A practical approach for sustainable Transit Oriented Development in Montevideo, Uruguay

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Abstract. The need for a proper development of transportation systems in modern smart cities is motivated and driven by relevant factors, including conceiving territorial and transportation planning as part of an unified urban activity. In this line of work, this article presents an empirical analysis of sustainable mobility under the Transit Oriented Development paradigm, focuses on properly capturing the relationships between urban environment, activities, and mobility, by analyzing diverse indicators. As a relevant case study, the article analyzes the current situation regarding sustainable mobility and Transit Oriented Development in the area surrounding Engineering Faculty, in Parque Rodó Neighborhood, Montevideo, Uruguay. Specific recommendations are provided to improve sustainable mobility under the studied paradigm.

Keywords: sustainable mobility; Transit-Oriented Development; public transportation; smart cities

1 Introduction

Mobility is a crucial component of modern smart cities, allowing daily activities social participation of citizens on urban areas [21]. The relationship of mobility with sustainable development has been recognized as one of the main issues to achieve the 2030 Sustainable Development Goals (SDG), as defined by the United Nation, since mobility is part of the great environmental challenges existing nowadays. Several of the defined SDG are related to sustainable mobility, including relevant issues as health and road safety, affordable and clean energy, economic growth, resilient infrastructure for sustainable cities, access to transportation modes and expanded public transportation, and sustainable consumption and production. Thus, promoting sustainable mobility has been a major concern and one of the toughest environmental and social challenges.

The main concepts of sustainability and sustainable development have been applied to conceive new approaches and models to guarantee mobility with a reduced environmental impact. Sustainable mobility is defined as the ability to "meet the needs of society to move freely, gain access, communicate, trade and establish relationships without sacrificing other essential human or ecological values, today or in the future" [29]. Three main pillars support the sustainable mobility paradigm: environmental, social, and economic [15]. These pillars must be properly respected to develop positive contributions, by collaborative efforts by public and private sectors, suitably considering citizens and their participation. Transit-Oriented Development (TOD) [7, 22] is a paradigm for urban planning and development that has revitalized city urbanization, by combining the renewal of suburban spaces and friendly walkable environments in neighborhoods. Although TOD has been successfully applied in USA, Europe, and Asia to ensure sustainable mobility and economic development, few proposals have applied the paradigm in Latin America.

In this line of work, this article presents a practical approach for analyzing and developing sustainable mobility initiatives under the TOD paradigm. The analysis is focused on properly capturing the relationships between urban environment, activities, and mobility. The main contributions of the research reported in this article are: the evaluation of the area surrounding Engineering Faculty, in Parque Rodó neighborhood using TOD indicators and the analysis of mobility demand through quantitative indicators and the formulation of several suggestions and recommendations to improve sustainable mobility in the studied zone, applying the TOD paradigm.

The article is organized as follows. Next section introduces the main concepts regarding sustainable mobility and TOD. A review of related works is presented in Section 3. The methodology applied for the analysis of the studied zone is reported in Section 4. Results and discussion of the analysis are presented in Section 5, and specific suggestions and recommendations to improve sustainable mobility under the TOD paradigm in the studied area are presented in Section 6. Finally, Section 7 presents the conclusions and the main lines for future work.

2 TOD approach

In the last thirty years, sustainability has been a major concern of modern society. The concept of sustainable development, i.e., development to fulfill important roles of nowadays without compromising the future, has been promoted to build a more equitable, environment friendly, and inclusive model of society.

The sustainable mobility paradigm integrates many relevant concepts, including those related with their impacts on environment and society [2]. Overall, the main idea is to consider mobility as a valued activity regarding environmental, social, and economic concerns [19]. One of the most studied aspects has been the impact of mobility on the environment, with the main idea of conceiving new transportation paradigms accounting for cleaner means, accessibility, and integration of people. Other important aspects have also been analyzed, including the impact on economy, and the overall quality of life (safety, health, etc.). Raising awareness and involving citizens are key aspects for sustainabe mobility. In turn, technology has been identified as one of the most valuable tools to help developing environmental friendly sustainable mobility. Different methods and indicators have been proposed to analyze means of transportation [12] and other important issues related to sustainable mobility.

In turn, the TOD paradigm for urban planning is a trendy model for planning sustainable urban communities by creating dense, walkable communities that greatly reduce the need for driving and energy consumption. The goal TOD is ensuring sustainable mobility and economic development, while protecting global energy. TOD has become a great prominence for urban planning and transport since the first proposals by Calthorpe [7] and Newman and Kenworthy [22] in the 1990s. The approach was later supported by the empirical works of Bertolini et al. [3, 4] and Cervero et al. [8, 9], among other authors.

TOD is the key to more sustainable, efficient, and equitable communities because it works under the "3Cs" concepts (compact, coordinated, and connected). In turn, it is related to other five principles for decision makers and urban planners strengthen their communities according to the TOD standard:

1. *Compactness*: The closer the activities are located between each other in a compact city/district, the less time consuming and energy is required.
2. *Density*: Instead of building out to increase the urban sprawl, TOD supports building up to create dense cities in a more compact way.
3. *Transit–public transportation*: Public transportation connects and integrates many distant areas around the city. A good public transportation planning that contemplate all area of a city creates an equitable and accessible city.
4. *Connectivity*: Create dense networks of streets and paths for pedestrians and cyclists as well as public transportation.
5. *Mix*: Plan for mix use in order to create shorter trips and more lively neighborhoods.
6. *Cycling*: Prioritize non-motorized transport networks. Cycling provides people an efficient and convenient way to travel for short/medium distances, increase accessibility as well as coverage of transit.
7. *Shift (to sustainable transportation modes)*: Closer locations between activities and a good transportation network do not imply people shift to sustainable transportation modes. Other actions are needed, such as regulating car parking and road use, to discourage the use of non-sustainable means.
8. *Walk*: Develop neighborhoods that promote walking creating vibrant, active streets where people feel safe.

In the related literature, TOD is conceived to hold urban sprawl, prioritizing sustainable mobility as well as driving to environmentally and economically-balanced growth TOD is closely related to the *smart growth* and *new urbanist* approaches [6] conceiving walkable, compact, pedestrian-oriented, and mixed-use communities centered around high quality public transport systems [26] reducing, in this way, the utilization of automobiles.

Several articles have defined a buffer of 400 m as the walkable distance to get to a bus stop and a buffer of 800 m as the walkable distance to get to a rail station [23, 24]. According to these radius, urban designers and planners design mixed used areas around bus stops and rail stations to promote sustainable mobility. Accessibility also plays an important role when designing a project based on TOD principles. The interaction between urban structure, accessibility, and travel behavior has been discussed for several authors [23].

Based on the TOD approach, this article presents an analysis of the zone surrounding Engineering Faculty in Parque Rodó neighborhood, describing the mixed uses of land (services, public spaces, open spaces, pedestrian paths and bike lanes, maintainance condition of the built environment and green places, bicycle parking facilities and transport nodes.) The data collected was examinated by some factors to characterize the built environment.

Furthermore, an empirical approach is followed to consider subjective opinions, based on personal questionnaires to people traveling from/to the area. The resulting data are processed and analyzed following a urban data approach, in order to extract useful information and elaborate specific suggestions towards a sustainable mobility plan in the studied area.

3 Related work

Sustainabile mobility has been an important concern for researchers in the last twenty years. Litman and Burwell [17] recognized that sustainable transportation initiatives must be developed considering a broad point of view, for properly capturing the interrelations between economic and social welfare, energy efficiency, ecological integrity, human health, and proper land use. The authors proposed a paradigm shift for rethinking transportation, considering different integrated solutions for sustainable transportation systems. Some of the proposed indicators for detecting trends, assessing and comparing activities, and evaluating policies related to sustainable transportation, are those considered in TOD principles.

The main concepts in TOD are strongly related to sustainability. One the one hand, successful examples of applying TOD in USA, Europe, and Asia, are commonly associated to mass rail systems. On the other hand, in Latin America, most of the TOD-related initiatives have been implemented on Bus Rapid Transit (BRT) or similar public transportation systems, which allow providing a cost-effective service more adapted to the economic reality of developing countries.

Hasibuana et al. [13] studied the applicability of TOD ideas for improving urban mobility in a case study in Jabodetabek, Indonesia, with more than 27 million population. The main results of the analysis showed that TOD concepts can definitely contribute to restructuring urban land use and growth, improving the modal share of public transportation and the quality of the urban environment. Loo and Verle [18] proposed a sustainable mobility approach oriented on people and places. Three lines were proposed for TOD planning: improving the built environment at both neighbourhood and city scales; improving walking and related urban planning/design related to public spaces; and encouraging non-uniform designs for different neighborhoods. A case study in Hong Kong, China, analyzed several indicators for five different neighborhood types. The authors recognized that further efforts are needed to quantify and fostering both direct and indirect benefits associated with TOD, benefits beyond traditional impacts on transportation. Tsigdinos et al. [27] studied surrounding zones of metro stations (line 4) in Athens, Greece, regarding several TOD features (density, walkability, public transportation, land uses, and public spaces).

Spatial analysis, indicators for categorizing TOD regions, multi-criteria analysis and geo-visualization were applied to identify differences between categories and contrast between central ans suburban stations. The authors found important limitations of the studied areas and common weaknesses of more than a half of the studied stations, which hinders the implementation of integrated transportation and urban planning strategies. Specific suggestions for improving the identified weaknesses were also proposed.

Woo [28] evaluated TOD features in Seoul, Korea, to characterize subway station areas and their neighborhoods, for a urban rail transit. Accessibility analysis and clustering methods were applied to categorize TOD types using the targeted 246 subway station areas at the neighborhood level. The main results of the analysis grouped the studied zones in four categories: (1) high-density mixed-use areas for residential and retail purposes, which have good accessibility; (2) moderate-density, with average accessibility and high-mixed land use; (3) compact business, mainly offices and commerce, with high accessibility and a high transit demand; and (4) compact housing with high-rise buildings, mostly used for residences. The study concluded that the period of urban development significantly affects the main features of each identified category. and category (2) offers the best option for urban redesign under TOD concepts.

In Latin America, TOD-related developments have been scarce. The region mostly focused on building and developing infrastructures based on mass transit corridors and BRT systems. Some articles argued that BRT systems, even though applying a more restricted paradigm, are able to produce a similar impact on land utilization than TOD strategies [9]. However, Moscoso et al. [20] stated that Latinamerican cities have considered BRT as a mobility solution, without integrating key TOD concepts to promote compact, dense, and well-connected urban development. Nevertheless, the most well-known BRT development in Latin America (Curitiba, Brazil) is also a model of TOD, due to a long-term integration of transportation and land use planning, which was crucial for the success of the mobility model. The land development impacts of BRT have been also studied in other Latinamerican cities, such as Bogota and Quito [5, 25].

Other analysis of sustainable transportation considering TOD-based indicators have been developed for specific cases, such as the study for universities in the Guadalajara metropolitan area, Mexico, by de Alba et al. [1].

The analysis of related works allows concluding that few articles have studied TOD analysis and characterization for specific cases in Latin America. This article contributes in this line of research, by proposing a TOD-based sustainable mobility analysis in a specific zone of Montevideo, Uruguay.

4 TOD-based sustainable mobility analysis for Engineering Faculty, Montevideo, Uruguay

This section describes the analysis of sustainable mobility and urban structure in the area surrounding Engineering Faculty, Montevideo, Uruguay, considering TOD-related indicators.

4.1 Motivation and objectives of the study

The objective of the study is to analyze how the studied area can be transformed in a walkable, compact, pedestrian-oriented, and mixed-use community, where people want to live and work, built around sustainable public transportation.

Since global concern of environmental pollution appeared, only few initiatives have been proposed towards sustainable mobility in Montevideo. Most of the recent initiatives focused on public transportation, e.g., electric buses were introduced in the system, and a few private initiatives, e.g., a leasing plan to acquire electric vans for last mile distribution of people and goods.

The studied area (called *The Isle*) is located nearby Engineering Faculty, in Montevideo. It is an area of $0.25\,\text{km}^2$ surrounded by about $1\,\text{km}^2$ of green areas (Parque Rodó/Rodó Park). Although The Isle is a residential area, where more than 5.000 people live, it has high daily flow of people traveling to/from services, institutions, green and recreation areas, and other places located in the zone. In this regard, this area creates opportunities for multi-modal travel, sustainable mobility and urban planning development based in TOD approach.

The studied area includes four avenues: Herrera y Reissig, where Engineering Faculty is located, Sarmiento, Sosa, and Bulevar Artigas. In 2021, Engineering Faculty has more than 10 000 students, 1 000 professors, and 200 employees. In addition, students and professors of other faculties also assist to lectures in Aulario Massera, a large classroom building nearby Engineering Faculty.

4.2 Methodology

The main details of the applied methodology are described next.

Overall description. The study is based on two methodological stages: i) applying urban data analysis to develop a spatial-functional definition of the study area; and ii) characterizing the current mobility in the studied area;

The proposed methodology combines different quantitative elements and analysis to identify the mixed uses of land in the area, transportation connectivity, and infrastructure for bikers and pedestrians, in order to improve accessibility and create opportunities for sustainable development in the area.

Data collection. Three main sources of data were considered in the study.

First, data from Google Maps (in JSON format) and from personal inspection (from photographs taken in the area) were collected to identify a spatial-functional definition in the studied area. The collected data include the following information about the environment: infrastructure for non-motorized traveling mode (pedestrian-only paths, bicycle paths, accessible ramps for sidewalks); land uses (commercial, residential, institutional); semi-public spaces (restaurants, education center, health center, sport centers); open spaces (green areas, parks, squares); the maintenance condition of the built environment and green spaces (bus stop shelters, sidewalks, bicycle paths); and parking facilities and transportation nodes (bicycle parking, and bus stops).

The study defines two areas for the analysis: The Isle, located within 400 m of Engineering Faculty, and an extended area delimited by a radius of 800 m from Engineering Faculty (mostly in directions North and East).

Second, the study gathered operational data (e.g., bus lines that operates in the zone, timetables, etc.) and also information about the available infrastructure (e.g., bus stops, bicycle lanes and bicycle parking facilities.) either from open data sources or by personal inspection.

Third, a survey was performed in-situ in the studied area, to gather data for the analysis and characterize sustainable public transportation in Montevideo [14]. Data from 617 persons were collected: 79 living in the area and 538 commuting from other zones of the city. The study identified four relevant groups of people: students of Engineering Faculty and attending Aulario Massera professors and employees of Engineering Faculty, people living in the neighborhood, and people working in the neighborhood. [14]

The survey focused on gathering mobility information for the four groups of people. The study reported in this article includes the most relevant information for the analysis: origin/destination of trips and relevant aspects of transportation mode(s) used for commuting. Interviews were performed in November–December 2019, from Monday to Friday, from 8:00 to 19:00. Weekend trips were not surveyed, as the mobility demand is significantly lower than working days trips.

Indicators/metrics. For the analysis of urban infrastructure, the study examined the surveyed area through different metrics, including:

– The existence and total distance of infrastructure for non-motorized traveling modes, including pedestrian paths and bicycle paths;
– The existence of different elements, such as ramps, on sidewalks that provide universal accessibility;
– To evaluate the land uses, the total area of commercial, residential, educational, recreation and green areas;
– The number of commercial areas in both areas, separated in public places (supermarkets, mini markets or food store) and semi-public places (restaurants, utility shops, health centers, and pharmacies);
– The number of bicycle parkings and bus shelters;
– The maintenance condition of the built environment (bus shelters condition, sidewalks, bicycle paths and green areas, evaluated in three qualitative categories (low, medium, and high). The analysis considers ‘The 8 principles of sidewalks’ [11] as reference for design and construction of sidewalks and the NACTO Urban Bikeway Design Guide as reference for bicycle paths.

For the mobility analysis in the studied area, two relevant (quantitative) sustainable mobility indicators proposed by the World Business Council for Sustainable Development were used:

– Distance between origin and destination of trips: the real distances that people travel, considering the zones that originate trips to the studied area and also the destination of trips that initiate in the studied area.

– Commuting travel time the average time spent by a person when traveling from/to the studied area. The average walking speed is assumed to be 5 km/h. For bus, the commuting travel time includes the time for a person to walk to the bus stop and the time waiting for the bus to arrive. For bicycles, the average speed is 13.5 km/h.

Methodology for data analysis. For the analysis of urban infrastructure, distances were computed using the Google Maps service, and both green and residential areas were computed using the Google Maps Area Calculator tool. The area of institutions and commercial buildings were measured by personal inspection, using a laser device. Furthermore, bus stops, bike roads, and bicycle parking were also identified by personal inspection to evaluate their maintenance conditions.

The overall characteristics of mobility demand in the area were studied in a previous article [14] using quantitative mobility indicators to evaluate the opportunities that the studied area offers for communication with other zones of Montevideo. According to Calthorpe [7], TOD is conceived to promote non-motorized transportation modes or public transportation instead. However, some studies [10,16] that travel behavior are more associated to human attitudes than to land use characteristics, influenced by certain factors as income, or household composition. On the other hand, Papa and Bertolini [23] stated that the travel behavior can change if other urban characteristics significantly change too (e.g., universal accessibility, good connectivity, safe neighborhoods and attractive streets that promote walking, etc).

5 Sustainable TOD analysis

The studied area was analyzed through TOD principles followed by decision makers and urban planners to strengthen their communities, and relevant indicators for sustainable development [24].

Compactness and mix. Citizens prefer traveling shorter distances to perform their activities, which implies the closer the activities are from each other, the less time required. The study identified that residents have first-needs stores only a few blocks away from home. Maps in Fig. 1 present accurate information about the location of different services, bus stops, bicycle parking, pedestrian only paths, and also identified land uses in the studied area. The upper map reports the information for the studied area (buffer area of 400 m), whereas the map at the bottom reports services in the extended area (buffer area of 800 m).

Public spaces. Public spaces contribute to enhance the beauty and environmental quality of neighborhoods, and also contribute to socialization and sustainability. The studied zone provides 0.217 km^2 of green areas, which corresponds to 40.6% of the overall land. The average distance for residents walk to a green area is 200 m. Regarding maintenance conditions, municipal workers are responsible for keeping green and public recreation areas clean and in proper conditions.

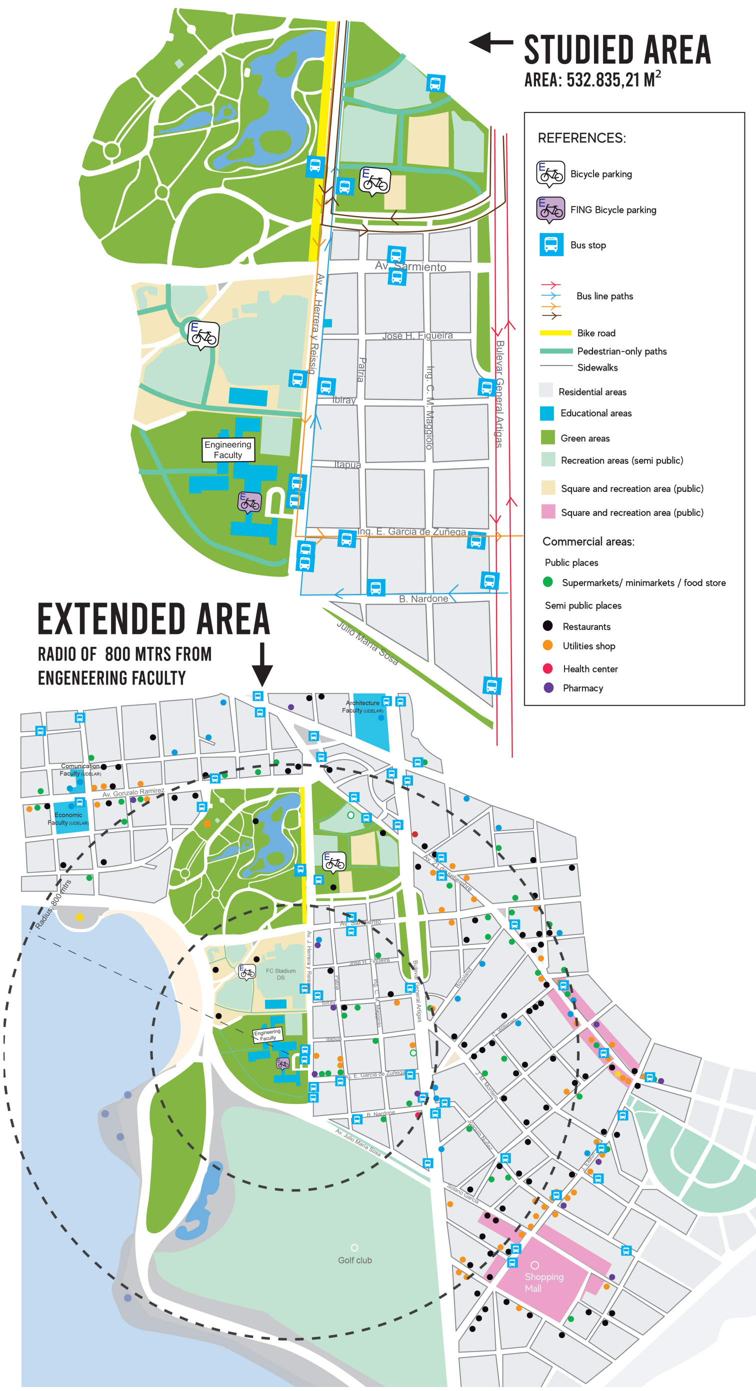

Fig. 1. Information for the studied area and the extended area

Density. Urban density is a fundamental principle of sustainable development. Dense development sustains public transportation, shortens travel distances and keeps travel cost affordable. For dense cities, the TOD paradigm supports building up instead of building out to avoid urban sprawl. In this regard, the study analyzed two criteria: residential density and commercial activities density. The residential density correspond to 13.18 residents/ha, and the commercial activities density (over total uses) is 0.1%. These figures confirm that the studied area is most a residential (rather than commercial) area of the city.

Transit–public transportation. A good public transportation service should connect many distant areas, creating a more accessible and equitable city. High bus frequencies and the existence of a bus stop in the proximity of residential areas is one of the principles of the TODs approach. The study identified 17 bus stops in the studied area, and residents can walk to them in less than 5 minutes from their homes. During working days, the bus service operates with a mean frequency of 12 to 17 minutes on peak hours (7:00 to 22:00), 25 to 35 minutes from 22:00 to 0:00, and low frequency between 0:00 and 5:00. On weekend days the demand is lower and so the frequency. In general, the maintenance conditions of bus shelters is low. The original design presents a sitting bench, a roof, a commercial panel, lighting, bus line signage and a trash bin. However, the majority of commercial panels, lightening and bus line signage are damaged; 7 out of 10 have the sitting bench, 15 out of 17 already have the roof, and the trash bin is missing in all of them. Moreover, 8 bus shelters are located closer the corner of the street, blocking the visibility for pedestrian that are crossing the street.

Connectivity and ciclying. Safety and comfortable walking and cycling contribute to the TOD approach. Relevant indicators to evaluate those sustainable mobility means are the proportion of pedestrian and cycling routes, intersections density, and the network connectivity. The proportion of cycling and pedestrian routes over the total road network is just 0.2%, a very small proportion. The intersection density in the area is 0.2 and the gamma index connectivity is 0.3, which are reasonable values for a residential neighborhood.

Infrastructure for pedestrians and walkability. Regarding design and maintenance conditions of sidewalks, the study analyzed the area through guidelines provided by municipal technicians and city planners to facilitate the design and construction of sidewalks [11], to encourage people to walk more in their daily routine. Overall, sidewalks on the studied area present a proper width that provides pedestrians a comfort and safety walking. Also, the studied area offers universal accessibility with curb ramps in every corner and at the entrance of pedestrian-only paths, providing easy access for people with reduced mobility (e.g., elderly and wheelchair users), people with temporary limitations, pregnant women, or parents with baby strollers. Public lightening is located in all sidewalks in the area, increasing the sensation of security while walking. In turn, vegetation is plentiful in the studied area, motivating people to walk and occupy urban public spaces. However, the connections of sidewalks to other means of transportation presents some issues, such as the lack of crosswalks, poor quality paving, crude design of urban furniture and vegetation, no tactile surfaces integrated into the sidewalks and few informative signage. Furthermore, the studied area present few initiatives to discourage the use of car in the area.

The bicycle path width in the studied area is 2.0 m (two-way bicycle lines with a yellow centerline), well below the minimum recommended of 2.5 m. For the intersection crossing markings, color pavement is used to increase visibility within conflict areas or across entire intersections. Elephant feet marks are also used as an alternative to dotted line extensions, to offer increased visibility. Relevant examples of bicycle path design in the studied area are shown in Fig. 2.

Bike lane signs and symbols　　Crossing lane

Fig. 2. Bicycle lane design in the studied area (Herrera y Reissig Avenue)

Shift. To promote sustainable mobility, parking and road use must be regulated to discourage the use of car. According to the guide by NACTO, the maximum recommended speed limits are 15 km/h for shared streets or alleys, 30 km/h for minor streets, and 60 km/h for major streets that have well-protected lines for pedestrians and bicycles. Car speed limit in the studied area is 45 km/h on streets and 60 km/h on avenues. There are no parking restrictions and no fee is charged for parking on the streets. Furthermore, there are three free car parking areas and many open places to park in. Overall, the studied area does not meet with the recommended speed limit and with other policies regulations in order to reduce the use of car and increase sustainable mobility.

Travel distances and percentage of trips. Regarding the number of trips from/to the studied zone, the main findings of the analysis is that many people travel from/to near locations: one third commute from/to less than 3 km away, and 60% from a maximum distance of 5 km). This tendency suggests that the impact of implementing sustainable mobility initiatives following the TOD approach, specially focused on accessibility to nearby locations, will be notable. Furthermore, the study also revealed that 95% of people make a round trip and more than 90% commute from/to the same location at least three times a week. These results demonstrate that mobility demands in the studied zone are regular and steady.

Commuting travel time. In line with the analysis of travel distances, Table 1 reports the average commuting travel times from/to the five most demanded origin/destination of trips to/from the studied zone, which are less than 4 km away from the studied zone. One neighborhood that is far away (Prado, 8 km from the studied zone) is also included to analyze the scalability to larger distances (no walking travels were registered for Prado).

Table 1. Commuting travel time to Engineering Faculty from the five most frequent neighborhoods as origin/destination of trips (in minutes).

neighborhood (average distance)	*bus*	*bicycle*	*walking*	*car*
Parque Rodó (∼ 1.0 km)	-	4.4	12.0	5.7
Cordón (∼ 2.5 km)	18.9	11.0	30.0	12.0
Tres Cruces (∼ 3.0 km)	21.2	13.3	36.0	15.2
Pocitos (∼ 3.5 km)	28.4	15.5	42.0	17.0
Centro (∼ 3.7 km)	24.4	21.4	44.4	20.8
Prado (8.0 km)	44.4	35.5	n/a	28.8

For nearby neighborhoods (up to 3.5 km from Engineering Faculty) bicycle is the fastest transportation mode. This is a relevant result, since a large percentage of travels have origin/destination in closer neighborhoods. Up to 8.0 km, car has similar travel time than bicycle and both are faster then bus, suggesting that public transportation is not optimized to provide an appropriate travel time. Even though bicycle is the most convenient traveling mode, the length of bicycle-only lanes in the studied area is not appropriate, as previously commented.

6 Suggestions and recommendations to improve sustainable mobility under the TOD paradigm

From the obtained results, there is evidence to confirm that sustainable mobility in the studied area can be enhanced considering specific TOD-related actions.

Extend the bicycle network. The studied area offers a very short bicycle network. The analysis suggest it should be extended along main avenues. This way, the studied area would be connected with relevant places by extending bicycle lanes: seaside (through Sarmiento), other faculties (through Ramirez and Herrera y Reissig), shopping center (through Sosa) and other major neighborhoods and the Terminal Bus Station in Montevideo (through Bulevar Artigas).

Signal locations for safe pedestrian crossing. A proper signaling of crossings improves walkability, pedestrian safety, and also promotes a better pedestrian behavior. The study also recommend installing a pedestrian crosswalk in front of Engineering Faculty, to improves accessibility for students.

Reallocate bus shelters for safe crossing. The study recommend reallocating eight bus shelters that are installed closer to corners, in order to improve pedestrian visibility when crossing. Car parking should be prohibited or discouraged in those locations where it implies a risk to pedestrians and other vehicles.

Re-pavement damaged sidewalks. The study recommend re-pavementing low-quality sidewalks, especially those damaged by tree roots, which pose a serious risk for universal accessibility. Also, this issue must be considered for the selection of trees, to avoid them cracking and raising the sidewalks. Sidewalk surfaces must be firm and leveled, for a proper use of wheelchairs, the elder, or people with temporary o permanent walking limitations.

Add tactile surfaces to guide blind or visually impaired people. The area does not provide elements to allow safe walking of visually impaired people. Guides are also missing on bus stops and other relevant locations and they must be properly installed to provide and improve universal accessibility.

Improve bus shelters. Comfort on bus shelter improves the image of public transportation. The study recommends an appropriate design to prevent bus shelter being so vulnerable to vandalism, using concrete or other highly resistant materials. Also, the design must provide better protection for adverse climate conditions (e.g., strong wind and rainy days). Every bus shelter must provide a garbage bin and a proper bench for people wait for the bus to arrive.

Promote walking and interaction with the environment. The study demonstrated that sidewalks play an important role in encouraging the interaction between people and the urban environment. Several actions must be developed to provide a better and more pleasant experience: improve information to guide pedestrian to reach destination, provide better and more functional urban furniture and vegetation (planter boxes, garbage bins, benches, etc.), to make the environment more attractive and improve the walking experience.

7 Conclusions and future work

This article presented an empirical analyzing of sustainable mobility under the TOD paradigm in the area surrounding Engineering Faculty, Universidad de la República, Montevideo, Uruguay. Several relevant indicators were studied to determine the reality and relationships between territory, activities, and mobility.

The study applied urban data analysis to identify a spatial/functional definition of the studied area, using operational data, personal inspection, and a survey performed in/situ in the original and an extended area.

The main findings of the analysis are related on the characterization of several TOD concepts and metrics, related to sustainable mobility. Based on the results of the analysis, specific recommendations are provided to develop a TOD-based approach to improve sustainable mobility in the studied area. The main goals of the proposed suggestions are related to improve the walking experience, provide universal accessibility, promote walking and bicycle, and the interaction with public transportation. This is a direct contribution oft he reported research, since no previous similar studies have been developed in Montevideo.

The main lines for future work are related to extend the analysis to consider other relevant TOD concepts and indicators to better characterize sustainable mobility and the impact of recommended actions in the studied zone.

References

1. Alba, H., Grindlay, A., Ochoa, G.: (in)equitable accessibility to sustainable transport from universities in Guadalajara metropolitan area, México. Sustainability 13 (2020)
2. Banister, D.: The sustainable mobility paradigm. Transport Policy 15, 73–80 (2008)
3. Bertolini, L.: Nodes and places: complexities of railway station redevelopment. European Planning Studies 4.3, 331–45 (1996)
4. Bertolini, L., Curtis, C., Renne, J.: Station area projects in europe and beyond: towards transitoriented development. Built Environment 38.1, 31–50 (2012)
5. Bocarejo, J., Portilla, I., Pérez, M.: Impact of transmilenio on density, land use, and land value in Bogotá. Research in Transportation Economics 40(1), 78–86 (2013)
6. Burchell, R., Listokin, D., Galley, C.: Smart growth: More than a ghost of urban policy past, less than a bold new horizon. Housing Policy Debate 11, 821–879 (2000)
7. Calthorpe, P.: The Next American Metropolis: Ecology, Community and the American Dream. Princeton Architectural Press (1993)
8. Cervero, R.: Transit-oriented development's ridership bonus:a product of self-selection and public policies. Environmentand Planning A: Economy and Space 39.9, 2068–2085 (2007)
9. Cervero, R., Dai, D.: BRT TOD: Leveraging transit oriented development with bus rapid transit investments. Transport Policy 36, 127–138 (2014)
10. De Vos J., Van Acker V., W.F.: The influence of attitudes on transit oriented development: an explorative analysis. Transport Policy 35,5, 326–329 (2014)
11. Dos Santos, P., Caccia, L., Barbosa, A., Zoppaas, L.: The 8 Principles of Sidewalks. World Resources Institute (2019)
12. Gudmundsson, H., Hall, R., Marsden, G., Zietsman, J.: Sustainable Transportation. Springer Berlin Heidelberg (2016)
13. Hasibuan, H.S., Soemardi, T.P., Koestoer, R., Moersidik, S.: The role of Transit Oriented Development in constructing urban environment sustainability, the case of Jabodetabek, Indonesia. Procedia Environmental Sciences 20, 622–631 (2014)
14. Hipogrosso, S., Nesmachnow, S.: Analysis of Sustainable Public Transportation and Mobility Recommendations for Montevideo and Parque Rodó Neighborhood. Smart Cities 3(2), 479–510 (2020)
15. Jeon, C., Amekudzi, M.: Addressing sustainability in transportation systems: Definitions, indicators, and metrics. Infrastructure Systems 11(1), 31–50 (2005)
16. Kitamura, R., Mokhtarian, P.: A micro-analysis of land use and travel in five neighborhoods in the San Francisco Bay area. Transportation 24, 125–158 (1997)
17. Litman, T., Burwell, D.: Issues in sustainable transportation. International Journal of Global Environmental Issues 6(4), 331–347 (2006)
18. Loo, B., Du Verle, F.: Transit-oriented development in future cities: towards a two-level sustainable mobility strategy. Urban Sciences 21, 54–67 (2016)
19. Marshall, S.: The challenge of sustainable transport. In: Layard, A., Davoudi, S., Batty, S. (eds.) Planning for a Sustainable Future, pp. 131–147. Spon (2001)
20. Moscoso, M., van Laake, T., Quiñones, L. (eds.): Sustainable Urban Mobility in Latin America: assessment and recommendations for mobility policies. Despacio: Bogotá, Colombia (2019)
21. Neckermann, L.: Smart Cities, Smart Mobility: Transforming the Way We Live and Work. Troubador Publishing Ltd. (2017)
22. Newman, P., Kenworthy, J.: The land use–transport connection: an overview. Land Use Policy pp. 1–22 (1995)

23. Papa, E., Bertolini, L.: Accessibility and Transit-Oriented Development in european metropolitan areas. Journal of Transport Geography pp. 70–83 (2015)
24. Renne, J.: From transit-adjacent to transit-oriented development. Local Environment 14:1, 1–15 (2009)
25. Rodriguez, D., Vergel, E.: Urban development around bus rapid transit stops in seven cities in latin-america. Journal of Urbanism: International Research on Placemaking and Urban Sustainability 11(2), 175–201 (2017)
26. Sung, H., Oh, J.: Transit-oriented development in a high-density city: Identifying its association with transit ridership in Seoul. Cities 28, 70–82 (2011)
27. Tsigdinos, S., Paraskevopoulos, Y., Rallatou, N.: Transit Oriented Development (TOD). Challenges and Perspectives; The Case of Athens' Metro Line 4. In: European Transport Conference (2019)
28. Woo, J.: Classification of TOD typologies based on pedestrian behavior for sustainable and active urban growth in Seoul. Sustainability 13(6), 3047 (2021)
29. World Business Council for Sustainable Development: The sustainable mobility project (2002)