Electric versus Diesel:

Operational Impacts on Buses' Life Cycles Due to Tropical Climate Conditions

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Abstract

This project's goal is to study the impacts that a tropical climate area such as PR has on the operational conditions and emission costs for energy production, consumption, and efficiency of EBs and DBs in order for being able to optimize an ideal electrified mobility transition in PR's surface public/collective transportation system. The buses' performances will be divided into two main parameters: operational and environmental. Replacing DBs with EBs does not become an easy decision since it involves a complex analysis that results in a reasonable debate if we really do not want to promote a superficial tradeoff in terms of the atmosphere consequential impacts. Approximately 70% of PR's population lives in areas with excellent solar resources [25]. This renewable source will provide a more resilient approach in case of outages occurring due to natural hazards events; and will likely influence public health and air quality to enhance by minimizing total emissions even though this is not certainly guaranteed [39]. As shown in this paper, a full day of bus service (12 consecutive hours) will evoke a near 60% discharge, which was equivalent to a 296.4 kilowatts-hours energy consumption on a low-season day; this energy loss can be gained in less than half of the service hours that it took to discharge by using a direct current fast charger. EMS are critical to increasing driving range, minimizing costs (monetary but environmentally speaking as well), and extending battery life, and they can be used to obtain the optimal management for the balance between comfort and range efficiency expected [33]. Aggressive adoption of cost-saving innovations in infrastructure, operation and administration would be paramount to ensure the cost-effectiveness of investments to provide comprehensive resilience enhancements [36].

Keywords
Operational Impacts, Operational Performances, Operational Conditions, Lifecycle, Tropical Climate, Tropical Weather, Puerto Rico, Electric Buses, Low or Zero Emissions Buses, Electrified Mobility, Diesel Buses, Motor Buses, Buses Fleets, Surface Collective Transportation, Surface Public Transportation, Transportation Infrastructure, Charging Infrastructure, Environmental Factors, Dynamometer Testing, Climatic Chamber, Environmental Chamber, Heat Waves, Rainfall, Floods, Storm Winds, Hurricanes, Earthquakes, Pollutant Emissions, Air Pollution, Fossil Fuels, Greenhouse Gases, Anthropogenies, Atmosphere, Air Quality, Climate Change, Public Health, Safety, Capacity, Hazards Prevention, Risks Prevention, Equity, Island-wide Accessibility, Inclusiveness, Metropolitan Bus Authority, Emission Costs, Energy Production, Energy Consumption, Resilience, Sustainability, Modern Civil Engineering.

Definitions of Concepts (The Basics)

- Hazard: Potential sources of dangers damage, harm, or adverse health effects [1].
- Exposure: Imminent hazard of dangers [1].
- Vulnerability: Susceptibility to the damaging effects of a hazard [1].
- Risk: Function of hazards, exposures, and vulnerabilities [1].
- Resilience: Adaptation capacity due to adverse circumstances. A resilient system must be capable of anticipating, resisting, and recovering from natural and non-natural climate disasters, as well as from anthropogenic actions and other possible situations, in a way that promotes a safe environment and a healthy future.
- Sustainability: The capability of a system to resiliently maintain itself in the long term.
- Diesel engines: Internal combustion engines that convert chemical energy in fuel to mechanical energy [2]. Diesel fuel is used in motor vehicles that use the compression ignition engine as buses does [3].
- Electric engines: Engines fueled solely by electricity sources such as battery power.
- Surface public/collective transportation: Public transportation alternatives to mobilize groups of people as a collective by means of road or rail [4].

Introduction

Puerto Rico's Tropical Climate & Natural Hazards' Background

The archipelago of approximately 100 miles long by 35 miles wide called Puerto Rico (PR) is in the path of tropical hurricanes in the Caribbean, suffering the direct and indirect effects of a tropical disturbance on average every 10 years [5]. In September 2017, two back-to-back hurricanes (Irma and María) hit the island, affecting the electric power supplies significantly as its outages lasted more than 10 months [6]. This blackout was the longest in the history of the United States (US), and the 2nd largest in the world on record [7]. As of June 30th, 2016, PR's electricity system had a generation capacity of 5,839 megawatts according to Puerto Rico Electric Power Authority (PREPA, or AEEPR by its acronym in Spanish) Fiscal Plan, with mixed technologies mainly based on burning fossil fuels [6]. According to a case study on the use of lower cost air quality monitors, the widespread reliance on backup generators for regular electric supplies appears to increase air pollution in San Juan Metropolitan Area (SJMA) [8] where about 40% of the island's population lives [6]. These small gasoline generators are many times being used as the main source of electricity due to hurricane's power outages, although they are not designed to be used for months without any rest period [9]. Aside from that, they are not taking into consideration the health pollutant exposure produced because of that practice either.

Another main characteristic of the archipelago's tropical climate is its hot temperatures. The National Weather Service (NWS) data average PR's temperature to be 82°F [5] while currently facing heat indices that can be felt up to 120°F considering humidity [10]. This outlier could be attributed to El Niño-Southern Oscillation (ENSO) phenomena as of 2023 in combination with the Saharan dust that departure in this zone. The combination of heat and humidity can also exacerbate pollution-related issues. On the other hand, precipitation on the island can be highly variable in both its temporal and spatial character [5], which can result in either heavy rainfall or droughts depending on the region and period. More recently, earthquakes have also been added to the equation of the environment-related hazards for PR as they strike more frequently since around the early 2020 pandemic. Contemporary climate changes have also attracted the rise of sea levels across the globe and PR is not the exception as seawater keeps getting broader as it warms [11]. 5 years later from the back-to-back (in September 2022), the hurricanes' threat continues to be evident as Fiona also hit the island doing its damage as well. All these extreme natural conditions affect the surface transportation resilience framework in their own ways. For instance, tropical climates can increase energy consumption in buses due to the need for constant air conditioning (AC) to maintain passengers' comfort, therefore impacting their overall performance [12].

Puerto Rico's Transportation Overview

Private vehicles (the majority being engine by internal combustion, i.e., gasoline and diesel) are the main source of mobility in PR since transportation infrastructures have been built in tune with the personal use of this medium. According to the US Census data, travel times for San Juan population by public transport are approximately 20 minutes longer than for those who travel via private vehicles [13]. This is also a manifestation of the fragmentation of surface public/collective transportation in PR, which makes possession of a private vehicle even more essential [14]. In fact, surface public/collective transportation is not an option for most Puerto Ricans. Even though their Integrated Transport Alternative (ATI, by its acronym in Spanish) multimodal system provides various surface transportation services such as the urban train, the Metropolitan Bus Authority (AMA, by its acronym in Spanish), Metrobus, Municipal Trolleys, and Minibuses (public cars), only the last two are available for outside the SJMA [15]. AMA is the main surface public/collective transportation system for the island aside from the urban train. Its bus rolling stock consists of 118 units of which 52 are powered by diesel-hybrid engines and the remaining 66 buses are diesel only engine powered, which are centralized within 8 municipalities in SJMA (i.e., 10% of island-wide municipalities) [16]. Oher than those, there it is a Southern Integrated Transportation System (SITRAS, by its acronym in Spanish) and the "Trolley Colegial", which are municipality-based systems made only for Ponce's population and UPRM students respectively. For reference, a ride from Mayagüez to San Juan takes approximately 2 hours and 45 minutes taking the North PR-2 route, and 2 hours and a half taking the South PR-2 route.

It is well known that even though diesel engines provide a wider range of durability than electric ones, diesel combustion processes emit inherent energy losses. Furthermore, diesel engines may experience additional wear and tear due to high temperatures and humidity, leading to increased maintenance/cooling requirements and costs (environmental and monetary speaking). Data from a case study on Tampa Bay demonstrates that power outages after hurricane Irma contributed significantly to fuel shortage chaos; "whereas transportation resiliency has traditionally focused on infrastructure and assets, fuel resources are an important consideration for preparing for disasters and to support response and recovery efforts" [17]. In the case of electric vehicles, hot temperatures can also affect battery performance and cooling requirements, potentially affecting the range and overall operations, as a previous model found [12]. Aside from the range issue, there are other limitations electrically speaking such as the battery production which rely on minerals (e.g., lithium) and the charging infrastructure which will demand significant power and space to accommodate equipment for large fleets deployments [18]. Nevertheless, electric fleets will have fewer moving parts and require less maintenance than diesel ones, resulting in lower operation costs over their life cycles. "A six-vehicle electric school bus pilot program in California (2016) concluded that while upfront costs for an electric school bus are much higher than for a diesel equivalent, reduced operating costs more than make up the difference" [19].

Objective

This project's goal is to study the impacts that a tropical climate area such as PR has on the operational conditions and emission costs for energy production, consumption, and efficiency of electric buses (EBs) and diesel buses (DBs). Since there is a growing consensus on the urgency for more sustainable patterns of transportation and, alongside that, urban air pollution should be a main concern of modern society, this theoretical comparison will align to promote a more resilient approach to one of the most concerning issues of modern civil engineering in one of the most related anthropogenies sectors involved. All these conditions and facts will be addressed in a life-cycled perspective to analyze its pros and cons of implementation. “A cleaner power grid and an increase in system charging efficiency (if better than 60-84%) would enhance the future benefits of electric buses” [20]. Being able to optimize an ideal electrified mobility transition from DBs to low or zero emissions buses is critical, and we must take into consideration not only its charging and overall infrastructure, but also public health factors such as air quality, climate change, safety (as in hazards prevention), and equity (as in island-wide accessibility and inclusiveness) in the most sustainable and cost-effective ways possible, given tropical climate potential risks.

Case Study Area

Puerto Rico's Brief History & Geography

PR is an archipelago in the Caribbean Sea of roughly 3,500 square miles composed of the main island, four small islands, and hundreds of cays and islets [21]. It is the easternmost island of the Greater Antilles chain and currently a territory of the US. Before their Spanish colonial rule, PR's native Taíno population called it "Borinquén", referring to themselves as "Boricuas", term which is still used today as an equivalent to "Puerto Ricans" [22]. This racial mix between Taíno, Spanish and American cultures remain influential in PR's society today, which is divided into 78 municipalities, including the municipality islands of Vieques and Culebra (around 3.2 million of habitants overall) [21]. Following in the US' footsteps, PR experienced rapid growth in population and in infrastructure development during the 1950's with a steady population growth rate until the late 1990's to early 2000's, but for the recent years there have been a decrease in population growth whereas the consequences and outcomes of urban sprawl remain [23]. Suddenly, the commonwealth declared a form of bankruptcy of more than $70 billion in 2017, same year that these American citizens found themselves in a humanitarian crisis with debilitated shortages of water, food, fuel, and other essentials due to hurricanes strikes [22]. For the purposes of this study, the scope of PR will be island-wide focused even though majority of the information comes from SJMA, which is in the northeast region and San Juan being the capital of the island. Other relevant municipalities that have some valuable information and therefore will be used to achieve the island wide perspective are Ponce (south region) and Mayagüez (west region), as presented below in Figure 1. Anyway, there is also further information from places around the world, but trying to maintain the tropical weather characteristics is a main consideration for the data research. In terms of time, the research timeline will be from 2017 to the present (2023), period where there have been plenty of natural hazard events occurring as this study develops. As backgrounded above, the tropical climate of PR nowadays involves not only hurricanes, which include heavy winds and rainfall, but also droughts, extremely hot temperatures with humidity, earthquakes, and many other climates changes consequences such as sea level rise (SLR). This climate's diversity is caused by several factors, but mainly by the winds and the geography of the island, which result in the orographic effect [5].

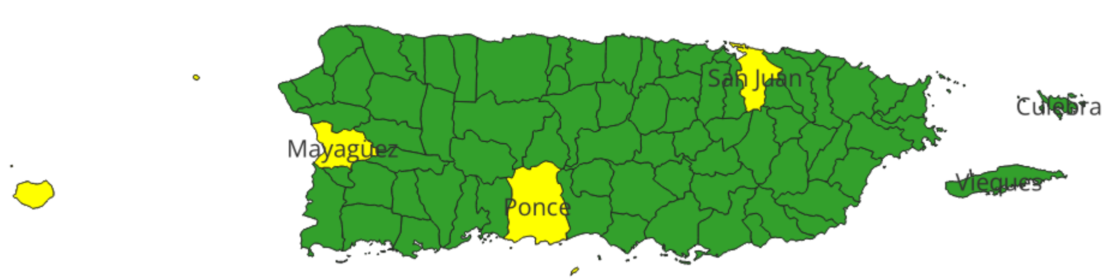


Figure 1: Map of PR's archipelago with relevant municipalities purposed for this study highlighted in yellow [made by HEVC using QGIS].

Literature Review

Problem Statement & Focus

Air pollution consists of diverse types (e.g., greenhouse gases), and the increased use of personal automobiles plays a significant role in more of those pollutant emissions being exposed to the atmosphere. Data obtained from an investigation by Infante and Acosta strongly suggests that motor vehicle traffic and fuel combustion are the principal pollution sources in Ponce aerosol particles [24]. As another paper suggests, "a key challenge is to turn the potential for renewable energy into a reality through a safe and reliable grid connection", and it could be possible given that approximately 70% of PR's population lives in areas with excellent solar resources [25]. Of course, PR's weather conditions will cause a variety of fluctuations in the power inputs and outputs. PR's annual average insolation in kilowatts-hours per square mile is presented below in Figure 2 [26] as reference to the widely potential on solar energy resources that PR has:

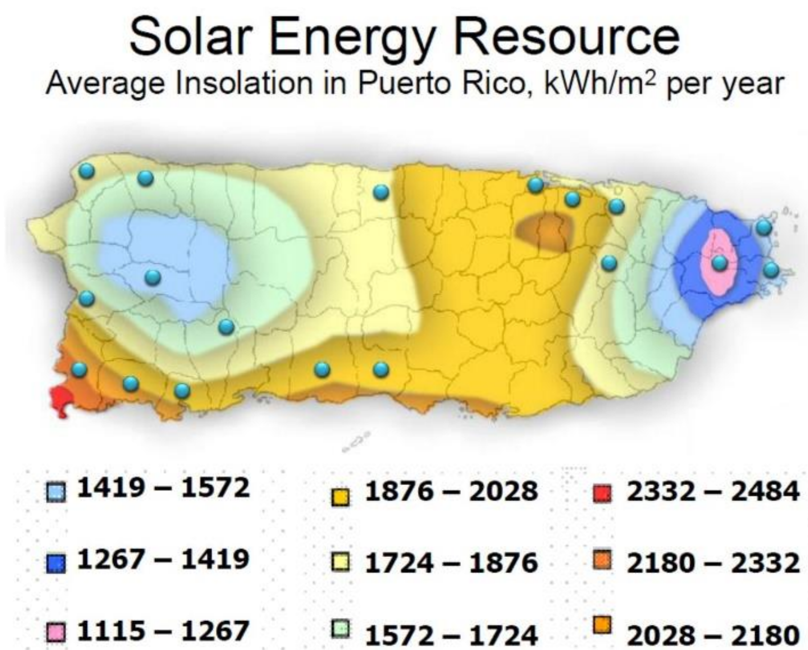


Figure 2: PR's annual average insolation in kWh/m² [26].

Instead, these insolated conditions can be taken as alarming. Extreme temperatures increase mortality, decrease labour productivity and cognitive performance, and even increase morbidity as empirical research can assure. Global warming is a major concern when assessing climate changes but estimating its costs in monetary terms is not enough since "when life or health are at stake, all people should be considered equal, whether rich or poor, alive or yet to be born" [27]. That is why to achieve improvements within these issues, there needs to be political approaches supported by scientific approvals that can slow down global warming to 1.5°C, as called for in the Paris Agreement, in order to benefit of a 5-fold decrease in the population exposed to unprecedented heat, as Lenton et al. findings estimate [27]. It is based on this statement that this research will not give so much importance to the monetary costs but instead will approach it from a holistic perspective focused on pollutant emissions and other environmental indicators, limited to the conditions exposed. This is an example of why nowadays engineering areas need to consider aspects from what other disciplines bring to the table since there is a common concern in climate change and the future wellbeing of everyone.

The engineered solution suggested here will cultivate a better understanding of a suitable and healthy transition into low or zero emissions engines and prove their alleged cons wrong. EBs are powered by batteries that require critical minerals, notably lithium, and their demand has recently rocketed in wealthy countries, including the US [28]. So, replacing DBs with EBs does not become an easy decision since it involves a complex analysis that results in a reasonable debate if we really do not want to promote a superficial tradeoff in terms of the atmosphere consequential impacts. For reference, the attached figure summarizes some of the pros and cons of the desiderated transition that must be put into a balance in order to achieve it, as broken down in Figure 3 [29]:

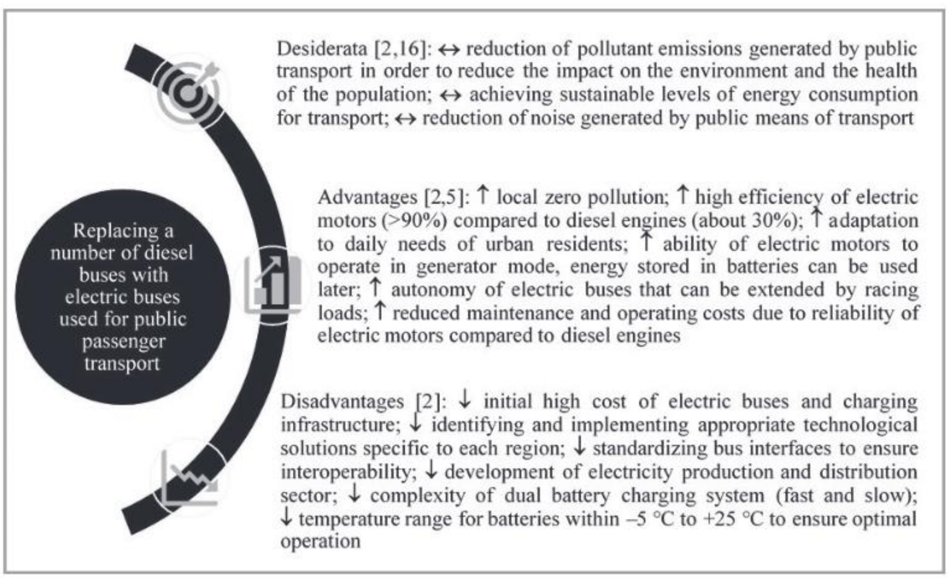


Figure 3: Desiderata, advantages, and disadvantages of the solution for replacing EBs for public transport [29].

Going straightforward to address the cons (i.e., disadvantages) presented in the figure above, the initial costs of buses can be surpassed in the long term as highlighted before [19]. As to the charging infrastructure initial costs barrier, the Infrastructure Investment and Jobs Act (IIJA) is a current existent aid that can serve as an inspirational policy for more to come that could address the rapid demand growth of the electrification system. Besides this unprecedented one, other funding policies must be driven on this matter, as they do in other affairs, so that the needed infrastructure can be fulfilled (for both fast and slow charging). Even though the extreme temperature in PR does not suits well to ensure optimal operation of EBs, the insolated position of the island can serve as a significant ally to produce the solar energy needed not only to recharge but also to be an integral part of road interconnected networks that could mitigate and prevent during tropical climate hazards as well. EBs consumptions vary significantly based on numerous parameters, but this study will be emphasized more likely to vehicular and external parameters, as classified in the model developed by Abdelaty and Mohamed [12]:

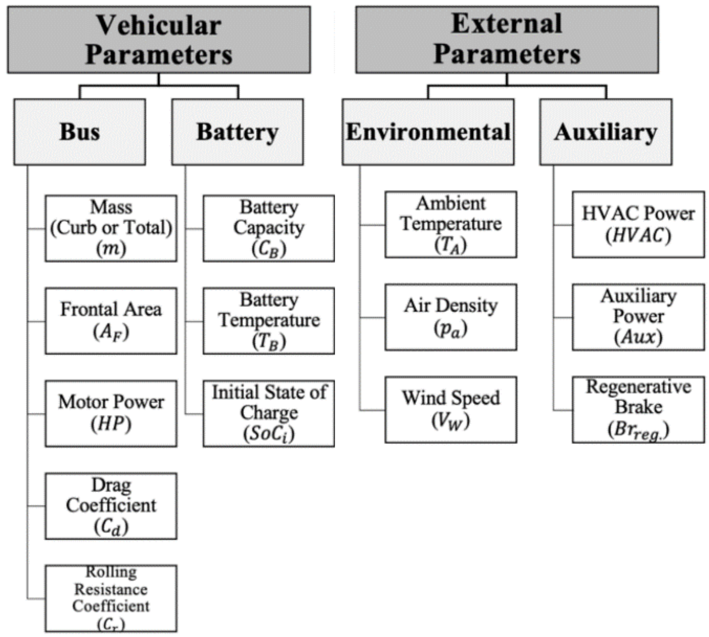


Figure 4: Parameters impacting the energy consumption of EBs (battery engine) [12]; some of them to be considered for this study.

To address the parameters impacting the overall performances of both DBs and EBs network systems under different operating conditions, such as for instance assuming rainy days occurring on every day of the week, some of the most influencing observed parameters related to this focus includes drainage systems, number of private cars, temporary bottlenecks, non-uniformity carriageway width, street connectivity, absence of bus priority measures, and bus stops, as resulted in Das et al. approach [30]. As for this study, the different parameters found and presented in this literature review will be blended to obtain the focus for the problem statement in question: How the operations of EBs versus DBs could be impacted under tropical climate conditions seen in PR? There is already a variety of studies regarding either hurricane-related weather events (i.e., rainfall, heavy winds, floods, etc.) or global warming-related issues (e.g., SLR, droughts, etc.) on transportation, but there is an evident research gap in contemporary studies for earthquakes' impacts on transportation power systems operating under extreme tropical climate environments. Indeed, earthquakes represent a significant hazard, which could be responsible for huge economic losses and human fatalities, also followed by potential tsunami alerts.

Methodology

Impactful Parameters & Analysis Model

Given the problem statement, the impacts on EBs and DBs will be divided into two main parameters: operational and environmental. For the operational parameters, the focus is determined to analyze the buses' performances during their life cycles, whereas for the environmental parameters the goal is to address the ecological impacts and sustainability due to the tropical climate conditions seen in PR towards achieving hazards preventions more effectively and contributing to a healthier transportation environment in the island wide. One parameter affair that can be seen related to both divisions is power energy, whose production and consumption contributes to climate changes while its efficiency is more of an operational related issue. These parameters are outlined in Table 1 below:

Table 1: Impactful parameters (for both EBs and DBs) to be considered.

Operational Parameters:	**Environmental Parameters:**
Range	Tropical Climate Conditions
Power Energy Efficiency	Power Energy Production & Consumption
Charging/Refuel Infrastructure	Public Health
Road Network	Air Quality
Speed & Acceleration	Land Use/Loss

Furthermore, there are other considerations within these general parameters that are going to be an essential part of the whole analysis. EBs' state of charge (SoC) can be reflected in both its ranges and efficiencies performed. The charging and refuel infrastructure for EBs and DBs respectively is another main consideration that could impact the range debate given the stations' availability; also having something to do with SoC, charging time and duration of the charge (in terms of EBs). The good faithed use of land is a critical consideration for the ecological preservation part of a healthier transition and knowing that there is already a lot of concrete-built spaces, it is not affordable to keep building new spaces instead of using those places that have already been established for refuel purposes. It is worth noting that solar panels should be allocated in buildings' ceilings, leaving the still available land free to use for agricultural sectors in which they can coexist. As for the public health and air quality parameters, society's wellbeing, and quality of life (QoL) are crucial factors to keep in mind given all the pollutants emitted to the atmosphere. Also, a safer surface public/collective transportation system that accommodates route stops in strategic locations could promote humans to do more physical activities by briefly walking from one bus stop to another. Similarly, island-wide accessibility in major extensions of the buses' network could give a wider inclusiveness to all regions and economic classes of the island's population. There could also be a strategic alignment for society to have more flexibility within their hours, giving more time availability because the functional buses' route planning eases that saving of time. Besides all these, energy power production and consumption need to mitigate its emission costs, its reliability on resources and its energy losses. Other considerations that could be indirectly addressed throughout this paper are capacity, load, capability, and life-cycled costs (environmentally and monetary speaking). As specified throughout this whole paper, tropical climate conditions refer to all the natural hazards' events occurring in PR from the past 6 years as of 2023, considering not only hurricanes but drought/rainfall seasons, earthquakes, extremely hot temperatures, SLR and beyond.

Once the considerations breakdown for each division of parameters had been settled, the objective of comparison will be applied based on the following model:

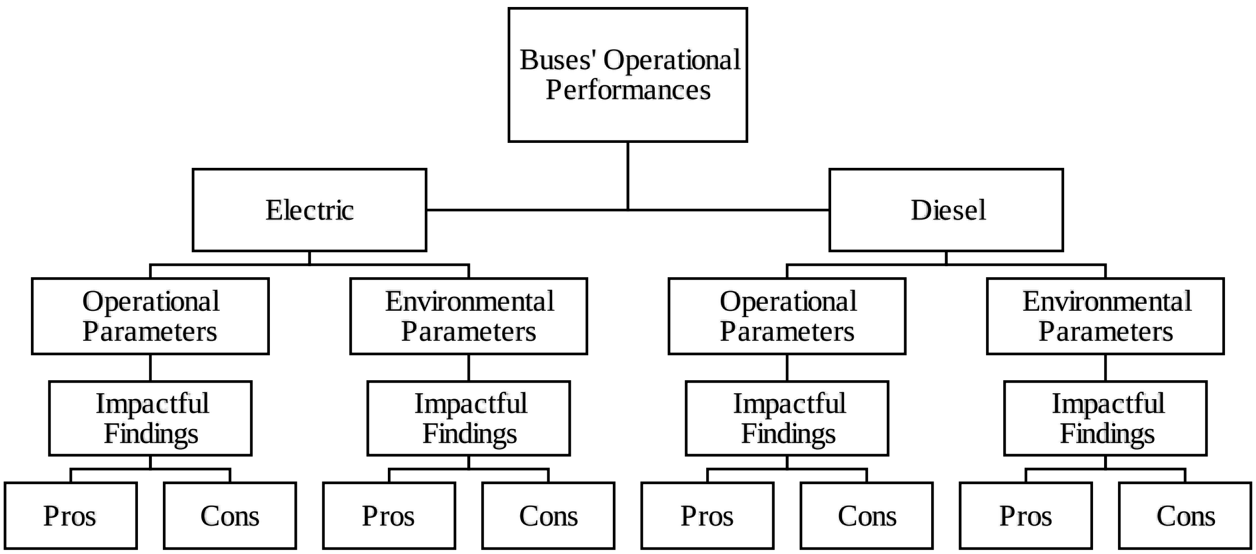


Figure 5: Model of Analysis for Buses' Operational Performances.

Constraints

Due to timeline constraints of this summer project, this final report will be developed in accordance with the literature review prior to the writing, supported by reliable data obtained by loggers installed in Texas A&M University (TAMU) EBs currently offering transportation services and other available information on the impacts that tropical climate would have on the fleet performances of EBs compared to DBs.

Procedure

Both operational and environmental parameters will be compared based on the impacts each one produces on EBs and DBs individually. The process will consist of reviewing the proper literature findings for each parameter on both types of buses given their respected considerations of focus. The installation and periodically swaps of data loggers in TAMU EBs will bring useful data and certainly provide inside experience to the researcher mindset in order to go over conclusions on whether this is or not a feasible proposition to implement in his beloved place of birth (PR)'s transportation system. Therefore, DBs findings will be put side by side with findings on EBs to analyze its pros and cons following the analysis model presented above in Figure 5. All this literature and data will be gathered into tables, graphics and written so it can be visually perceived and discussed.

Discussion of Findings

Intrinsically, the distribution on this discussion is intended to address first the infrastructure impacts which will have more of an operational perspective that could include monetary measurements, whereas for the second part of the discussion, the measurement is more inclined into a life-cycled analysis considering human and nature factors by addressing the environmental, health and society perspectives purposed for the desiderated approach.

Infrastructure

Following the statements by Satterfield and Schefter [31], the availability of electric charging infrastructure is crucial to the continuous growth of electrified mobility. Level 1 & 2 chargers (120 volts & 240 volts respectively, both alternate current power) add around 3 to 4 miles and 10 to 20 miles of electric range per hour of charging, respectively. Beyond that, direct current fast chargers are intended to add a substantial charge in a short amount of time since it converts alternate electricity into direct current to deliver charge at high power. [31]. Charging infrastructure for large EBs deployments will require significant power (such as what supplies the direct current fast chargers) and space to place that equipment [32]. The AC system draws electrical energy from the main battery, and since cabins should ensure passengers' comfort while simultaneously using the least energy possible, a suitable strategy is required to optimize the power utilization [33] given that this substantial energy consumption coming from the AC could contribute to a significant reduction of range availability in EBs [34]. Energy Management Systems (EMS) are critical to increasing driving range, minimizing costs (monetary but environmentally speaking as well), and extending battery life, and they can be used to obtain the optimal management for the balance between comfort and range efficiency expected [33].

In terms of DBs there is a completely different story to aboard. After hurricane Irma passed through Tampa Bay, the share of stations without diesel ranged from 50% to 60% [17]. In PR, as of June 2018 (around 9 months later), AMA alone estimated a total value of damage (i.e., the amount needed to bring the infrastructure to a state of good repair including the additional amount required to make enhancements to increase resilience) of around $16.4 million [35]. One of the challenges in PR's surface transportation is the lack of funding available for maintenance and improvement and in top of that, it seems that fully half of PR Highway and Transportation Authority (PRHTA)'s revenues are pledged to debt repayment [35]. Addressing the 5 critical areas affected by PR's climate trends, identified by Molano-Santiago [36] as pavement performances in flood-prone zones, characteristics of water-crossing bridges, slope failure susceptibility, heavy vehicle traffic, and disrupted traffic operations, would contribute to a significant enhancement of transportation resilience by ensuring infrastructure sustainability, operational continuity, and potential reduction of agency costs associated with recurrent repairs and maintenances. Aggressive adoption of cost-saving innovations in infrastructure, operation and administration would be paramount to ensure the cost-effectiveness of investments to provide comprehensive resilience enhancements [36].

Environment, Health & Society

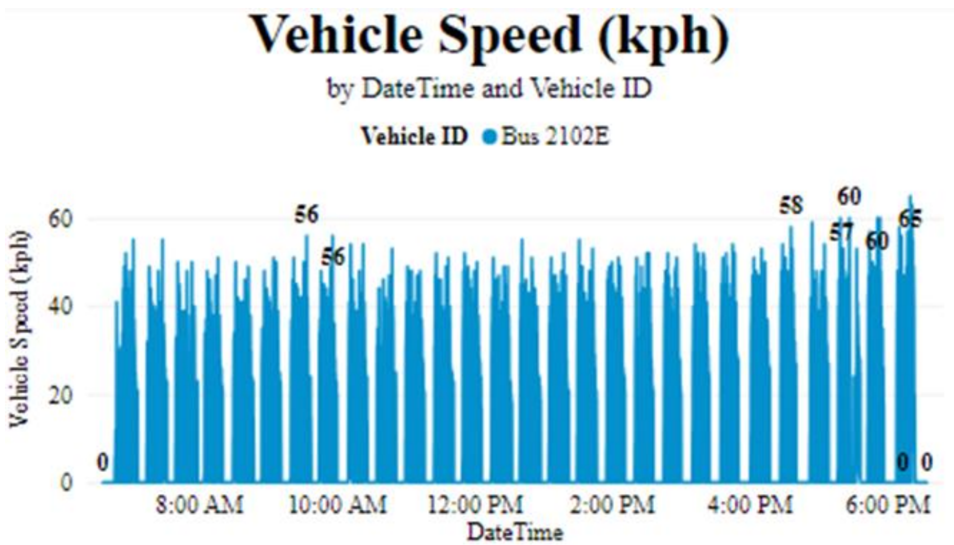
The PR's Climate Change Council (PRCCC) identified 240 bridges within the coastal zones, exposing them to SLR and extreme coastal weather; bus service disruptions and weather-related congestion along coastal and flood-prone highways were also identified as a threat to traffic operations [36]. When bridges suffer incapacitating damage such as foundation scours their highways traversing barriers are compromised. Moreover, the back-to-back hurricanes caused widespread failures not only on the power grid, roads wash-out and bridges scour, but on telecommunications, vegetation, coastal erosion, river floods and other slope failures as well. The extent of these wind damages was aggravated due to the island' mountainous topography which evokes wind acceleration effects around it. Changes in wind energy would vary with topography and exposure depending on exact location and period. These considerations can be important in prioritizing transportation signage resiliency in segments within a particular region exposed to high winds conditions as compared to other regions in the island wide. [36].

Keeping in mind the way air/wind flows, now consider the complex mixture of thousands of gases and fine articles (i.e., soot) that contain more than 40 toxic air pollutants [37] being exposed to the atmosphere as we breathe. The prevalence of diesel-powered engines makes it almost impossible to avoid its exhausts. For instance, this exposure can cause coughs and aggravated asthma [37]. In fact, its long-term exposure poses the highest cancer risk of any toxic air pollutant, as evaluated by the California Environmental Protection Agency's Office of Environmental Health Hazard Assessment (OEHHA) [37]. Compared with DBs, EBs have zero exhaust emissions during the operation period, require less motor maintenance while having higher operation efficiency, as Mao et al. proved [38]. Contrastingly, it is worth to note that minimizing total emissions does not guarantee health impacts and exposure to be minimized [39].

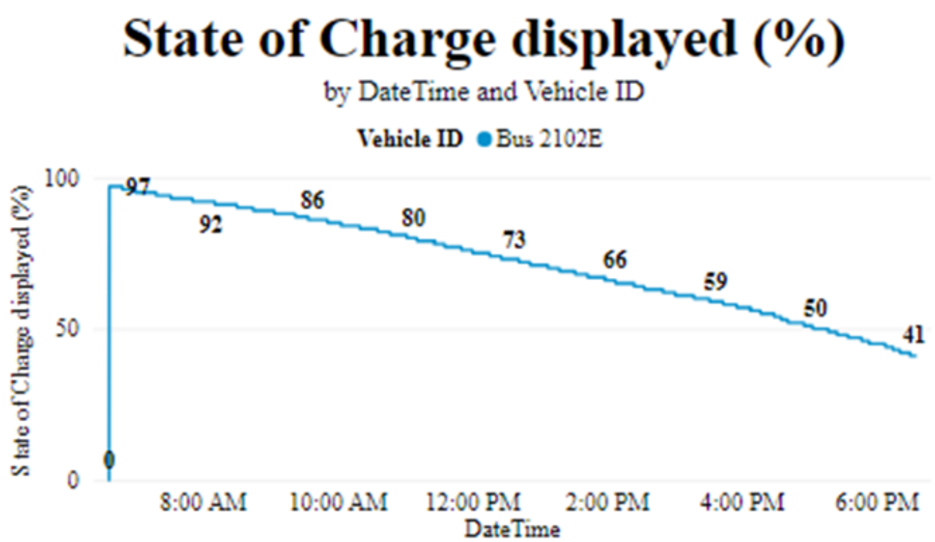
Air quality not only has effects on public health, but also imposes a significant social cost, since exposure to its pollution results in higher rates of morbidity, absenteeism, partial disability, and productivity losses [40]. Boricuas outside SJMA (i.e., about 60% of island' population [6]) suffer of huge difficulties of accessing to health' services exclusively located in metro area because of the distances [14], and so there is an inaccessibility/inclusiveness issue in top of all mentioned above. An evident correlation between long-travel times to get to treatment with the increase of mortality risks and decrease of QoL has been proved in research by Moist et al. as reported in Pacheco-Cruz' paper [14]. Surface public/collective transportation' accessibility island wide needs to be in accordance with geographic distances across strategical locations to provide every population sector and economic class with an affordable and effective alternative, also considering all discussions above.

Graphics

To complement all the literature review above, the data on TAMU EBs aided with a visual-friendly perspective on some related considerations for analyzing the EBs' operational performance. Figure 6 below represents real-world data performance of a TAMU EB (ID: 2102E) on a full day of service (June 22nd, 2023, from around 6:45 am to 6:25 pm):



6.a



6.b

Figure 6: Graphics for bus 2102E Speed (kph) & SoC (%) on 6/22/23 [made by HEVC using Power BI].

As a result, from Figure 6 it can be noted a near 60% discharge from a 12-hour continuous service. Beyond that, Figure 7 shows the behavior of battery power in watts as a function of current in amperes and voltage in volts, given a full day (12-hour continuous service) of discharging:

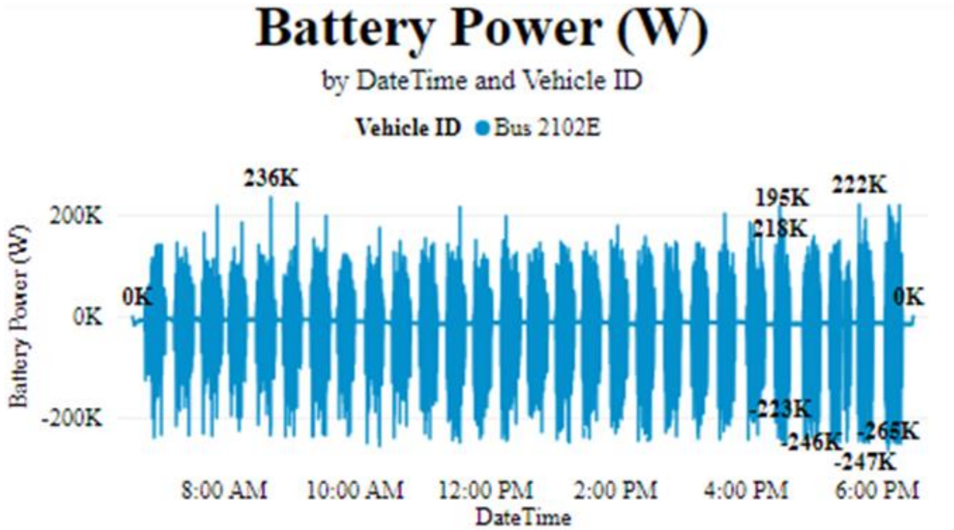
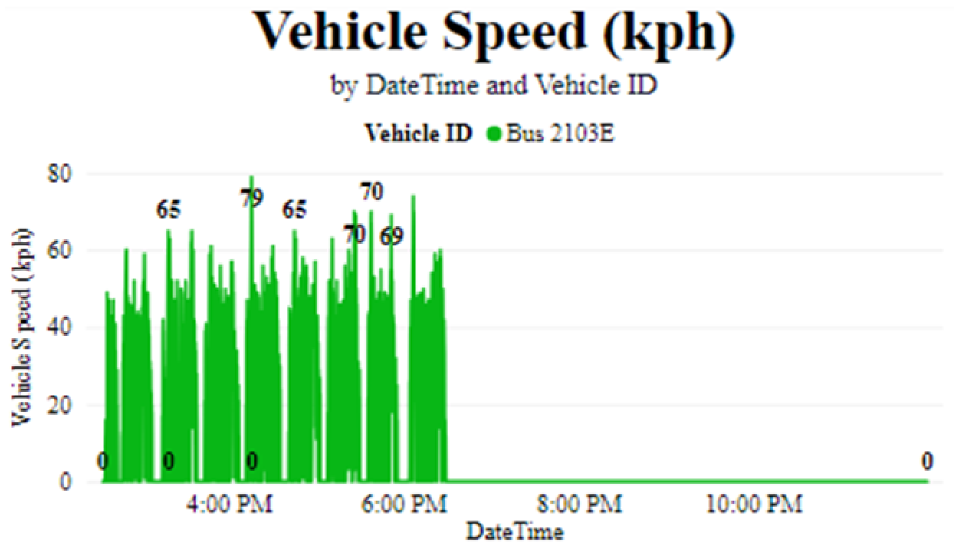


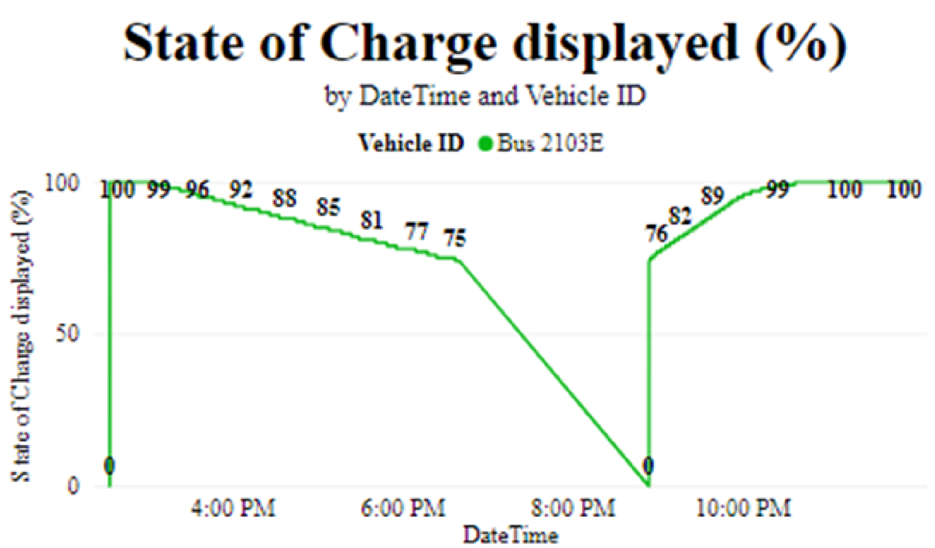
Figure 7: Graphic for bus 2102E Battery Power (W) on 6/22/23 [made by HEVC using Power BI].

The average battery power on a 12-hour continuous service day resulted in -24.7 kilowatts. That translates to an energy consumption (negative sign) of 296.4 kilowatts-hours. If this average consumption is rounded up based on engineering judgement, it means that a near 60% discharge will roughly equivalate to a 300 kilowatts-hours loss on a full day of service (12 consecutive hours).

TAMU EB (ID: 2103E) performance on a 4-hour continuous service day (June 26th, 2023, from around 2:30 pm to 6:30 pm) is represented in Figure 8 below, this one including an overnight charge:



8.a



8.b

Figure 8: Graphics for bus 2103E Speed (kph) & SoC (%) on 6/26/23 [made by HEVC using Power BI].

As a result, from Figure 8 it can be noted a 25% discharge from a 4-hour continuous service. Full recharge was then recovered in less than half of the service hours (from around 8:55 pm to 10:40 pm). Furthermore, Figure 9 shows the behavior of battery power in watts as a function of current in amperes and voltage in volts, given a 4-hour continuous service day of discharging with an additional 2-hour period of charging:

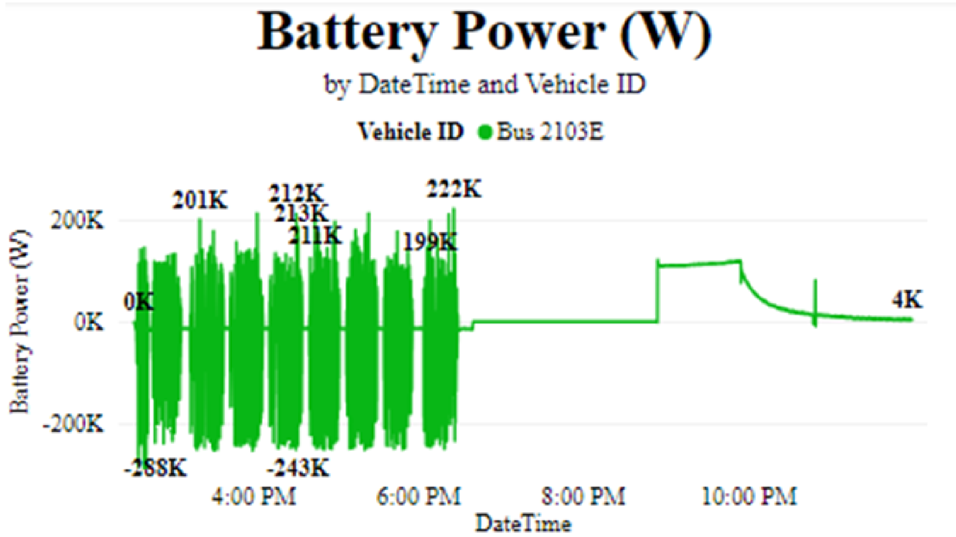


Figure 9: Graphic for bus 2103E Battery Power (W) on 6/26/23 [made by HEVC using Power BI].

The average battery power on a 4-hour continuous service day (i.e., discharging), including 2 additional hours of charging, resulted in 28.7 kilowatts. That translates to an energy production (positive sign) of 172.2 kilowatts-hours. This means that a 25% discharge on a 4-hour continuous service with a 2-hour recharge overnight was equivalent to an average energy gain of 172.2 kilowatts-hours. All these results provide a better understanding of what to expect in order to get into planning buses' systems, as well as for how direct current fast chargers work based on real-world usage data. It is important to note that all this data on TAMU EBs were collected during the summer, where demand of passengers (i.e., students) is at its lowest season. However, summer temperatures in Texas are accurately PR-like.

Conclusions

This research project analyzes the impacts that a tropical climate area such as PR has on the operational performances of EBs compared to DBs. The range advantage that DBs have over EBs can be compensated with proper usage of EMS that optimize EBs' range availability while providing the adequate cabin temperature to ensure passengers' comfort; also, while extending battery life of EBs because of using the least energy possible. Addressing charging infrastructure availability is essential in order to surpass the supply and distribution advantage that DBs currently have over EBs; and the reuse of already built spaces needs to be a priority over building brand new spaces. As shown in this paper, a full day of bus service (12 consecutive hours) will evoke a near 60% discharge, which was equivalent to a 296.4 kilowatts-hours energy consumption on a low-season day. This energy loss can be gained in less than half of the service hours that it took to discharge by using a direct current fast charger, as proved in another low-season day which consisted of a 4-hour continuous service day (i.e., discharging), including 2 additional hours of charging. This other day resulted in 172.2 kilowatts-hours of energy gain (production). Even though it was not explicitly addressed in this paper, all these issues, from range to power energy and charging, can be affected as well due to factors such as the road network and driver behavior in terms of speed, brakes, and accelerations. The insolated position of the island could lead to a safer grid connection through a renewable source such as solar energy. This reliable resource will provide a more resilient approach in case of outages occurring due to natural hazards events; and will likely influence public health and air quality to enhance by minimizing total emissions to the atmosphere even though this is not certainly guaranteed. Furthermore, PR's surface public/collective transportation' accessibility needs to be extended island wide in order to address other societal factors in its population. All these considerations will contribute to optimizing an ideal electrified mobility transition from DBs to low or zero emissions buses in a life-cycled perspective.

Recommendations

Research Gaps

- Studies on Earthquakes/Tsunamis' Impacts on Transportation: There is already a variety of studies regarding either hurricane-related weather events (i.e., rainfall, heavy winds, floods, etc.) or global warming-related issues (e.g., SLR, droughts, etc.) on transportation, but there is an evident research gap in contemporary studies for earthquakes' impacts on transportation power systems operating under extreme tropical climate environments. Indeed, earthquakes represent a significant hazard, which could be responsible for huge economic losses and human fatalities, also followed by potential tsunami alerts.

Resilience & Sustainability

- Leadership in Energy and Environmental Design (LEED): Implementing green and holistic concepts in, for instance, the recycling of refuel-purposed spaces to be renewed into charging infrastructure will optimize a healthier environment.
- EMS: Proper usage of EMS will increase range availability and battery life because of using the least energy possible [33,34].
- Solar Energy Resource: The insolated position of the island will lead to a safer grid connection and provide a more resilient approach in case of outages occurring due to natural hazards events [25,26]. Solar panels should be allocated in buildings' ceilings, leaving the still available land free to use for agricultural sectors in which they can coexist.
- Environmental Policies: There needs to be more political approaches supported by scientific approvals that can slow down global warming to 1.5°C, as called for in the Paris Agreement, in order to benefit of a 5-fold decrease in the population exposed to unprecedented heat [27].
- Mitigate to Be Prepared: Resilience is the capacity to anticipate, adapt, resist, and recover from adverse circumstances in a way that promotes a safe environment and a healthy future. For a system to maintain itself in the long term (i.e., to be sustainable enough), mitigation plays a significant role by keeping track and record of risks in order to have a better understanding of how to be prepared.

Data Analysis

- Real-world and Lab-simulated data: For future developments of this proposal, there are plenty of real-world and lab-simulated potential data to collect that could be useful in further extensions. The testing of environmental factors on the buses' operational performances could combine dynamometer technology with either a climatic chamber or any other simulators depending on the purpose to simulate them being driven under tropical weather conditions, which could range from 80°F to 120°F. Besides that, more data loggers need to be installed consistently on vehicles to keep growing databases and, therefore, knowledge.
- Broader Parameters & Analysis: Following Table 1, there are more considerations within and beyond the general parameters established for this project that are going to be an essential part if an extended analysis arises. Furthermore, the analysis of pros and cons

needs to be detailed with accurate mathematical expressions and calculations. The voltage and current function is translated into consumption/production data as exercised in this paper, and this need to be studied in relation to speed, brake and acceleration data to obtain a wider understanding of their consequential impacts on performance.

For Society

- Island-wide Accessibility: Island-wide accessibility will impact on the population positively if planned properly. This network could give a wider inclusiveness to all regions and economic classes of the island's population.
- Walkability, Convenience & Comfort: Briefly walking from one bus stop to another will promote humans to do more physical activities, therefore enhancing public health. There should also be a strategic alignment for people to have more flexibility within their hours, giving more time availability because the functional buses' route planning eases that saving of time. Additionally, proper usage of EMS could ensure passengers' comfort in terms of the AC system' management [33,34].

For the Surface Public/Collective Transportation System

- SJMA-Ponce-Maya Route Connection: This potential bus route network would provide a better island wide connection to address the 60% of PR's population left aside [6].
- Multi- & Inter-Disciplinary Approach: To solve climate change and other contemporary issues, every discipline has its own useful perspective to contribute in order to address the transition in the most inclusively effective ways possible.

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