EVALUATION OF URBAN HEAT ISLAND FOR PUEBLA CITY, MEXICO

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ABSTRACT

A study for urban heat island (UHI) detection was focused on the historic center of Puebla City, México. For this study, a polygon was chosen, accounting for 45 points covering the main area where most historic buildings from the XVI century are located, plus high rates of traffic vehicle circulation takes place. After that, there are formulated routes to collect data in order to cover all points during three hours. The evaluation of UHI occurrence was done based on both environmental and landscape parameters, registering values for relative humidity (RH, %), light intensity (I, lux), temperature (T, °C), noise (decibels, dB), vegetation, pavement materials, height and main use of buildings, presence of water bodies and vehicle traffic flow rate. Data collection was done in two weather conditions: *summer* (warm and wet season) and *fall* (dry and windy season); at three hourly ranges: *morning* (6–9), *afternoon* (12–15) and *evening* (18–21). For data analysis a "traffic light" was formulated, with green being good, yellow being concern and red being critical. For this step the difference between maximum and minimum values was divided in three groups, plus an annular presentation (from center to outside morning, afternoon, night) allowed to make evident how the parameters evolved during the day. Results from temperature allowed to classify 6 sites as probable UHIs, a conclusion which is reinforced by the lack of vegetation, pavement material, building usage and amount of vehicles passing by. Another critical parameter is noise, since almost 50% of the sites have values above the recommended for healthy environments (<60dB) in the morning, and 11% of the sites are unacceptable at all times.

Keywords: urban heat island, vehicle traffic, noise, environmental parameter, landscape parameter.

1 INTRODUCTION

Sustainability of cities is highly related to efficient use of their resources, basically there is a need for closing cycles considering actions focused on reducing: natural resources consumption, residue generation and pollution of air, soil and water. Additionally it should be considered propose actions to reduce a motorized transport mobility, energy consumption and social segregation. Some authors have considered approach the problem through a sustainability analysis by using indicators considering *land use* (space use, building density, preservation including heritage), *public space-urban shape* (developing public spaces, green areas, quality and public health), *mobility* (reduction of motorized transport), *metabolism* (use of energy, water, residues management, water, air and light pollution), *social cohesion, economic aspects, process method* (integrated planning) [1].

Additional effort should be put to analyze Heritage Centers in the frame of the concept of sustainability, and diagnosis should be based on social dynamics, changes of usage for different buildings and their impact onto environment, economic development and heritage preservation. The HQDIL method where each letter means H= heritage and resources, Q= quality of the local environment, D= improve diversity, I= improve integration, L= social link; this method can be used for a site classification, starting from a diagnostic of phases such as: 1) *the vision phase*. Perception of problems; 2) *the analysis phase*. Inventory of the situation strengths and weaknesses; 3) *the design phase*. Research and analysis of solutions; and 4) *the implementation phase*. The constructed space can be classified as residential, non-residential, non built, and facilities. Also it is recommended that the diagnosis of sustainable

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development should account for: *Potentialities or strengths* (rich built heritage with high architectural value), *Dysfunctions or weaknesses* (vacant housing stock, deterioration), *challenges* (preservation of built heritage, improvement of non built spaces); The mentioned phases should be crossed with the objectives and targets [2].

In order to get a sustainable environment, especially at Heritage Centers, it is important to diagnosis Urban Heat Islands (UHI) which are related to urbanization factors, with the undesirable decline in natural land and vegetation. An approach to quantify the UHI effect by an intensity factor implies the calculation of the mean radiant temperature (Tmrt), this is one of the most important meteorological parameters, its calculation requires information on air temperature, radiant temperature, relative humidity, wind speed and CO_2 concentrations, radiation data can be obtained from a meteorological station, Lazovic et al [3] reported doing measurements in three periods of the day: the morning (8–9), noon (12–13) and afternoon (18–19), during 2 summer days, they estimated the Tmrt using globe temperature or the mean radiant flux density of a human body [3].

There are some reports pointing to the fact that UHI is due to effects like: a) lack of evaporative surfaces (vegetation); b) physical characteristics of the pavement surfaces such as concrete, asphalt, materials which absorb solar radiation; c) human activities that produce heat, for instance thermal conditioning of buildings, industrial activities, vehicles; the occurrence of a, b and c factors favor an increase in high pollutant levels altering the radiative nature of the atmosphere promoting surface and atmospheric temperature changes. Attenuation can be enforced by implementing green corridors, green infrastructure, urban parks, green vegetation, passive cooling of buildings, green roofs, urban water, replacement of urban materials for instance color façade [4]. Reinforcing this approach can be cited an analysis of UHI at Phoenix [5], authors point out that the characteristics of built surfaces have strong influence on the amount of heat adsorbed, and recommended actions to reduce heat adsorption mentions things like light colored facades, reflective roofs, cool pavement, which act increasing the amount of pervious surfaces that release heat quickly once the sun sets, plus they allow rain to be absorbed into the ground helping to recharge the aquifer, addition of vegetation in places sparsely vegetated and in roofs will be helpful in UHI reduction.

From the previous paragraphs it is obvious that a UHI diagnosis based on environment and landscape parameters should be useful to propose actions which will be helpful for Heritage Centers be oriented to get a sustainable status.

Based on 75 papers it is reported a systematic review of factors contributing to UHI effect [6], authors accounted for spatial and temporal factors. Factors affecting UHI intensity: Area/percentage of vegetation, UHI seasonal variation, Urban (built-up) area/city size, UHI day/night variation, Population, area/percentage /proportion of waterbody, area/percentage of road/pavement, biophysicalindices/ components, impervious surface, ground surface emissivity/irradiance/albedo, social and economic variables (investment, energy consumption)landscape metric/ecology, area/percentage /density of buildings, bare soil, soil moisture, elevation. The impact of different spatial-temporal factors on UHI effect varies between the type of satellite imagery used and the methodology applied to derive the UHI intensities; for instance: Remote sensing images obtained with satellites allow derive the Land Surface Temperature (LST) and UHI intensity factor (UHII). Review accounts for techniques like Moderate Resolution Imaging spectroradiometer (MODIS), Advanced Spaceborne Thermal Emissions (ASTER), thermal infrared (TIR). Land cover has been calculated as a ratio of satellite spectral bands to each other, an example is the Normalized Difference of Vegetation Index (NDVI).

A study based on satellite photographs [7] was developed for a large urban area, which was chosen to explore how the thermal environmental conditions are related to microclimatic changes, the area was divided in sections, with different urban patterns, each grid was classified according to land use, land cover, building density and NDVI. To obtain high-density street-level air temperature observations, a network Instrumentation considered 100 instruments (HiSAN) which recorded data every hour, this data confirmed a temporal variation of air temperature (Ta), but these measurements were insufficient to explain the microclimate at various areas. Authors point out that understanding relationships between urban development patterns and geographical features is crucial when examining the thermal conditions in urban environments.

For the city of Berlin in Germany, it was done a study using satellite image [8], since urbanization is the primary driving factor of UHI, authors proposed a linear regression between LST and Impervious Surface Area (ISA) at the urban and rural environment, each ISA measurements was regionalized by using a Kernel Density Estimation (KDE). The LST and the ISA_{KDE} are linearly related and the slope represents the increase of LST from the natural surfaces at the rural region to the impervious surface in urban regions and it is defined as Surface UHII, for this study represented by SUHII.

A review of influence of meteorological characteristics such as wind, precipitation, cloud coverage, fog and air quality onto UHI was reported [9], authors point out that precipitation can mitigate UHI effects but its capability is dependent on both intensity and duration of rainfall. Wind can play a role by introducing cooler sources and discharging excess urban heats, its impact depends on speed and direction of wind. Cloud coverage mitigation capability onto UHI is dependent on height and amount of clouds, if there is a high amount of clouds. Air pollution can act onto UHI by reducing short wave solar radiation absorption, although under certain conditions absorption of long wave radiation can be enhanced.

Since Land Surface Temperature (LST) is influenced by wind direction, surface type, vegetation density, land use, etc. An analysis of how LST is affected by other factors is presented in a study for two Indian cities [10], which have different patterns in land cover (LC), NDVI, LST, surface energy balance (SEB), land use (LU). They found that built up land is one of the major factors for UHI, the formation of surface urban heat island (SUHI) is attributed to anthropogenic sources affecting the boundary layer and local circulation in the urban area, allowing the energy accumulation. Authors focused their measurements for various natural and anthropogenic materials. In respect of other materials, soil temperature is higher during the day, and lower after sunset, reaching values similar to the vegetation temperature. Soil showed typical behavior of quickly heating up during the peak hours of the day, when the sun shines brightly above the horizon and also quickly cool down during the latter part of the day; otherwise the temperature of the road surface is maximum during the nighttime because it is a black surface. At summer season temperature trend for different land covers, it was observed that during day follows the order soil > road > concrete > vegetation, while at night the order switches to (road & concrete) > soil > vegetation. Also, land surface temperatures in summer are higher than in winter or monsoon seasons.

Based on natural surfaces (bare soil) and using selected meteorological and energy variables like Temperature, surface albedo, turbulent latent and sensible heat fluxes the Canadian Land Surface Scheme (CLASS) represents an approach to model UHI. An improvement to assess UHI, is represented by the implementation of the Town Energy Balance (TEB) for urban surface simulations [11], this approach resolves urban radiation and turbulent energy partitioning better than CLASS, since TEB accounts not only for bare soil but also it computes radiation and energy budgets separately from canyons and roofs, anthropogenic heat fluxes from traffic can be incorporated.

Simulation of UHI should consider climate conditions, in order to develop sustainable built models, for this objective an overall focus on climate conditions is a vital aspect for estimating and mitigating the UHI effect. There are three different types of UHIs based on heights of measured locations: the Urban Surface Layer (USL), the Urban Canopy Layer (UCL) which includes the space between ground and mean roof height, and the Urban Boundary Layer (UBL), which is located above the UCL [12]. This classification of UHIs should account for a reference environment comprising meteorological input based on: mean radiant temperature, wind speed, relative humidity, water vapor pressure, metabolic rate; as well as the Universal Thermal Climate Index (UTCI) a reference environment which represents the same dynamic physiological response in the human body as in actual thermal conditions having air temperature (Ta), wind velocity= 0.5 m/s, 50% of RH (Ta<29°C).

Results presented in this study are focused on Puebla Historic Centre which in 1987 was recognized by the United Nations Educational Scientific and Cultural Organization (UNESCO) as Heritage Site. In 2012 it was formulated a plan for regeneration and re-densification of the Historical Center of Puebla. In this frame it is presented an evaluation of UHI for the Historic Center of Puebla starting with registers of air temperature (T, °C), light intensity (I, luxes), Relative humidity (RH, %), noise (R, dB), and an inventory of the landscape materials like pavement, vegetation, usage of buildings.

2 METHODOLOGY

The city of Puebla is located at 2135 meters above sea level, with defined climate seasons in spring weather is dry and warm, in summer hot and wet, in fall dry and mild; and in winter cold and dry.

Historically, the city was founded in 1531, the historic center was laid out in a rectangular grid with orientation northeast–southeast, this place has retained its integrity as urban network in which there are located many religious, public and residential buildings which exemplifies the evolution of the city during the XVI and XVII century. The Historic Center of Puebla is about 3.398 km^2, and it is limited by the following avenues and streets: at the East (E) the 5 de Mayo Boulevard, at the North (N) the 18 E–W street, at the South (S) the 31 E–W Street; and the West (W) the 11 N–S Avenue, in this polygon it is happening an overcrowding trend in commercial uses, public and private vehicle traffic and loss of citizen residence use.

The first step for doing the UHI analysis was defining that data collection would take place at cross streets, then from 216 possible sites, 45 priority points were chosen, the sampling criteria considered those points close to an historical building or those at which it is known the environment face critical issues by either commercial activities or vehicle traffic. Also, at this time it was planned a route to collect data in a 3 hours period, considering hourly times from 6–9, 12–15, and 18–21 hours; collection route started at the South with the number 1 over the 31 East street, and ending at the North with the number 45 over the 18 East street.

This study registered information of environmental and landscape parameters as follows:

2.1 Environmental parameters

This set of parameters was registered with the Mastech Environmental Multimeter, and it comprises measurements of: Air Temperature (T, °C), Solar radiation intensity (I, luxes), Relative Humidity (RH, %), wind velocity (v, $m\text{-}s^{-1}$), Noise (R, dB). Measurements were done in two weather conditions; the first in June which corresponds to summer (hot and wet) and the second one in September which is fall (dry and mild).

2.2 Landscape parameters

This group of parameters was evaluated considering visual observation and register of the presence of: a) *vegetation* being either trees, gardens or others; b) *water bodies* mainly as fountains or ornaments; c) *pavement materials* accounting for asphalt, hydraulic concrete, and paving stone; d) *Motorized vehicle traffic*; e) *Building height and usage*. These observations were done considering the four corners at the cross street, each corner was referred by point and orientation having 1–N, 1–W; 2–N, 2–E, 3–S, 3–W, 4–S, 4–E for each of the 45 points.

2.3 Traffic parameters

Once collected both the environmental and the landscape parameters, it was analyzed which points are critical in several parameters, mainly reflecting an UHI, and at these points it was done a survey for vehicle traffic estimation having the following categories; automobile, bus, truck, motorcycle and bicycle.

3 RESULTS AND DISCUSSION

3.1 Environmental parameters

Measurements were done in two conditions: June (Hot and Wet) and September (Cool and dry). In order to estimate if there is a correlation between the air temperature (T) with Relative Humidity (RH), radiation or light intensity (I), wind velocity (v) and Noise (R), all collected data were analyzed with the Software Design Expert 11. It was found that correlation values are weak, since residuals are under 0.6. For luminosity (I,T) R^2=0.574; for wind velocity (v,T) R^2= 0.251, for Noise (N,T) R^2=0.105, and only the pair of relative humidity (RH, T) showed a strong negative correlation R^2=–0.97, that means that as Relative Humidity goes higher exerts a cooling effect since the air temperature tends to decrease. In Fig. 1 it is shown the interaction RH-T, each point represents 1 lecture and in general the blue markers belong to the morning, the green to the noon and the red ones to the night.

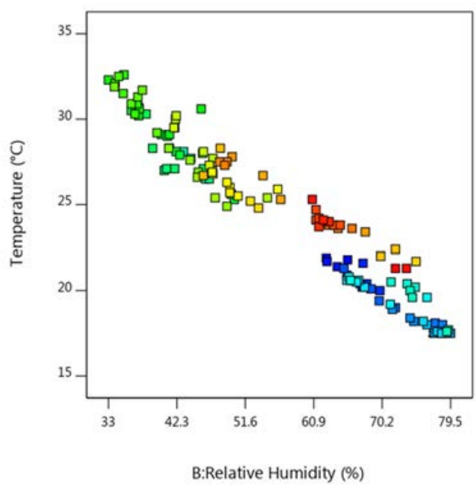


Figure 1: Statistical correlation between relative humidity and temperature.

The air temperature data were organized in a "traffic light" mode in order to visualize temperature trend during the day. For doing this the temperature interval (maximum–minimum) was divided in three ranges the first was assigned green (17.5–22.5°C), the middle yellow (22.5–27.5°C) and the high red (22.5–32.6°C). Also, it was used a 3 concentric rings arrangement, morning lecture 6–9 hours is the inner ring, the noon lecture 12–15 hours is the middle ring, and the night lecture 18–21 hours is in the outer ring, this representation allowed to classify the sites by its temperature evolution during the day, results are shown in Fig. 2.

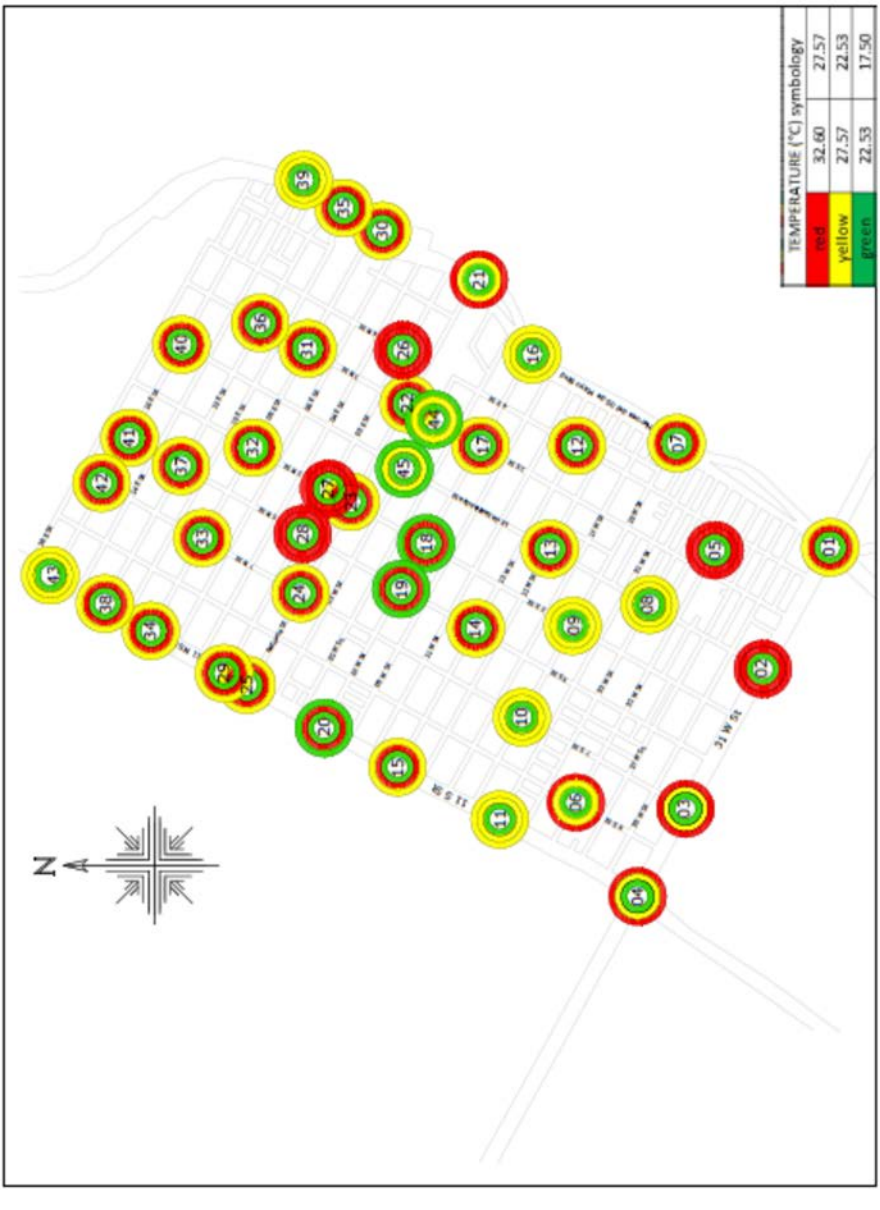


Figure 2: Traffic light representation for air temperature (T).

From this representation it is possible to sustain that there are sites that clearly classify as UHI since they exhibit a green–red–red trend in temperature which means that these points go to high temperatures and stay like that, registered values for this category during summer amount 11%, and they drop to 2% in fall; also there are some points which exhibit a green–yellow–red trend, which means it takes place a slower raise in temperature but heat is accumulated during the afternoon–night, in summer this trend represents 9% and drops to 4% in fall. The green–red–yellow trend in June amounts 53% of the sites, which also drops to 18% in fall, this last set is of concern since at the afternoon–night their temperature decrease but do not reach the comfort status represented by the green range. The ideal condition should be the one that raise its temperature (yellow or red) but at night has the capacity to return to the comfort of the green range; the sequence green–yellow–green amounts 4% in summer and increase to 29% in fall, similar phenomena took place for the green–red–green trend which is 7% in summer and raise to 27% in fall. Analyzing the ongoing temperature trend morning–noon–night, data can be grouped in 6 categories, which are reported at Table 1.

Another point of concern is the Noise parameter, for these data it was built a "traffic light" plot similar to the one for temperature. Data scaling was done considering the minimum (51 dB) and the maximum (78dB) registered values, and color scale was divided in green (noise<60 dB), yellow (60–68 dB) and red (>68 dB), see Fig. 3. Based on the Guidelines for the use of the environment protection [6], the green values can be classified as *moderate noise*, the yellow ones as *low noisy* and the red ones belong to the *upper noisy* environment. An effort to set up a noise trend morning–noon–night based in combinations starting with Green–Green–Green and ending with the Red–Red–Red, it should amount 27 combinations, from these were excluded 7combinations which are empty. The most meaningful combinations are the Red–Red–Red (13.3%), the Yellow–Red–Yellow (11.1%), Red–Yellow–Yellow and the Yellow–Yellow–Yellow (8.9% each), and the Green–Yellow–Yellow with Yellow–Red–Red (6.7% each) which represents a total of 55.6% of the evaluated sites. Registered values does not follow a predictable trend, as it can be observed at the dot plot presented in Fig. 4, where it is evident that most of the registers fall in the noisy range N>60dB).

According to the Meteorological Station MMPB (Puebla airport) which is a non-urban environment maximum wind velocity in June was 45 km h^{-1}, and in September was 26 km h^{-1}; while at Puebla historic center wind velocity maximum values reach a maximum of 9 km h^{-1} in the morning, 15.84 km h^{-1} at noon and 16.56 km h^{-1} at night.

Table 1: Temperature evolution trend.

% points June	% of points September	Register time		
		6–9 hours	12–15 hours	18–21 hours
4	29	Green	Yellow	green
16	20	Green	Yellow	yellow
9	4	Green	Yellow	red
7	27	Green	Red	green
53	18	Green	Red	yellow
11	2	Green	Red	red

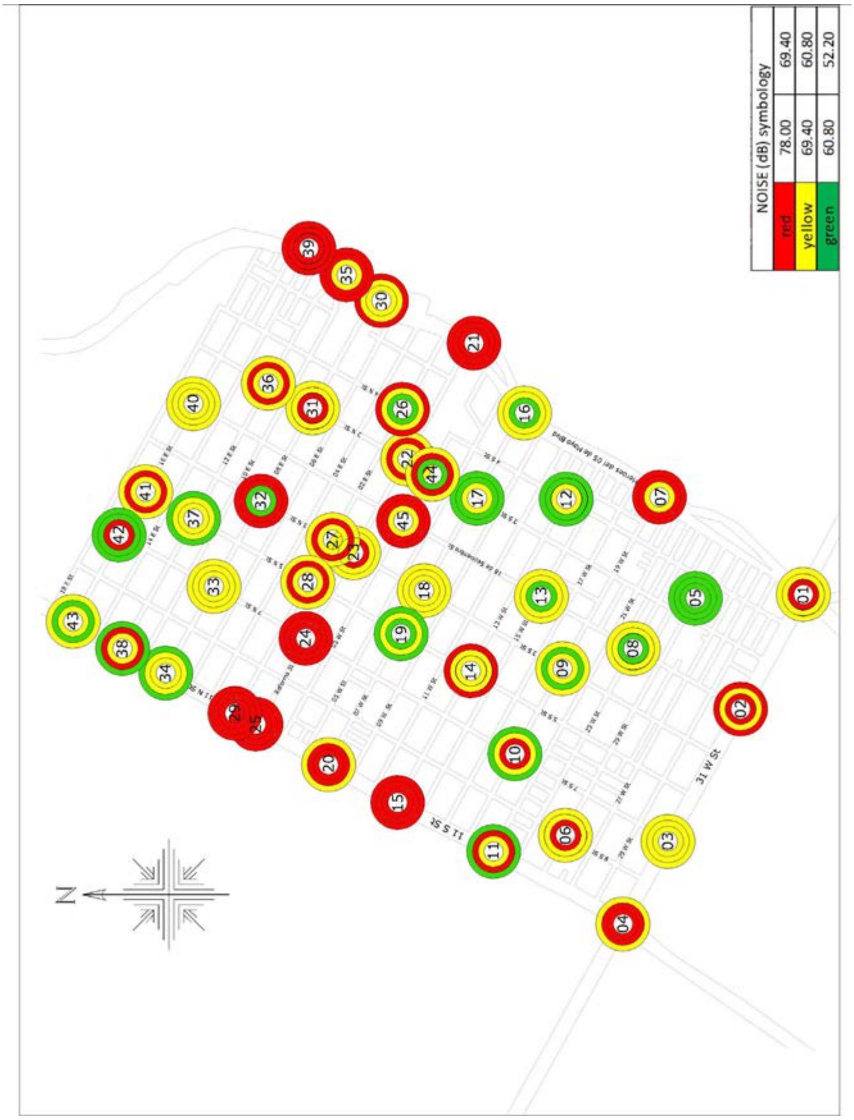


Figure 3: Traffic light representation for environmental noise.

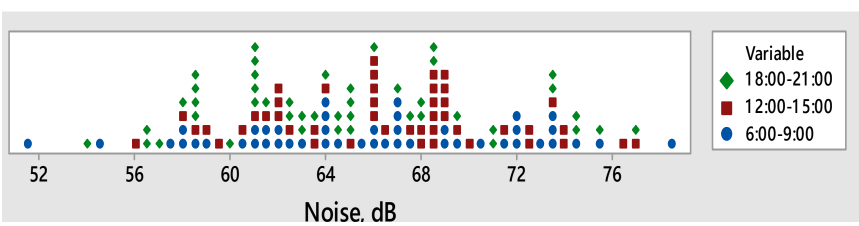


Figure 4: Distribution of environmental noise.

3.2 Landscape parameters

Based on the official data from the Mexican National Institute of Geography and Statistics (INEGI) the city of Puebla has a lack of green areas, in 2015 it was estimated in 1.88 m^2 $person^{-1}$, data that is far away from 9–11 m^2 $person^{-1}$ which is the recommendation of the World Heatlh Organization [13]. This fact was corroborated with the vegetation survey at the historic center, since only 9% of the points are nearby green areas having mainly trees.

The pavement materials at each point are classified as asphalt (11%), hydraulic concrete (4%), paving stone (55%) and 30% or the points have a combination of the materials, this means that at the cross street one branch is made of pavement while the others can be paving stone or asphalt. Evaluation of buildings main usage was divided in 10 classes, data are reported in Table 2.

As it can be observed activities at the historic center are mainly commercial. In respect of buildings height, it was found that buildings adjacent to the cross streets, most of them are two floor, with heights between 8–10 meters. Finally, in respect of water bodies, it was found that only 15% of the points have fountains.

From the air temperature and noise data it was chosen points which exhibit the same trend in temperature (Green–Red–Yellow), and also in Noise (Red–Red–Red), these points were the 25 and 29. At both points it was done a traffic survey.

3.3 Traffic parameters

Survey was realized during two hours in the highest activity period of the citizens, in the morning from 7:00–9:00, and at night from 18:00–20:00. The vehicle survey was performed for point 25 and 29, these points were chosen because both exhibit the same traffic light for noise in summer was green–red–yellow, and in fall was green–yellow–yellow; also these points are nearby so it was possible to assess how vehicles from point 29 are affecting traffic at point 25. For this point 25, it was considered that the phase sequence can take place in 3 branches: Access point #1 arrives from west and can move W–S (1–2), W–E (1–3) or make a turn W–N (1–4); access point #2 arrives from South and can move S–N (2–4) or S–E (2–3); access point #4 runs N–S (4–2), these movements are graphically described in Fig. 5.

The plot of the collected data during the survey are shown for each access point, as follows in Fig. 6 for access point #1, in Fig. 7 for access point #2, and in Fig. 8 for access point #4.

Table 2: Buildings main usage.

Buildings usage class	% of 45 points
Commercial	65
Residential	13
Park	4
School	2
Government dependences	3
Hospital	2
Church	5
Public Square	2
Cultural (museums and others	3

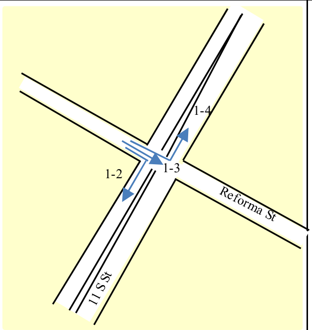
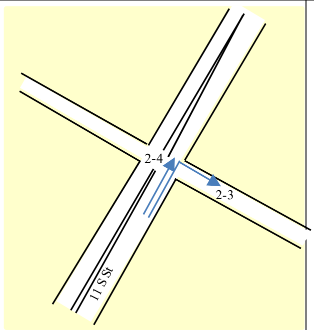
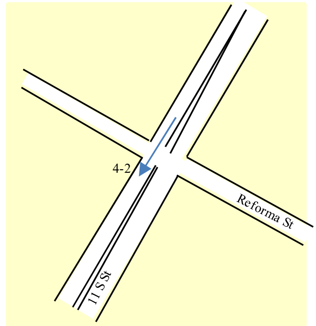
Access point #1	Access point #2	Access point #4
		

Figure 5: Phase sequence to point #25.

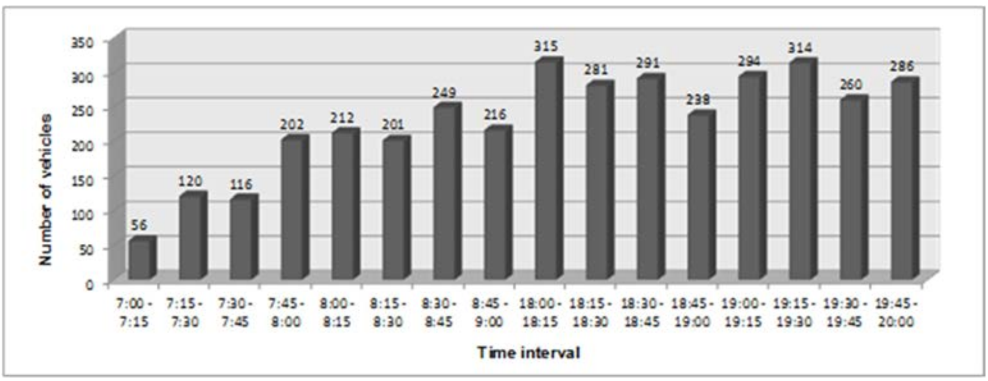


Figure 6: Access point 1 West–East direction of point #25 – movements 1–2, 1–3 y 1–4.

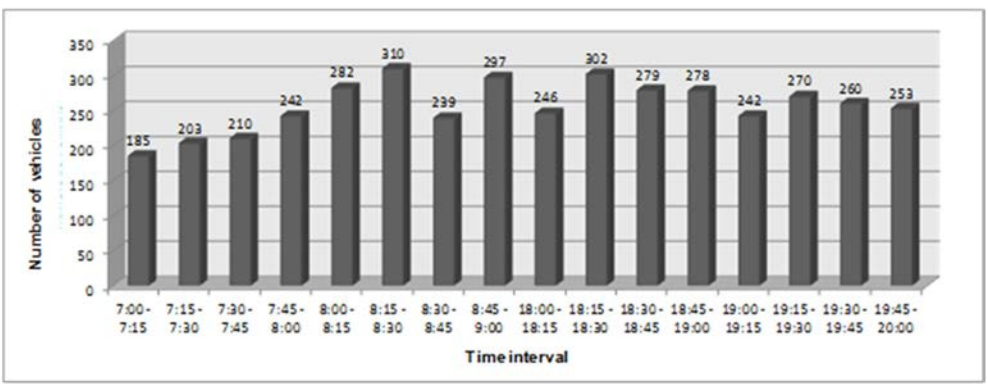


Figure 7: Access point 2 South–North direction of point # 25 – movements 2–3, 2–4.

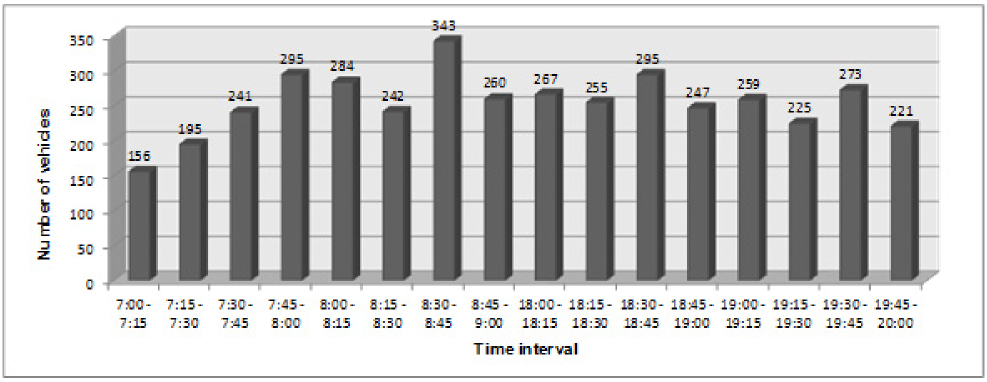


Figure 8: Access point 4 North–South directions of point # 25 – movement 4–2.

For point 29 there are 3 branches: Access point #3 arrives from East and can go across to W (3–1), make a turn to S (3–2) or go to N (3–4) but it can make a turn and receives inflow of branches #3 and #4; Access point #2 runs S–N (2–4); finally #4 comes from N and can make a turn to W (4–1) or go to S (4–2) a graphical description of these access points is presented in Fig. 9. Plots of the number of vehicles for each branch are not included.

Vehicle classification from points 25 and 29 is shown in Table 3, from these data it is evident that major contribution to vehicle traffic comes from automobiles, and both points (25 and 29) exhibit similar behavior since at point 25 amounts 93% of the vehicles, while at point 29 is 88%.

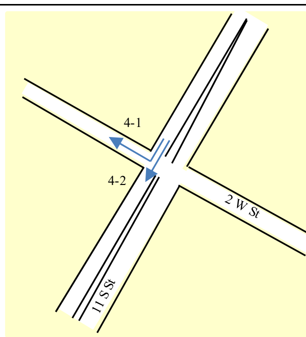
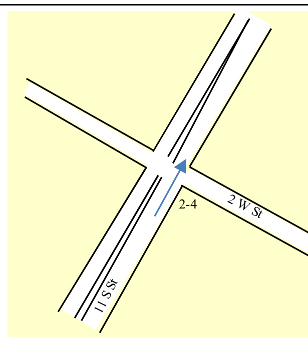
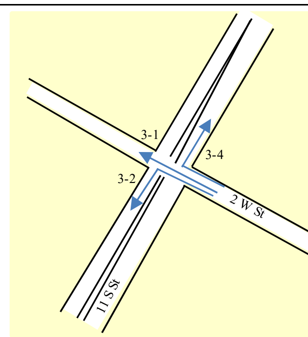
Access point #4	Access point #2	Access point #3
		

Figure 9: Access point 4 North–South directions of point # 25 – movement 4–2.

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Table 3: Vehicle survey.

Vehicle class	Point 25	Point 29
Automobile	10924	9717
Minibus	–	415
Buses (2 axis)	63	73
Trucks (two axis)	158	205
Heavy goods truck	197	142
Articulated bus	63	135
Heavy goods vehicle (3 axis)	17	10
Heavy goods vehicle (4 axis)	–	2
Motorcycle	274	249
Bicycle	111	96

4 CONCLUSIONS

Results of this study provide evidence about what factors affect the sustainability of the historic center of Puebla. In the group of environmental parameters the relationship between air temperature and relative humidity is considered good, he maximum wind velocity is about 30% of the values registered at rural environment. But high concern is raised in the noise parameter, since most of the sites fall in the noisy range.

In the group of landscape parameters it was confirmed that presence of vegetation is very low (<25%) in respect to international standards; also the mixture of pavement materials enhance the low heat reflection. The main usage of buildings is commercial,

But the major concern is about the amount of vehicles which circulate through the historic center, the traffic survey evidenced that private cars presence is about 90% of the total vehicles.

Based on this diagnosis is recommended to discourage the use of private vehicles at the historic center, encourage the presence of green roofs or walls; these two parameters being modified should decrease the UHI effect.

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