Geospatial Analysis of Public Transportation Accessibility for University Students: A Case Study from Mexico

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Abstract. This study analyzes the mobility needs of the students of the Universidad de Sonora and the coverage of the public transportation service in the metropolitan area of Hermosillo, Sonora, Mexico, using georeferencing and data processing techniques. Based on a database of 20,827 students enrolled in the 2023-1 school year and the geographic locations provided by GPS tracking of buses. Significant disparities were identified in commuting times and availability of stops from different neighborhoods. The results underscore the need for a multifaceted approach to improving student mobility, including optimizing bus routes, strategically relocating bus stops, and increasing service frequency.

Keywords. GIS, urban mobility, commute time.

1 Introduction

Student mobility is a critical factor that directly influences university students' accessibility to education. In rapidly growing cities like Hermosillo, Sonora, Mexico, the efficiency of public transportation plays a pivotal role in enabling access to higher education. This study focuses on analyzing the coverage and frequency of public transportation services in the metropolitan area of Hermosillo for students at the Universidad de Sonora (UNISON), with the aim of identifying areas for improvement that could support the implementation of a sustainable electric transportation program for students, thereby enhancing their mobility options.

Currently, the municipal government of Hermosillo offers a transportation service that covers rural areas near the city for students who commute daily to their schools. This study provides insights to support the expansion of this service, which aims to introduce electric transport units for both rural and metropolitan areas.

The city's transportation services are managed by the Institute of Mobility and Transportation of the State of Sonora (IMTES), which offers real-time geographic location tracking for urban buses through a public access application called "UNE Sistema Integral de Transporte.

"For this study, we developed an application that accesses the UNE web service that captures the positions of buses on the available routes every minute, storing this information in a database. This record has been foundational for our georeferenced analysis of territorial coverage and bus frequency at each stop.

Additionally, we utilized data provided by the Universidad de Sonora, which includes the residential locations of its students. This information serves as a crucial resource for understanding the transportation needs of various neighborhoods in relation to the university campus.

Situated in the city's geographic center, the campus enrolled 20,827 students during the first semester of 2023.

Hermosillo is a city with a desert climate, characterized by extreme summer temperatures. In summer, the average temperature varies between 42 and 49.5 °C [1], making walking to bus stops and waiting for buses a health risk for public transportation users. Moreover, the introduction of electric buses in areas with such challenging conditions requires an understanding of distances, inclines, potential user numbers, and climate factors to accurately determine the energy requirements for each bus unit.

This research addresses three main aspects: the geographic distribution of students, the efficiency of bus routes serving the university, and travel times from different neighborhoods to the campus. By analyzing these factors, we aim to gain a deeper understanding of the mobility challenges faced by students, provide actionable data to the municipality of Hermosillo for the implementation of the student transportation program, and propose data-driven solutions to enhance their transportation experience.

2 Literature Review

Public transportation plays a vital role in addressing various mobility challenges, such as the lack of transportation options for non-drivers, the high cost of automobile ownership, emissions, traffic congestion, parking limitations, road accidents, and infrastructure costs. One of the most effective ways to tackle these issues is through economic evaluation, which involves quantifying and comparing the marginal impacts—both benefits and costs—of different transportation options in a standardized format [2].

In Hermosillo, the Non-Governmental Organization "Hermosillo, ¿Cómo Vamos?" publishes annually economic and well-being indicators for the city. In 2022, they reported that only 23 percent of the population used public transportation, a significant decrease from 35 percent in 2019. During the same period, the number of registered vehicles in the city surged from 460,443 to 595,628, reaching 613,706 vehicles by 2023 [3,4]. According to the Population

Census INEGI of 2020 [5], Hermosillo had 936,000 inhabitants at the beginning of the decade, implying a ratio of 1.5 people per vehicle in the city. This trend towards increased car ownership underscores the challenges facing public transportation in the region.

Studies on public transportation systems in various cities provide insights into improving service coverage and efficiency. For instance, Tao et al. [6] used regression trees to determine the acceptable walking distance (AWD) to bus stations in Minneapolis, finding that population density directly influences this distance: the higher the density, the greater the acceptable distance. Similarly, O'Sullivan et al. [7] in Calgary, Canada, found that public transportation users walked an average of 327 meters to reach a bus stop, with the 75th percentile walking up to 450 meters. They cited earlier research indicating that reducing walking distances increases the number of passengers served.

In a related study in Delhi, India, Bivina et al. [8] examined maximum walkable distances to light rail stations, discovering that users are generally willing to walk up to 800 meters, or about 10 minutes. They also identified factors that encourage public transport use, such as perceived safety around stops, the cleanliness of sidewalks, police patrols, and adequate street lighting.

Further research by Berrebi et al. [9] in U.S. cities like Portland, Miami, Minneapolis/St. Paul, and Atlanta, examined the occupancy rates of public transportation systems. They concluded that routes with higher bus frequency have a greater occupancy rate per trip, while those with low frequency are more sensitive to changes in service frequency. This finding aligns with the research by Soczówka et al. [10], which identified a correlation between travel time and bus stop access time, indicating that passengers are willing to walk further to a stop if their planned trip is longer.

Technological advancements also play a crucial role in improving public transportation systems. Zacepins et al. [11,12] proposed the use of low-cost Raspberry Pi devices with GPS modules to record the position of buses and transmit this data to a central computer, allowing users to access real-time location information for public transport units. Their study highlights the importance of georeferencing techniques for

enhancing the precision and clarity of public transportation studies, particularly in student communities.

The optimization of public transportation systems is further explored in studies like that of Alam et al. [13], who identified seven internal factors under the control of transit administrators and operators, and one external variable—the price of fuel—that significantly impacts the demand for public transportation trips. These factors, including coverage, transportation offer and rate, average distance, service frequency, entry hours, and safety, suggest that transit authorities have substantial influence over the number of users of the public transport system.

In the context of electric transportation, Yao et al. [14] conducted a study in the Daxing District of Beijing, demonstrating that the operating costs of an electric fleet can be reduced by strategically using 25 and 15-passenger buses during different times of the day and optimizing battery recharging times with standardized charging stations.

The importance of addressing the quality of suburban transportation services is evident in the study by Sosa-Huerta [15], which focused on rural towns in the northeastern area of Hermosillo. The study concluded that immediate intervention by authorities is necessary to improve service and reduce the disparity in quality between urban and suburban transport.

The following section details the data sources, analysis tools, and methodology used in this study. In the results section, we present maps showing the geographical coverage of routes serving the main residential neighborhoods of university students, along with tables detailing walking times to stops, waiting and travel times, and total travel time from home to campus. Finally, we offer conclusions and recommendations for implementing a service coverage program for university students in Hermosillo.

3 Materials and Methods

3.1 Data Sources

This study utilized anonymized records from the neighborhoods where students enrolled in the 2023-1 school year at the Universidad de Sonora reside. These records were preprocessed to correct spelling errors in the registration data, allowing for an accurate count of students per neighborhood. Additionally, minute-by-minute geospatial data on bus operations for all routes and stops within the Hermosillo public transportation system during 2023 were analyzed. This data provided insights into the frequency of bus visits to stops and the travel times for each route during January of that year.

3.2 Analysis Tools

In this research, Python served as the primary tool for both data processing and statistical analysis, taking full advantage of its robust ecosystem of libraries specifically designed for Geographic Information System (GIS) tasks. These libraries were particularly well-suited to the geospatial aspects of the problem, enabling effective visualization and exploration of spatial data.

To calculate the distances between geographic coordinates, the Haversine formula was implemented, providing a straightforward and reliable method based on spherical geometry. Additionally, the OpenRouteService API [16] was employed to estimate walking times between points, offering a practical solution for incorporating real-world pedestrian travel times into the analysis.

4 Methodology

4.1 Identification of the Neighborhoods with the Highest Concentration of Students

In this study, we analyzed the Universidad de Sonora's database for the 2023-1 school year, which includes a total of 20,827 enrolled students. The primary objective of this analysis was to identify the neighborhoods within the Hermosillo metropolitan area that have the highest concentration of students from this institution.

Our findings revealed that seven neighborhoods collectively house 2,746 students, representing 13.18 percent of the total student population.
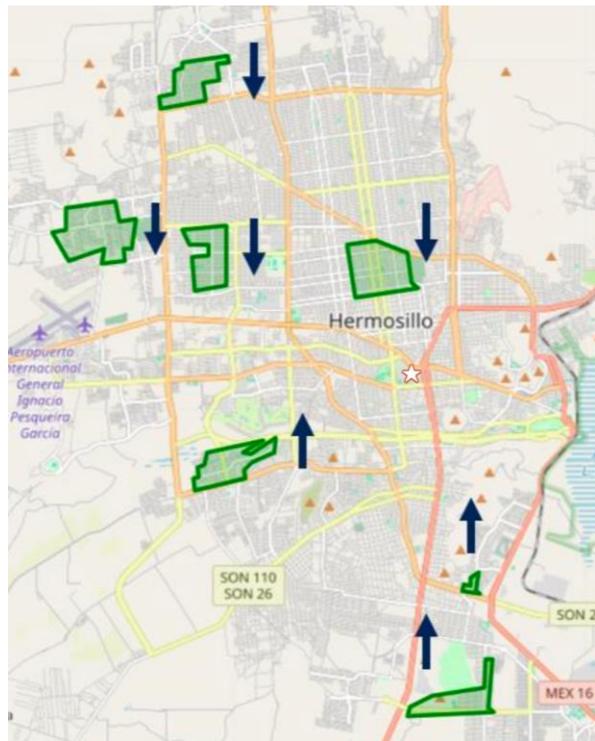
Fig. 1. Location of neighborhoods and direction of travel to reach the campus of Universidad de Sonora (white star in map)

4.2 Analysis of Bus Routes Serving the Universidad de Sonora

To identify the urban transportation routes that serve the Universidad de Sonora (Unison), we analyzed data from bus stops in Hermosillo as recorded in the transportation system of the Institute of Mobility and Transportation of the State of Sonora (IMTES).

Using the Haversine formula, which accurately calculates the distance between two geographic points based on their latitudes and longitudes, we determined the distance from each bus stop on the routes to the geographic coordinates of the Unison campus.

This analysis allowed us to identify which bus routes provide direct or nearby access to the university, facilitating a better understanding of the connectivity and accessibility of public transportation for students.

4.3 Identification of the Nearest Bus Stops to Selected Neighborhoods and the University

A georeferenced analysis was conducted to individually examine the neighborhoods, identifying the bus stops located within each neighborhood's perimeter or, when necessary, the closest stops outside the neighborhood boundary. The results section presents maps illustrating the routes and locations of these nearest stops to facilitate better data interpretation.

When determining the closest bus stops to each residential area, it's important to acknowledge the challenge of achieving absolute accuracy without knowing the exact location of each student's residence within the neighborhood. Distances between a student's home and the bus stop can vary significantly depending on their position within the neighborhood. To address this, we propose using the center of the neighborhood as a reference point, providing a balanced approach that considers both students living near and far from the bus stops.

Additionally, it is essential to consider the direction of travel for urban transport buses from the stop to the university. The route from south to north may have different travel times and distances compared to the opposite direction on the same route. This directional information is crucial for accurately calculating the travel time a student would spend commuting from their home to the university. Therefore, identifying the bus stops with routes heading directly to the campus is a critical part of this analysis.

4.3.1. Analysis of Neighborhood Locations

As illustrated in Figure 1, the neighborhoods of Villas del Real, Puerta Real, Sahuaro, and Balderrama are situated to the north of the Universidad de Sonora (Unison). Therefore, commuting from these areas to the campus involves a north-south route. Conversely, the neighborhoods of Las Lomas, Altares, and Residencial Villa Bonita are located to the south of Unison, making the commute from these sectors a south-north journey. To provide a clearer understanding of these travel directions, Table 1 details the direction of travel from each neighborhood to the university.

Table 1. Direction of travel from the neighborhood to the university campus

Neighborhood	Direction of travel
Altares	South to North
Balderrama	North to South
Las Lomas	South to North
Puerta Real	North to South
Residencial Villa Bonita	South to North
Sahuaro	North to South
Villas del Real	North to South

Table 2. Bus stops in the North to South and South to North direction for each bus route

Route	North to South	South to North
101	101-1	101-92
102	1001-124	1901-1
201	201-44	201-123
202	202-104	202-29
401	401-111	401-47
402	402-1	402-68
501	501-86	501-12
601	601-2	601-70
1001	1001-75	1001-2
1002	1001-1	1001-2
1301	1301-43	1301-117
1601	1601-43	1601-80
1602	1602-88	1602-92
1701	1701-121	1901-154
1702	1702-4	1702-76
1801	1801-50	1801-1
1802	1802-5	1802-53

Table 3. Color coding for maps indicating travel times from homes to nearest bus stops

Less than 5 minutes away	(green)
Less than 10 minutes away	(yellow)
Less than 15 minutes away	(orange)
Less than 30 minutes away	(red)
Less than 45 minutes away	(purple)
Less than 1 hour away	(black)
More than 1 hour on the road	(gray)

To this end, some end-to-end bus stops have been defined in order to identify which are the stops on the routes that go north, and which go south, as seen on Table 2.

4.4 Estimation of Total Commute Time

Travel times from home to the university were calculated by summing the following components:

– Walking time from home to the nearest bus stop.
– Waiting time at the bus stop.
– Bus travel time from the stop to the university.

4.4.1 Walking Time Assessment to Nearest Bus Stops

To estimate the time it takes for a student to walk from home to the nearest bus stop, various points within each neighborhood were analyzed. Walking times ranged from 5 minutes to 1 hour, depending on the specific location within the neighborhood.

To clearly visualize these variations, we created maps with colored dots for each neighborhood. These maps highlight the areas closest to and furthest from bus stops, providing a clear representation of the differences in walking time within each neighborhood.

Walking distances and travel times from home to the nearest bus stop were calculated using the OpenRoute Service API [16]. After obtaining the travel times for individual locations, the times were averaged for each neighborhood to provide a representative estimate of travel time within each area.

4.4.2 Determining Bus Frequency at the Stop

The frequency of bus arrivals at the stop closest to each neighborhood will be determined by counting the number of visits made by buses on the routes that pass through the various neighborhoods and reach the Universidad de Sonora. Additionally, the time intervals between consecutive bus arrivals at each stop will be calculated to estimate the waiting time for passengers. The necessary data will be sourced from the bus location database, covering all days in January 2023.

To perform this analysis, we sort and filter the input dataframe based on route information, then calculate time differences between consecutive

Table 4. Neighborhoods with the highest number of students enrolled at the Universidad de Sonora during the 2023-1 semester

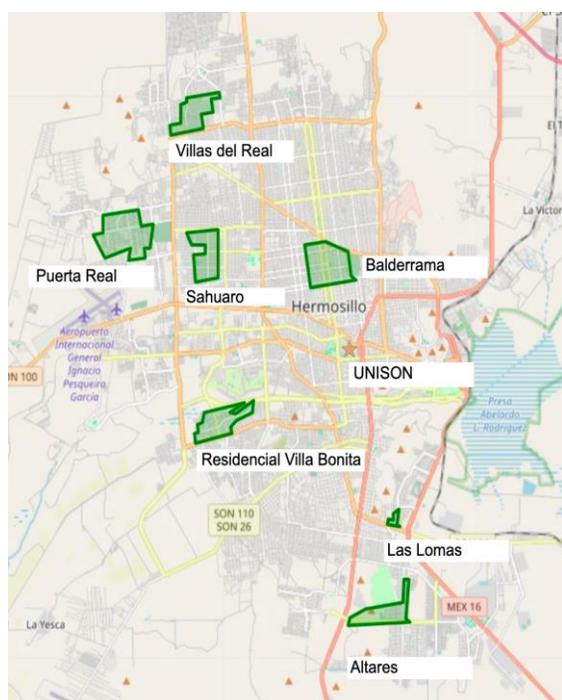| Neighborhoods	Number of students
Altares	527
Residencial Villa Bonita	475
Puerta Real	432
Las Lomas	357
Sahuaro	340
Villas del Real	311
Balderrama	304

Fig. 2. Geographic location of neighborhoods with the highest concentration of Universidad de Sonora students

visits for each unique combination of geohash (latitude and longitude encoded into a short string of letters and numbers), day, and hour.

This data is further processed through a series of aggregations and transformations, including expanding the dataset, computing visit counts per geohash for each hour and day, and calculating the mean daily visits per geohash. The final step involves filtering the results for a specific geohash. This methodical approach provides a comprehensive analysis of bus visitation patterns, offering valuable insights into the temporal and spatial distribution of bus visits at each stop.

4.4.3 Geohash Assignment for the Target Neighborhoods

The designated route traverses the residential district and continues toward the Universidad de Sonora. Using this data, we will determine the time, measured in minutes, required for a bus to complete the full route.

To identify the closest bus stops to the Universidad de Sonora (UNISON), the following procedure was followed:

4.4.4 Calculating Distances Using UNISON Coordinates

The geographical coordinates of the Universidad de Sonora (latitude 29.083 and longitude -110.962) were used as the reference point for this analysis.

To calculate the distance between the UNISON coordinates and the coordinates of each bus station, the Haversine formula was employed. The Haversine formula is a trigonometric function used to determine the distance between two points on a sphere, such as the Earth, based on their latitude and longitude values.

4.4.5 Identification of the Nearest Bus Stops

The starting and arrival points of the trip were identified by determining the bus station closest to the neighborhood and the stop nearest to the university along the corresponding route.

We systematically analyzed all available bus stops, calculating the distance between each stop and the UNISON coordinates using the Haversine formula.

The stops with the shortest distance to UNISON were identified as the closest.

4.4.6 Estimation of Travel Time

The travel time from the student's neighborhood to the Universidad de Sonora was calculated using the identified bus stops.

This process involved loading all stops along the route, starting from the stop closest to the neighborhood and ending at the stop nearest to the Universidad de Sonora.

Table 5. Neighborhoods and closest bus stop to their central point

Neighborhood	Nearest bus stop	Distance to its center (Km)	Route	Travel direction
Altares	202-38 López Riesgo y Adolfo López Mateos	0.60	202	South to North
Balderrama	1601-71 Monteverde y Saturnino Campoy	0.19	1601	North to South
Las Lomas	201-151 Boulevard Paseo Las Lomas y Paricutín	0.11	201	South to North
Puerta Real	1001-112 Avenida Gaspar Luken / Puerta Triana	0.69	1001	North to South
Residencial Villa Bonita	1802-66 Boulevard Solidaridad y Los Olmos	3.01	1802	South to North
Sahuaro	1001-128 Avenida Perimetral Norte y Carlos Balderrama	0.10	1001	North to South
Villas del Real	1702-21 Lázaro Mercado y Boulevard Luz Valencia	0.27	1702	North to South

To ensure accuracy, the time between each stop along the route was determined, and these individual times were summed to obtain the total travel time.

The following formula (1) was applied:

$$t = dv. \tag{1}$$

The distance d was calculated using the latitude and longitude information between the stops. To determine the speed v, we applied the standard speed established by the Mexican Transport Institute, which is 30 km/h for secondary and tertiary streets [17].

These calculations were made under ideal conditions, without accounting for traffic delays. This implies a scenario where there is no congestion or other disruptions. However, it is important to recognize that in real-world situations, travel times may vary due to traffic, traffic lights, and other factors that can influence the duration of the journey.

4.4.7 Data-Driven Calculation of Travel Times

Using the identified bus stops in the neighborhoods as starting points and the bus stops closest to the university campus as endpoints, we computed travel times by filtering our recorded data to isolate trips between these specific stops, identified by their respective geohashes. We sorted and filtered the data, creating shifted columns to facilitate the calculation of time differences between paired entries, allowing us to determine travel durations. To enhance data quality, we set a threshold to exclude potential outliers, specifically filtering out trips that exceeded one hour in duration.

4.4.8 Validation of Estimated Waiting Times

As a validation measure, the times estimated by UNE were compared with the results obtained in this analysis. The results are shown in the next section.

4.4.9 Assessing Optimal Travel Times for Pedestrian and Vehicle Commutes to the University

To determine the optimal travel times for both pedestrian and vehicular routes to the university, we used the Google Maps API [18].

The analysis was conducted by selecting the initial bus stops in each neighborhood as starting points and the bus stops closest to the university as endpoints.

This approach provided precise estimates of travel durations for walking and private vehicle use, allowing for a comparative analysis with public transportation options.

Table 6. Average walking time in minutes to the nearest bus stop in each neighborhood

Neighborhood	Average walking time (minutes)
Las Lomas	2.4
Villas del Real	6.9
Sahuaro	7.8
Altares	8.1
Balderrama	8.3
Puerta Real	11.5
Residencial Villa Bonita	45.6
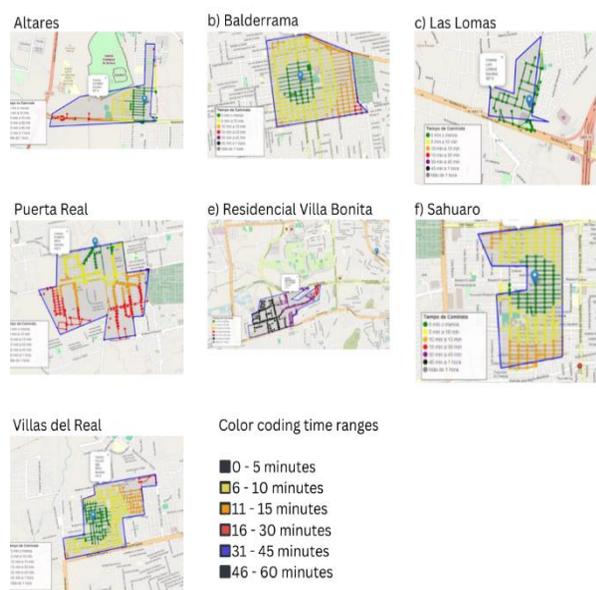
Fig. 3. Color coded isochrones of walking time to the bus stop in the seven neighborhoods of interest

5   Results

5.1 Student Distribution Across Neighborhoods

An analysis of the database containing 20,827 students enrolled in the 2023-1 school year revealed that the seven neighborhoods with the highest student populations are spread across different areas of the city. Table 4 provides a summary of these neighborhoods, highlighting those with the largest number of students enrolled at the Universidad de Sonora.

The student population of these neighborhoods represents 13.18 per cent of the total students enrolled during the spring 2023 semester.

5.2 Bus Routes and Nearest Stops

In this study, seventeen bus routes passing near the Universidad de Sonora were identified. A focused analysis was then conducted on the seven neighborhoods with the highest student population density. For each of these neighborhoods, the nearest bus stop to its geographic center was determined, along with the corresponding bus route. Additionally, the distance between this stops and the neighborhood center was calculated. The detailed results of this analysis are presented in Table 5.

5.3 Travel Times

The estimation of travel times was conducted through a tripartite analysis, considering the following components: (1) pedestrian travel time to the stop, (2) waiting time at the stop, and (3) the duration of the bus journey to the university.

5.3.1   Walking time

To quantify pedestrian travel time, a method based on isochrones was employed. This involved calculating isochronous lines for various points at different distances from the bus stop closest to the geographic center of each community studied. Using the OpenRouteService [16], we obtained temporal data for these different distance ranges. From this information, we calculated the average time required to reach the bus stop in each analyzed neighborhood.

In this study, color coding was implemented for the temporal ranges in the isochrone maps to effectively visualize the accessibility of bus stations. As shown in Figure 3, four of the seven communities analyzed predominantly display green and yellow tones, indicating that students in these areas can reach bus stops within a 5 to 10-minute walk from their homes.

The Las Lomas neighborhood is particularly noteworthy, as it exhibits an optimal distribution of stops. In this area, the average pedestrian travel

Table 7. Comparison of walking times to bus stops

Origin	Bus stop	Computed walking time range	Open Route Service	Google Maps API
Puerta de Triana, Puerta Real	Parada 1001-112 Puerta Real	0 - 5	5	5
Gilberto "Sahuaripa" Valenzuela 149, Altares	202-38 Altares	0 - 5	5	6
Miguel Castro Servín 2, Altares	202-38 Altares	6 - 10	5 - 10	9
Lic. Enrique A. Michel 59, Cerro	202-38 Altares	16 - 30	15 - 30	16
Cefalu 2, Villa Bonita Residencial	1802-66 Residencial Villa Bonita	31 - 45	30 - 45	44
Roberto Reynoso Dávila 100, Villa Bonita Residencial	1802-66 Residencial Villa Bonita	46 - 60	45 - 60	54

Table 8. Frequency of visits to the bus stop

Neighborhood	Bus stop	Route	Bus visit Frequency	Average wait time (minutes)
Balderrama	1601-71	1601	1.16	55.7
Las Lomas	201-151	201	1.34	48.6
Altares	202-38	202	1.46	45.9
Puerta Real	1001-112	1001	1.57	40.5
Sahuaro	1001-128	1001	1.94	32.3
Residencial Villa Bonita	1802-66	1802	2.88	20.7
Villas del Real	1702-21	1702	3.47	16.7

time was estimated at just 2.4 minutes, as detailed in Table 6.

In contrast, the Puerta Real and Residencial Villa Bonita neighborhoods present the least favorable conditions for accessibility to bus stops, due to the considerable distance separating them from these stops. The situation is particularly critical in Residencial Villa Bonita, where the average pedestrian travel time to the closest stop with buses heading to the university was calculated at 45.6 minutes.

To validate the accuracy of our isochrone maps, a comparative analysis of pedestrian travel times from various points within these neighborhoods to the nearest stop was conducted. This validation process utilized multiple georeferencing services, with the detailed results presented in Table 7.

The analysis of the data reveals a significant discrepancy in travel times from the Residencial Villa Bonita neighborhood to the nearest bus stop.

This substantial variation in access times warrants special attention in our study on public transportation accessibility for university students,

as it highlights a critical barrier to equitable transit access. It suggests not only longer commute times but also heightened health risks due to prolonged exposure to high temperatures, intense sunlight, and potentially dangerous environmental conditions during the summer season. These factors could adversely impact students' well-being, underscoring the need for targeted interventions.

5.4 Waiting Time at the Bus Stop

Data on the average intervals between bus visits to the stops were derived from processing records in the bus trip database, and these details are presented in Table 8.

The analysis suggests a strong inverse relationship between visit frequency and average wait time: neighborhoods with higher bus visit frequencies generally experience shorter wait times, while those with lower frequencies face longer waits. The data also reveals significant disparities in service levels among neighborhoods. For example, Villas del Real enjoys the highest

Table 9. Comparison of waiting times at bus stops

Origin bus stop	Route	Neighbourhood	UNE reported wait time	Computed wait time	Difference in time	Variation factor
1802-66	1802	Residencial Villa Bonita	29	20.7	8.4	0.7
1702-21	1702	Villas del Real	9	16.7	7.7	1.9
201-151	201	Las Lomas	23	48.6	25.6	2.1
202-38	202	Altares	18	45.9	27.9	2.6
1601-71	1601	Balderrama	21	55.7	34.7	2.7
1001-128	1001	Sahuaro	12	32.3	20.3	2.7
1001-112	1001	Puerta Real	12	40.5	28.5	3.4

Table 10. Starting and ending bus stops for traveling from the neighborhood to the university campus

Neighborhood	Route	Starting bus stop	Ending bus stop
Altares	202	202-38	201-2
Balderrama	1601	1601-71	1601-79
Las Lomas	201	201-151	201-2
Puerta Real	1001	1001-112	501-122
Residencial Villa Bonita	1802	1802-66	501-122
Sahuaro	1001	1001-128	501-122

visit frequency (3.47 visits per hour) and the shortest average wait time (16.7 minutes), whereas Balderrama experiences the lowest visit frequency (1.16 visits per hour) and the longest average wait time (55.7 minutes).

A comparative analysis was conducted between the waiting times at selected stops, as reported by the official UNE Sonora website [19], and the times calculated by our research team. The results of this comparison are presented in Table 9.

The data presented in Table 9 reveals significant discrepancies between the waiting times reported by the Institute of Mobility and Transport for the State of Sonora in the UNE webpage and those computed by the research team across various bus stops in the metropolitan area.

Notably, the Variation factor, which represents the ratio of computed wait time to UNE reported wait time, exhibits considerable fluctuation, ranging from 0.7 to 3.4.

Specifically, the Puerta Real bus stop on Route 1001 shows the highest variation factor of 3.4, indicating that actual waiting times are substantially longer than reported. Conversely, the Residencial Villa Bonita stop on Route 1802 has a variation factor of 0.7, suggesting that the reported wait time exceeds the computed value.

5.5 Commute Time by Bus to the University

As part of this study, we conducted precise geolocation of the origin and destination points for the analyzed bus routes.

Specifically, we identified the coordinates of the bus stop nearest to each studied neighborhood (departure point) and the stop closest to the university that is served by the corresponding route (destination point), as detailed in Table 10.

Travel durations between the initial and terminal bus stops were calculated by virtually following the bus routes.

Table 11. Computed transit times between the neighborhood bus stop and the campus bus stop

Neighborhood	Computed travel time (route tracing in minutes)
Balderrama	4.3
Residencial Villa Bonita	8.7
Sahuaro	13.0
Puerta Real	21.2
Altares	21.9
Villas del Real	26.9
Las Lomas	45.1

This process involved computing the distance from the starting bus stop to each subsequent intermediate stop using the Haversine formula, then calculating the travel time for each segment. These values were then aggregated to determine the total journey time to the final destination. The resulting data, which capture the temporal and spatial characteristics of student commutes to the university campus, are comprehensively presented in Table 11.

The transit times calculated by following the bus routes represent an optimal scenario, free from factors such as traffic congestion or other delays. It is important to note that this methodology does not account for variables like traffic, traffic light synchronization, road incidents, detours due to public works, or other elements that could impact the actual duration of journeys.

As a result, under real operating conditions, travel times can fluctuate significantly due to the interaction of these multiple factors.

To contrast these computed travel times, we filtered our recorded data to isolate relevant trips between the starting and ending bus stops, identified by their respective geohashes. This process involved data sorting, selective filtering, and the creation of shifted columns to facilitate the comparison of consecutive records.

By calculating the time differential between these paired entries, we obtained actual travel durations. To enhance data quality, we set a threshold to exclude potential outliers, specifically filtering out trips that exceeded one hour in duration. This approach allows us to observe the differences between the computed times from the

traced routes and the calculated averages from the recorded bus trips.

5.6 Total Bus Travel Times

Table 13 presents a synthesis of the total travel times from student residential areas to the Universidad de Sonora. A detailed analysis of these data reveals that the neighborhoods of Residencial Villa Bonita, Altares, and Puerta Real exhibit the longest journey durations.

This observation warrants special attention regarding campus accessibility and its implications for the student population residing in these areas.

The results of this study reveal significant findings regarding student mobility to the Universidad de Sonora. There is considerable variability in walking times to bus stops, ranging from 2.4 minutes in Las Lomas to 45.6 minutes in Residencial Villa Bonita, indicating the need to reevaluate the placement of stops in certain neighborhoods to enhance accessibility.

Waiting times at stops vary from 16.7 to 55.7 minutes. Although this variation is less pronounced for two bus routes, there is still room for improvement in bus frequency on certain routes. Neighborhoods with lower bus visit frequencies and longer wait times, such as Balderrama and Las Lomas, could benefit from service enhancements to improve accessibility and reduce wait times.

The substantial difference in travel times (from 6.6 minutes for Balderrama to 56.2 minutes for Residencial Villa Bonita) suggests the need to optimize some routes or consider express services for more distant neighborhoods. The Villa Bonita neighborhood, lacking a bus stop within its perimeter, necessitates a long walk for students who do not have other means of transportation.

The variation in total travel time, ranging from 63.2 minutes for students in Sahuaro to 122.5 minutes for those in Residencial Villa Bonita, underscores the significant mobility challenges faced by some students.

Although the distance between their homes and the university could often be covered more quickly by walking, the extreme summer temperatures in Hermosillo—sometimes exceeding 45°C [1] —make walking hazardous. As a result, many students prefer to wait for the bus, despite the extended travel time, to avoid the health risks

Table 12. Travel time of traced routes and recorded bus trips

Neighborhood	Computed travel time (traced routes)	Computed travel time (our data)	Standard Deviation	Time difference
Altares	21.9	37.9	4.8	16.0
Balderrama	4.3	6.6	1.4	2.3
Las Lomas	16.8	26.2	4.8	9.4
Puerta Real	21.2	36.4	8.2	15.2
Residencial Villa Bonita	8.7	56.2	3.2	47.5
Sahuaro	13.0	23.0	8.2	10.0
Villas del Real	26.9	46.8	4.5	19.9

Table 13. Total travel time in minutes from students' homes to the university campus

Origin bus stop	Route	Neighborhood	Average walking time (minutes)	Average waiting time (minutes)	Computed travel time (our data) (minutes)	Total time (minutes)
1802-66	1802	Residencial Villa Bonita	45.6	20.7	56.2	122.5
202-38	202	Altares	8.2	45.9	37.9	92.0
1001-112	1001	Puerta Real	11.5	40.5	36.4	88.4
201-151	201	Las Lomas	2.4	48.6	26.2	77.3
1601-71	1601	Balderrama	8.3	55.7	6.6	70.6
1702-21	1702	Villas del Real	6.9	16.7	46.8	70.5
1001-128	1001	Sahuaro	7.9	32.3	23.0	63.2

Table 14. Optimal travel time between on car and walking versus the total travel time on bus

Route	Neighborhood	Optimal travel time on car (minutes)	Optimal travel time on foot (minutes)	Total travel time on bus (minutes)
202	Altares	16	122	138
1601	Balderrama	4	31	35
201	Las Lomas	12	84	96
1001	Puerta Real	20	144	164
1802	Residencial Villa Bonita	6	37	43
1001	Sahuaro	12	92	104
1702	Villas del Real	24	156	180

associated with exposure to such high temperatures.

5.7 Modal comparison of Travel Times

A comparative analysis of transportation modes (see Table 14) reveals significant disparities in travel efficiency across various methods of commuting to the university. The optimal commute times, both for walking and driving, from the neighborhood bus stop to the bus stop near the university were calculated using the Google Maps API [18]. The data demonstrates that pedestrian travel consistently outperforms public transportation in terms of total journey time across all examined neighborhoods. Furthermore, the

results highlight a substantial temporal advantage for private vehicle use over public transit options. The extent of this disparity is particularly striking, with travel times by public transportation being observed to be as much as eight times longer than those associated with private vehicles. These findings underscore the considerable time cost differential between automotive and public transit modalities in the context of university commutes from the studied neighborhoods.

Public Transport authorities or the university should consider implementing express routes designed to serve neighborhoods farthest from the university campus.

6 Conclusions

This study offers a comprehensive view of the mobility needs of Universidad de Sonora students, highlighting significant disparities in travel times from various neighborhoods. The findings underscore the imperative need to adopt an integral approach to improve student mobility. Key recommendations include optimizing bus routes to reduce travel times, especially in peripheral neighborhoods, strategically relocating stops to minimize walking distances, and increasing service frequency on key routes to reduce waiting times and improve the overall student experience.

To address the specific needs of neighborhoods with prolonged travel times, such as Residencial Villa Bonita, alternative solutions could be considered, such as dedicated transportation services like the one planned for implementation or incentives for vehicle sharing.

An approach by geographic zones and socioeconomic levels could ensure equitable and fair planning, thus improving accessibility for all students. These improvements would not only benefit student punctuality and well-being but could also have a positive impact on their academic performance and participation in university activities.

Regarding the potential introduction of electric buses for student transportation, it is imperative to emphasize the need for a more comprehensive study that incorporates a multidimensional analysis. This analysis should consider factors such as the geographic location and socioeconomic level of the various neighborhoods. It is particularly relevant to focus on low-income communities located in the urban periphery or rural areas, whose residents face more significant challenges in completing their university studies.

Implementing a more efficient and accessible transportation system for these students could have a transcendental impact on their possibilities of completing their higher education. This, in turn, could translate into better opportunities for socioeconomic mobility and an increase in their future professional quality of life.

In future research, we will explore other aspects to determine the areas where the introduction of an exclusive transportation service for students would have the greatest impact. Additionally, comparative studies with other institutions could identify best practices in student mobility that could be applied in similar contexts in other Latin American cities.

This work underscores the importance of user-centered urban and transport planning that provides valuable information for informed decision-making to significantly improve access to and efficiency of transportation services for the student community.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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