# COMPARISON OF PEDESTRIANS PARTICULATE MATTER INHALATION FOR DIFFERENT ROUTES IN URBAN CENTERS

**I. D. do Vale, A. S. Vasconcelos, G. O. Duarte, M. V. Faria, F. Pereira, X. Melo, H. Santa-Clara**

## ABSTRACT

The objective of this study is to compare pedestrian's PM inhalation in urban routes with the same origin/destination, but with different distance, topography and traffic volumes. Results provided from a numerical methodology were compared to in-situ measurements using a portable laboratory.

Numerically, each route was divided into segments with different slopes, speeds and PM concentration, allowing estimations of inhaled PM. The routes were also performed with a personal laboratory to collect data of PM concentration, heart rate, speed and altitude. Also, pedestrian minute ventilation was obtained from heart rate using a relation previously achieved under laboratory environment.

Experimental data indicates that the shortest and more polluted route presents ~20% more PM inhalation than alternative routes. The numerical method presents differences up to 7% when compared to experimental data, indicating good agreement.

This methodology is a good tool to help city planners defining policies to reduce PM exposure along urban corridors.

## 1 INTRODUCTION

Most of the world population lives in big urban areas with consequent air pollution problems, which are the cause of several health issues. The European Union estimates that human exposure to fine particulate matter (particulate matter smaller than 2.5 micrometers - $PM_{2.5}$) is the cause of ca. 350000 premature deaths each year, representing a reduction of almost a year in the average life expectancy (EEA, 2009).

Pedestrians are more vulnerable to environmental pollution exposure and have physical efforts that require higher air inhalation than other transportation modes (Adams, 1993). Consequently, pedestrians' mobility in modern cities should have a major role in urban planning.

Several authors have studied the particulate matter (PM) concentrations in urban centers, whether comparing the type of transport mode used (Jiao and Frey, 2013; Kaur et al., 2005a) or the type and characteristics of the road (Adams et al., 2001; Adams, 1993; Kaur et al., 2005b). Jiao and Frey (2013) compared the PM exposure on three different transportation modes (pedestrians, cars and buses) conducted within a one and half hour time period on pre-selected round trip routes in Raleigh, NC. They concluded that in general, pedestrian and bus modes have higher $PM_{2.5}$ concentrations among the measured transportation modes.

Kaur *et al.* (2005a) investigated the pedestrian exposure to $PM_{2.5}$ along a major road in Central London, UK. During a four-week field campaign, groups of four volunteers collected samples in the morning, lunch and in the afternoon, in a heavily trafficked route and a backstreet route using five modes of transport (walking, cycling, bus, car and taxi). The authors concluded that there was no evidence to suggest a statistically significant difference between the routes analyzed. Greaves *et al.* (2008) studied the factors that affect PM exposure concluding that wind speed, traffic volumes and clearway operations (independent of traffic volumes) were significant predictors in addition to the previous $PM_{2.5}$ concentrations. The experiments were performed along a busy roadway in Sydney, Australia. $PM_{2.5}$ was measured on second-by-second interval basis using a portable aerosol monitor, while simultaneously recording location with a personal GPS device. A digital voice recorder was also used to record any events or circumstances, perceived to notably increase potential $PM_{2.5}$ levels.

Adams *et al.* (2001) studied the PM exposure in cyclists in a central route and in secondary side streets. They found that the central route exposure levels were higher than the other routes, and there was a significant difference between the main route exposures and the side street route exposures.

Although several studies have already developed research in the area of PM exposition, and in the comparison of different routes, all of them require in-field measurements, with consequent demand of time and resources. Therefore, the purpose of this study is to compare different routes in urban centers regarding pedestrians PM inhalation by defining a numerical method to account for the PM exposure (time and concentration) and typical ventilation rates according to the physical requirements due to speed and road slope using a numerical method. Additionally, local measurements were made in order to benchmark the results obtained.

## 2 METHODOLOGY

In order to accomplish the proposed objective, a methodology based on numerical simulation and bibliographic data was used. This methodology was also benchmarked using experimental data acquired with a portable laboratory.

The PM inhalation depends on the PM concentration in the atmosphere, pedestrian minute ventilation (VE), which depends on the physical effort, and the time that the pedestrian is exposed to the ambient and can be estimated using equation 1.

$$PM_{inhaled}[\mu g] = PM_{concentraton}[\mu g/m^3] \times VE[m^3/\min] \times time[\min] \quad (1)$$

This approach was used to analyze three different route options for the same origin-destination (OD) pair. Each route was divided into segments, which accounts for different path characteristics, for instance, the change to a new block, a significant variation in road slope and also the existence of singularities (such as crosswalks). Consequently, a segment is created if road slope varies more than 1%; if the pedestrian stops, namely in signalized pedestrian crossings and if the segment length is over 50 m.

For each segment the average slope was estimated using data from Google Elevation API. To associate the speed, VE and PM concentration that best fit a given segment it was necessary to estimate the comfort walking speed under different road slopes.

Three volunteers performed several trips with different road slopes to find their comfort speeds. These values were also used to obtain a correlation between VE and slope for their average walking speeds, measured under laboratorial conditions in a treadmill, as well as a correlation between heart rate (HR) and VE.

## 2.1 Physiologic data collection under lab conditions

The protocol was based on results from on-street measurements to obtain a correlation between speed and slope. Prior to the laboratory essay, each volunteer registered his resting HR, in bpm, immediately after waking up for three consecutive days. In the laboratory setting, weight and height were measured to the nearest 0.1 unit on a scale with an attached stadiometer (model 770, Seca; Hamburg, Deutschland). The VE (l/min) was measured in resting conditions with the participants in the seated position. Inspired and expired gases were measured continuously in field, breath by breath, through a portable gas analyzer (K4b2, Cosmed, Rome, Italy), which had been previously validated by McLaughlin (2001). The K4b2 weights 475 g and is not expected to significantly affect the energy demand of the subjects (Flouris, 2005). Table 1 presents the characteristics of the three volunteers.

**Table 1 Volunteers' parameters.**

| Volunteer | Gender | Height, cm | Age, yrs | Weight, kg | Average walking speed, km/h | VE resting, l/min |
|---|---|---|---|---|---|---|
| A | M | 171.2 | 29 | 65.9 | 5.80 | 8.69 |
| B | F | 171.9 | 34 | 64.8 | 5.22 | 8.36 |
| C | F | 165.0 | 24 | 50.0 | 5.47 | 9.89 |

The results obtained show a strong correlation between VE and slope and between HR and VE, for a comfort walking speed (Figure 1 and Figure 2, respectively).

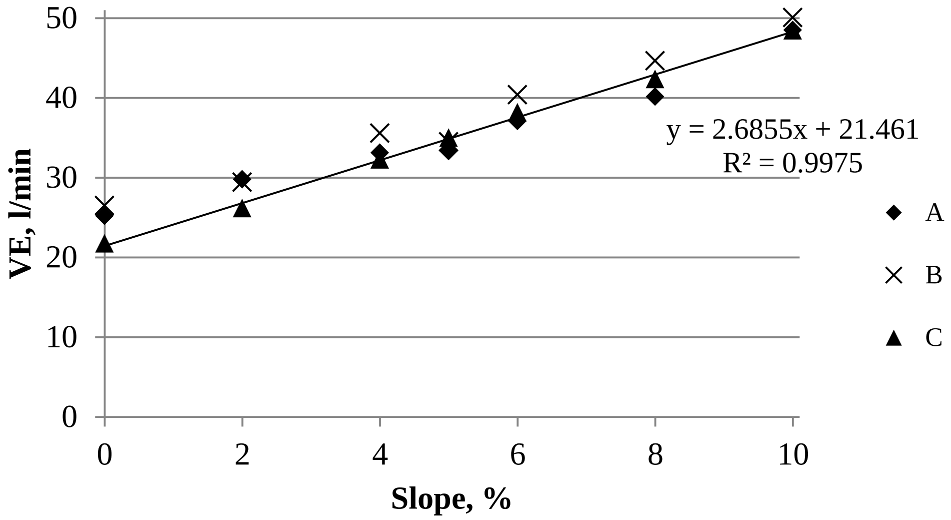


**Figure 1 Relation between slope and ventilation rate for the three volunteers**

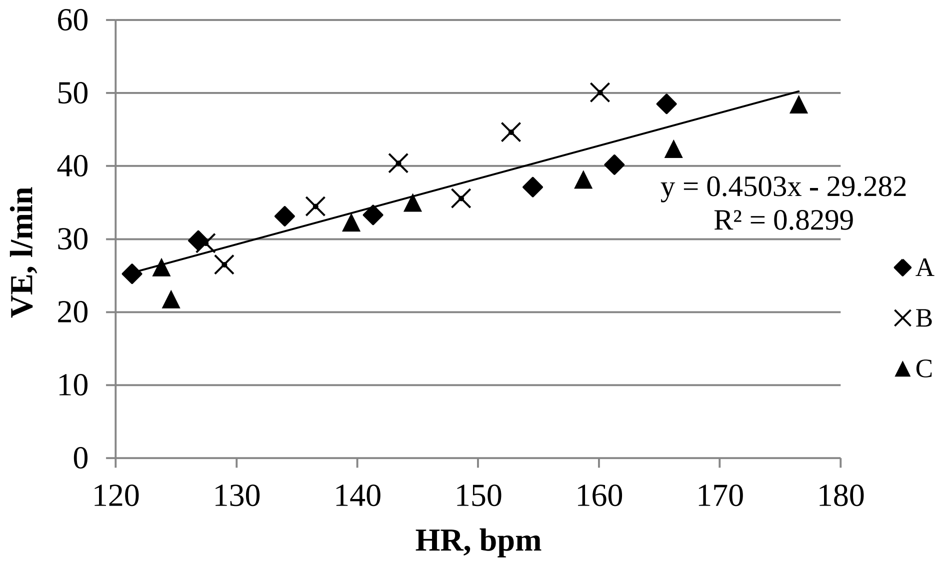


**Figure 2 Relation between heart rate and ventilation rate for the three volunteers**

## 2.2 Case study

Three routes were chosen to evaluate whether different road characteristics lead to significant differences in PM inhalation for pedestrians. These routes have the same origin in Av. Fontes Pereira de Melo/Rua Martens Ferrão and destination in Av. Duque de Ávila/Av. Defensores Chaves, as shown in Figure 3.

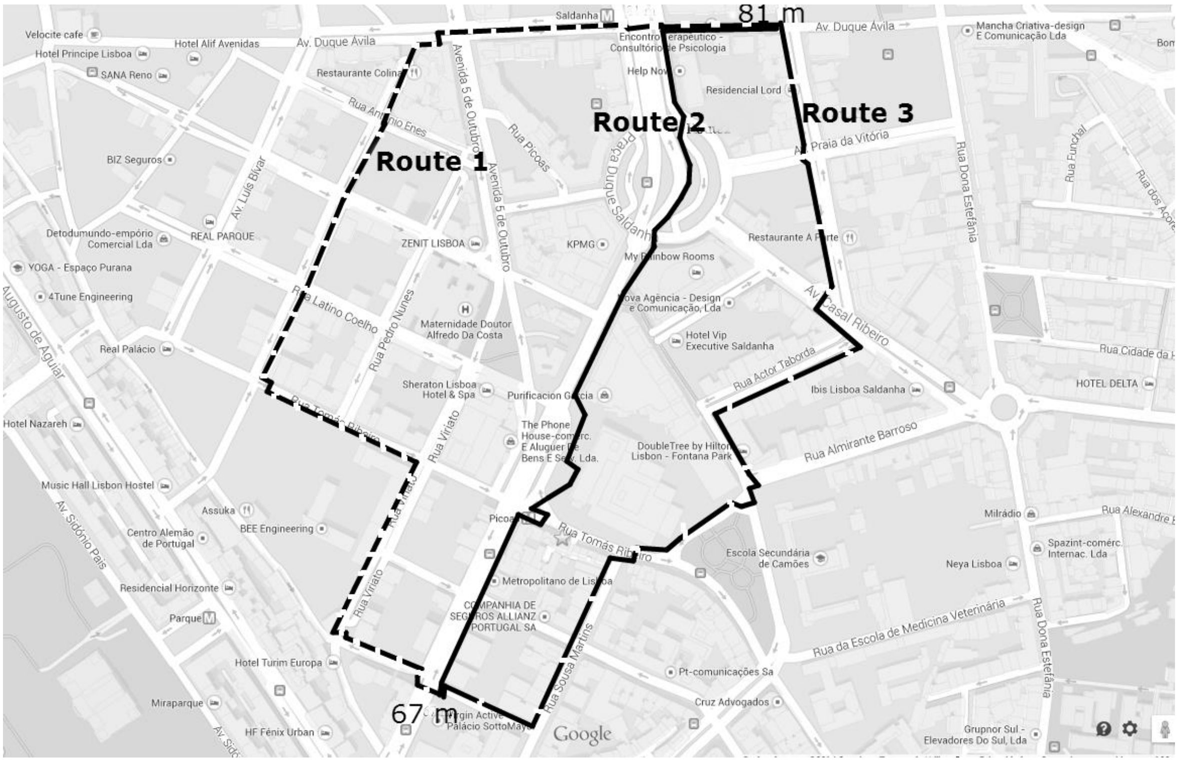


**Figure 3 Case study routes. Source: Google Maps**

The routes have different characteristics regarding length, traffic volume, topography and road width. Route 2 is the shortest, main road and higher traffic volumes (four lanes each way). It has little vegetation and wide sidewalks, although generally crowded. Routes number 1 and 3 are secondary with low traffic volumes and one or two lanes each way. Route 1 is the longest, presenting a considerable amount of vegetation and the lowest average weighted slope. It has segments with only one lane and low transit volume, wide sidewalks and one bike lane. Route 3 is not as long as route 1 and has lower amount of vegetation and narrower sidewalks. It is the route with the highest weighted average slope and, in most of its length, there is only one lane in each way with low transit frequency. Table 2 presents the different characteristics of the analyzed routes.

**Table 2 Characteristics of the three routes in uphill direction.**

| | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| Length | 1298 m | 904 m | 1114 m |
| Maximum slope | 7.3 % | 3 % | 6.6 % |
| Minimum slope | -10.2 % | -1.2 % | -3.7 % |
| Weighted average slope - $\overline{x}$ | 1.24 % | 1.41 % | 1.44 % |

Weighted average slope was obtained using the following equation:

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i w_i}{\sum_{i=1}^{n} x_i} \tag{2}$$

Where $x$ [m] is the distance of segment *i* and $w$ is the slope of segment *i* [%].

For each segment a value of slope, speed and length was estimated. Route 1 was divided in 48 segments, route 2 in 29 and route 3 in 41 segments. Using the correlation shown in Figure 1, each route segment was assigned a correspondent VE, while the PM concentrations were estimated using data from Liu and Frey (2011) where $PM_{2.5}$ concentration factors are presented for different road types, road level of service and climate conditions. Off-peak period was assumed, representing free flow traffic conditions, wind speed representative of Lisbon values was considered to be equal to 3.3 and a D stability class (average value between classes A and G) was assumed, following the guidelines proposed by the Environmental Protection Department of Hong Kong (Environmental Protection Department, 2005). The $PM_{2.5}$ concentrations obtained using this method refers only to the increment of traffic.

## 2.3 In-situ measurements

The estimates provided by the numerical methodology were benchmarked using second-by-second data acquisition through a portable laboratory (MoveLab). It consists of a 40-liter backpack with a built-in structure designed to place the components: a particulate matter analyzer Grimm 1.101 dust monitor (GRIMM Aerosol Technik GmbH & Co. KG, Ainring, Germany) and a laptop. The dust monitor measures PM ranging from 0.4 to 15 μm in diameter and is a small portable unit, suitable for ambient air measurements, which allows continuous data collection, accounting particulate concentration (counts $l^{-1}$) or mass concentration ($\mu g\ m^{-3}$). In the chosen configuration, data was recorded at the maximum frequency allowed, every six seconds and was calibrated according to manufacturer's standards prior to the measurements. The user also carried an armband GPS and a chest band HR synchronized with a watch (*Polar* model RS 800), logging data at 1 Hz.

Figure 4 shows the MoveLab configuration used in the field measurements, which also includes a portable numerical pad that is useful to mark pedestrian crosswalks.

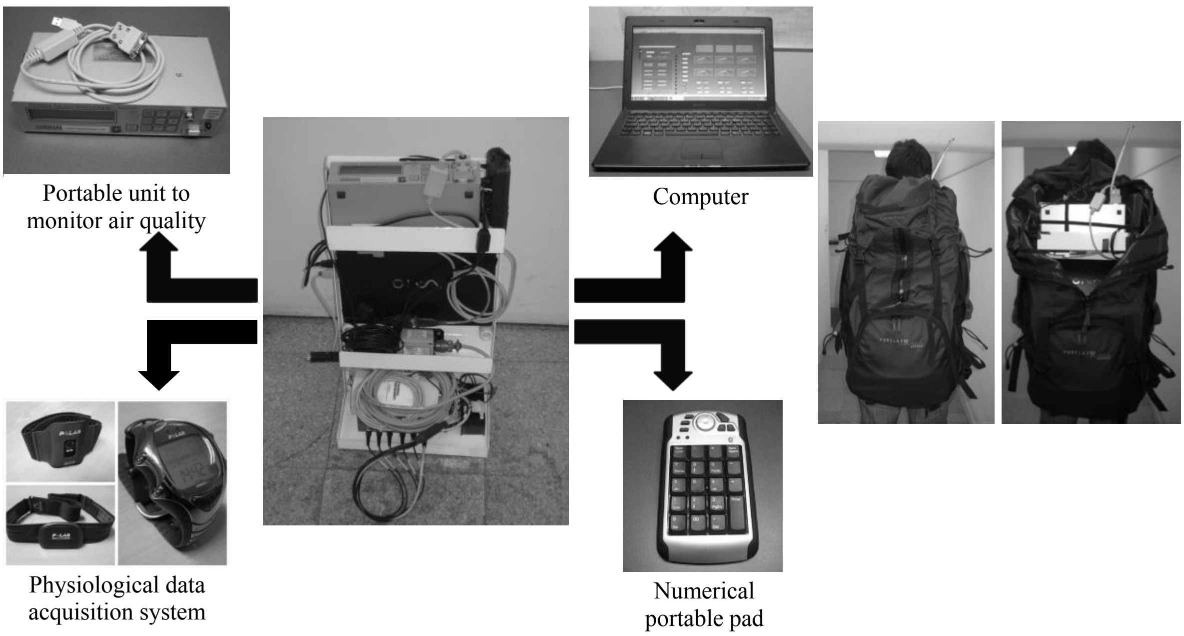


**Figure 4 MoveLab**

PM concentration, heart rate, time and distance were collected in a second-by-second basis on the routes studied. Between March 11th and March 13th 2014, four field measurements were made and, in order to ensure constant traffic level and meteorological conditions, the 3 routes were performed in less than 2 hours during off-peak periods. This guarantees that all the routes were measured with the same climate and traffic conditions, thus, a comparison between routes is independent of these externalities. Meteorological conditions for the days when field measurements occurred are shown in Table 3.

**Table 3 Meteorological conditions. Source: IPMA**

| Date and time | T, ºC | Relative humidity, % | Pressure, mbar | Wind speed, km/h |
|---|---|---|---|---|
| 2014-03-11 15h | 21.2 | N/A | 1016.2 | 16.6 |
| 2014-03-11 16h | 21.9 | 35 | 1015.9 | 15.8 |
| 2014-03-11 17h | 21.9 | 33 | 1015.9 | 14.4 |
| 2014-03-12 10h | 12.2 | 67 | 1022.6 | 16.9 |
| 2014-03-12 11h | 13.6 | 59 | 1022.9 | 11.9 |
| 2014-03-12 12h | 16.3 | 48 | 1022.5 | 10.1 |
| 2014-03-12 13h | 17.8 | 40 | 1021.8 | 12.2 |
| 2014-03-13 10h | 12.7 | 76 | 1025.0 | 12.2 |
| 2014-03-13 11h | 14.5 | 66 | 1025.0 | 9.4 |
| 2014-03-13 12h | 15.9 | 57 | 1024.6 | 6.8 |
| 2014-03-13 15h | 19.4 | 48 | 1022.9 | 9.7 |
| 2014-03-13 16h | 19.7 | 51 | 1022.5 | 13 |
| 2014-03-13 17h | 19.4 | 49 | 1022.5 | 14 |

Due to the variations between days found in the field measurements (Table 6) and the differences between modeled and measured PM concentrations, the comparison between routes was made using relative values, assuming route 2 as reference. In order to compare the two approaches followed in this work (based on numerical and measured data) the values obtained from the numerical approach were also analyzed assuming route 2 as reference.

## 3 RESULTS AND DISCUSSION

The results obtained, using the numerical approach, are presented in Table 4, where total PM inhalation is the sum of PM values for each segment.

**Table 4 PM inhalation for the three routes using numerical data**

| | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| Time (min) | 15 | 11 | 13 |
| Average Speed (m/s) | 1.38 | 1.29 | 1.37 |
| Average VE (l/min) | 29.0 | 27.3 | 28.2 |
| Average PM concentration (µg/m$^3$) | 0,99 | 1,66 | 1,05 |
| Total PM inhalation (µg) | 0,44 | 0,49 | 0,38 |
| Total PM inhalation (% of route 2) | 89,7% | 100,0% | 77,6% |

Route 2 is the one presenting the higher values of PM concentration, as expected, considering that this is the main road, with values of route 1 presenting ca. 60% of the average PM concentration of route 2. Considering that route 2 is the less physiologically demanding (lower average VE values) and the shortest path (see Table 2) when analyzing PM inhalation this variation is less significant: considering route 2 as a reference (100%), a pedestrian that chooses route 1 inhales ca. 90% of those who chooses route 2 and 78% if choosing route 3.

Results of trip duration, PM concentrations, HR measurements and estimated VE obtained from the measured data are shown in Table 5, Table 6 and Table 7, respectively. It is possible to observe that route 2 is the fastest path and presents the highest values of $PM_{2.5}$, with the exception of day 12, where route 3 had the highest value. It is also shown a considerable variation of $PM_{2.5}$ between days, due to different traffic conditions. Comparing the measured PM concentration results with those obtained from the literature, it is observed that those measured are almost twice the value modeled. This can be explained by the fact that modeled values refer only to traffic sources and measured values refer to all sources (including resuspension of particles).

**Table 5 Trip duration for the three routes in the four measured days**

| | | Route 1 | Route 2 | Route 3 |
|---|---|---|---|---|
| Time, min | 11.03.2014 | 16,1 | 10,2 | 13,1 |
| | 12.03.2014 | 14,4 | 10,0 | 13,6 |
| | 13.03.2014 | 15,3 | 10,9 | 14,1 |
| | 13.03.2014 | 15,6 | 12,5 | 14,2 |
| | **Average** | **15,3** | **10,9** | **13,7** |
| | SD | 0,74 | 1,13 | 0,52 |

**Table 6 $PM_{2.5}$ concentrations for the three routes in the four measured days**

| | | Route 1 | Route 2 | Route 3 |
|---|---|---|---|---|
| $PM_{2.5}$, μg/m$^3$ | 11.03.2014 | 4,9 | 8,1 | 5,1 |
| | 12.03.2014 | 5,9 | 6,3 | 7,4 |
| | 13.03.2014 | 12,0 | 15,6 | 12,1 |
| | 13.03.2014 | 10,2 | 12,3 | 10,7 |
| | **Average** | **8,2** | **10,6** | **8,8** |
| | SD | 3,4 | 4,2 | 3,2 |

**Table 7 Heart rate and VE for the three routes in the four measured days**

| | HR, bpm | | | VE, l/min | | |
|---|---|---|---|---|---|---|
| | Route 1 | Route 2 | Route 3 | Route 1 | Route 2 | Route 3 |
| 11.03.2014 | 136,1 | 139,5 | 126,0 | 32,0 | 33,6 | 27,5 |
| 12.03.2014 | 124,4 | 120,7 | 129,8 | 26,7 | 25,1 | 29,2 |
| 13.03.2014 | 125,9 | 123,4 | 123,3 | 27,4 | 26,3 | 26,2 |
| 13.03.2014 | 130,6 | 124,1 | 128,4 | 29,5 | 26,6 | 28,5 |
| **Average** | **129,3** | **126,9** | **126,9** | **28,9** | **27,9** | **27,8** |
| SD | 5,2 | 8,5 | 2,9 | 2,4 | 3,8 | 1,3 |

The HR values for the three routes present similar values, with route 1 being the most demanding. HR values were converted to VE using the correlation equation in Figure 2 and the results obtained are very similar to those found using the previous method.

Figure 5 presents the results found for the comparison of the three routes using both approaches.

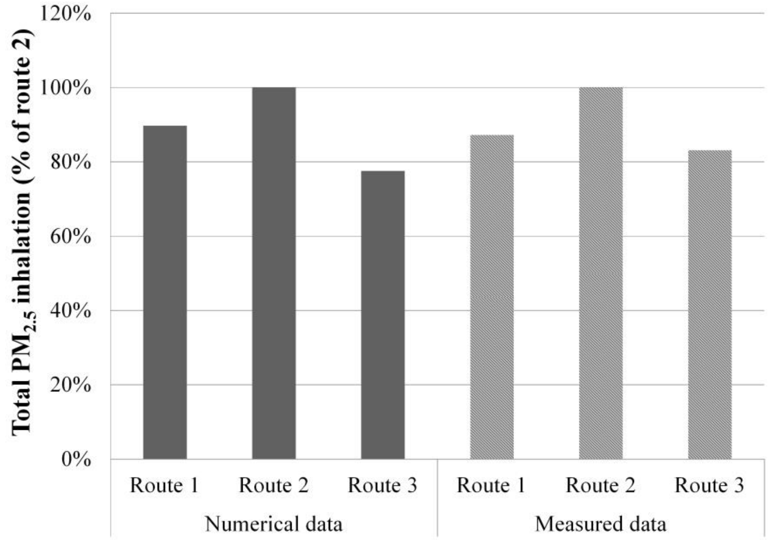


**Figure 5 Comparison of $PM_{2.5}$ inhalation using numerical and measured data**

From Figure 5 it is possible to observe that both methodologies present similar results regarding PM inhalation in a comparative approach. Route 2 presents the higher values followed by route 1, with ca. 88% of route 2 values and route 3 is the one with lower impact with values of 78% and 83% for numerical and measured data, respectively. The two approaches present the highest difference in route 3 due to variations in trip time achieved by the numerical and measured methods, as can be seen by comparing Table 4 with Table 5.

## 4 CONCLUSIONS

The objective of the present work was to compare different routes in urban centers regarding pedestrians PM inhalation by defining a method to account for all vectors of PM exposure (PM concentration, exposure time and minute ventilation) using a numerical approach and compared to in-situ measured data.

Three alternative routes for the same OD pair were divided into segments with different slopes, speeds and PM concentrations. Literature presents traffic related PM concentrations (generic values based on road characteristics) that allowed to estimate the PM inhalation for the different routes studied based on weather conditions and traffic characteristics. Minute ventilation was obtained from correlations between VE and slope and VE and HR using a treadmill in a laboratory environment.

Additionally, in-field measurements were made to compare the estimated PM inhalation values with numerical data. Results show that the numerical and experimental approaches present the same trend for the comparison of the different routes, proving the usefulness of the developed numerical methodology.

Although PM concentration is significantly higher in the higher traffic flow route, there is not a direct relation between the route with the highest PM concentration and PM inhalation (see routes 1 and 3). Route 2 always presents the worst scenario, followed by route 1 (with ca.88% of route 2 values). Route 3 presents the lower impact, with values of 78% and 83% comparing to route 2 for numerical and measured data, respectively.

Pedestrians' PM inhalation is very dependent on time and PM concentration, but also on physical activity: experimental results indicate that the shortest and more polluted route presents 25% higher PM concentration, but pedestrians' PM inhalation is only 20% higher, due to the fact that this is the shortest route and therefore pedestrians are exposed for less time and are subject to less physical effort when compared to the other routes. Consequently, it is very important to have an indication of the pedestrian physical activity (due to its speed and road properties), that can be related to the minute ventilation.

The results from the present study should be incorporated in city planning improvement, defining policies to reduce PM concentration on major pedestrian corridors or deploying infrastructures that contribute to reduce the physical effort in areas where PM concentration is higher.

## 5 ACKNOLEGMENTS

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