, diesel, hybrid, plug-in hybrid and electric.

In a first analysis, it is observed that the results obtained are of the same order of magnitude as the values in the literature for all categories. From the literature, only Wu Geng's article considers parking and none considers tolls. [5]

With regard to taxes, it is difficult to understand specifically which taxes are considered as in many of the articles this information is not specified. Unlike the present study, which distinguishes the ISV from the IUC, for example.

When calculating the mean error of the TCO of each literature in relation to the results by category, it was concluded that the most similar cases (mean error <31%) are, in order of increasing error, the article by Kate Palmer et al. (California), Wu Geng et al. (Germany) and Jens Hagman et al. (Sweden). With the exception of California (10% average error), errors are higher due to the TCO of electric vehicles, which could mean that the biggest difference in costs will be related to BEV costs (i.e., acquisition, incentive, electricity price, maintenance, depreciation, taxes and insurance). For example, for the case of Germany, the TCOs of internal combustion vehicles have an error of only 3% and an error of 99% for the electric. It is in this same article that the author (Geng Wu et al.) includes costs related to the charging and batteries of electric vehicles that the others do not consider. This could lead to higher TCO of the tram. [5], [33], [34]

Analyzing, for example, the case of Sweden, the acquisition cost of an electric vehicle and the price of electricity are lower, maintenance is zero (in the period considered) and the incentive is higher than in Portugal. [33] Although there are some costs higher than those in Portugal (e.g., insurance), the absolute values indicate that the TCO of a BEV in Sweden is much lower than in Portugal. In terms of cost per kilometer, for BEV in Sweden: the costs of insurance, taxes, purchase and sale and fuel are higher. While the incentive is superior and maintenance is nil. As for a petrol vehicle, the higher costs (€/km) for Sweden in relation to the purchase and sale are offset by the lower tax costs and the cost of parking and tolls (which are not considered). Since the price per kilometer of fuel and maintenance is the same as in Portugal, this results in a TCO (€/km) quite similar for petrol cars.

A big factor in the differences in these costs could be the total mileage/period considered. The present study assumes a time period of 12 years, corresponding to the vehicle's total lifetime. While the articles in the literature assume a period between 3 to 6 years, corresponding to the time of ownership of the vehicle for an individual. Annual mileage is similar across all studies (same order of magnitude) and therefore the biggest factor is in fact the assumed time period.

The average total cost in Portugal is €334/month and €537/month, according to Autocustos and the results, respectively. Fixed costs represent 52% and 71% and variable costs 48% and 29%, according to Autocustos and the results obtained, respectively. [4] It is concluded that the values obtained are higher than the Autocosto values, however they are of the same order of magnitude. Autocustos reveals average statistical values at national level, according to the values provided by users, while the results obtained are specific to AML.

3.3.2. Public and shared transport

The results (€/km) for different transports, as well as the average value, are presented in the following Figure 2.

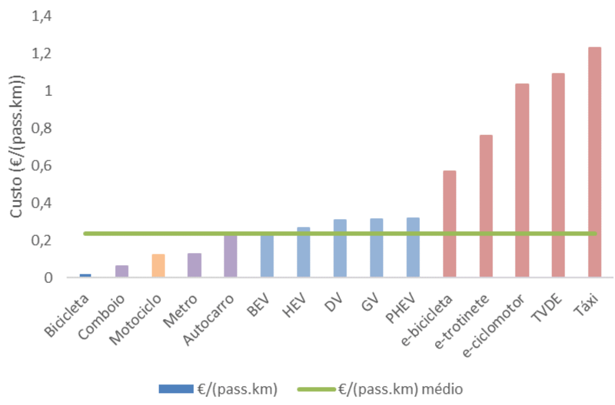

Figure 2-Cost (€/km) for private cars: electric (BEV), hybrid (HEV), diesel (DV), petrol (GV), plug-in hybrid (PHEV) and other transports: train, underground, bus, conventional bicycle, electric bicycle, electric scooter and electric motorcycle, TVDE, taxi and conventional motorcycle.

The results for two scenarios with alternative modal splits in the AML are found below. According to alternatives 1 and 2 (Figure 3), it was possible to observe the impacts on average cost, energy consumption and CO_2 emissions, in relation to the original scenario. The functions are related to graphs in the form of a percentage reduction compared to the original scenario (Figure 4 and Figure 5). Since the results have the same trend, the remaining results are aggregated in weighted average and present in Table 5 and Table 6.

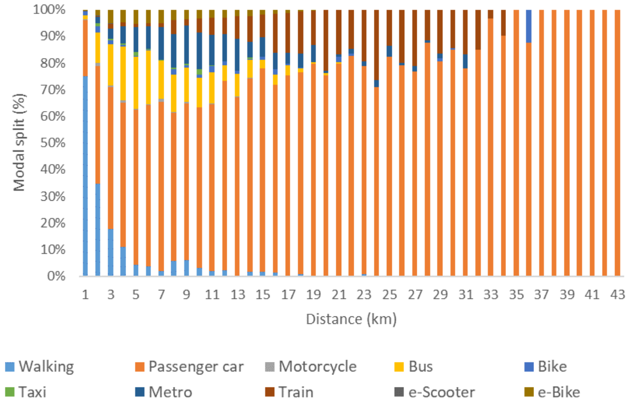

Figure 3-Modal split of trips in alternative 1 with distance.

Table 5 - Impact of scenarios 1 and 2 on mean values of transport users of AML, of energy consumption, CO_2 emissions and costs of transports.

Resultados	Unidades	Média (original)	Média (alternativa 1)	Média (alternativa 2)
Consumo energético	MJ/(pass.km)	2.27	1.93	1.29
	Var. % face ao original	-	*-15%*	*-43%*
Emissão CO_2	g/(pass.km)	142	115	59
	Var. % face ao original	-	*-19%*	*-58%*
Custo total	€/mês	292	242	207
	Var. % face ao original	-	*-18%*	*-30%*

Table 6 - Impact of scenarios 1 and 2 on total energy consumption and CO_2 emissions of AML.

Resultados	Unidades	Total (original)	Total (alternativa 1)	Total (alternativa 2)
Consumo energético	TJ	39.77	36.66	24.87
	Var. % face ao original	-	*-8%*	*-37%*
Emissão CO_2	ton	2497	2204	1132
	Var. % face ao original	-	*-12%*	*-55%*

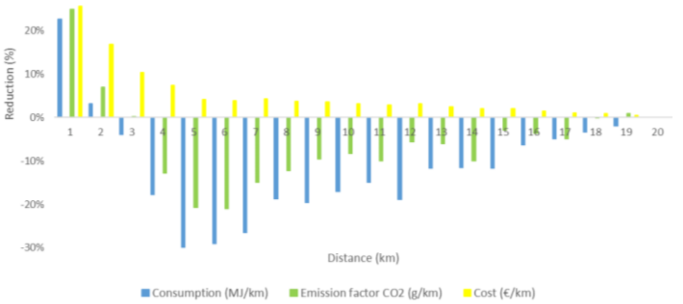

Figure 4 - Reduction (%) of the following variables in relation to the original: mean CO_2 emission factor (g/km), mean consumption (MJ/km) and mean cost (€/km) with distance, based on the alternative scenario 1.

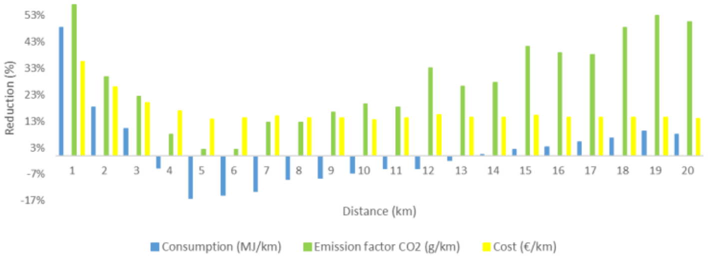

Figure 5 - Reduction (%) of the following variables in relation to the original: mean CO_2 emission factor (g/km), mean consumption (MJ/km) and mean cost (€/km) with distance, based on the alternative scenario 2.

Figure 4 shows that the average cost (€/km) of alternative scenario 1 is lower than the average cost of the original scenario. As expected, as the cost per kilometer of public transport and soft modes is lower than the average cost of the Although the cost per kilometer of shared mobility is higher, the total number of trips that have been replaced by these modes is low and therefore not enough to cause an increase in the average total cost. Up to 2 km, there is a reduction in energy consumption and CO_2 emission, however from this distance onwards, there is an increase in these parameters. Although active and shared mobility causes a small decrease in consumption and emission, the underground and bus consume (MJ/km) much more than the car and by increasing the use of these transports, it causes an increase in average consumption as well.

Similarly, although the underground has zero emissions, the very high emissions Since those responsible for the increase in consumption are the bus and the underground, it was expected that when considering the number of passengers, the interpretation would be very different. Table 5 and Table 6 show that all impacts were positive with the implementation of alternative scenarios. Alternative 1 leads to a reduction in emission, consumption and monthly cost, compared to reality, and alternative 2 leads to even greater reductions. Underground and bus, with high occupancy rates, correspond to low consumption and emissions (MJ/(pass.km) and g/(pass.km)) (zero emission for the metro). As for the absolute values, all other transports have lower consumption than the conventional car and hence the reduction. The greatest impact observed was in fact on CO_2 emissions, as many of the transports considered in these scenarios are electric.

In conclusion, the greater the use of transport with low (or zero) consumption and emission, the greater the average positive impact on energy, environmental and economic performance. Thus, observing the positive impact that exists in a greater use of shared mobility, active modes, public transport and even a replacement of the conventional car by electric. The AML citizen would save on average 64 €/mês or 107 €/month, according to alternative scenarios 1 and 2, respectively. The emission of 293 tons (scenario 1) or 1365 tons (scenario 2) of CO_2 (per day) would also be avoided and 3.11 TJ (scenario 1) or 14.9 TJ (scenario 2) of energy consumption (per day) would be saved. emissions, the very high emissions

4. Conclusions

With the advancement of the present environmental situation, the future of the transport network is aligned with an efficient management of public, shared, private transport and active mobility, ideally, with a minimum emission of pollutants from the fleet. The range of distance to be covered determines not only the emissions and energy consumption, but also the cost per kilometer and the number of transports that cover certain distances.

From COPERT, functions for energy consumption and emission of pollutants were obtained with speed, for the following transports: car, motorcycle, taxi and bus. With the analysis of mobility patterns in Lisbon (IMob), functions of velocity with distance were obtained. These are distinguished according to traffic mode for bus, car, train, according to distance range for bicycle and without variable for motorcycle, taxi and on foot. The intersection of the two results allowed us to obtain functions for energy consumption and pollutant emission with distance, for a distance range up to 20 km.

Regarding energy consumption, the car has the greatest representation overall across all distance ranges. The transports with the highest consumption (MJ) according to the distance ranges are: up to 6 km, bus and car; between 6 to 10 km, underground, car and bus; between 10 to 13 km, train, underground and car; between 13 to 20 km, train and car. The average consumption per passenger*kilometer is 1.42 MJ/(pass.km) and the average consumption per kilometer is 7.04 MJ/km (increases with increasing distance). The transport responsible for the highest CO_2 (g) emissions are the bus and the car, reducing with increasing distance. The local pollutants most emitted by buses and cars are NOx and CO and by motorcycle CO, NMVOC and VOC.

The analysis of travel between AML municipalities reveals that, in intra-municipal trips, the most used transports are the car and walking. Lisbon is the municipality with the largest number of trips, with a maximum for intra-municipal trips, which are more evenly distributed across all modes. A homogeneous modal split of travel between municipalities is reflected in lower energy consumption and CO_2 emissions.

Private cars are still the mode of transport of choice for the vast majority of the population in Lisbon, the costs associated with this ownership (TCO) include variable and fixed costs over a period (assumed) of 12 years, with a total mileage of 200000 km. The costs included are: incentive, purchase and sale, periodic inspection, insurance, ISV, IUC, parking, toll, maintenance and fuel. The car categories analyzed and compared are the following: plug-in hybrid (0.397 €/km), petrol car (0.392 €/km), diesel (0.387 €/km), hybrid (0.333 €/km) and electric (0.282 €/km). A comparison with the literature reveals that the results obtained are of the same order of magnitude as the literature values for all categories and allows us to conclude that a major factor in the differences in these costs may be the total mileage/period considered, as well as the country of the case study. Of the other transports, those with the lowest cost per kilometer are public transport and motorcycle, followed by shared mobility and finally TVDE and taxi. The car's weighted average TCO is 536.74 €/month and 0.39 €/km.

By forcing an alternative modal split that favors trips made by shared mobility, active and public transport (0 to 20 km) to the detriment of trips made by car, there is a positive impact in terms of energy, environmental and economic performance. The AML citizen saves 64 €/month, 3.11 TJ and avoids the emission of 293 tons of CO_2. Additionally, by replacing trips made by conventional cars with electric cars, it saves 85 €/month (per user), 14.9 TJ (per day) and avoids the emission of 1365 tons of CO_2 (per day).

Something to take into account for future work is the recommendation of a more suitable software (instead of Excel) for processing IMob data and obtaining functions for consumption and emissions, like Matlab or Phyton. In addition, it is suggested to use a more recent and complete fleet (technologies such as electric vehicles, latest EURO standards, etc.) as input in COPERT to obtain the functions. The results obtained, may benefit from an increase in information on mobility patterns, so that they can be more generalized and applied to different regions of the country. This work can be applied in a tool for providing information to the user. Allowing to obtain the monthly expense of the user's car, as well as the alternatives using the same credit.

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