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Smart City: A Mobility Technology Adoption Framework Incorporating Surface-Level Technical Analysis

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Abstract

Rising urban population, aging infrastructure, and increasing capital maintenance costs call for more efficient use of limited available resources. To address these concerns, the use of technology for urban infrastructure management and operational efficiency comes naturally with emerging technological advancements. Although there have been analyses on how to conceptually design a smart city from the ground up, they are often less applicable in transforming existing cities into smart ones. Retrofitting existing infrastructures requires integration and synergies with existing systems. Given the broad scope of smart cities, this paper equips planners with surface-level considerations in adopting smart mobility solutions. This provides an avenue to assess project feasibility, risk management, and investment requirement. The process is presented via a replicable framework with a use case with simplistic approaches that do not require complex constraints or modeling. The framework streamlines how to deduce a feasible set of user-centric smart solutions, which are then ranked according to their impacts for implementation priority. Middle East Technical University campus located in Ankara (Turkey) is considered for the use case. The main outcomes for the use case are deducing high-impact smart solutions based on the proposed framework. Preliminary system design analyses are showcased for three high-ranked solutions: electric vehicle charging station installation and investment optimization, autonomous electric shuttle system design, and bus network electrification strategies.

Keywords

Smart Campus, Smart Mobility, Smart Transportation, Electric Vehicle Charging Stations, Electric Autonomous Shuttles, Electric Buses

1. Introduction

A smart solution is the use of technology to streamline operational efficiency, sustainability, cost savings, and system integrity. However, the definition of "Smart City" is deemed to be a moving target-what was considered smart several years ago and may no longer be considered smart today.

A review of smart city-related papers is done to observe mutual domains across various definitions. Common recurring domains are technology, sustainability, productivity, and innovation (Bıyık et al., 2021; Yigitcanlar et al., 2019). The smart city is also asserted as the utilization of Information and Communication (ICT) to enhance performance efficiency (Silva et al., 2018). Despite various definitions of smart cities, they all have a common goal (Yigitcanlar et al., 2018), which is to address urban challenges such as service shortages and operational inefficiencies.

The global market size for smart cities is projected to extend to USD 463.9 billion by 2027 (Grand View Research, 2020). Smart mobility, a sub-segment of the overall market, is projected to be valued at USD 70.46 billion by 2027 (Singh & Mutreja, 2020). Such staggering market size is attributed to a rising urban population, which puts pressure on more efficient use of limited resources and capacity utilization. Notably, various stakeholders may have different visions and emphasis on development goals (Bıyık et al., 2021; Yigitcanlar et al., 2019). This incoherent visioning fundamentally drives away synergies between smart solutions, and is sidetracked by lavish conceptual visions (Angelidou, 2014), without tangible benefits to end-users. Smart city projects are also capital intensive, regardless of the development strategy: either transforming a traditional city or developing a smart city from scratch (Angelidou, 2014). For over a decade, several cities across the world are still a "work in progress" in pursuit of the desired outcome (Yigitcanlar & Lee, 2014). This reflects the lack of integration between academic theories with industry practices. In addition, most smart systems are developed in silos, which requires building the overall smart city ecosystem from the bottom up. Ultimately, real-world practices often outstrip academic analyses (Lee et al., 2014). There have been analyses on how to conceptually plan or design a smart city from the ground up, but they are less applicable in transforming existing traditional cities into smart ones. Transforming traditional cities requires retrofitting existing infrastructures via integration and synergies.

A replicable use-case-supported framework to transform and facilitate existing cities to adopt smart solutions is absent. Thereby, making it hard for planners to adopt smart solutions. There have been comprehensive System Engineering theories proposing consumer-driven system designs (Hari et al., 2002), but simplification of system design process is needed to harness vision and collaboration between laypersons and experts (Porru et al., 2020). Thus, there is a need for a simplified and adoptable framework that is substantiated with surface-level analytical procedures, for planners to peruse in assessing project feasibility, and investment requirement and essentially gauge interests from various stakeholders. This surface-level analysis is a crucial step before investing resources in system design.

Focusing on the transportation domain, this paper presents end-to-end practical and adoptable framework to understand what smart solutions are impactful for stakeholders and users, how to prioritize them, and strategize their deployment. A use case is then presented as a framework walkthrough for Middle East Technical University (METU) campus. Processes commence by understanding the built environment, and assessing current systems. A feasible set of smart solutions are then deduced based on understood demand and supply gap, which are then ranked through a ranking methodology to identify high-impact smart solutions. Several system deployment strategies for top-ranked solutions are then shown in greater depth, supported by simple technical analyses and numerical results.

The innovative value proposition of this paper includes a user-centric system selection mechanism, and several technical analyses with surface-level considerations, that do not require complex constraints or modelling, rather a simplistic approach with minimal data requirement. These analyses can be adopted by planners to gauge initial system design requirements. The main contributions of this study are as follows:

- Presents an adoptable framework for smart campus transformation and smart mobility solution design.
- Surface-level analytical models with minimal input requirements are developed and implemented for three case studies. These models are replicable by planners to understand preliminary system requirements.

2. Research Framework

There exist various established system development models, such as waterfall, agile and lean method. While each method carries its own merit, they each have its disadvantages. Therefore, there has been a study that develops hybrid models merging best practices (Lalmi et al., 2021). There has also been a specific-use model tailored towards smart city transformation that accounts for the complexities exclusive to smart city planning (Secinaro et al., 2021).

This paper proposes a codified common sense of which a smart city transformation is to be approached by planners, manifested through a practical and replicable framework, developed to optimize investment cost for users' benefit. Main goal of this framework is to systemize the understanding of existing systems and their unmet demands, ultimately to excogitate a set of high-impact smart solutions. Presented framework portrays the correlation in sequential manner in which development is suggested to be approached. The framework is coordinated into three modular phases as Figure 1.

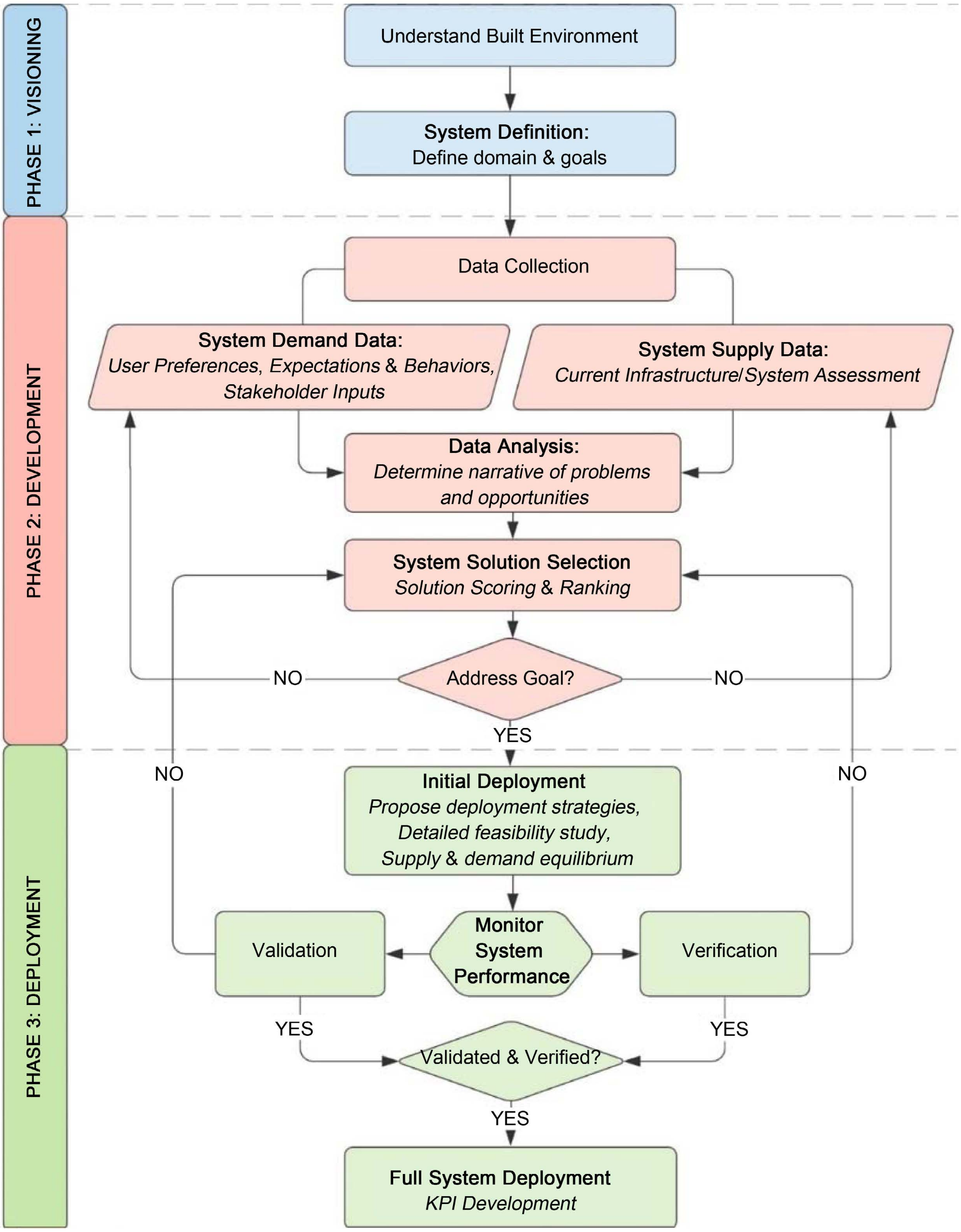


Figure 1. Smart campus transformation conceptual framework.

2.1. Phase 1: Visioning

The main goal in this phase is to set focus and constraints around project development. The process commences by understanding the built environment, where the smart solutions are to be deployed. Various classifications of the built environment provide a facet of understanding to the overall landscape. Classifications include geographic, local policies, underlying economic activities, demographic, and mobility patterns.

Subsequent step is to define domain and goals. It is imperative to center planning initiatives on a specific domain, which can be defined as the area of interest, mobility, energy, safety, healthcare, etc. Defining a domain enables planners to identify domain-centric stakeholders and constraints to provide an articulated project scope. It can also ensure financial feasibility, given a finite funding and varying levels of interest from funding entities. Selectivity, synergy, and prioritization are imperative to avoid being sidetracked by lavish developments. Project goals can then be outlined based on stakeholder requirements, within the defined project domain.

2.2. Phase 2: Development

Next phase is to develop a data collection plan consistent with domain and goals defined in Phase 1. Two types of data, system demand and supply, act as two ends of a balanced scale. Demand data are indicators of users' expectations, preferences, and behavior, along with stakeholders' requirements. User surveys may be conducted to understand perception toward existing systems and preferences or expectations for system improvement. Stated and revealed preferences need to be analyzed to identify effective factors leading to users' choices (Soltanpour et al., 2020). Reciprocally, supply data includes specifications of existing infrastructure or systems in place, and how are they being utilized. Analyses such as system capacity, utilization rate and life cycle may provide an understanding of existing systems. A holistically-narrated view weaved from demand and supply data can be used to identify gaps, and subsequently assess how smart solutions can intermediate. Life cycle analyses should also comply with the industry life cycle standards such as ISO/IEC/IEEE/15288 (International Organization for Standardization, 2015), but for the purpose of this research, it only aims to facilitate preliminary analyses.

Given finite resources, not all solutions are feasible to be implemented at once, which calls for a solution ranking approach to determine which solutions should be prioritized. Note that users' preferences and the system supply performance are correlated, and they may both alter in response to the implemented solutions. Thus, at the system solution selection step, planners need to project any potential demand and supply changes due to implemented solutions, and revisit the system design iteratively until an optimized set of solutions can be synergized.

2.3. Phase 3: Deployment

Upon selection of solutions to be implemented, planners need a mechanism to assess their impacts before being fully deployed. Being able to analyze utilization and performance data of implemented system throughout deployment period is a crucial step to mitigate the risk of over or under-designing the system. Additionally, given the rapid nature of new technologies' development, what was relevant at time of planning and may no longer be as relevant by final implementation. Hence, it is crucial to keep the proposed solutions up-to-date. Deployment strategies include:

- *Incremental implementation*: System deployment in tranches enables performance monitoring over time and make projections, whether it can achieve intended goals upon the full deployment.
- *Small-scale implementation*: System deployment in a smaller scale provides meaningful interim data to be observed against the intended impacts of fully deployed solutions. This allows system design enhancement towards full deployment.

Throughout the implementation period, it is essential to validate and verify the system solutions. System validation is ensuring the right system is built according to demands, while system verification determines if the system was built right, according to project goals, industry standards and upgrade capabilities. Planners need to constantly verify if proposed solutions address the pre-determined project goals, and validate that an appropriate system was built based on demands.

3. Case Study

In this section, Middle East Technical University (METU) is chosen for a case study to present a walkthrough of the proposed framework (**Figure 1**). This case study showcases adoptability of the proposed framework and presents a guideline to planners on how to streamline smart campus transformations.

3.1. Phase 1: Visioning

3.1.1. Understanding Built Environment

The campus land area spans across 11,100 acres. It is a gated campus, with defined mobility boundaries, and low level external traffic. The main transportation mode is walking, as core academic areas are laid out on a flat topography. Recently, expansion for new academic and residential zones prompts for new developments on rolling terrains, which makes walking and biking challenging, and fuel demanding for vehicles. The campus accommodates 5000 employees and 22,000 students. It encapsulates a wide array of operations including academia-based, retail, commercial, and recreation.

3.1.2. Define Domain and Goals

METU Strategic Plan 2018-2022 entails development visions across various domains, from management efficiency, to building energy, and transportation (Middle East Technical University, 2017), of which, the transportation domain is selected for this study. In this regard, one specific goal was adopted from the blueprint to as the core goal: "*Improving on-campus transportation system in an environmental sensitive, energy efficient, intelligent, unobstructed, accessible, safe manner with a mass transportation system by reducing private vehicle traffic, providing the necessary physical infrastructure to encourage pedestrian and bicycle circulation*".

3.2. Phase 2: Development

3.2.1. System Demand and Supply

A comprehensive mobility survey is conducted to obtain information on the system demand. The survey entails 50 questions on various topics related to existing mobility services. Survey design principle revolves around understanding current mobility trends and stated preferences over various hypothetical mobility scenarios. Topic includes opinions on autonomous vehicles, mode choices on campus, bus usage and electric vehicles. Detailed survey structure and topics explored are presented in Table 1. Survey are distributed both with physical copies

Table 1. Classification of mobility survey questions and explored topics.

Classification	Topics	Details Explored
Autonomous Vehicles (AV)	Travel Route	Desired Origin-Destination
	Opinions	Willingness to use AV
		Perceived safe operating speed
Mode Choice	Factor	Being Private vs Public option
		Cost, Comfort, Time, Reliability, Safety
	Frequency of use	Usage frequency for various mobility modes on campus
	Opinions	Campus walkability
		Campus Biking & Hitching
Bus Usage	Frequency of Use	Routes most used
		Opinions on non-bus users
	Factors encouraging use	Opinions on features of the bus app
		What would encourage a more frequent bus use
	Smart Infrastructure	Smart Mobility App Features
		Smart bus stop Features
Other Mobility	Car Sharing	Willingness to use Intra-campus car sharing
		Type of vehicles preferred
	Micro mobility	Location of docking station
	Parking	Highly used parking spaces
		Preferences for off-campus parking lots
Electric Vehicles (EV)	Preferred Incentive	Elasticity to adopt EV with various incentives
	EV Adoption	Factors deterring adoption
		Opinions on Hybrid as an alternative

and online, through various mechanisms that is strategized to capture responses from students, academics and administrative personnel. The total number of respondents is 1155 with 73% online respondents and 27% in-person interviews. Response size is approximately 5% of the campus population. General narrative extracted from the conducted survey provides the general perception towards the existing mobility infrastructure, smart infrastructure expectation, and stated preferences over various topics. For this paper, only relevant subsections of the survey results will be discussed, consistent to analysis topics.

System supply is assessed by reviewing the campus current infrastructure capabilities and limitations. This assessment includes traffic operation, pedestrian and bicyclist safety, parking operations, ICT capabilities, and campus ridesharing. There are several published papers (Alayli, 2006; Altintasi, 2013; Altintasi & Tuydes-Yaman, 2016; Altıntaşı & Tüydeş Yaman, 2016; Gulluoglu, 2005; Karatas, 2015; Karatas & Tuydes-Yaman, 2018) considering METU as their case study providing information on the system supply. These papers are also used to explore additional information regarding system demands.

3.2.2. Data Analysis: Assessment of Current Systems

In this section, various elements of the campus transportation system are assessed qualitatively and quantitatively. This is imperative to identify existing issues and define a feasible set of smart solutions. For example, several aspects of infrastructure assessment done in 2019 include:

- Campus intersections are not equipped to provide traffic data.
- Bus system maximizes coverage instead of headway. System suffers from schedule deviations.
- Fiber optic network is available throughout campus, but no campus-wide Wi-Fi available.
- There are 81 parking areas providing 2583 spaces.
- Insufficient bike lanes on campus due to the limited roadway width.
- Majority of vehicles operated are private vehicles.

3.2.3. Feasible Set of Smart Solutions

A narrative of problems, demands, and opportunities are understood through survey outcomes, engagement with stakeholders and comprehension of existing infrastructures. A list of feasible set of smart solutions is then outlined, as per **Figure 2**.

3.2.4. System Solution Selection

A preliminary step in selecting high-impact solutions is to map proposed solutions against pre-defined goals (**Figure 2**). Solutions with more linkages to various goals deserve higher merits for prioritization. To assess impacts of each solution on each goal, impact indicators are defined and quantified. Then, a ranking methodology is developed to determine which solution should be prioritized for implementation. This process determines an overall ranking of solutions and

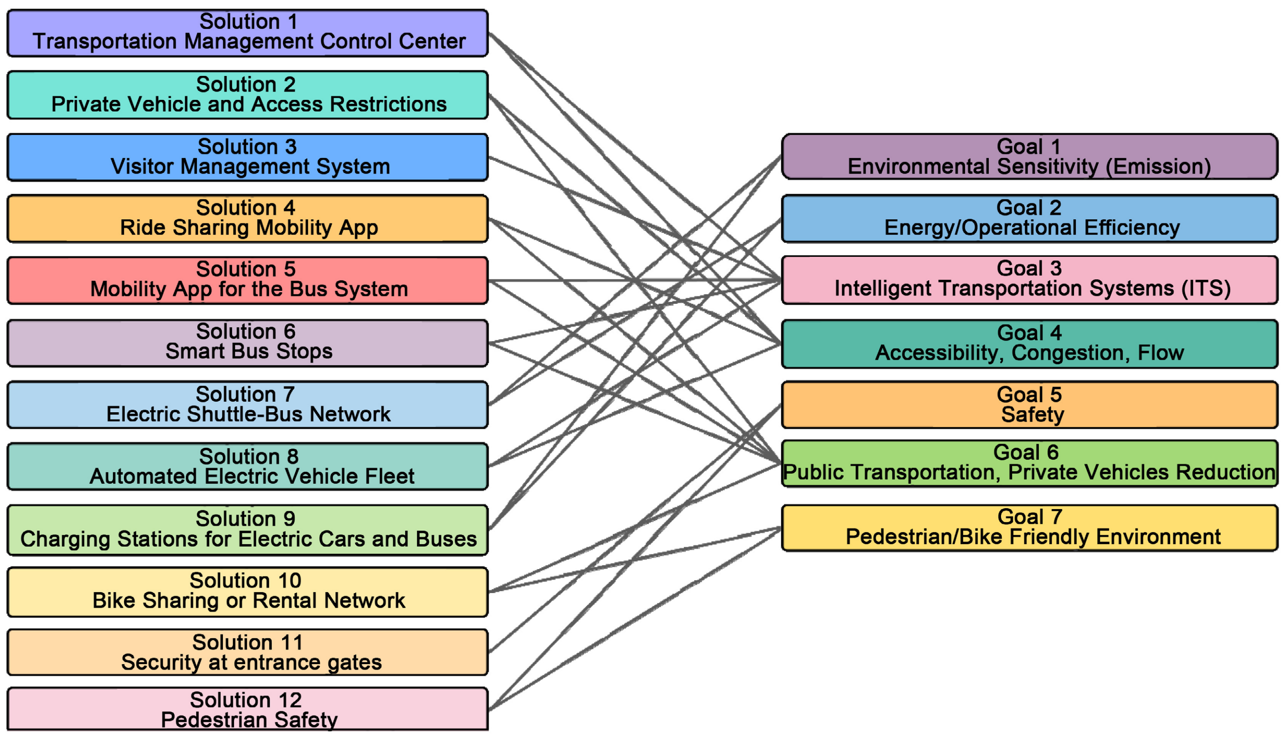


Figure 2. Corresponding proposed smart solutions with project goals.

identifies its priority. Impact indicators are assessed in two formats: a binary approach with 0 or 100 score, and a three-level impact with 50, 75, and 100 scores. Then, for each solution, the weighted average score is measured over all indicators defined by stakeholders (Table 2). Finally, solutions are ranked based on their scores to indicate prioritization. Based on this ranking, system planners may justify solutions selection depending on available budget. Detailed benefit/cost analyses or feasibility studies can further be done for top-ranked solutions.

3.3. Phase 3: Deployment

In this section, three stages of the deployment phase are discussed: initial system deployment, validation and verification, and full deployment. The initial system deployment and full deployment strategies are presented with a simple technical analysis for three selected smart solutions, namely, developing EV charging infrastructure, system design for autonomous electric shuttles, and fleet electrification of the bus system. These three solutions are ranked 1st, 2nd and 4th in the solution impact matrix (Table 2) and chosen for further analyses due to their high environmental impact scores.

3.3.1. Initial System Deployment

System Analysis 1: EV Charging Stations

To determine the optimum number of chargers, system users' trip length distribution to access the campus (obtained from mobility survey respondents

Table 2. Proposed solutions and impact indicators matrix.

Project	Cost* (WF: 1)	Emissions Reduction (WF: 0.75)	Cost Saving* (WF: 1)	Revenue Generation (WF: 1)	Technical Feasibility (WF: 0.75)	Technology Risk (WF: 0.75)	Budget (WF: 0.75)	Environmental Impact (WF: 0.75)	Demand (WF: 1)	Score
Charging Stations for Electric Cars & Buses	Medium	Yes	High	Yes	Yes	High	Yes	High	High	**79**
Electric Shuttle-Bus Network	High	Yes	High	Yes	Yes	High	Yes	High	High	**76**
Bike Sharing or Rental Network	Low	Yes	Low	Yes	Yes	Low	Yes	Medium	Medium	**76**
Automated Electric Vehicle Fleet	High	Yes	Low	Yes	Yes	High	Yes	High	Medium	**68**
Mobility App for Bus System	Low	No	Low	Yes	Yes	Medium	Yes	Medium	High	**68**
Smart Bus Stops	Medium	No	Low	Yes	Yes	Medium	Yes	Medium	High	**65**
Ride Sharing Mobility App	Low	No	Low	Yes	Yes	Medium	Yes	Low	Medium	**63**
Visitor Management System	Low	No	Low	Yes	Yes	Low	Yes	Low	Low	**63**
Private Vehicle & Access Restrictions	Low	Yes	Low	No	Yes	Low	Yes	Medium	Low	**62**
Transportation Management Control Center	Low	No	Low	No	Yes	Medium	Yes	Medium	Low	**51**
Pedestrian Safety	Low	No	Low	No	Yes	Low	Yes	Low	Low	**51**
Security at entrance gates	Low	No	Low	No	Yes	Medium	Yes	Low	Low	**49**

WF: Weight Factor; Low < $500,000; Medium $500,000 to $1,000,000; High > $1,000,000.

living off-campus) is used to formulate an optimization problem. According to the mobility survey, 60% of participants plan to buy an EV sometime in the future. This stated preference is used as a surrogate value for EV market share among travelers. The campus records 15,000 average daily vehicle inflow. According to the conducted campus-wide survey, the minimum and maximum length of trips to access the campus are stated by survey participants as 1, and 25 miles with an average distance of 8.3 miles (**Figure 3**).

Differences between desired and remaining battery life upon reaching campus for all users are summed up to identify total required electric power demand that determines the required number of chargers. Two classes of EV users are assumed in specifying desired battery charge based on the availability/non-availability of chargers at home. Then, each class is further subcategorized into sub-classes based on their remaining battery charge upon reaching campus, 20%, 40%, 60% and 80%. For users with access to chargers at home, their available battery power is assumed to be able to support a round trip from home to campus. For others, it is assumed that campus chargers are the only available source of charging. Detrimental impact of adverse weather (winter season) and minimum range of battery level (10% to 20% of capacity) are also reflected as a factor. To identify the number of chargers, following optimization problem is defined:

$$\min B = \sum_{t=1}^{T} b_t n_t^y \tag{1}$$

$$\text{s.t. } \sum_{t=1}^{T} n_t^y p_t \tau_t = \sum_{t=1}^{D} \sum_{c=1}^{C} \max \left\{ \rho_y \gamma_c N_y \delta_i \left(\sigma \lambda_c d_i - \eta r_c \right) \middle/ \left(\sum_{j=1}^{D} \delta_j \right), 0 \right\} \tag{2}$$

Table 3 presents the notation and assumed values for each parameter and variable in the formulation. The objective function is the required budget to install chargers, which is aimed to be minimized. The constraint is the power conservation equation. Left and right-hand sides of the equation indicate the total electric power delivered by the chargers, and the total electric power required to serve the EVs, respectively.

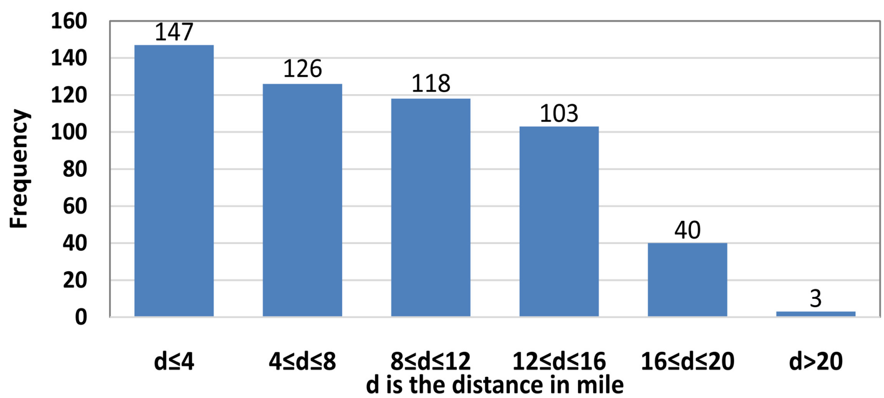


Figure 3. Toward-campus trip length distribution.

Table 3. Formulation notations.

#	Definition	Value
n_t^y	Total number of charger type t by year y	Decision Variable
b_t	Installation and infrastructure cost for a unit of charger type i	Level 2 = 2 K USD; Level 3 = 40 K USD
p_t	Power of charger type t (based on the existing charging technologies)	Level 2 = 10 kW; Level 3 = 50 kW
τ_t	Daily utilization hours of charger type t ($out\ of$ 10 $hours\ total\ daily\ operation$)	Design A: - charger Level 2 = 10 hours - charger Level 3 = 10 hours Design B: - charger Level 2 = 5 hours - charger Level 3 = 10 hours Design C: - charger Level 2 = 5 hours - charger Level 3 = 5 hours
T	Number of charger types	2 (Level 2 and Level 3)
C	Number of EV user categories (*Category code-Home charger availability-Battery level upon reaching campus*)	Class 1 - Yes - 20% Class 2 - Yes - 40% Class 3 - Yes - 60% Class 4 - Yes - 80% Class 5 - No - 20% Class 6 - No - 40% Class 7 - No - 60% Class 8 - No - 80%
ρ_y	Penetration rate of EV in year y (determined based on the stated preference from the conducted survey)	60%
γ_c	Penetration rate of category c (needs to be identified after the implementation, uniform distribution is used here)	12.5% (uniform distribution on all 8 categories)
N_y	Total daily campus inflow in target year y (per year inflow reported by the gates RFID readers)	15,000 veh/day (12,000 veh/day for 2015 with 5% growth rate till 2020)
η	Battery power (for the new generation of EVs)	70 kWh
r_c	Remaining battery life in percentage for category c	Assigned based on C
σ	Average electricity usage efficiency of EVs	0.34 kWh/mile
λ_c	Distance adjustment factor for category c (a safety factor to ensure that the users will have enough battery power to make their trips)	2 for users with access to EV chargers, and 6 for other users
d_i	distance traveled by users of distance-distribution category i between their living area and campus (median values)	Refer Figure 3
δ_i	Frequency of distance-distribution category i	Refer Figure 3
D	Number of distance-distribution categories	6 (refer Figure 3)

To capture the discrepancies in implementation and usage of the chargers, three different design classifications are tested. Design A assumes that charging spaces would be evacuated once the battery reaches desired state of charge. This is monitored by applying a penalty function on the system fee once parking duration exceeds the required time to reach the desired state of charge. Design B and C assumes an inefficient use of chargers such that charging spaces would not be evacuated exactly when batteries are fully charged, thus causing delay in power delivery and reduce system proficiency. Assuming a 10-hour total daily operational time, Design A considers a utilization of 10-hour for each Level 2 and Level 3 chargers (100% utilization time). Design B assumes a utilization of five-hour for Level 2 chargers (50% utilization time) and 10-hour for Level 3 chargers (100% utilization time). Design C assumes a utilization of five-hour for each Level 2 and Level 3 chargers (50% utilization time).

A Simple linear optimization tool (MATLAB) is employed to solve the proposed analytical model utilizing input parameters in Table 3. The number of required EV chargers corresponding to each design classification, their budget and installation phases is depicted in Figure 4. It can be observed that the number of chargers and installation cost for Design A and Design C are optimized with only Level 2 chargers, while Design B optimization yields only Level 3 chargers. Note that these numbers of chargers are estimated to cover electricity power demand at a single design year in the future to meet the 60% market penetration rate of EVs. A multi-stage development should be considered in this regard. Presented analysis is simplistic in nature, which is meant for preliminary system design and understanding investment requirements. Further technical

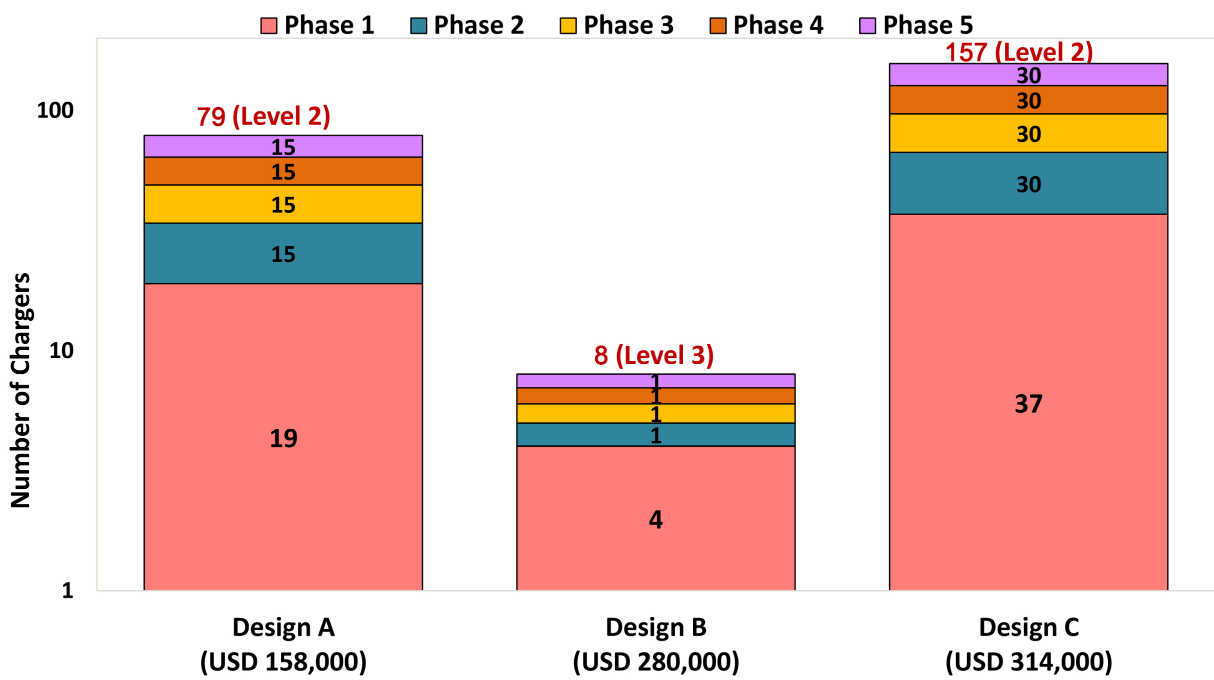


Figure 4. Cost, installation plan, and number of chargers required for each system design.

design for charging station placement optimization that considers trip trajectories and wider array of parameters could be utilized in order to obtain a more operational investment cost and system requirements (Fakhrmoosavi et al., 2021; Ghamami et al., 2020; Kavianipour et al., 2021).

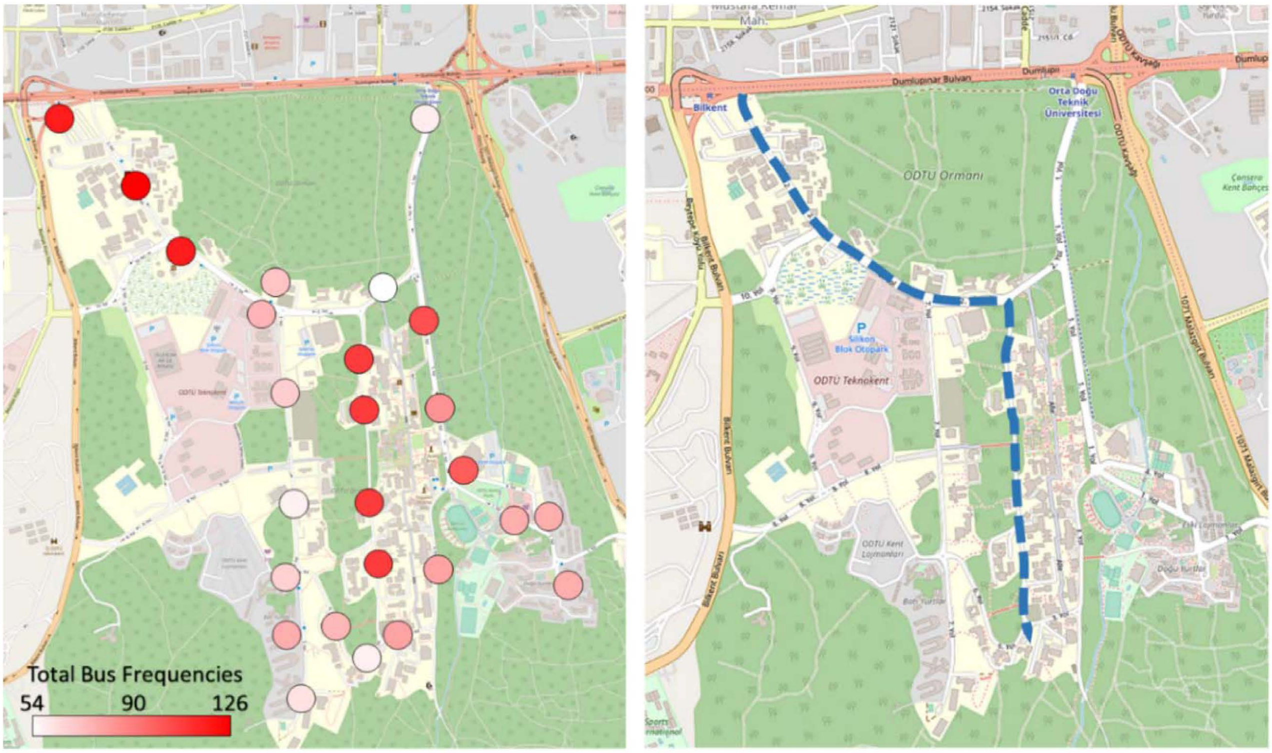
System Analysis 2: Autonomous Electric Shuttles

To design an autonomous electric shuttle system, first a proper route for autonomous shuttles is to be identified based on the current bus service network as a surrogate for the system demand distribution. Then, analyses of ridership and emission savings are presented. Lastly, trade-off analyses of implementation and operation costs for these autonomous shuttles are compared with required investment to serve similar demand with diesel buses.

Identifying a proper route for autonomous shuttle operation requires several considerations. First, the selected route should be traveled with minimal number of maneuvers (left/right turns and intersection crossings) to accommodate a simplified maneuverability of autonomous shuttles. Second, the route should use as much ridership capacity as possible, due to the significant required investment for such systems. The third important factor is the route length that controls the system cost. Although choosing a longer route covers more locations and resulting in higher ridership, it increases the headway (travelers' waiting time) and implementation cost (due to fast charging requirement). So, the length and path of the route should be identified in a way that the benefits of the system deployment outweigh these costs. In addition, the system should provide an adequate coverage to serve the main origin-destination pairs of the campus.

Determining a route that includes the highest number of transit travelers (demand) on campus is the first step. Since there is no recent study providing trip distribution over the campus, the total bus frequency at each station is used as a surrogate to identify the route with the maximum demand for transit users. The stops with their serving routes and total frequency are illustrated via a spectrum color code in **Figure 5(a)**. This figure indicates that the route starting from the North-West of the campus, where a metro station entry is located, crossing the campus main roundabout, and extending toward south is the route with the highest bus frequency, illustrated in **Figure 5(b)**. This route does not require any complex maneuver, crosses only few intersections and roundabouts, and is about 1.8 miles long. Importantly, the proposed route also covers zones with highest travel demand based on a recent trip distribution study (Alayli, 2006).

Next step is to understand proposed system ridership capacity relative to incumbent bus ridership capacity. In this section, the ridership capacity is analyzed regardless of the temporal and spatial distribution of the passenger demand. Assuming an operation speed of 25 mph (average design speed of autonomous shuttles in the market), a trip can be traveled in 4.5 minutes in the proposed route (with length of 1.8 miles). Considering 10 stops with 30 seconds dwell time at each stop (reasonable value for a shuttle with 10-passenger capacity), the total stoppage time will be three minutes. Assuming one and half minute



(a) (b)

Figure 5. (a) Total bus frequency at each stop, (b) route proposed for autonomous shuttles.

marginal time for possible delays, the route travel time will be nine minutes in total. As the shuttle is driverless, it can be operated continuously with 9-minute headway. Therefore, for the eight hours of operating time, a single shuttle can make more than 50 trips. Then, a shuttle with 10 passenger capacity can serve a maximum of 900 passenger-miles in a day (50 trips × 10 passengers × 1.8 mile). In comparison, a bus with passenger capacity of 50, needs to accomplish 10 trips to provide 900 passenger-miles ridership to match estimated capacity of a single automated electric shuttle.

The average battery size of automated electrical shuttles accommodates around nine hours of operations, which is adequate to serve daily operating hours uninterruptedly (for charging) and thus there is no need for a Level 3 (fast) charger installation. However, a Level 2 charger should be installed for each shuttle to be used over non-operational hours at their parking spaces, providing a fully charged battery overnight. Overnight charges could also avoid day-time peak electricity demand and benefit from lower off-peak electricity rate. This also avoids imposing additional energy load on the grid, in hope that no grid capacity upgrade would be necessary.

Considering the Carbon Dioxide (CO_2) emission rate of 75 gram per mile for a diesel bus (Karatas & Tuydes-Yaman, 2018), the equivalent diesel bus produces around 1.35 kg CO_2 per day covering the proposed route with the length of 1.8 miles. Therefore, this amount of CO_2 emission can be reduced in a day by introducing a single electrical autonomous shuttle to the proposed route. A comparison of cost breakdown between an electric shuttle and a diesel bus is illustrated in Table 4. Different components of the costs are calculated for the proposed route to be served with the electric autonomous shuttle versus the alternative diesel bus. For a fair comparison, the cost associated with 50 trips made by an electric shuttle is compared with the cost associated with 10 trips made by a diesel bus.

According to Table 4, the total daily cost associated with an electric autonomous shuttle and an alternative diesel bus (operational costs of fuel and maintenance, excluding the purchase cost) are $6 and $60.05, respectively. Considering 250 business days in a year, these values turn into the annual costs of $1500 and $15,000. Assuming 10 and 20-years lifetime for the autonomous electric shuttle and diesel bus, and considering no expected salvage value and an interest rate of 4%, the net present values for the two systems are −$640,000 and −$804,000, respectively. This shows superiority of autonomous electric shuttle relative to the alternative diesel bus in terms of purchase and operating costs, in addition to the aforementioned emission-saving benefits.

System Analysis 3: Bus Fleet Electrification

In this section, a design for electrifying bus network project is provided. First, general specifications of the campus bus network are presented. Then, generated emission by the current bus system is estimated, followed by electric energy consumption for each route if diesel buses are replaced by electric buses. Based on the required energy and generated emission, a strategic plan is provided to electrify the bus network over a 10-year time period including the level 2 charging stations that are needed to support these EVs.

The campus contains 11 bus routes, with total route length of 50 miles. Each

Table 4. Autonomous electric shuttle versus diesel bus cost breakdown.

	Electric Shuttle	Diesel Bus
Purchase Price	$250,000	$600,000
Fuel/Electricity Cost	$3 per day[a]	$12 per day[b]
Maintenance Cost	$3 per day[c,*]	$10 per day[d]
Social Cost of CO_2 Tailpipe Emission	0	$0.05 per day[e]
Operator Wage	0	$38 per day[f,g]

a) 0.11 USD/kWh × 0.34 kWh/mile × 1.8 mile/trip × 50 trip/day = 3 USD/day. b) 3.3 USD/gallon × 0.2 gallon/mile × 1.8 mile/trip × 10 trip/day = 12 USD/day. c) 0.03 USD/mile × 1.8 mile/trip × 50 trip/day = 3 USD/day (Fitzgerald et al., 2017). d) 0.55 USD/mile × 1.8 mile/trip × 10 trip/day = 10 USD/day (Guo, 2016). e) 0.04 USD/kg CO_2 × 0.075 kg CO_2/mile × 1.8 mile/trip × 10 trip/day = 0.05 USD/day. f) From Equation (1) travel time of the bus in the proposed can be calculated as: TT = 1.8⁄2.5 + 5 × 2⁄60 = 15 min. g) Driver wage will be: 15.16 USD⁄hour × 0.25 hour⁄trip × 10 trip⁄day = $38 USD/day. *Values do not reflect battery deterioration cost.

route is coded by color names. Route specifications such as route length, number of stops, frequency, number of buses serving the route and headway route are gathered for analysis. The speed limit is 30 mph campus-wide. Considering frequent decelerations and stops at intersections and stations, an average speed of 25 mph is assumed for bus operations. An average dwell time of 2 minutes is also assumed for all bus stops (Fricker, 2011). With these simplified assumptions, the average travel time of a bus in a certain route is estimated as follows:

$$TT_i = \frac{L_i}{U_i} + \left(B_i \times DT\right) \tag{3}$$

where,

TT: average route travel time of route *i*.

L: length of route *i*.

U: operational bus speed at route *i*.

B: number of stops in route *i*.

DT: dwell time at stops.

Based on the average travel time obtained from Equation (3), the daily maximum transit capacity of each route is calculated. Assuming a passenger capacity of 60 per bus, the maximum transit capacity (passenger-mile per day) is calculated by multiplying passenger capacity of each bus with bus frequencies and length of routes.

Next is to understand the emission production and fuel consumption of diesel buses. Assuming a diesel bus uses 0.2 gallon of fuel and produces 75 gram of CO_2 per mile, multiplying these rates with length and frequency of the routes provides the total daily emission production and fuel consumption. To calculate the share of each bus, these values are divided by the number of buses operating in each route:

$$E_i = \frac{e \times L_i \times \lambda_i}{B_i} \tag{4}$$

$$F_i = \frac{f \times L_i \times \lambda_i}{B_i} \tag{5}$$

where,

E_i: daily produced emission by a single bus in route *i*.

F_i: daily fuel consumption by a single bus in route *i*.

e: emission production rate (CO_2 gram per mile).

f: fuel consumption rate (gallon per mile).

L_i: length of route *i*.

λ_i: bus frequency (number of departures) in route *i*.

B_i: number of buses operating in route *i*.

Figure 6(a) illustrates the total daily produced emission for each route, and emission production by a single bus in each route. Note that there is a direct correlation between fuel consumption and emission production. Intuitively,

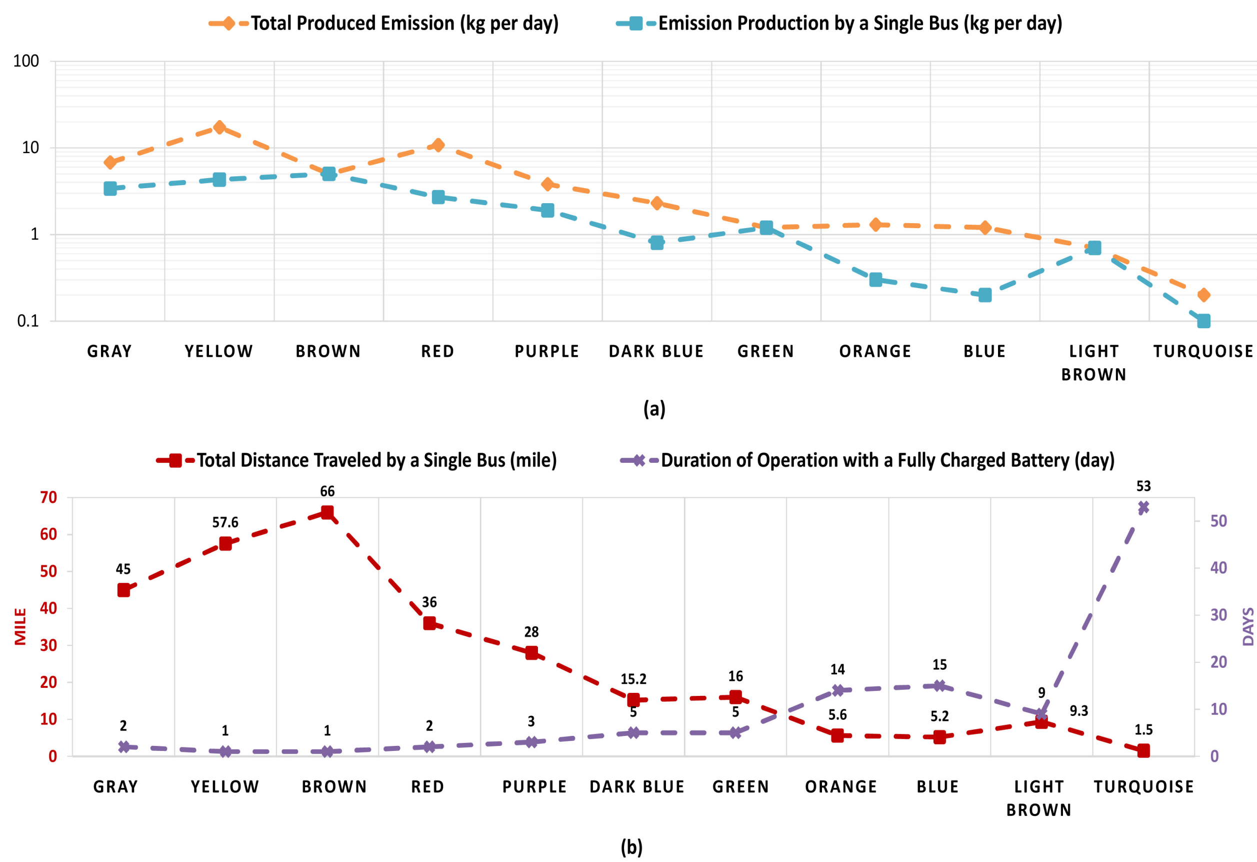


Figure 6. (a) Total daily emission production and fuel consumption in each route, (b) Total daily traveled distance, travel time and fully-charged operational duration for each bus.

routes with higher potentials for fuel consumption savings and emission reduction should have higher priority to be electrified. According to Figure 6(a), the route with highest priority for electrification is Brown Route, followed by Yellow, Gray, Red, Purple, Green, Dark Blue, Light Brown, Orange, Blue and Turquoise Route. To determine the required numbers and types of charging stations supporting the electric bus network, first the required daily energy is estimated and compared with available battery capacity for each operating bus. This is identified by assessing the operation time and traveled distance of a bus in each route and comparing those values with the operating range (battery range) of electric buses. Based on this comparison, the required charging technology (Level 2, Level 3, or battery swapping) for each route can be determined. If operational range for any given bus in each route can serve at least 1-day of operation, no fast charging is required as they can be charged overnight.

Based on the operational details**,** multiplying the number of trips that a single bus makes in a day by the length of the route provides the total distance traveled by a single bus, as per Figure 6(b). A typical operation range of a 40-foot electric bus in the market is between 90 to 150 miles depending on weather condition, road specifications (grade and super-elevation), and driver behavior. It is assumed that the battery of an electric bus needs to be recharged before it drops below 10% of its capacity. Therefore, the practical operation range of the electric bus in this study is assumed to be between 80 and 135 miles for a fully charged battery. Considering this range, the duration (number of days) that an electric bus can operate in each route before it needs to be recharged is calculated by dividing battery range with total distance travelled by a single bus. The sustainable operation duration by a single fully-charged battery is shown by a yellow-dotted line in **Figure 6(b)**. These values are calculated conservatively considering the lower bound of the battery range and are round to a lower integer value.

The red-dotted line in **Figure 6(b)** indicates that no Level 3 (fast charging) station is needed for the current bus routes, since a fully-charged battery can serve all routes for at least a full-day operation. Additionally, the maximum distance traveled by a bus in a day is 66 miles (Brown Route), which is less than the minimum range of an electric bus battery. Thus, it is proposed to install only level 2 chargers at the bus parking hub. Note that the electricity supply requirements during the non-operational hours should also be considered.

Next, a strategy for installation of Level 2 chargers over a 10-year planning horizon of the electrified bus network is developed. The operational duration of a fully-charged electric bus in each route is directly related to its total traveled distance. On the other hand, emission reduction and fuel consumption, which are the bases of route prioritization, are direct functions of the total traveled distance of buses in each route. Therefore, routes with higher priority of electrification require a greater number of chargers to be installed. In order to identify the minimum number of chargers required to supply the energy to operate electric buses in each year, Equation (6) is utilized.

$$N_Y = \left\lceil \sum_{i=1}^{Y} \sum_{j=1}^{R} \frac{1}{D_j} \times B_{ij} \right\rceil \tag{6}$$

where,

N_Y: cumulative number of required Level 2 chargers at target year Y.

i: year index.

j: route index.

Y: target year.

R: number of routes (rings).

D_j: duration of operation with a fully charged battery (number of days) in route j.

B_{ij}: number of electric buses introduced to route j in year i.

$\lceil\ \rceil$: ceiling function.

A robust scheduling over the 10-year project period is required to assign the charging days for each bus to be able to accommodate all charging requirements with the minimum number of chargers identified by above relation. There are currently 30 operating diesel buses. Given the project budget, it is proposed to replace three diesel buses per year. **Figure 7** shows a breakdown of which 3

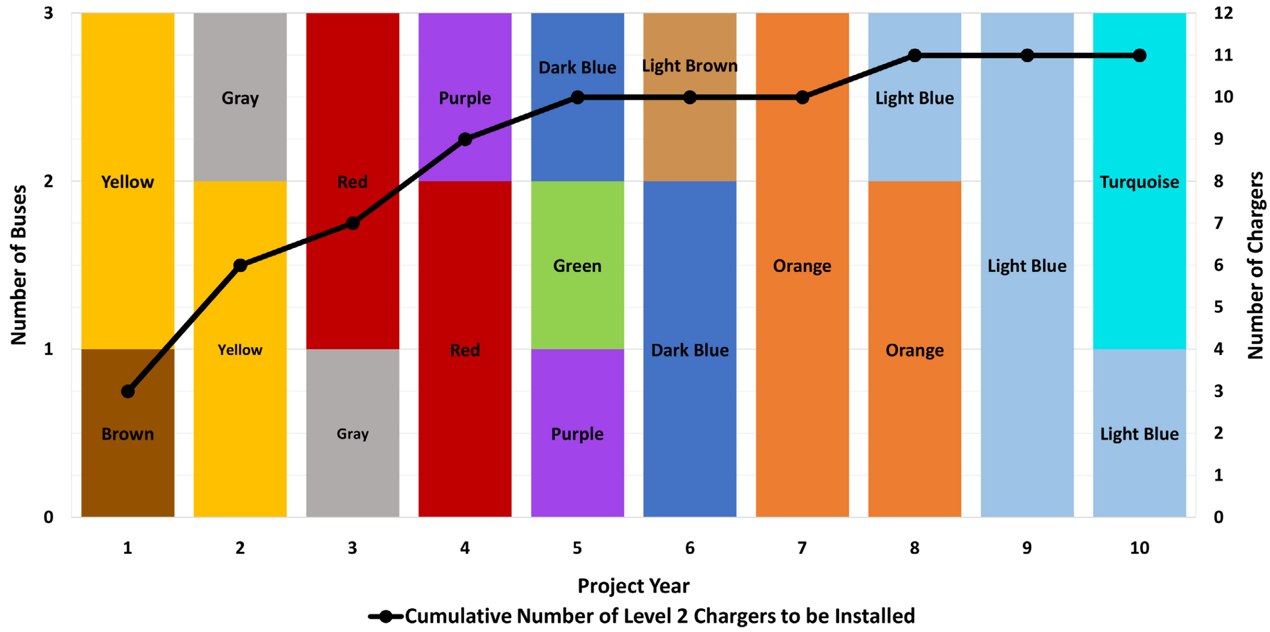


Figure 7. Bus replacement schedule for each route and Level 2 charging station installation plan.

busses from which route (colored bars), is prioritized for electrification throughout the proposed 10-year span. The black line which corresponds to the secondary vertical axis denotes the cumulative number of Level 2 chargers to be installed throughout the project period.

3.3.2. System Validation & Verification

For any given solution deployed, it is prudent to perform iterative supply and demand rebalancing towards an optimized equilibrium. A different solution being deployed alters the system supply, which in turn might indirectly alter the system demand. Planners would need to evaluate interim demands for deployed systems and balance service supply to achieve optimal service equilibrium. Monitoring plans can be done through Key Performance Indicators (KPIs) for each deployed solution. KPIs can be reviewed periodically to verify and validate system relevance and design architecture. Sample KPIs adopted from the strategic plan are:

- The number of riders for autonomous electric shuttles.
- Total CO_2 reduction per year by electric buses/electric autonomous shuttles.
- Total autonomous/electric miles driven per month.
- Bus maintenance cost savings per year.
- Charging station kWh consumption.

4. Conclusion

Most mobility systems were designed for a long-term lifespan, and may have not foreseen the current pace of technological advancements and users' sophisticated preferences. With rapid urbanization and motorization, some of those designs may reach their capacity sooner than anticipated, and some may become obsolete and inefficient. Thus, it is essential to leverage today's technological capabilities to solve those problems. To do this efficiently, planners need to synergize their planning around high-impact solutions for various stakeholders. Superficial implementation of new technologies without assessing the needs and potential outcomes may result in wasteful extravagant investments. The practical framework presented for smart mobility adoption in this study assists system planners with identifying what solutions are best to be deployed and provides surface-level analytics on deployment strategies. There may be a plethora of smart solutions relevant to a given area, but there are a limited number of monetary resources to deploy all of them. Therefore, identifying only high-impact solutions, and ranking them accordingly provides a streamlined and focused development strategy. A decision modelled upon fact-based analysis offers not only socioeconomic welfare gains, but also cost savings to project financiers in avoiding resources spent on low-quality solutions. The conceptual framework presented by this paper is tagged with a case study, where a walkthrough of the framework is portrayed. Three specific smart solutions are evaluated, autonomous electric shuttles, charging infrastructures for EVs, and bus network electrification. Presented technical analyses provide planners with a surface-level guideline for preliminary system design and considerations. Presented surface-level technical analysis is a stepping-stone for smart mobility solutions to go mainstream. Lessons learned for a campus of similar built environments are:

- EV charging stations can be deployed in phases over a span of several years for financing feasibility, risk management, and ensuring system utilization. Equations (1) & (2) can provide an estimation of investment cost and the number of charging stations required to be installed.
- Autonomous electric shuttles are superior to diesel buses in terms of emission-saving benefits, purchase, and operating costs for short-distance routes.
- Bus network electrification can be prioritized by identifying routes with the highest fuel consumption and emission production. No level-3 chargers are required for the system and electric buses are able to operate without recharging mid-day for a campus-wide service where routes are relatively short. Overnight charging may utilize lower electricity rates and avoid imposing strenuous demand on the electric grid.

Future studies would include monitoring deployed systems at the campus, and comparing their actual utilization rate, investment cost, and system impacts based on early projections made in this paper. This framework and its analytical insights could also be applied for projects in other universities, and potentially extended to larger urban areas. The presented analyses, however, are not intended to be a final form, rather a starting point to facilitate project prioritization, understanding of system requirements, and value proposition to project financiers.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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