Exploring the use of mobile sensors for noise and black carbon measurements in an urban environment

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Mobile measurements have been collected on a bicycle equipped with a global positioning system (GPS) in a few connecting streets in Gent (Belgium). The 1-s sound pressure levels and 1-s black carbon concentrations were measured. In addition, 5 continuous monitoring fixed stations connected to building facades were used. Different processing methods are compared, based on different temporal and spatial weighting aggregations. The possibility to take profit of the fixed stations to refine estimations is tested, according to the noise levels collected at fixed stations and the distance between mobile and fixed sensors. In a last step, route selection based on travel distance, noise levels and black-carbon measurements is explored based on the data obtained.

1 Introduction

In an urban environment, high concentrations of airborne pollutants and high noise levels are a threat for the health of inhabitants. Static maps revealing the yearly averaged levels within streets have to be made by governments to reveal black points. Such maps have to be communicated to the population as well [1]. Producing accurate maps is not an easy task. Such maps can rely on both measurements and modeling [2][3]. Dynamic monitoring maps can be a complement to those static maps. They are relevant for revealing zones and periods with a high pollution impact. They could also help in developing tools to optimize the motion strategy of pedestrians and cyclists with regard to exposure to pollution and noise. Such tools would be useful for promoting non-motorized displacements and to stress the need for abatement strategies [4][5][6].

Introducing heterogeneity in sensor networks can be efficient to reduce measurement costs and guarantee a good accuracy and spatial resolution: (i) sensors of different qualities can be spread over the network to reduce costs [7], (ii) the number of sensors can be reduced by relying on the good correlations generally observed between traffic parameters, noise levels and pollutant concentrations [8][9][10], (iii) estimations can be based on both fixed and temporary sensors to increase the spatial area covered [11].

Mobile measurements, aiming at monitoring noise levels or pollutant concentrations based on measurements collected by a moving operator (pedestrian, cyclist, etc.) are gaining interest. They allow covering large spatial zones with a single sensor and thus reduce monitoring costs [12][13]. Those methods can be extended to participatory sensing [14][15]. However the reliability and the statistical issues inherent to those methods (number of samples needed, processing of the data, etc.) have to be assessed.

The purpose of this paper is to explore how mobile measurements should be processed and combined with fixed measurements to obtain reliable estimations given the strong variability of the data collected. Mobile measurements have been collected on a bicycle equipped with a global positioning system (GPS), in an area of Gent (Belgium). The 1-s evolution of the sound pressure levels and the black carbon (BC) concentrations were measured. In addition, 5 monitoring fixed stations continuously measuring noise levels were placed at building facades. It is expected that the mobile measurements give access to an increased spatial resolution unaffordable at reasonable cost through modeling, while the fixed stations guarantee a sufficient accuracy.

The high spatial resolution obtained enables evaluating exposure during displacements inside the city. Therefore, pedestrians or cyclists could optimize their trips based on three parameters: exposure to noise levels, exposure to black carbon concentrations, and trip duration. An example of route choice optimization is given in the last section of the paper.

2 Site description and instrumentation

Microphones were placed at 5 locations in a few neighboring streets in the inner city of Gent, Belgium. The microphones were placed at the facades of buildings, at heights between 3 and 5 m. A detailed description of the noise measurement set up can be found in [7]. Three microphones were closely located near a crossing of the Doornzelestraat and the Sleepstraat; see Figure 1. Those are busy 2-lane streets. Doornzelestraat is characterized by many bus passages and Sleepstraat is characterized by many tram passages in both directions. Two microphones were placed in calmer streets; one in the Bomastraat, where the traffic intensity is much lower, and one in Nieuwland, which is a one-way street, the calmest one considered.

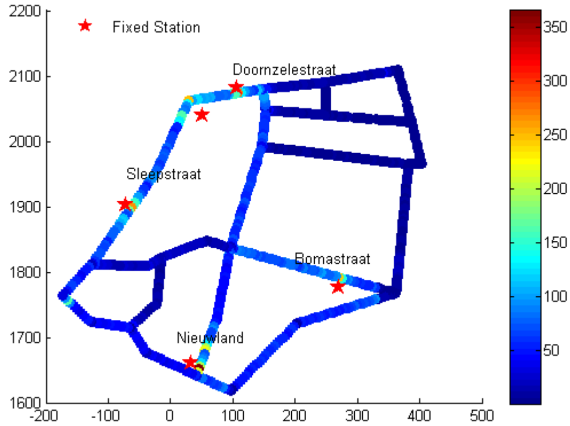

Figure 1: Overview of the fixed microphone locations, and number of mobile measurements collected per point (in seconds)

A mobile measurement campaign was conducted between 04/04/2011 and 18/05/2011. Each measurement consisted of a 20 minute bicycle ride in the zone considered, at a random time of the day. The operator was equipped with a global positioning system (GPS), a microphone and a black carbon measurement device, all carried in a backpack. Black carbon concentrations were measured with a microAeth® Model AE51; the inlet flow duct was placed outside of the bag, at the height of the head. The microphone was placed 10 cm below the inlet duct. Devices were synchronized and the data was captured at 1s intervals.

Positions given by the GPS are mapped to a fixed grid with a resolution of 5 m, giving a total number of 662 points on the road network. Measurement data are aggregated on this grid. A total amount of 7 h and 51 min of data have been collected. The zone was unevenly covered by the experiment as rides followed random paths. The number of samples (in second) collected for each point of the network is given in Figure 1.

3 Estimation of noise levels

3.1 Data analysis

The very short term sampling inherent to mobile measurements results in a strong variability in the data collected. The average of the standard deviations of noise levels collected at each of the 662 points amounts to 4.5 dB(A). This variability has three causes: (i) the small duration of each passing by at a given point (only a few seconds) that makes samples sensitive to the dynamics of traffic (one vehicle in the vicinity of the point or not), (ii) the small amount of samples (43s of sampling on average per point), (iii) the heterogeneity in the sampling instants, that may fall during noisy or less noisy times of the day. This variability is too high for producing a useful noise map unless the number of samples is highly increased. In this paper, a method is proposed to reduce this variability without increasing the sampling costs.

3.2 Reduction of spatial variations

The causes (i) and (ii) generate a strong spatial variability between measurements (noise levels differ a lot between two points at a distance of 5 m). To reduce this variability, each $L_{Aeq,1s}$ value collected at one given point in the network is replaced by an acoustical average of the noise levels collected in the vicinity during the same minute. It is expected that, since the speed on the bike differs from the speed of motorized vehicles, this consideration of the local sound environment smoothes the influence of the distance between the bicycle and the closest motorized vehicles. A Gaussian filter is applied to give a greater weight to data collected at a closer distance (σ = 20 m ; thus data collected at a distance of 0 m and 50 m have a weight of 1 and 0.05 in the average, respectively). Hence this process smoothes short distance spatial variation, but it preserves the influence of network layout on noise levels (increase of noise levels in busy streets, noise variations around intersections, etc.).

3.3 Correction with fixed stations

However, the map produced with this filtering method is still affected by the heterogeneity within sampling instants (cause (iii)). Measurements at fixed stations are used to reduce this variability.

To each point i of the network (662 points) corresponds a sampling period s_i, when measurements were collected at i (s_i covers several groups of samples, each of few seconds). The noise levels collected at the 5 fixed stations are averaged for each s_i giving $L_{FS}^{s_i}$. $L_{FS}^{s_i}$ values vary on a range of 5 dB(A), according to the sampling periods s_i, whether if s_i falls during noisy or less noisy times of the day.

Hence the difference $d_i^{s_i} = L_i^{s_i} - L_{FS}^{s_i}$ is calculated, where $L_i^{s_i}$ is the mean of noise levels measured at i during s_i. This difference reveals the influence of the network configuration (layout, distance to the first intersection, busy street or not, etc.), on noise levels at i. Moreover it highlights the fact that noise levels are generally more important on the road than on the facades. $d_i^{s_i}$ takes values between -12.1 and 12.1 dB(A) on the network, with an average of -1.2 dB(A). Note that this value is negative though noise levels are generally higher on the road than on facades. Indeed three fixed stations are placed at Sleepstraat and Doornzelestraat which are locations where noise levels are higher than the average of the network.

Finally, as one is interested here in noise levels along the road, the noise level L_i^S at i during the whole sampling period S of the experiment ($S = \bigcup_{i=1:662} s_i$) is determined with: $L_i^S = d_i^{s_i} + L_{FS}^S$. This makes the assumption that the differences between the noise levels along the network do not vary between sampling periods, which is consistent with results from [11].

The noise map obtained is shown in Figure 2. It reveals higher noise levels on Sleepstraat, where tramways are frequent, and lower noise levels on inner roads. The spatial noise variations within each street are also estimated; this high resolution allows the assessment of noise exposure along trips.

Moreover, the procedure smoothes the short distance spatial variations, which were due to the small duration of passing byes. This is proved by calculating the standard deviation of noise levels estimated for a sample of points located in the vicinity (distance smaller than 20 m) of each point of the network. The average of those standard deviations amounted to 2.2 dB(A) without spatial aggregation, while it is only 0.9 dB(A) after aggregation.

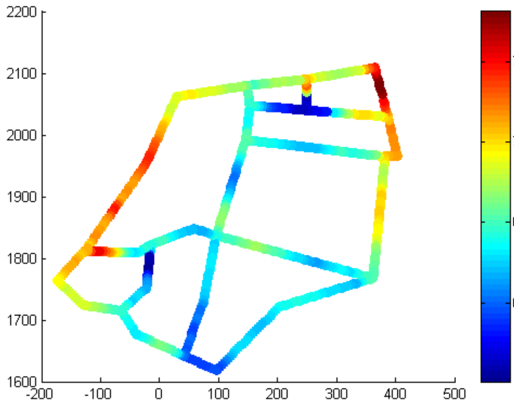

Figure 2: map of L_{Aeq} values, estimated with mobile $L_{Aeq,1s}$ measurements corrected with noise measurements collected at the 5 fixed stations

4 Estimation of black carbon concentrations

4.1 Reduction of spatial variations

The estimation of black carbon concentrations is achieved with a similar approach. It relies on the 1-s time history of black carbon concentrations C_{1s} measured on the bike, combined with noise values measured at the fixed stations. To smooth the short distance spatial variations, similarly to the processing method for noise data, the C_{1s} values are replaced by the weighted average of the concentrations collected during the same minute and in the vicinity (the same Gaussian function with σ = 20 m is used).

4.2 Correction with measurements collected at the fixed stations

Similarly to the section 3.3, concentrations estimated directly from the mobile measurements are corrected to account for the influence of the sampling instants. However, the only continuous measurements available are noise levels measured at the 5 fixed stations. This is a typical situation in heterogeneous sensor networks where the aim is to rely on the relations between noise levels and black carbon concentrations to reduce the costs of monitoring while preserving the accuracy of estimations [10].

Hence relations between noise levels and BC concentrations are investigated first, in order to estimate BC concentrations at the fixed stations for the different sampling periods s_i. Unfortunately, the correlation between overall A-weighted noise levels and BC concentrations C_i averaged at each point of the network (sample of 662) is only moderate (correlation $R_{LAeq,log10(C)}$ = 0.64). This suggests that BC concentrations cannot simply be estimated in terms of noise levels through a relationship of the type: $\log_{10}\left(\tilde{C}\right) = f(L_{Aeq}) = a + b \times L_{Aeq}$ (the concentrations estimated with f will be called $\tilde{C}$ while C represents the measured concentration). A closer look into the data shows that the parameters {a, b} of the linear regression vary over different periods of the day. Indeed, whereas noise levels measured on the road are closely related to traffic noise emissions, BC concentrations accumulate and are impacted by meteorological parameters that vary along the day. Pronounced peaks of BC concentrations are generally observed in the morning and evening during commutating periods.

As a consequence, a set of 24 couples of parameters $\{a^h, b^h\}$ were estimated, linking noise levels to BC concentrations for each hour h of the day. Mobile BC concentrations $\tilde{C}_{1s}$ are estimated through the following relation: $\log_{10}\left(\tilde{C}_{1s}\right) = f^h\left(L_{Aeq,1s}\right) = a^h + b^h \times L_{Aeq,1s}$. The validity of this approach is checked by averaging $\tilde{C}_{1s}$ values at each point i of the network, and comparing it to concentrations measured. A correlation $R_{\tilde{C}_i,C_i} = 0.77$ is obtained, outperforming the correlation R=0.60 if estimates are calculated without segregating the different periods of the day.

Hence the relations and the parameters $\{a^h, b^h\}$ can be used to estimate the concentrations at the fixed stations $\tilde{C}_{FS}^{s_i}$ and $\tilde{C}_{FS}^{S}$ that correspond to each period s_i and to the whole period S, with $L_{FS}^{s_i}$ and L_{FS}^{S} values as input, respectively. In this way the variations in BC concentrations that are due to the layout (increase in busy streets or in narrow streets, etc.) can be distinguished from the variability caused by different sampling instants (for example the higher levels when the sample is taken during rush hour). Finally, the concentration $\tilde{C}_i^S$ is estimated at i with: $\tilde{C}_i^S = C_i^{s_i} + \tilde{C}_{FS}^{S} - \tilde{C}_{FS}^{s_i}$.

The map obtained is shown in Figure 3. High concentrations are estimated in Sleepstraat and Doornzelestraat, which are busy streets. Note that the procedure is not sufficient to smooth all the short distance spatial variations (consecutive points with concentrations significantly different still remain). Those variations do not reflect reality and would disappear if more samples were taken per point of the network. This can also be obtained by decreasing the spatial resolution. Moreover, unexpectedly high concentrations are obtained at the eastern part of the network, which could indicate non-traffic related sources.

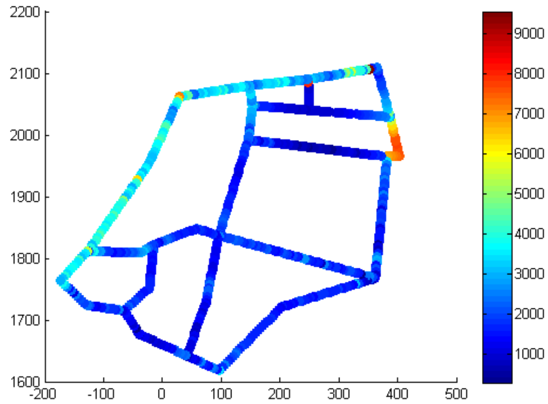

Figure 3: map of black carbon concentrations, estimated with mobile black carbon measurements and noise measurements collected at the 5 fixed stations

5 Route choice selection

The assessment of noise levels and black carbon concentrations with a high spatial resolution enables extending classical travel costs along the network with personal exposure, and consequently the selection of the healthiest and quietest routing options. One method to enable such a selection is proposed in this section, based on the maps that correspond to the whole sampling period S. Note that in practice this method should rely on the fixed monitoring stations to deduce current noise levels and black carbon concentrations and select dynamically the best options.

The three parameters selected to define the global cost of a routing option are the exposure to noise levels, the exposure to black carbons, and the trip duration. The trip duration is expressed in seconds. A mean walking speed of 1.4 m/s is considered. Speed variations along the trip are not considered. The total exposure to noise levels is obtained by calculating the Sound Exposure Level (SEL) that is the acoustical sum of $L_{Aeq,1s}$ values estimated along the trip. Similarly, the Black Carbon Exposure Level (BCEL) is obtained by summing the C_{1s} values estimated along the trip. Note that costs are expressed with total exposure levels instead of average exposure levels (which would require dividing by the duration of the trip), to account for the impact of different trip durations on exposure.

Fixing the relative contribution of each parameter to the overall cost is not the goal of this work; a cost of 1/3 is arbitrarily given to the best option regarding each of the three parameters. Thus an option that minimizes simultaneously the three parameters would have a cost of 1 (such an option does not always exist). Costs are supposed to evolve linearly with each parameter: a cost of 2/3 is given when the trip duration is doubled, when the BCEL is doubled, or when the SEL is doubled (+ 3 dB(A)).

The best routing choices are selected with an adaptation of the Dijkstra's algorithm [16], which searches for routing options with the lowest costs. The three best options are calculated. Note that, when calculating the $n+1^{th}$ best option, a cost $c^{n+1} = \alpha \times c^n$ is given to each link of the n^{th} best option, to find paths sufficiently different ($\alpha = 1.5$).

An example of route selection is given in Figure 4. In this example the best option if one focuses on the trip duration is the 3rd path (in pink): trip duration of 531 s. However this route passes along Sleepstraat that is a busy street: hence the total noise exposure is SEL = 95.9 dB(A) and the total BC exposure is BCEL = 1.79 mg.s/m^3.

The best option if the three parameters are taken into consideration is the 1st path (in black). It avoids the busy streets while increasing moderately the trip duration. Hence the exposure to noise and black carbon is low, with SEL = 92.8 dB(A) and BCEL = 1.35 mg.s/m^3, respectively. This option offers the best compromise for the costs defined.

Note that calculations are very fast (only a few seconds), making it possible to inform dynamically pedestrians or bicyclists on the best travelling options.

Table 1: Comparison of the three best routing options.

Path	Cost	Trip duration [s]	SEL [dB(A)]	BCEL [mg.s /m^3]
1st	1.1	554	91.6	1.04
2nd	1.3	610	92.8	1.35
3rd	1.9	531	95.9	1.79

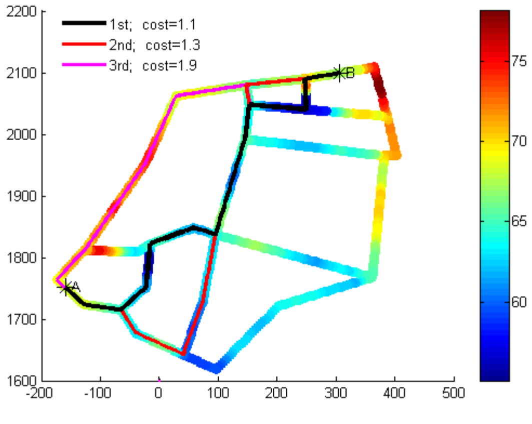

Figure 4: Search of the route choice option that minimizes the cost of a travel from A to B

6 Summary and discussion

A method is proposed in this paper to estimate noise levels and black carbon concentrations in an urban area, with a high spatial resolution (5m), based on mobile measurements combined with measurements at fixed stations. Mobile measurements have been collected on a bicycle equipped with a global positioning system (GPS), in an area of Gent (Belgium). The 1s-evolution of the sound pressure levels and the black carbon concentrations were measured (7 h 51 min of data collected). In addition, 5 fixed monitoring stations were placed at building facades to collect continuously noise levels. A method is proposed to process the data from mobile measurements and combine them to fixed measurements to obtain reliable estimations in spite of the strong variability of the data collected.

Data are processed in four steps to estimate noise levels along the road network: (i) GPS coordinates are aggregated along the road into a fixed grid with a resolution of 5 m, (ii) $L_{Aeq,1s}$ value are spatially aggregated (weighted average of data collected at less than 50 m and during the same minute), to reduce the variability due to the short term sampling, (iii) the difference between noise levels collected on the bike and the average of noise levels at the fixed stations when mobile data were collected is calculated for each point of the network, to highlight the influence of the road network on noise variations, (iv) this difference is added to the average of noise levels at the fixed stations, to reveal noise levels along the network.

The estimation of black carbon concentrations uses the same principle. However estimations of BC concentrations at the fixed stations during the different sampling periods are not directly measured, but are instead estimated through a relationship that uses as input noise levels at the fixed stations and time of the day.

Finally, the noise levels and black carbon concentrations estimated are used to optimize trips over the network according to the three following parameters: trip duration, total exposure to noise levels and total exposure to BC concentrations. An illustration of such optimization shows the interest for cyclists or pedestrians to have this information: it can guide them through optimized routes offering a compromise between trip duration and exposure.

This research is a first step towards the development of tools that enable the reduction of exposures. Further investigations will help to improve such tools. Firstly, the dynamic estimation of noise levels and concentrations could be improved by considering meteorological parameters, optimizing the number and location of fixed stations, and optimizing the routing for mobile measurements based on levels and standard deviations measured at the first tours. The higher the standard deviation at one given point, the higher the number of samples should be. Secondly, the estimation of exposure along trips would profit from taking inhalation rates into account [17][18], or accounting for the dynamics of displacement [19]. Finally, other parameters could be included to extend the study. Parameters such as number of crossing, cleanliness, pavement, vegetation, etc., can also influence the walkability of a street [20][21].

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References

[1] Directive 2002/49/EC of the European Parliament and Council of 25 June 2002 relating to the assessment and management of environmental noise.

[2] EA King, H. Rice, "The development of a practical framework for strategic noise mapping", *Appl. Acoust*. 70, 1116–1127, 2009

[3] D. Manvell, L. Ballarin Marcos, H. Stapelfeldt, R. Sanz. "Sadmam - Combining measurements and calculations to map noise in Madrid", *Proceedings of Internoise 2004, Prague, Czech Republic* (2004)

[4] D.J. Briggs, K. de Hoogh, C. Morris, J. Gulliver, "Effects of travel mode on exposures to particulate air pollution", *Env. International.* 34, 12–22 (2008)

[5] E.A. King, E. Murphy, "Reducing pedestrian exposure to environmental pollutants: a combined noise exposure and air quality analysis approach", *Transp. Res. Part D,* 14, 309-316 (2009)

[6] Y. Zhou, J. Levy, "The impact of urban street canyons on population exposure to traffic-related primary pollutants", *Atm. Env.* 42, 3087–3098 (2008)

[7] T. Van Renterghem, P. Thomas, F. Dominguez, S. Dauwe, A. Touhafi, B. Dhoedt et al., "On the ability of consumer electronics microphones for environmental noise monitoring", *J. Environ Monit*. 13, 544–552 (2011)

[8] S. Weber, "Spatio-temporal covariation of urban particle number concentration and ambient noise", *Atm. Environ*. 43(34), 5518-5525 (2009)

[9] A. Can, L. Dekoninck, M. Rademaker, T. Van Renterghem, B. De Baets, D. Botteldooren, "Noise measurements as proxies for traffic parameters in monitoring networks", *Sci Total Environ.* 410-411, 198–204 (2011)

[10] A. Can, M. Rademaker, T. Van Renterghem, M. Van Poppel, V. Mishra, J. Theunis, A. Touhafi, B. De Baets, D. Botteldooren, "Correlation analysis of noise and ultrafine particle counts in a street canyon", *Sci Total Environ.* 409, 564-572 (2011)

[11] A. Can, T. Van Renterghem, M. Rademaker, S. Dauwe, P. Thomas, B. De Baets, D. Botteldooren, "Sampling approaches to predict urban street noise levels using fixed and temporary microphones", *J. Environ Monit.* 13, 2710-2719 (2011)

[12] G. Bennett, E.A. King. J. Curn, V. Cahill, F. Bustamante, H.J. Rice, "Environmental noise mapping using measurements in transit", *Proceedings of ISMA 2010 including USD* (2010)

[13] N. Bukowiecki, J. Dommen, A.S.H. Prévôt, R. Richter, E. Weingartner, U. Baltensperger, "A mobile pollutant measurement laboratory—measuring gas phase and aerosol ambient concentrations with high spatial and temporal resolution", *Atm. Environ*. 36, 5569–5579 (2002)

[14] Maisonneuve, N. "Participatory noise pollution monitoring using mobile phones", *Information Polity*. 15, 51–71 (2010)

[15] J. Burke, D. Estrin, M. Hansen, A. Parker, N. Ramanathan, S. Reddy, M. B. Srivastava, "Participatory Sensing", WSW'06 at SenSys 06, October 31, 2006, Boulder, Colorado, USA (2006)

[16] E.W. Dijkstra, "A Note on Two Problems in Connexion with Graphs", *Numerical Mathematics*, 1, 269-271 (1959)

[17] A. McNabola, "Relative exposure to fine particulate matter and VOCs between transport microenvironments in Dublin: Personal exposure and uptake", *Atm. Env.* 42, 6496–6512 (2008)

[18] L. Int Panis, B. de Geus, G. Vandenbulcke, H. Willems, B. Degraeuwe, N. Bleux, V. Mishra, I. Thomas, R. Meeusen, "Exposure to particulate matter in traffic: A comparison of cyclists and car passengers", *Atm. Env*. 44, 2263-2270 (2010)

[19] M. Ishaque, R. Noland, "Simulated pedestrian travel and exposure to vehicle emissions", *Transp. Res. Part D.* 13, 27–46, (2008)

[20] C. Kelly, "A comparison of three methods for assessing the walkability of the pedestrian environment", *Journal of Transport Geography*, 19(6), 1500-1508 (2010)

[21] H.C. Borst, S.I. de Vries, J.M.A. Graham, J.E.F. van Dongen, I. Bakker, H.M.E. Miedema, "Influence of environmental street characteristics on walking route choice of elderly people", *Journal of Environmental Psychology*, 29, 477–484 (2009)