Sustainable urban mobility: comparison of two university campuses using multi-criteria analysis

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Abstract*– Urban mobility is currently being challenged to become more sustainable. In this sense, decision-making seeks to choose the best alternatives based on evidence. To this end, the development of indicators and indices serves as a tool for evaluating the initial situation and the impact of new projects. The present study focuses on developing a sustainable mobility index for the campuses of the Universidad Nacional del Sur (UNS) in Bahía Blanca, Argentina, based on the analysis of indicators related to non-motorized means of transport, electric micro-vehicles and use of public transport. After collecting data and performing the calculations, it was determined that the Alem campus obtained a value of 0.724 for the index, while Palihue reached 0.458, indicating that Alem has a 58% higher level of sustainable mobility. This is due to a greater number of bicycles and bus lines in the Alem campus area. While it is suggested to improve pedestrian infrastructure and increase bus lines in Palihue, a higher use of electric micro-vehicles was observed in this campus. The analysis carried out in this work seeks to collaborate in the decision-making process of sustainable mobility policies to be applied in both campuses, which can have a positive impact at the city level, considering that university environments are fundamental to generate sustainable habits in the community.

***Keywords*— University campus, Sustainable mobility index, Multi-criteria analysis, Latin American mid-sized city.**

I. Introduction

Nowadays, society in general is very interested in achieving an increasingly sustainable urban mobility. For this purpose, it is necessary to find a balanced relationship between the three pillars of sustainability: environmental respect, social inclusion and economic development [1]. It is well known that mobility is a central axis for the performance of cities, but at the same time it generates several problems, including air and noise pollution, road accidents, social inequity, high costs of public transportation, among others. Additionally, urban mobility encompasses various interest groups such as pedestrians, drivers, and cyclists, who have different (and often conflicting) priorities and perspectives regarding the use of urban mobility. Thus, developing urban mobility solutions demands tools that can harmoniously analyze these diverse priorities and perspectives. In this sense, multi-criteria decision-making tools provide a proper and sound approach [2, 3, 4].

Moreover, it can be considered that societies aiming to achieve sustainable mobility should promote active mobility and public passenger transport. In this way, people would be placed at the center of urban mobility, displacing the current role of the private vehicle. Undoubtedly, improving the sustainability level of mobility is aligned with some of the Sustainable Development Goals (SDGs) proposed by the United Nations, mainly with SDG 11 (sustainable cities and communities), SDG 13 (climate action), SDG 3 (good health and well-being), and SDG 10 (reduced inequalities), among others. It should be considered that sometimes studying an entire city can be very complex, so it is possible to analyze the sustainability level of mobility at universities, considering them as estimating indicators of what is happening at the city level [5, 6].

In this sense, it is very useful to have indicators and indices that allow the level of sustainability of mobility to be quantified in some way. This type of tool enables decision makers to select the best alternatives based on evidence [7, 8]. Thus, a sustainable mobility index (SMI) would evaluate not only cities and different urban areas, but also the impact that the development of new projects could have.

The aim of this study is to develop a SMI to assess the levels of mobility sustainability at the two campuses of the Universidad Nacional del Sur (UNS) in Bahía Blanca, a mid-sized city in Argentina. To achieve this sustainable mobility index, a multi-criteria approach has been used. This approach has proven capable of addressing similar issues in urban mobility in general [2], as well as in university environments [9, 10]. Therefore, it is interesting to note that in previous studies it was determined that the private car is the main vehicle used as transportation in both campuses analyzed [11, 12, 13], as well as at the city level [14, 15], which leads to the need to somehow estimate the level of sustainability that each campus has. This task is not only developed for the purpose of a purely scientific analysis, but also with the objective of collaborating with decision-making on sustainable mobility policies on university campuses. As mentioned before, university environments allow the development of habits in the community that can be extended to the city level.

II. Study area

This paper focuses on the study of the two campuses of the Universidad Nacional del Sur (UNS) in Bahía Blanca, Argentina. In 2024 the UNS had an enrollment of 35182 active students, 3326 teachers and 602 non-teaching staff [16]. According to estimates, considering the enrollment by careers, 53% of the university population attends the Alem campus, while the remaining 47% does so at the Palihue campus. However, it should be taken into account that the university has a departmental system, so it is possible that students in courses that are mainly taught in Alem may have to take classes at the Palihue campus and vice versa. Fig. 1 shows the location of each of the UNS campuses in the city of Bahía Blanca in relation to the microcenter.

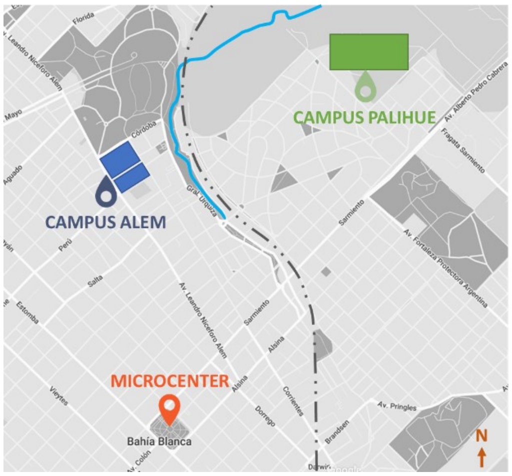

Fig. 1. Location of the Alem and Palihue Campus of the UNS, in reference to the microcenter of Bahía Blanca, Argentina. Napostá stream in light blue, and railway tracks in dotted line. Source: Own elaboration.

The first campus is called Alem, after the name of the avenue where it is located. It is the iconic campus of the university and it is mainly dedicated to Engineering, Chemistry, Biology, Geology, Physics, Mathematics and Humanities. This campus is located 2.5 km from the city center and is easily accessible from different parts of the city by several means of transportation. Fig. 2 shows the main points of relevance for this work, such as the bicycle lanes adjacent to this campus and the bus stops, as well as the bus lines that pass through them. Also, the midpoint of the campus from where the relevant distances considered in the different indicators will be measured is shown. It should be noted that there is a free bus service provided by the UNS to connect both campuses, which has a frequency established every 20 minutes during peak hours and it is known that in the main peak hours it is not enough to transport the number of passengers, who must choose to take a paid bus service (line 503) [12]. On the other hand, there is also an intercity bus line (line 319) from the city of Punta Alta (30 km from Bahía Blanca) that stops at the Alem campus.

The second campus is called Palihue, after the name of the neighborhood in which it is located. This campus is relatively new in age and has a large space not only for classrooms and buildings, but also for recreation. Mainly in this campus are located the careers of Law, Economics, Architecture, Geography, Management Sciences and Computer Science. This campus has two main accesses, one on San Andres Street, located 3.1 km from the center, and the other on Cabrera Avenue, 3.7 km from the center. The location of this campus does not allow for easy access from different parts of the city, due to the fact that it is located within an area delimited by certain infrastructures, such as the neighborhood in which it is located, the proximity to the railroad lines, as well as to a main avenue (see Fig. 1). In addition, there is a natural stream (Napostá) that runs along the northern part of the campus through which there is no access. Fig. 3 shows the main points of relevance regarding active mobility (San Andres access bicycle lane and Cabrera access bicycle path) and public transportation adjacent to this campus. It also shows the midpoint of the campus from which the distances considered for the different indicators are measured.

Fig. 2. A detailed view of the surroundings of the Alem Campus of the UNS in relation to active mobility and public transportation. On the left is the satellite image, and on the right, you can see: green lines represent the bicycle lanes, red squares identify the bus stops, the numbering corresponds to the bus lines that stop there, and blue dot is the midpoint of the campus. Source: Own elaboration.

Fig. 3. A detailed view of the surroundings of the Palihue Campus of the UNS in relation to active mobility and public transportation. Above is the satellite image, and below are the following: green lines represent the bicycle lanes, red squares identify the bus stops, the numbering corresponds to the bus lines that stop there, and blue dot is the midpoint of the campus. Source: Own elaboration.

III. METHODOLOGY

A. General aspects

It is known that multicriteria analysis methods are widely used in a variety of applications related to decision making [17, 18, 19, 20]. The application of a multi-criteria approach to an urban mobility index seeks to improve urban transportation while promoting sustainability. Due to the complexity involved in the study of urban mobility, a comprehensive evaluation framework that incorporates various sustainability indicators and the diverse views of stakeholders is needed [21, 22].

This paper uses a methodology similar to that applied in [2] to assess the aggregation of indicators. For this reason, we propose in this work a sustainable mobility index for university campuses (SMIUC), to evaluate the level of sustainable mobility in both UNS campuses. In this way, a single value will be obtained that will allow quick comparison, considering the aggregation of all indicators which are weighted according to a hierarchical structure [23]. In particular, in this study the indicators will not be grouped by themes, since we are only focusing on non-motorized means (walking and cycling), electric micro-vehicles and public transport use for the analysis. As in [9], the weights of each indicator are determined by a group of professionals from the researched institution (UNS), leveraging their experience and insights from previous mobility studies. Their familiarity with the particularities of both campuses ensures accurate weighting. This is done considering a method similar to the Analytical Hierarchical Process (AHP) and considering that the sum of all weights is equal to 1 ($\sum_{i=1}^{n} w_i = 1$). The aggregation of the indicators is performed by a weighted linear combination, as shown in equation 1 of SMIUC.

$$SMIUC = \sum_{i=1}^{n} k_i w_i \, x_i^{norm} \tag{1}$$

Where:
k_i: constant that takes value 1 or -1 depending on the influence of the indicator on the level of sustainability;
x_i^{norm}: normalized value for indicator i;
w_i: weight for indicator i;
n: number of indicators.

As mentioned, the indicators x_i must be normalized since they are on different scales. Normalization will allow the correct aggregation in the index calculation. A simple normalization method based on linear variation will be used for quantitative indicators, considering a standardization range (maximum and minimum value) for each indicator, as shown in equation 2, while qualitative indicators will have a differentiated treatment, considering appropriate scales for each one. Each particular case will be detailed in the following section.

$$x_i^{norm} = \frac{x_i - x_i^{min}}{x_i^{max} - x_i^{min}} \tag{2}$$

Where:
x_i: is the observed value of indicator i;
x_i^{min}: is the minimum possible value for indicator i or for the standard range;
x_i^{max}: is the maximum possible value for indicator i or for the standard range.

B. Indicators

The indicators selected for this analysis were determined to obtain an index to evaluate the sustainability of mobility, considering indicators associated with active mobility, electric micro-vehicles and public transport. Some indicators were selected from the works of [9] and [10]. It was also decided to use other indicators appropriate to the study area. Based on this, eight key indicators were determined to evaluate each campus, and to build the SMIUC index aggregately.

- **Distance to bicycle lanes**: Determine the main distance, in meters, from the midpoint established for each campus (see Figs. 2 and 3) to the nearest bicycle lane. For this indicator, the ruler tool of the Google Earth Pro software was used. The standard range for normalization was taken as 0 to 1000 meters.
- **Bicycle lanes condition**: Evaluate the general condition of the bicycle lanes, considering the correct demarcation, roadability, and safety. To determine the condition, a visual inspection of the bicycle lane network was conducted, a task that is already being carried out in other parts of the city [24]. This indicator is measured on a scale of excellent, very good, good, regular, and bad or no bicycle lanes. To quantify this indicator, a standard range for normalization from 0 to 1 is considered, being 1 excellent, 0.75 very good, 0.50 good, 0.25 regular, and 0 bad or no bicycle lanes.
- **Number of bicycles**: Count the average number of bicycles per hour during midday hours in the areas surrounding each campus. The standard range for normalization is 0 to 200 bicycles per hour. To obtain these data, manual counts were performed by direct observation of videos generated in situ, during midday peak hours, both in an area of high relevance for the Alem campus (corner of Cordoba Street and Alem Avenue) during the period August 2023 to August 2024 [11], as well as in the two accesses to the Palihue campus during September 2022 [12, 13]. Both analyzed periods are comparable since they consider times of the year of high academic activity in both campuses.
- **Pedestrian sidewalks condition**: Evaluate whether pedestrians have adequate sidewalks to reach each of the campuses safely and comfortably. To quantify this indicator, a standard range is considered for

normalization from 0 to 1, being 1 excellent, 0.75 very good, 0.50 good, 0.25 regular, and 0 bad or no sidewalk. To determine the condition of the sidewalks, a visual inspection was made.

- **Distance to bus stops**: Determine the main distance, in meters, from the midpoint established for each campus (see Figs. 2 and 3) to the nearest bus stop. For this indicator, the ruler tool of the Google Earth Pro software was used. The standard range for normalization was taken as 0 to 1000 meters.
- **Number of bus lines**: Determine the number of bus lines that stop near each campus. For this accounting, the route of all bus lines was observed using the geolocation tool of the municipality (https://www.gpsbahia.com.ar/). The standard range for the normalization of this indicator is 0 to 10 bus lines.
- **Number of electric micro-vehicles**: Count the number of electric micro-vehicles (scooters, motorcycles and bicycles) per hour on average during midday hours in the areas surrounding each campus. The standard range for normalization is 0 to 20 electric micro-vehicles per hour. As with the indicator for the number of bicycles, the values for this indicator were obtained through manual counts by direct observation of videos generated in the most relevant areas of both campuses, during midday peak hours.
- **General access**: Evaluate the general condition of access, not only immediate to the campuses, but also contemplate connectivity with the rest of the city. This indicator is measured on a scale of excellent, very good, good, regular and bad. To quantify this indicator and then add it to the indicator, a standard range is considered for normalization from 0 to 1, with 1 being excellent, 0.75 very good, 0.50 good, 0.25 regular, and 0 bad.

As previously mentioned, each of these indicators has an associated weight, determined according to the experience of a group of professionals and researchers from the Universidad Nacional del Sur. Table I shows the weights assigned to each indicator, as well as the impact it has on sustainable mobility, by means of the k_i value in equation 1. It should be noted that, as in [2], k_i will be +1 when the increase in the evaluated indicator has a positive impact on the sustainability level, otherwise k_i will be equal to -1.

Considering the above indicators and the values of weight and k_i, the SMIUC could vary between -0.3 and 0.7, so that at the end of the calculation the SMIUC value will be normalized to range between 0 and 1, thus facilitating the analysis of the sustainability level of each campus and the index comprehension.

TABLE I
WEIGHT AND k_i VALUE ASSOCIATED WITH EACH ASSESSED INDICATOR

Indicator	**Weight**	k_i
Distance to bicycle lanes	0.15	-1
Bicycle lanes condition	0.10	+1
Number of bicycles	0.15	+1
Pedestrian sidewalks condition	0.15	+1
Distance to bus stops	0.15	-1
Number of bus lines	0.15	+1
Number of electric micro-vehicles	0.05	+1
General access	0.10	+1

IV. RESULTS AND DISCUSSIONS

This section presents the evaluation of each of the analyzed indicators, as well as their values according to the proposed methodology. Finally, the normalized values of the indicators, the calculation of the SMIUC index and the comparison between both campuses are presented.

A. *Distance to bicycle lanes*

Bahía Blanca has a bicycle lane network of approximately 24 km, which is currently being expanded (see Fig. 4). Although it can be seen in Fig. 2 and 3 that the bicycle lane reaches both campuses, the distance between the bicycle lane and the midpoint of the campus was determined in order to be fair with the distances that a cyclist must travel on average to access the cycling infrastructure. It should be noted that within the campuses there is no exclusive bicycle lane. In this sense, it was determined that the distance to the bicycle lanes is 80 meters for the Alem campus and 390 meters for the Palihue campus.

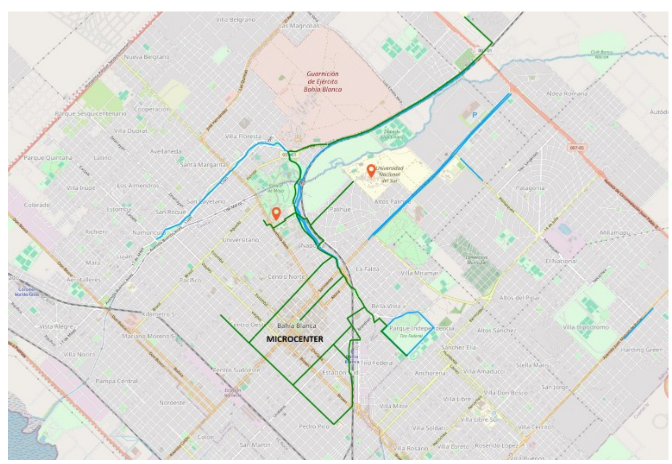

Fig. 4. Bicycle lane network detail of Bahía Blanca city. The green lines show the bicycle lanes, while the light blue lines show the bike paths. The red dots are the locations of the campuses. Source: Municipality of Bahía Blanca (https://www.bahia.gob.ar/mapas/ciclovias/).

B. *Bicycle lanes condition*

In general, the network of bicycle lanes is well delimited; however, water puddles and differences in level can be detected mainly in Campus Alem (see Fig. 5). In addition, it should be considered that they are all two-way and that their current width is acceptable for circulation. In particular, the Alem campus has a bicycle lane that surrounds the building, but it is not yet fully connected to the bicycle lane network (see Fig. 4), which is intended to grow to the northwest side of the city, thus losing connectivity with the current network. Fig. 6 shows the main characteristics of the bicycle lanes around the Alem Campus.

Fig. 5. Water puddles and slopes in the bicycle lanes around the Alem campus. Source: Own elaboration.

Fig. 6. Bicycle lanes surrounding the Alem campus. Source: Own elaboration.

On the other hand, the Palihue campus has the particularity that it has a bicycle lane that arrives at the San Andres access and a bicycle path that reaches the Cabrera access, both of which are in good condition. Fig. 7 shows images of the bicycle lane and path that reach the Palihue campus through both accesses. It should only be noted that sometimes pedestrian traffic on the bicycle lane that borders San Andres Street is hindered by pedestrians, since it is difficult for pedestrians to enter due to the lack of sidewalks or because the existing ones are interrupted by watering grass or parked vehicles. However, in this case the infrastructure exists, it is just used by the wrong actors. For these reasons, we consider that the condition of the bicycle lanes in the Alem case is good because of the water puddles, while for the Palihue campus it is very good, despite the fact that they are sometimes obstructed by pedestrians.

Fig. 7. Bicycle lane and path around the Palihue campus, on the top the entrance from San Andres and on the bottom the access from Cabrera. Source: Own elaboration.

C. *Number of bicycles*

As mentioned in the methodology, the number of bicycles circulating per hour was obtained through manual counting by direct observation of videos generated in situ at midday peak hours for each campus. Based on the count, the number of bicycles per hour was found to be higher in the Alem campus area (128 bicycles per hour) than in the Palihue campus (50 bicycles per hour).

D. Pedestrian sidewalks condition

Through the visual evaluation of the surrounding areas of both campuses, it was observed that the Alem campus has better infrastructure available for pedestrians, and that it has adequate sidewalks in the vicinity (see Fig. 8). Although the Palihue campus is located in a quiet, tree-lined neighborhood, which is ideal for pedestrian circulation, it does not have good infrastructure for safe travel on foot. This is due to the fact that the access on San Andrés Street does not have adequate sidewalks (in some cases nonexistent) or they are obstructed by parked vehicles, as well as being a neighborhood called a park, there is a lot of irrigation which wets the areas where pedestrians should walk (see Fig. 9). As previously mentioned, this situation, coupled with the lack of lighting at night, means that pedestrians decide to walk along the bicycle lanes, obstructing the path of cyclists, who have to mix on the street with larger motorized vehicles (see Fig. 10). This particular situation occurs mainly in the access through San Andres Street where 91% of pedestrians arrive [13]. The access through Cabrera Street is less used by pedestrians since it does not directly connect both campuses, nor the main residential area where non-Bahia Blanca students are housed. It should be noted that the percentage of students enrolled at UNS who are not from Bahía Blanca is approximately 45% [16]. Because of these circumstances, the condition of the sidewalks is considered to be very good on the Alem campus and regular on the Palihue campus.

Fig. 8. General condition of the sidewalks in the Alem campus area. Source: Own elaboration.

Fig. 9. Particular conditions of the sidewalks on the Palihue campus (San Andres access). Source: Own elaboration.

Fig. 10. Pedestrians walking along the bicycle lane near the San Andres Street access to the Palihue campus. Source: [25].

E. Distance to bus stops

Considering a midpoint in both campuses for the calculation of distances (see Figs. 2 and 3), it was determined that the distance to the nearest bus stop is greater in the Palihue campus (390 meters) compared to Alem (100 meters). On the other hand, it can be said that the Alem campus is more surrounded by bus stops due to a greater number of bus lines. Fig. 11 shows the nearest bus stop to each campus.

Fig. 11. Bus stops closest to each campus. Above Alem campus and below Palihue campus (San Andres access). Source: Own elaboration.

F. Number of bus lines

As shown in Fig. 2 and 3, and as just mentioned, more bus lines arrive at the Alem campus (7) than at the Palihue campus (3), including the inter-campus bus line. It can be seen that only at the entrance to the Palihue campus on San Andrés Street do the buses arrive at the gate, but people then have to walk inside the campus to reach their final destination, since no bus enters the campus. At this point it is worth mentioning that the distance between the two entrances to the Palihue campus is 1.4 km [26]. Due to the lower number of bus lines to this campus, it is observed that the buses arrive overcrowded. In addition, it should be noted that the bus stop on Cabrera Street is approximately five blocks from the exit point. On the other hand, on the Alem campus, there are more bus lines and they are well distributed among the bus stops in the surrounding area.

G. Number of electric micro-vehicles

As mentioned in the methodology, the number of electric micro-vehicles circulating per hour was obtained through manual counting by direct observation of videos generated in situ during midday peak hours for each campus. It is worth remembering at this point that the electric micro-vehicles were considered to be bicycles, motorcycles and scooters, which are very incipient in our city [14]. Based on the count carried out, it was detected, in the same time slot, that the number of electric micro-vehicles per hour is higher in the area of the Palihue campus (12 electric micro-vehicles per hour) compared to the Alem campus (5 electric micro-vehicles per hour).

H. General access

A visual inspection of the surrounding area of both campuses and the context of the city shows that the case of the Palihue campus is more particular since it is located within a neighborhood considered a park delimited by certain infrastructure characteristics (such as the railroad lines) that give it the character of a closed neighborhood. In this sense, between the two campuses there is a railroad crossing which generates few sectors where it is allowed to pass using any means of transportation (on foot, bicycle, public transportation). The case of the Alem campus is different since it is more directly connected to the different zones of the city. In this sense, this indicator is established as very good for the Alem campus while for the Palihue campus it is determined as good.

I. SMIUC index

Finally, based on all the data collected, the value of each of the proposed indicators is obtained, which are presented in Table II, together with their respective normalized value. As previously mentioned, each of the analyzed indicators has an associated weight, determined according to the experience of a group of professionals and researchers of the UNS, as well as a value of constant k_i related to the impact that such indicator has on sustainability (see Table I).

TABLE II
INDICATOR VALUE FOR EACH CAMPUS AND ITS STANDARDIZED VALUE

Indicator	Campus Alem		Campus Palihue	
	x_i	x_i^{norm}	x_i	x_i^{norm}
Distance to bicycle lanes	80	0.08	390	0.39
Bicycle lanes condition	Good	0.50	Very good	0.75
Number of bicycles	128	0.64	50	0.25
Pedestrian sidewalks condition	Very good	0.75	Regular	0.25
Distance to bus stops	100	0.10	390	0.39
Number of bus lines	7	0.70	3	0.30
Number of electric micro-vehicles	5	0.25	12	0.60
General access	Very good	0.75	Good	0.50

Table III shows the final calculation of the SMIUC for each of the campuses. As can be seen, the Alem campus obtained a higher value than the Palihue campus, 0.724 for the first and 0.458 for the second. In this sense, it can be said that the Alem campus has a 58% higher sustainable mobility level than the Palihue campus. This significant difference in the SMIUC index value is primarily due to the higher number of bicycles per hour and the greater number of bus lines operating in the Alem campus area compared to the Palihue campus. Meanwhile, in the rest of the indicators Alem campus has slightly better performance than Palihue campus. Based on this analysis, it should be taken into account that it is necessary to improve the infrastructure for pedestrians arriving at the Palihue campus as well as to encourage more bus lines to reach this area to facilitate mobility by this means of transportation. On the other hand, regarding the number of bicycles, it should be taken into account that only the midday peak time is being considered, so that in other time slots the number of this type of vehicle could be higher. It is important to consider that only the midday peak hour was considered because it was at that time when the count was carried out on the Alem campus, without having data from other peak hours. On the other hand, although the use of electric micro-vehicles is very incipient in the city, it is observed that on the Palihue campus their presence is greater than on the Alem campus.

TABLE III
SMIUC INDEX FOR EACH CAMPUS

Indicator	Campus Alem	Campus Palihue
	$k_i w_i x_i^{norm}$	$k_i w_i x_i^{norm}$
Distance to bicycle lanes	-0.0120	-0.0585
Bicycle lanes condition	0.0500	0.0750
Number of bicycles	0.0960	0.0375
Pedestrian sidewalks condition	0.1125	0.0375
Distance to bus stops	-0.0150	-0.0585
Number of bus lines	0.1050	0.0450
Number of electric micro-vehicles	0.0125	0.0300
General access	0.0750	0.0500
SMIUC	**0.4240**	**0.1580**
SMIUC^{norm}	**0.7240**	**0.4580**

V. Conclusions

Indicators and indices that allow quantifying the sustainability mobility level enable decision-makers to decide on the best alternatives based on evidence. The analysis carried out in this work shows that it is necessary to promote sustainable mobility measures in both analyzed university campuses.

Based on the development of a sustainable mobility index for the campuses of the Universidad Nacional del Sur of Bahía Blanca (Argentina), it was determined that the Alem Campus obtained a better index value (0.724) compared to the Palihue Campus (0.458), considering data collected during the midday peak hours. A greater positive impact on the index value was detected due to the indicators related to the number of bicycles and the number of bus lines, which are higher in the Alem Campus area than in the Palihue Campus. In this regard, it should be noted that the first campus is located in an area that is more easily accessible by any means of transportation, while in the case of the second campus we considered that it would be necessary to encourage active mobility and the use of public transportation by providing better infrastructure.

It is known that university environments allow the generation of habits in the community that can be extended to a city level. For this reason, the work developed in this study not only has scientific purposes, but also has the objective of collaborating with decision-making on sustainable mobility policies on university campuses, considering that they can be extrapolated to the city.

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