SHORT DISTANCE URBAN TRIPS: COMPARISON OF THE IMPACTS OF DIFFERENT TRANSPORT MODES

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ABSTRACT

The main objective of the present work is to develop a methodology that allows determining indicators to compare short distance urban trips (urban trips were assumed to be less than 3 km) using different transport modes such as soft modes (only walking was considered), public transports (bus and metro) and private cars, taking into account internal costs (time and distance) and external costs (energy consumption, CO_2 and local pollutants emissions).
The methodology adopted consists in doing in situ measurements for all transport modes (walking, bus, metro and car) using a portable laboratory developed for this purpose which allows monitoring pedestrians' trips in terms of route, time and distance.
For estimating the external costs (energetic and environmental impacts) the authors used the EMEP CORINAIR methodology which allows taking in consideration cold start emissions. In urban settings, considering short distance trips cold start emissions assume a very important role since a substantial number of trips are mainly done under these conditions.
The methodology developed was applied to a case study in the city of Lisbon. Results allowed the authors to conclude that in the situations where it is easy to park (low demand scenario) the private car presents the best ratio distance / time but when there is a high parking pressure, car is the worst transport mode. Walking only is competitive with other transport modes for very short distance trips (below 1 km) while metro trips tend to have a good relation distance – time but only for longer trips (above 2.5 km).
Relatively to the energetic and environmental analysis, the private car has always the higher energy consumption and emissions per trip.

Keywords: *Transport modes, short distance urban trips, energetic and environmental analysis*

INTRODUCTION

In the late 20th century reports such as the Club of Rome (Meadows, 1972) and Our Common Future (WCED, 1987), started to alert people to the environmental issues. Later, Kyoto Protocol targets, health problems, the awareness to the resources scarcity as well as climate changes have led to the need of seeking for environmental sustainability and energetic efficiency.

Nevertheless, urban mobility patterns are dominated by motorized trips, in particular by private cars. These have been leading to a continuous increase in transportation externalities over the last years, representing environmental degradation as well as quality of life decrease. The high number of motorized vehicles circulating in urban environment frequently cause congestion with impacts on trip time, energy consumption and environmental impacts (Vasconcelos *et al*., 2005; Silva *et al*., 2005).

There are few research projects comparing the impacts of different transport modes in urban settings (small scale) (Bouwman, 2000) so, in this context, the main objective of the present work is to develop a methodology that allows determining indicators to compare short distance urban trips using different transport modes such as soft modes (only walking was considered), public transports (bus and metro) and private cars.

METHODOLOGY

In the present research the authors characterized short distance urban trips (urban trips were assumed to be less than 3 km) using four transport modes: soft mode (only walking), public transports (bus and metro) and private cars, taking into account the internal costs (time and distance) and the external costs (energy consumption, CO_2 and local pollutants emissions).

Considering that the objective was to characterize short distance trips, modal shifts were not considered. The exception is the conjugation of soft mode with motorized modes, as walking is necessarily part of all trips.

The methodology consists in doing in situ measurements for all transport modes (walking, bus, metro and car) using a laboratory developed for this purpose which allows monitoring individual mobility regardless the transport mode (see Figure 1). The measurements were made on working days by twelve volunteers, seven female and five male with ages between 25 and 49 years and with an average walking speed of 1,45 m/s.

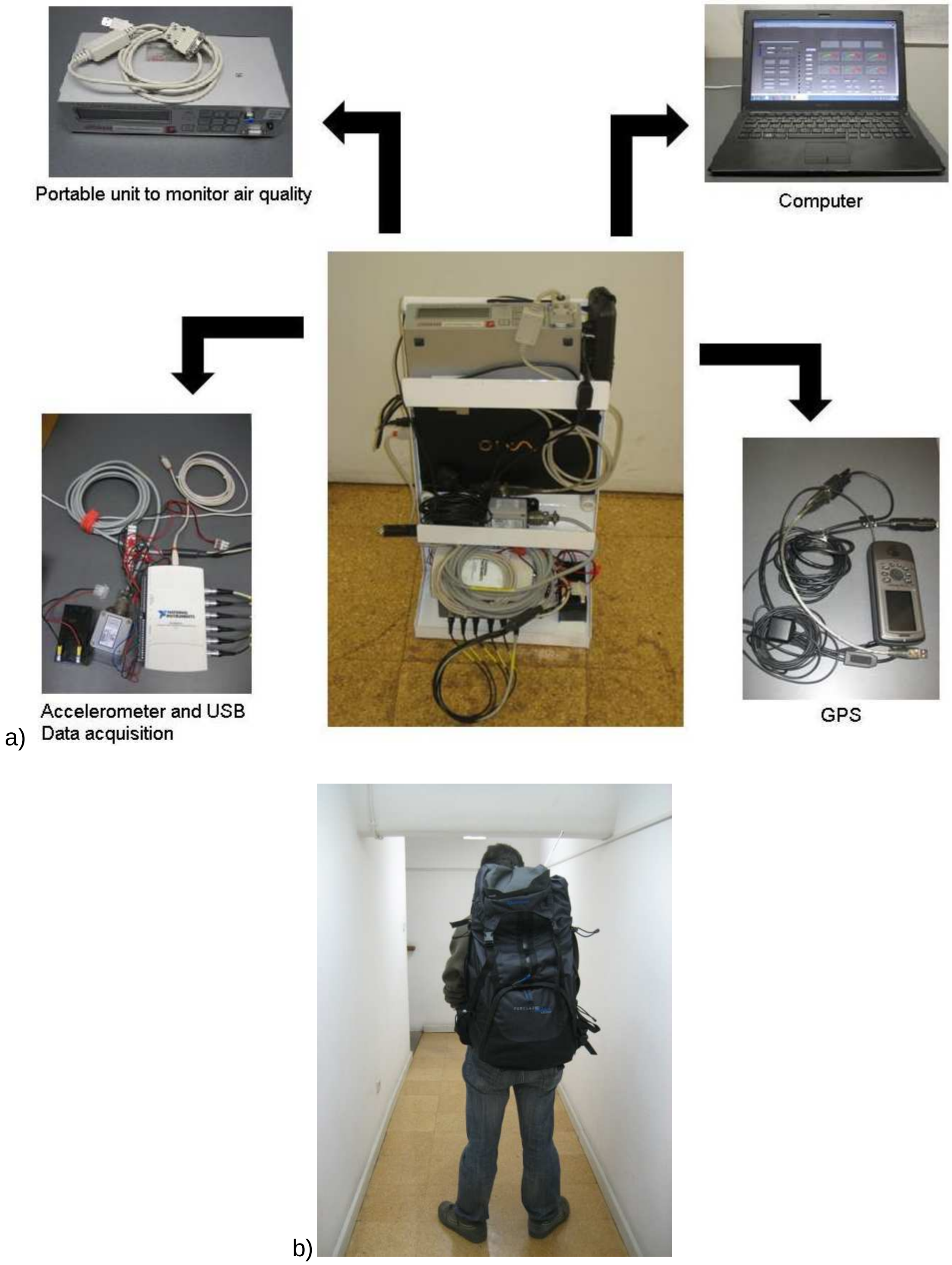

Figure 1 – a) Components of the laboratory to monitor individual mobility; b) Laboratory in use

The laboratory consists in:

- a GPS – Garmin Etrex Vista with barometric altimeter;
- an accelerometer (that registers information for the cases where there is no GPS coverage) – CORRSYS-DATRON Navigation Sensor Modules that

combines a solid-state, tri-axial rate gyro with a single-, dual- or tri-axial accelerometer;

- USB Data acquisition – National Instruments 6211 is a bus-powered USB M Series multifunction data acquisition module optimized for superior accuracy at fast sampling rates;
- a computer (to collect and register all data) – Sony Vaio Serie X; and
- a portable unit to monitor air quality – Grimm 1.101 capable of simultaneous measurements of Inhalable, Thoracic and Alveolic (respirable) dust masses ranging from 1 to 65.000 $\mu g/m^3$.

This laboratory allows monitoring pedestrians' trips in terms of route, time, distance and air pollutant emissions. In the present work air pollutant emissions were not measured because the portable unit only allows monitoring air pollutants emissions from the pedestrian point of view (exposure) and the objective of this research is to compare each transport mode emissions.

Internal costs: time and distance

Walking mode

To characterize the walking mode, trips, as a pedestrian, were made in Lisbon in order to determine the average density of singularities that could change reference free-flow speeds from the literature (Fruin, 1971; TCQSM, 2003), namely marked crosswalks and pedestrians crossing signs. Furthermore, crossing and waiting times were registered. Using the obtained data, reference free-flow speeds from the literature (Fruin, 1971; TCQSM, 2003) were corrected with the influence of these singularities.

In order to determine the distribution of pedestrian crossings per kilometer a total of 495 measurements were made whereas in what concerns to the crossing and waiting times the authors made around 800 measurements for pedestrian crossing signs, 355 for marked crosswalks and 190 measurements when there were no crosswalks, in order to achieve statistical relevance for the results.

Public transports

For transit buses the authors measured distances as a pedestrian when reaching bus stop and from the bus leaving stop to the final destination for pre-defined pathways (using Google Maps). Additionally, average waiting times for the transit buses have been measured in situ and compared with the literature (reference values for Lisbon) (Câmara Municipal de Lisboa, 2005). Approximately 300 waiting time measurements were made for 73 different buses (86% of the daily buses circulating in Lisbon).

In what concerns to the metro, the average waiting time was determined considering that it is half of the frequency of the circulations. The average time to go from the surface to the metro boarding piers and from the boarding piers to the surface was measured in situ, in a total of 155 measurements. All these times include the ticket validation which is important as the system used (see Figure 2) physically separates the boarding piers from the station exterior and all commuters must pass through it. Accordingly to Silva *et al.* (2006), who measured commuting times on multimodal transport stations, the average ticket validation time is 3.06 sec ± 0.76 sec.

Figure 2 – Lisbon Metro ticket validation system

For each metro line only the stations in the urban center were considered. Around 160 time measurements were made for 37 stations (82% of the urban metro stations in Lisbon).
Concerning the walking distance to the metro station it was assumed to be half of the distance between two stations.
Reference commercial speeds of 14.7 km/h for transit buses (Source: Carris) and 27 km/h for Lisbon Metro were used (Plano de Mobilidade de Lisboa, 2004).

Private car

In order to characterize urban trips using private cars the authors initially used a developed laboratory (Gonçalves *et al.*, 2005; Gonçalves, 2009) to monitor commuting trips of volunteers in order to determine the time/distance as a pedestrian (from the origin to the car and from the car to the destiny), the average time to find a parking space, the time lost to park, the time spent in the car without circulating (with the car stopped) and the time lost to get a parking ticket.
However, data collected for the private car trips did not exhibit statistical relevance yet, so the authors investigated three scenarios assuming different values for the time/distance as a pedestrian and for the parking search time:

- Low demand scenario – this scenario is considered for low population density zones, non-commercial areas, facility excess areas, in other words, areas where it is easy to find a parking space. In these areas the probability to find a parking space close to the final destination is higher and so the time/distance as a pedestrian is smaller;

- Balanced scenario – it is assumed for areas where there is a balance between rotation and saturation. This is an intermediate scenario between low demand and high parking pressure scenarios;
- High parking pressure scenario – this is an opposite scenario to the low demand, here demand is greater than supply, being also the time/distance as a pedestrian higher.

In Lisbon on-street parking is usually cheaper than off-street parking (Plano de Mobilidade de Lisboa, 2004) consequently drivers tend to cruise to park. Therefore, in the present research only on-street parking was characterized.

External costs: energetic and environmental analysis

To estimate the total exhaust emissions (CO, NO_x, VOC, CO_2 and PM) the authors used the EMEP CORINAIR methodology (Ntziachristos *et al.*, 2009; Joumard *et al.*, 1999). This methodology is a European reference in this matter allowing estimating emissions of the most important air pollutants, produced by different vehicle categories. According to this methodology, total emissions from road transport are calculated as the sum of hot emissions (when the engine and the catalyst, if existent, are at their normal operating temperature) and cold start emissions (emissions during transient thermal engine operation) (Ntziachristos *et al.*, 2009). This allowed having in consideration the extra emission over the emissions that would be expected if all vehicles were only operated at thermally stabilized engine operation. In urban settings, considering short distance trips cold start emissions assume a very important role as a substantial number of trips are mainly done under these conditions.
Summarizing, total emissions can be calculated using the following equation:

$$E_{Total} = E_{hot} + E_{cold} \tag{1}$$

where:

E_{Total} – Total emissions (g) of any pollutant for the spatial and temporal resolution of the application;

E_{hot} – Emissions (g) during stabilized (hot) engine operation;

E_{cold} – Emissions (g) during transient thermal engine operation (cold start). (Ntziachristos *et al.*, 2009)

Hot emissions

Hot exhaust emissions depend on a variety of factors such as the vehicle speed, age, engine size and vehicle weight. The formula to be applied to calculate pollutants hot emissions (CO, NO_x, VOC and PM) as well as the total fuel consumed by vehicles of the specific class is:

$$E_{hot;i,k,r} = N_k \times M_{k,r} \times e_{hot;i,k,r} \tag{2}$$

where:

$E_{hot;i,k,r}$ – Hot exhaust emissions of the pollutant i [g], produced in the period concerned by vehicles of technology k driven on roads of type r;

N_k – Number of vehicles [veh] of technology k in operation in the period concerned;

$M_{k,r}$ – Mileage per vehicle [km/veh] driven on roads of type r by vehicles of technology k;

$e_{hot;i,k,r}$ – Emission factor in [g/km] for pollutant i, relevant for the vehicle technology k, operated on roads of type r. (Ntziachristos *et al.*, 2009)

To calculate end-of-pipe CO_2 emissions it is necessary to take into account the other carbon atoms emissions (in form of CO, VOC, EC and OM in PM) as represented in equation 3. (Ntziachristos *et al.*, 2009):

$$E_{CO_2,k,m} = 44.011 \times \left(\frac{FC_{k,m}}{12.011 + 1.008 r_{H:C,m} + 16.000 r_{O:C,m}} - \frac{E^{CO}_{k,m}}{28.011} - \frac{E^{VOC}_{k,m}}{13.85} - \frac{E^{EC}_{k,m}}{12.011} - \frac{E^{OM}_{k,m}}{13.85} \right) \quad (3)$$

Cold-start emissions

Assuming that cold start emissions are a function of ambient temperature, average speed and travelled distance, excess emissions can be expressed as:

$$Excess\,emission = \omega \times \left[f(V) + g(T) - 1 \right] \times h(\delta) \quad (4)$$

where:

Excess emission – for a trip, is expressed in g;

V – Mean speed in km/h during the cold period;

T – Temperature in ºC (ambient temperature for cold start or engine start temperature for starts at an intermediate temperature);

$\delta = d/d_c$ – Undimensionned distance with: d – travelled distance; d_c – cold distance;

ω – Reference excess emission (function of temperature and speed). (Joumard *et al.*, 1999)

In Figure 3 and in Figure 4 are examples of the ratio between total emissions and hot emissions (for CO_2, CO and NO_x) for diesel and gasoline cars, respectively, considering an average speed of 20 km/h. As it can be seen cold start emissions represent a considerable excess over hot emissions being particularly significant in the first two kilometers.
CO_2 cold start emissions and fuel consumption present a smaller penalty on total emissions whereas local pollutants (CO, VOC, PM, NO_x) cold start emissions can be several times higher than hot emissions (accordingly to Blackwood *et al.* (1998) a diesel engine particle emission rate can be 7 times greater when it is cold than when it is warm) (Silva *et al.*, 2004; Blackwood *et al.*, 1998).
Gasoline passenger cars with engine size below 1,4 l and diesel passenger cars with engine size below 2,0 l, to the legislation standards: ECE 15/04 (only gasoline), Conventional (only diesel), Euro 1, Euro 2, Euro 3 and Euro 4, correspond to 71% of the Portuguese fleet, so example results are shown only for these group of vehicles.

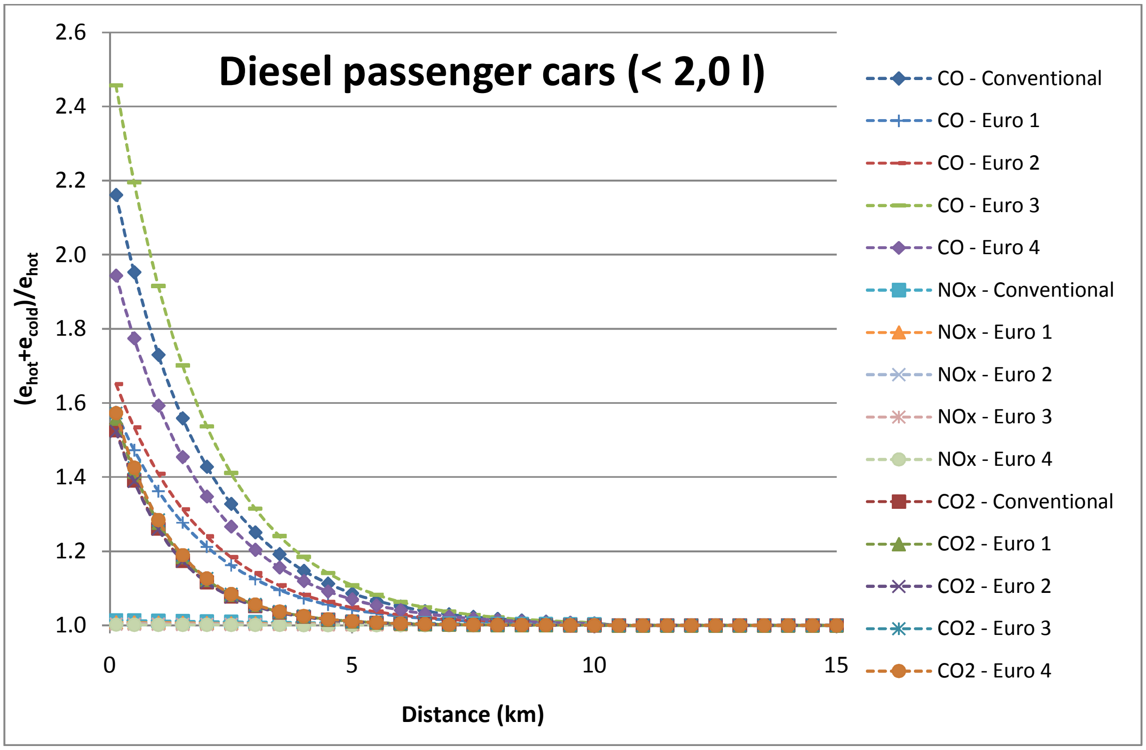

Figure 3 – Ratio between total emissions and hot CO, NO_x and CO_2 emissions for diesel cars (< 2.0 l)

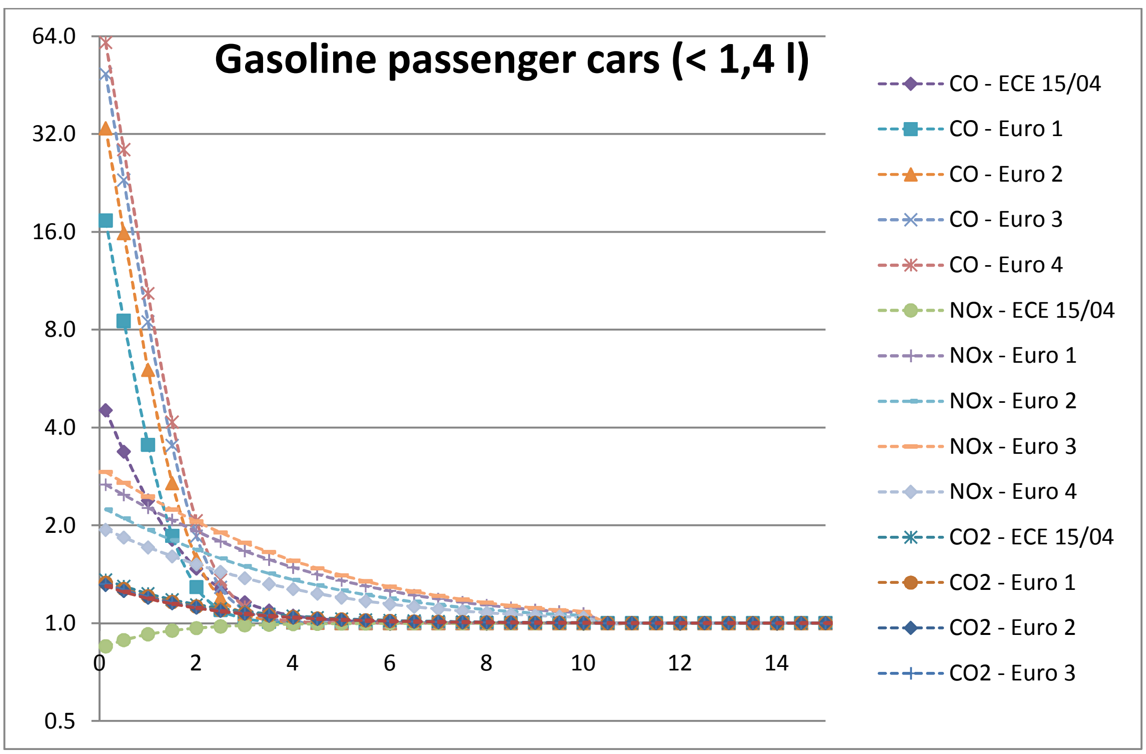

Figure 4 – Ratio between total emissions and hot CO, NO_x and CO_2 emissions for gasoline cars (< 1.4 l)

To characterize energetically and environmentally the urban trips it was necessary to determine the average Portuguese vehicle. The national fleet was characterized according to the fuel type, legislation standard and engine size. Figure 5 and Figure 6 show the total emissions for the average Portuguese vehicle on trips up to 3 km.

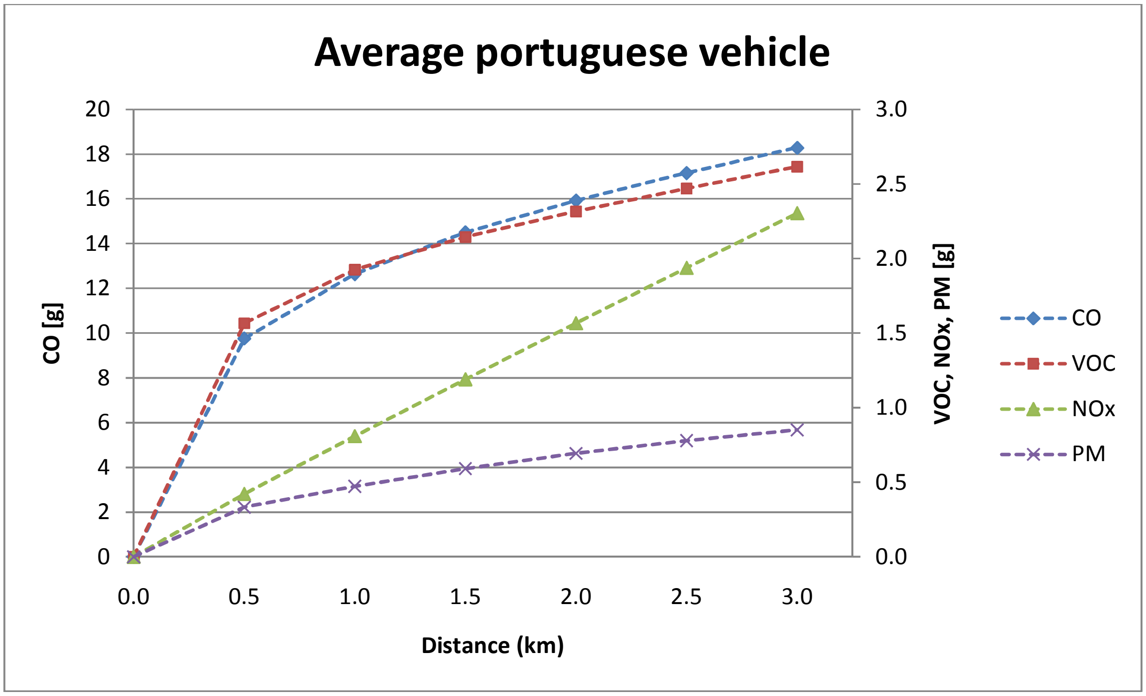

Figure 5 – CO, VOC, NO_x and PM total emissions to the average Portuguese vehicle [g]

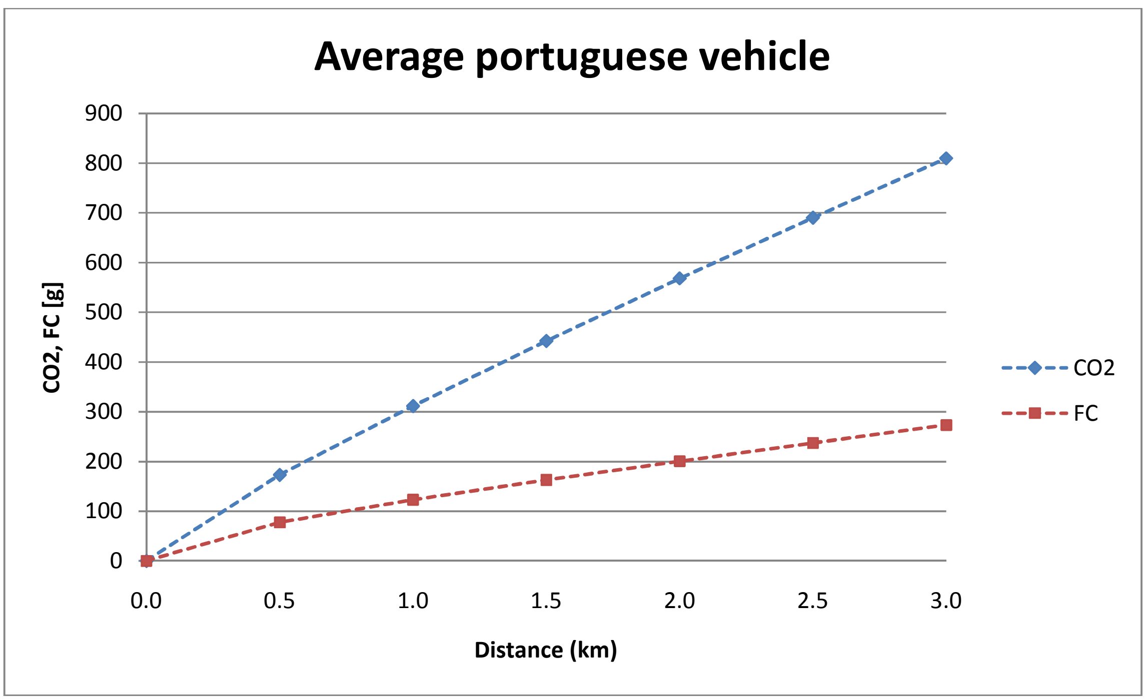

Figure 6 – CO_2 and FC total emissions to the average Portuguese vehicle [g]

For each pollutant, Table I presents the best fit equation and the respective data correlation (R-squared). These equations are valid for $x \leq 10$ km, varying linearly after that point, according to the average hot emissions.

Table I – Best fit equations for CO, VOC, NO_x, PM, FC and CO_2 total emissions for the average Portuguese vehicle

	CO	**NO_x**	**PM**	**VOC**	**CO_2**	**FC**
Best fit equation	y = 9.717ln(x) + 0.5079	y = 0.3584x - 0.2417	y = 0.3963ln(x) + 0.0512	y = 1.0048ln(x) + 0.1715	y = 117.54x - 36.42	y = 36.862x + 6.9704
R-squared (R^2)	0.9740	0.9996	0.9925	0.9686	0.9989	0.9976

RESULTS

Walking mode

To characterize the walking mode it was considered Fruins' (1971) free-flow walking speed (1,35 m/s) corrected by the influence of the waiting time on pedestrian crossing signs.

An intensive field work was made in order to characterize these influences. Table II and Table III present the distribution of pedestrian crossings per kilometre and the average waiting time for pedestrian crossing signs, respectively.

Table II – Distribution of pedestrian crossings per kilometre (95% confidence interval)

	Total crossings per kilometre	**Pedestrian crossing sign**	**Marked crosswalk**	**No crosswalk**
Average	10.4	2.8	4.6	3.0
Standard deviation	3.6	3.1	2.8	3.0
Margin of Error (%)	3.1%	9.8%	5.4%	8.7%

Table III – Average waiting time for pedestrian crossing signs (95% confidence interval)

	Pedestrian crossing sign
Average (sec)	10.9
Standard deviation	15.4
Margin of Error (%)	9.8%

When reaching a marked crosswalk or with no crosswalk pedestrians usually do not need to stop only reducing their speed so it was assumed that the waiting time in these cases was zero. The measurements made for marked crosswalks showed that only in a few cases (4 in

355 measurements) the pedestrians really needed to stop and in these cases the waiting time was below 3 seconds.

Knowing the distribution of pedestrian crossings per kilometre and per type (pedestrian crossing signs, marked crosswalks and no crosswalks) (Table II) and knowing the average waiting time for each crossing type (Table III) it is possible to determine an *attenuation factor* (f_a) to add the influence of waiting time to free-flow speed (v_{ff}):

$$v_{corrected} = v_{ff} \times f_a = 1{,}30 m/s \tag{5}$$

where:

$v_{corrected}$ – corrected speed [m/s];
v_{ff} – free-flow speed [m/s];
f_a – attenuation factor.

The *attenuation factor* can be obtained using the ratio of the time to do 1 km in free-flow speed and the time to do 1 km in free-flow speed adding the average waiting time on pedestrian crossings (around 31 seconds per kilometer). With these results the authors obtained an *attenuation factor* of 0.96 (resulting in a corrected speed of 1.30 m/s).

This result can be validated using data from volunteers free-flow and non free-flow walking speed. Five of the twelve volunteers made trips with and without pedestrian crossings in order to compare the influence of pedestrian crossings in their average free-flow speed. Results obtained are presented in the following table:

Table IV – Volunteers free-flow and non free-flow walking speeds

Free-flow speed (m/s)	1.50
Non free-flow speed (m/s)	1.45

Calculating the *attenuation factor* with these results and applying equation 5 the corrected speed would be 1.31 m/s what corroborates the obtained result (1.30 m/s).

Table V shows the average crossing time for each pedestrian crossing type. As it can be seen for the pedestrian crossing signs the crossing time lost is the highest. This is explained by the fact that usually pedestrian crossing signs are located on avenues (larger that normal streets). On the other hand the need to cross a street without having a crosswalk mainly occurs in older neighbourhoods of the city where streets are narrower and so the crossing time is obviously the smallest.

Table V – Average crossing time for different pedestrian crossings (95% confidence interval)

	Pedestrian crossing sign	Marked crosswalk	No crosswalk
Average (sec)	6.7	5.9	4.3
Standard deviation	2.8	2.2	1.7
Margin of Error (%)	2.9%	3.9%	5.4%

Public transports

Relatively to transit buses, the average waiting time obtained from measurements was of 6.2 minutes differing from literature (Câmara Municipal de Lisboa, 2005) in 1.2 minutes (see Table VI). This difference can be explained by the fact that measurements were made during rush and non rush hours while in the literature it were considered only morning and afternoon rush hours (during rush hours the time interval between circulations usually is smaller).

Table VI – Transit buses average waiting time (95% confidence interval)

	Measurements	Literature
Average	6.2	5.0
Standard deviation	4.8	1.0
Margin of Error (%)	8.8%	4.3%

The average distance obtained, from the origin to the bus stop and from the bus leaving stop to the final destination, was of 290 meters which is of the same order of magnitude of the average distance between bus stops in Lisbon (from 200 to 250 meters in the city center (Plano de Mobilidade de Lisboa, 2004)).

In what concerns to the metro, Table VII presents the data used to characterize this transport mode.

Table VII – Metro characterization data

Distance between stations (m)		722
Waiting time (sec)	**Working days**	183
	Weekend	224

The distance between stations was calculated based on the metro lines length and the number of stations (Table VIII).

Table VIII – Number of stations and length of each metro line

	Number of stations	Length (km)
Green Line	13	8.9
Red Line	9	6.8
Yellow Line	8	5.9
Blue Line	15	10.9
TOTAL	45	32.5

Table IX presents the average time to go from the surface to the metro boarding piers and from the boarding piers to the surface. These times were measured in situ.

Table IX - Average time to go from the surface to the metro boarding piers and from the boarding piers to the surface (95% confidence interval)

	Surface – Boarding piers (sec)	Boarding piers – Surface (sec)
Average	85	100
Standard deviation	37	37
Margin of Error (%)	9.6%	8.3%

Private car

As previously mentioned for private cars the sample size was not sufficient to achieve statistically significant results. Therefore, the authors present results from data collected (Table X) and three scenarios based on theoretical knowledge and taking into account that the results depend on the day period and location of origin and destination.

Table X – Data collected for private cars (95% confidence interval)

	Average	Standard deviation	Margin of Error (%)
Parking search time (sec)	48	69	34%
Time as a pedestrian (sec)	115	65	13%
Time lost to park (sec)	17	18	26%
Time spent with the car stopped (sec)	81	51	15%
Time to get a parking ticket (sec)	79	32	21%

Polak *et al*. (1990) found that parking search time in central city areas vary between 1 and 10 minutes. Additionally, the Lisbon Mobility Plan (Plano de Mobilidade de Lisboa, 2004) says that on average it takes 9.4 minutes to park in Lisbon (value based on stated preference surveys). Therefore, the authors assumed that for a low parking demand areas (low population density zones, non-commercial areas, facility excess areas, etc) the average parking search time is around 1 minute while if it is a zone with a high parking pressure (greater demand than supply) then, the average parking search time is of 10 minutes (parking search time from 1 to 20 minutes). When there is a balance between rotation and saturation, the average parking search time will be about 5 minutes (from 1 to 10 minutes) (Table XI).

Regarding the average distance as a pedestrian it is related to the availability of parking places. If it is a low demand area the probability to find a parking place close to the final destination is higher but on high parking pressure areas this is more unlikely to occur. Hence, the authors considered the average distances as a pedestrian shown on Table XI.

Table XI – Parking search time and average distance as a pedestrian considered for each scenario

Scenario	Parking search time (min)	Average distance as a pedestrian (m)
Low demand	1	25
Balanced	5	125
High pressure	10	250

For the present research the scenarios assumed can occur both in the origin and destiny but also can occur only in one of the endpoints of the trip. Thus, the authors had to create 9 different combinations of walking distances (see Table XII).

For example, on the origin if the car is parked on a low demand area the pedestrian will have to walk (on average) 25 meters but the destiny may be a high parking pressure area and so the pedestrian will have to walk 250 meters to the destiny, what makes a total of 275 meters as a pedestrian.

Notice that, even though there are scenario combinations with the same walking distance, the final results are different because each scenario has different parking search times (see Figure 8).

Table XII – Walking distances combinations for each scenario (m)

Origin \ Destiny	Low demand	Balanced	High pressure
Low demand	50	150	275
Balanced	150	250	375
High pressure	275	375	500

Comparison of transport modes in urban trips

In the next pictures and tables, results for each scenario (low demand, balanced and high pressure) are presented, comparing in terms of time and distance all the transport modes studied.

Only in Figure 7 all the transport modes are presented. In the scenarios defined variation occurs only for the private car line. Walking, metro and bus characteristics are not influenced, thus, it is irrelevant to present all the graphs.

For each scenario, a ranking of the best transport mode available is made, considering different trip lengths (Table XIII, Table XIV and Table XV).

Low demand scenario

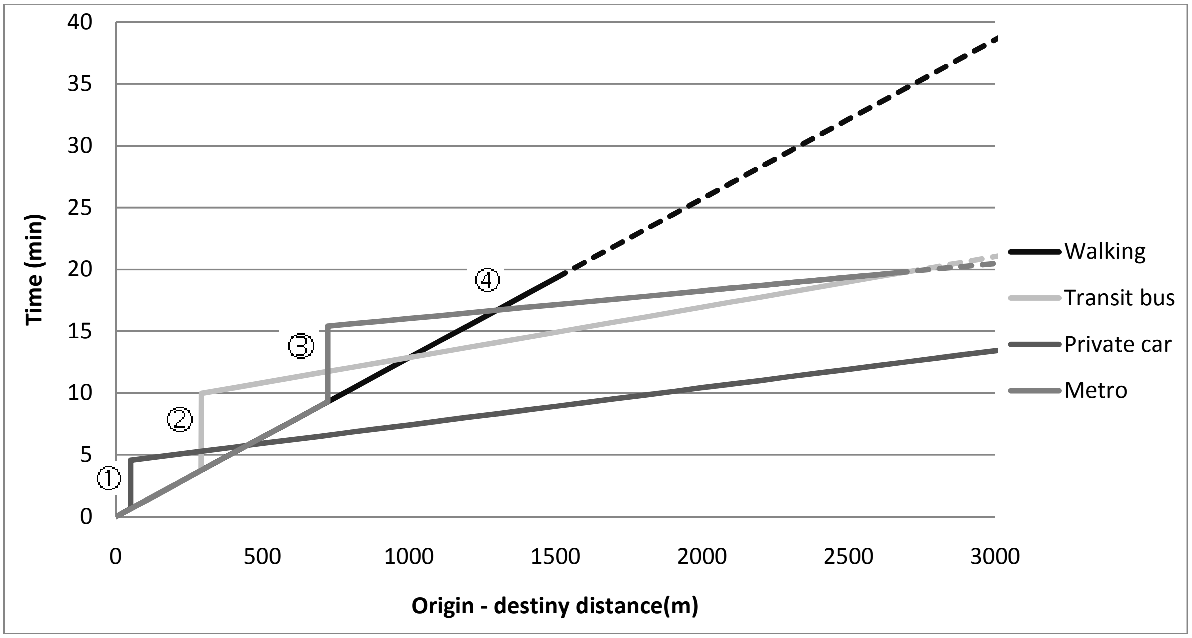

Figure 7 – Comparison of different transport modes for low demand areas (50 m)

Relatively to Figure 7 it is important to observe that:

① Private car – the first 50 metres are the distance as a pedestrian that varies linearly according to the pedestrian walking speed. Then, it is possible to observe an increase in time that represents the sum of the times that make part of the trip, causing an increase in its' duration, but do not correspond to an increase in the distance (parking search time, time lost to park, time spent with the car stopped and time to get a parking ticket). Finally, it has a linear trend accordingly to the car commercial speed (20 km/h).

② Transit bus – for the distance as a pedestrian, around 290 meters, the line follows the pedestrian average walking speed. Above this, the bus line has a linear behaviour according to the bus commercial speed (14,7 km/h). The vertical line represents the average waiting time (6.2 min).

③ Metro – relatively to the metro it is the same approach as transit bus and private car, but in this case the average walking distance is of around 720 m and the vertical line correspond to the waiting time plus the time to go from the surface to the metro boarding piers and from the boarding piers to the surface.

④ Walking – the walking line has a linear trend according to the pedestrian average walking speed.

As an example, in Figure 8 it is shown a comparison of the influence of different walking distances on the private car performance. It can be seen that an increase of just 100 m on walking distance causes an increment on the total trip time of more than 1 minute what, in short distance trips, is very significant.

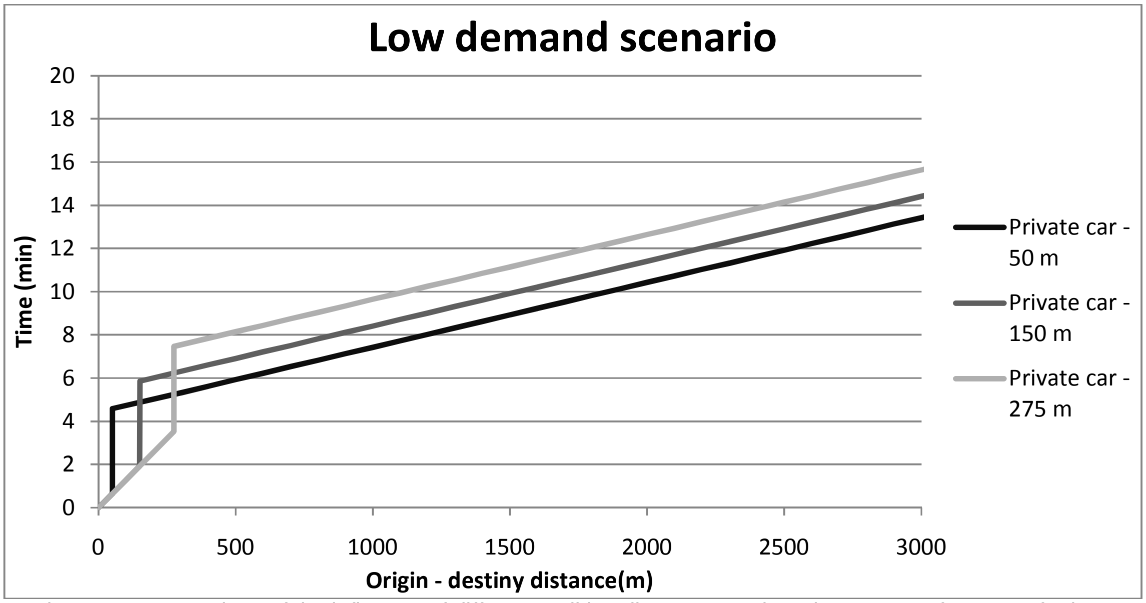

Figure 8 – Comparison of the influence of different walking distances on the private car performance for low demand areas

Table XIII shows the transport modes ranking to the low demand scenario, for different trip lengths and for each private car walking distance.

Table XIII – Transport mode ranking for different trip lengths to the low demand scenario (150 and 275 m)

		Best available transport mode			
Private car walking distance	**Trip length (m)**	**1st**	**2nd**	**3rd**	**4th**
150 m	500	Walking (6.4 min)	Private car (6.9 min)	Transit bus (10.8 min)	-
	1000	Private car (8.4 min)	Walking and transit bus (12.9 min)		Metro (16 min)
	1500	Private car (9.9 min)	Transit bus (14.9 min)	Metro (17.1 min)	Walking (19.3 min)
	2000	Private car (11.4 min)	Transit bus (16.9 min)	Metro (18.3 min)	Walking (25.7 min)
	3000	Private car (14.4 min)	Metro (20.5 min)	Transit bus (21 min)	Walking (38.3 min)
275 m	500	Walking (6.4 min)	Private car (8.1 min)	Transit bus (10.8 min)	-
	1000	Private car (9.6 min)	Walking and transit bus (12.9 min)		Metro (16 min)
	1500	Private car (11.1 min)	Transit bus (14.9 min)	Metro (17.1 min)	Walking (19.3 min)
	2000	Private car (12.6 min)	Transit bus (16.9 min)	Metro (18.3 min)	Walking (25.7 min)

		Best available transport mode			
Private car walking distance	**Trip length (m)**	**1st**	**2nd**	**3rd**	**4th**
	3000	Private car (15.6 min)	Metro (20.5 min)	Transit bus (21 min)	Walking (38.3 min)

On low demand areas for very short distance trips (less than 1 km) walking is the best solution, after that private car exhibits the more favorable relation distance – time. Next follows the transit bus and finally the metro. When considering longer trips (more than 2.5 km) metro tends to be better than transit bus due to its' higher commercial speed. Above 1 km walking becomes the worst transport mode available.

Balanced scenario

Table XIV presents the transport modes ranking to the balanced scenario, for different trip lengths and for each private car walking distance.

Table XIV – Transport mode ranking for different trip lengths to the balanced scenario (150, 250 and 375 m)

		Best available transport mode			
Private car walking distance	**Trip length (m)**	**1st**	**2nd**	**3rd**	**4th**
150 m	500	Walking (6.4 min)	Transit bus (10.8 min)	Private car (10.9 min)	-
	1000	Private car (12.4 min)	Walking and transit bus (12.9 min)		Metro (16 min)
	1500	Private car (13.9 min)	Transit bus (14.9 min)	Metro (17.1 min)	Walking (19.3 min)
	2000	Private car (15.4 min)	Transit bus (16.9 min)	Metro (18.3 min)	Walking (25.7 min)
	3000	Private car (18.4 min)	Metro (20.5 min)	Transit bus (21 min)	Walking (38.3 min)
250 m	500	Walking (6.4 min)	Transit bus (10.8 min)	Private car (11.9 min)	-
	1000	Walking and transit bus (12.9 min)		Private car (13.4 min)	Metro (16 min)
	1500	Private car and transit bus (14.9 min)		Metro (17.1 min)	Walking (19.3 min)
	2000	Private car (16.4 min)	Transit bus (16.9 min)	Metro (18.3 min)	Walking (25.7 min)
	3000	Private car (19.4 min)	Metro (20.5 min)	Transit bus (21 min)	Walking (38.3 min)
375 m	500	Walking (6.4 min)	Transit bus (10.8 min)	Private car (13.1 min)	-

		Best available transport mode			
Private car walking distance	**Trip length (m)**	**1st**	**2nd**	**3rd**	**4th**
	1000	Walking and transit bus (12.9 min)		Private car (14.6 min)	Metro (16 min)
	1500	Transit bus (14.9 min)	Private car (16.1)	Metro (17.1 min)	Walking (19.3 min)
	2000	Transit bus (16.9 min)	Private car (17.6 min)	Metro (18.3 min)	Walking (25.7 min)
	3000	Metro (20.5 min)	Private car (20.6 min)	Transit bus (21 min)	Walking (38.3 min)

For the balanced scenario the transit bus is much more competitive with the private car than for the low demand scenario. For short distance trips only for the case where walking distance is 150 m the car reveals a better performance, in the other cases transit bus is slightly better.

Again, considering longer trips, the metro tend to be the best transport mode showing a better relation distance – time.

High pressure scenario

On Table XV is shown the transport modes ranking to the high pressure scenario, for different trip lengths and for each private car walking distance.

Table XV – Transport mode ranking for different trip lengths to the high pressure scenario (275, 375 and 500 m)

		Best available transport mode			
Private car walking distance	**Trip length (m)**	**1st**	**2nd**	**3rd**	**4th**
275 m	500	Walking (6.4 min)	Transit bus (10.8 min)	Private car (17.1 min)	-
	1000	Walking and transit bus (12.9 min)		Metro (16 min)	Private car (18.6 min)
	1500	Transit bus (14.9 min)	Metro (17.1 min)	Walking (19.3 min)	Private car (20.1 min)
	2000	Transit bus (16.9 min)	Metro (18.3 min)	Private car (21.6 min)	Walking (25.7 min)
	3000	Metro (20.5 min)	Transit bus (21 min)	Private car (24.6 min)	Walking (38.3 min)
375 m	500	Walking (6.4 min)	Transit bus (10.8 min)	Private car (18.1 min)	-
	1000	Walking and transit bus (12.9 min)		Metro (16 min)	Private car (19.6 min)
	1500	Transit bus (14.9 min)	Metro (17.1 min)	Walking (19.3 min)	Private car (21.1 min)

Private car walking distance	Trip length (m)	Best available transport mode 1st	2nd	3rd	4th
	2000	Transit bus (16.9 min)	Metro (18.3 min)	Private car (22.6 min)	Walking (25.7 min)
	3000	Metro (20.5 min)	Transit bus (21 min)	Private car (25.6 min)	Walking (38.3 min)
500 m	500	Walking (6.4 min)	Transit bus (10.8 min)	-	-
	1000	Walking and transit bus (12.9 min)		Metro (16 min)	Private car (20.9 min)
	1500	Transit bus (14.9 min)	Metro (17.1 min)	Walking (19.3 min)	Private car (22.4 min)
	2000	Transit bus (16.9 min)	Metro (18.3 min)	Private car (23.9 min)	Walking (25.7 min)
	3000	Metro (20.5 min)	Transit bus (21 min)	Private car (26.9 min)	Walking (38.3 min)

Considering high parking pressure scenario, the considerable time lost to find a parking place (10 minutes) plus the time spent in the car without circulating and the time lost to get a parking ticket makes the private car the worst of the transport modes. In this case, for trips shorter than 2 km, transit bus is the best solution and after that metro presents the best relation distance – time.

Energetic and environmental analysis

As explained earlier, to estimate the total exhaust emissions (CO, NO_x, VOC, CO_2 and PM) the EMEP CORINAIR methodology was used. To the private car, due to their importance on short distance trips, cold start emissions were considered. However, for transit buses these emissions were not assumed because buses circulate all day long and so cold start emissions have a small influence on total emissions.
Considering the private car, emissions were calculated having into account the national average occupation rate 1.3 (Vasconcelos *et al.*, 2009) and for the transit bus the emissions are per seat (considering 70 seats per bus). Relatively to the metro, being electrically powered, it does not emit locally so emissions were not considered.
Table XVI shows the energetic and environmental characterization for a 1.0 km urban trip. Private car has always the higher energy consumption and emissions per trip.

Table XVI – Energetic and environmental characterization of an urban trip of 1.0 km

	Energetic consumption (MJ)	CO (g)	CO_2 (g)	PM (g)	VOC (g)	NO_x (g)
Private car	4.06	9.72E+00	2.40E+02	3.64E-01	1.48E+00	6.22E-01
Transit bus	0.26	5.84E-02	1.90E+01	9.19E-03	2.06E-02	1.97E-01

CONCLUSIONS

The main objective of the present work was to develop a methodology that allows determining indicators to compare short distance urban trips using different transport modes such as soft modes (only walking was considered), public transports (bus and metro) and private cars taking into account internal costs (time and distance) and external costs (energetic consumption, CO_2 and local pollutants emissions).
Three different scenarios for private car were defined due to the lack of statistical relevance for the data collected. For the three scenarios (low demand, balanced and high pressure) the authors assumed different values for the time/distance as a pedestrian and for the parking search time, based on bibliography data.
From the case study results it is possible to conclude that for small distance trips (less than 3 km) for the low demand scenario, with a small parking search time, the private car is the more competitive allowing to travel more within less time.
Relatively to the balanced scenario transit bus presents a very similar performance to the private car, with only slightly better results.
Finally, in what concerns to the high parking pressure scenario, private car reveals the worst relation distance – time as a result of the high parking search time. In this case transit bus is the best transport mode.
In what concerns distance – time relation, private car reveals to be a good option for low parking demand scenario and even to a balanced scenario but it is important to be aware that it has the worst energetic and environmental performance, as shown with the energetic and environmental analysis. Walking is the best transport mode for very short distance trips but it is only competitive with the other transport modes for distances below 1 km. It is also important to refer that soft modes do not have CO_2 and local pollutant emissions associated.
Metro also do not have CO_2 and local pollutant emissions (do not emit locally) associated, but relatively to the distance – time relation it only appears to be a good solution for longer trips (above 2.5 km).
Concerning the external costs, the private car has always the higher energy consumption and emissions per trip. In what concerns energy consumption car presents a 16 times higher consumption while, relatively to the pollutants emissions it can be up to 165 times higher (CO emissions case).

NOMENCLATURE

CO	Carbon monoxide
EC	Elemental carbon
e_{cold}	Cold start emissions (g/km)
e_{hot}	Hot emissions (g/km)
FC	Fuel consumption
NO_x	Nitrogen oxides

OM Organic mass
PM Particulate matter
VOC Volatile organic compounds

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