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A quantitative, equitable framework for urban transportation electrification: Oakland, California as a mobility model of climate justice

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ABSTRACT

This paper implements a framework that catalogs and maps opportunities at a city level to support the electrification of the transportation system in an equitable way. Leveraging on the use of hyper-local air quality data, paired with sociodemographic indicators, we evaluate the framework in the City of Oakland, CA under a context of public and private transport areas to prioritize interventions and incentives, while reducing environmental hazard exposure under an equity focus. Following the recognition of racial and socio-economic disparities, the subsequent steps of implementing operational strategies are to identify specific bus routes in the city in which decarbonization would render the highest impact with respect to the distribution of environmental burden, and to identify regions in which private vehicle interventions would render the highest impact with respect to racial and social equity and mobility.

1. Introduction

1.1. Background

Global greenhouse gas (GHG) and local pollutants from transportation emissions, are an increasing driver of our climate crisis [1]. Airborne pollutants from internal combustion engine (ICE) vehicles include not only carbon dioxide (CO_2) and methane (CH_4) which are the leading drivers of climate change, but also aerosol particles, such as $PM_{2.5}$, sulfur dioxide (SO_2), and nitrogen oxides (NOx) which form layers of smog, degrading urban air quality [2]. These emissions have shown direct ties to chronic respiratory and cardiovascular diseases, which disproportionally impact vulnerable segments of the population such as children, the elderly, and those with long hours of outdoor exposure [3,4,5], but most noticeably the health impacts of poor air quality are disproportionally prevalent in low-income communities, who are predominantly Black, Indigenous, and people of color (BIPOC), due to a variety of factors including historical housing segregation and environmental racism in infrastructural planning [6].

Underlying urban conditions are drivers for subsequent disparities in transportation-related emissions exposure. For example, more BIPOC communities (27%) live near major roads compared to the total population (29%) [7], increasing their immediate exposure to motor vehicle emissions [7,8–11] and overall adverse health outcomes [12]. In addition to the transportation-related emissions, the cumulative exposure from different emission sources tends to reaffirm a consistent trend in disparity exposure, with BIPOC experiencing 1.28× the pollution burden than the total population [13], with the previously described health consequences for this population segment [14].

As these disparities in transportation-related pollution burden persist and new technologies that offer low-emission alternatives to transportation are developed, governing bodies should emphasize alleviating the racial and socioeconomic disparities in the distribution of environmental burden.

To both reduce the pollution from the transportation sector and mitigate climate change, cities are moving towards developing policies that promote low-carbon transportation systems. An approach that has gained much attention in many places is that of electrification of both public and private transportation means, which, when coupled with a clean electricity generation mix, can drastically improve air quality conditions and contribute to a decarbonized future while increasing energy security [15,16,17,18].

To facilitate this transition to emission-free transportation systems accessible to all, governments have offered subsidies for the purchase of

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personal electric vehicles (EVs) [17] [19,20]. The high cost barrier and the perceived limited availability of EV charging points have been shown to be the greatest factors in the adoption of personal EVs [21]. However, despite the subsidies' impact in increasing affordability and accelerating the EV market, they remain largely inaccessible to low-income [22], and BIPOC communities. In fact, the majority of EV ownership and the redemption of its corresponding incentives have been dominated by high income households [23,24,25]. Additionally, the charging infrastructure required to support EV adoption, has been deployed unequally across race and income, with Black- and Hispanic-majority neighborhoods having lower access to them [26]. These economic and infrastructural disparities highlight the imbalance in access to environmental goods and clean energy technologies across income brackets and racial groups.

Generalizing the current conditions, evidence points to urban programs and policies that, by excluding equity in its design process, have originated –or perpetuated– disparate environmental impacts, often on BIPOC communities and those of lower socioeconomic status [27]. As regulations and programs to support the overhaul of the transportation sector move forward, an increased focus on patterns of asymmetrical environmental burden, or environmental injustice, is therefore needed more than ever to prevent or undo the damage of inequitable infrastructure development [28].

From a public-service perspective, cities and transit agencies have looked to public transit electrification as a means of achieving environmental justice [29,6,30]. Major cities and transit agencies have implemented programs to deploy electric bus fleets in low-income, environmentally burdened communities [31]. However, under a situation where the costs of purchasing, maintaining, and installing charging infrastructure for electric bus fleets is still relatively high, it is critical that resources for electric bus deployment is prioritized in disadvantaged communities where diesel bus emissions place the most burden [32] and could similarly have the highest societal and environmental impact. With finite resources for bus electrification, data driven decisions are required to identify the regions in which bus electrification would render the highest impact with respect to the distribution of environmental burden.

To address both personal and public transportation issues from a consistent planning-process perspective, we develop and apply a theoretical frame to utilize a spatially resolved environmental justice index in the City of Oakland, California (CA) to be used in the transition process to an electrification of the ground transportation sector while mitigating urban environmental injustice. Our results aim to represent an added tool for local decision makers to use for targeted interventions at a public, community level (*e.g.,* via electrification of public transport buses), as well as at a private, individual level (*e.g.,* via incentives for increased EV ownership). We focus this work in CA where the transportation sector accounts for approximately 40% of the state's yearly GHG emissions [33], and in the city of Oakland, CA, where close to 60% of its yearly GHG emissions derive from its transportation sector [34].

1.2. Equity-oriented Interventions in Public Transit and Car Ownership

Other than housing, Americans spend more on transportation than on any other household expense (food, education, and health care) [35]. Hence, many links tie equity to the transportation sector [36]. With transportation being such a central aspect of life, one's mobility, both physical and economic, rely on the transportation systems set in place. Ensuring transportation justice across the entire transportation system can be partitioned into the individual transportation justice approaches to both public and private means of transportation [37–39].

Public transportation is widely viewed as a means of reducing transportation related emissions and a single passenger's carbon footprint, by providing a low emissions alternative to driving and facilitating compact land use [40,41]. However, the exhaust released from ICE buses become heavily concentrated on roads with bus routes on them, adversely impacting the health of the neighborhoods within close proximity [42].

Although public transportation ideally lowers vehicle miles traveled and offers a possibly more affordable mode of transport for low income households, vehicle ownership has been identified as a predictor of employment and possibilities to exit welfare, representing a significant economic mobility driver [43]. In the United States, vehicle ownership is not only nearly ubiquitous but is trending upwards, with 93.3% of households reporting access to at least one vehicle in 2020, increasing from 79% in 1969 [44,45]. Despite the pervasiveness of vehicle ownership in the United States, BIPOC tend to have lower vehicle ownership rates, which consequentially detriments corresponding employment rates [45,46]. Hence, having access to this mean of transportation can improve access to employment opportunities, educational and health services, access to food, and other necessities [47,48].

As a critical example, the inaccessibility of suitable jobs for low-income, primarily Black communities has been attributed in the past to the physical distance separating these communities from business centers [49] and used as a basis by many federal welfare reform programs to determine that improving public transportation services will reduce inner-city unemployment [43]. However, more recent evidence has shown that the mode of transport (rather than the distances) plays a larger role in job accessibility for low income households [50], meaning that public transportation covering different geographic distances is not necessarily a completely sufficient alternative for reaching job markets [50,51,52], and further efforts need to be contemplated to benefit welfare recipients and woman headed households [50,53]. Hence, deeper holistic approaches to support both public and private means of transportation focusing on minority and disadvantaged communities could enable greater societal outcomes.

1.3. Understanding the Landscape of Transportation Justice in Oakland

In recent decades, there have been two major demographic and economic changes in the City of Oakland, CA and its neighboring cities: (1) Oakland has been subject to gentrification and the consequential marginalization of BIPOC [54], (2) The emergence of Silicon Valley has resulted in a shift from business centers being concentrated in San Francisco, to being dispersed across the South Bay Area where tech giants establish their headquarters [55]. The relocation of business centers and resultant change in commute patterns have not only increased traffic-related air pollution along Oakland's highways [56], which connect San Francisco and South Bay Area, but it exacerbates the existing mobility inequities, concerning both transportation mobility and economic mobility. Given the marginalization of BIPOC in Oakland and the evolving relocation of business centers surrounding Oakland, a diversity in modes of transportation could enable a sustainable transportation transition to ensure job accessibility and economic equity.

Therefore, to mend this mismatch in the accessibility of job and services while maintaining –or reaching– sustainability goals, it is necessary to make clean private vehicles accessible to low-income, BIPOC communities. The key optic necessary to guide this transition is restorative equity, which aims to repair the harm of both the disparate environmental pollution and the loss of job opportunities in disadvantaged communities [57].

In the context of our region of focus, low-income households in the neighboring San Francisco Bay Area spend a slightly smaller proportion of household expenditures on transportation and face cost as a barrier to vehicle ownership; they are less likely to drive alone and are more likely to carpool, walk, or travel by bus to work; and have somewhat shorter commute times [47]. These types of characteristics, when measured and spatially resolved, along with information about environmental exposure and vulnerable populations, can help identify prioritization approaches for targeted incentives. Coupling this framework with the knowledge of Oakland's long history of environmental injustice [58] and marginalization of BIPOC communities due to institutional racism

[59] and recent gentrification [54], can create space for restorative equity [38].

1.4. Mapping Opportunity Areas for Transportation Interventions

In this contribution we implement a framework that maps out opportunities at a city level for electrifying the transportation system in an equitable way. We enhance an existing environmental justice (EJ) index, CalEnviroScreen [60], by resolving it into a city, focusing on transportation-related variables, akin to [61], while incorporating granular air quality data from Ref. [62]. We then utilize this EJ index as building block to identify which bus routes fall in the regions with the most vulnerable populations and highest environmental burden, so it can complement ongoing studies and help elevate the need for these bus routes to be prioritized in the transition to zero-emission (e.g., electric) buses. Emphasizing the procedural inequity aspect, we identify means of community engagement by estimating the rooftop solar PV potential of houses in blocks in the immediate vicinity along the proposed electrified bus routes. For identifying where to prioritize incentives for private electric vehicles, we create a decision layer in addition to the EJ index consisting of private transportation consumption data that corresponds with low-income households that display characteristics of either *captive public transport ridership*, which refers to the dependence on public transport due to inaccessibility of vehicle ownership, or *forced car ownership*, which refers to the compulsion to bear the disproportionate financial burden of car ownership in order to access services and necessities. These decision layers could serve to identify at high spatial resolution the areas for potential focused interventions in terms of incentives or support programs.

2. Data and Methods

2.1. Air quality

Air quality measurements of nitrogen monoxide (NO), nitrogen dioxide (NO_2), and black carbon (BC) concentrations from Ref. [62] are used. Data points with air pollutant concentrations less than zero and data points in the top 5th percentile of data points are excluded to reduce potential outliers.

2.2. Environmental Justice (EJ) Index

Data for environmental justice indicators related to transportation are gathered from CalEnviroScreen 3.0 [60]. The indicators, collected and aggregated at a census tract level and used to develop a decision layer related solely to transportation, are, in pollution: *ozone*, $PM_{2.5}$, and *diesel PM* concentrations; *traffic*; and for vulnerable population: *asthma*, and *cardiovascular disease* cases; *poverty; unemployment*; and *housing burden*.

Diesel PM emissions concentrations are collected for each 4 × 4-km grid statewide, and aggregated by census tract [63]. Due to limitations of air monitoring stations, spatial models were created to estimate *ozone* and $PM_{2.5}$ concentrations based on air monitoring stations within a 50-km proximity of each census tract [64,65].

Air quality attributes are enhanced with hyper-local data from Ref. [62] to supplement the existing indicators which were estimated using proxy models due to inconsistent distribution of air monitoring stations across census tracts, while following Ref. [66] methodology to handle empty values and missing data.

These data are further complemented with other socioeconomic indicators that pertain to those vulnerable to transportation related air pollution. Sensitive populations indicators include *asthma rate, cardiovascular disease*, and *low birth-weight infants*, which are all impacted by poor air quality [60]. Furthermore, we add an indicator called *percent vulnerable age*, which is calculated as the percentage of residents in a census tract either younger than 5-years of age or older than 65-years of age. This data is collected through Ref. [67], which compiles data from the 2010 census [67].

Additional socioeconomic factor indicators include *poverty, unemployment*, and *housing burden*, for which we posit have a direct impact on one's ability to own a car [60].

For each indicator, we normalize the values across all census tracts in Oakland to visualize the percentiles of each indicator in each census tract. To combine these indicators into an index, we follow the methodology from Refs. [61, 66]. Indicators are weighted equally and aggregated by their mean values to produce the Pollution Burden and Population Characteristics scores. The Pollution Burden score and the Population Characteristics score are each normalized and multiplied together to produce the EJ index for the census tracts of Oakland, as shown in equation 1,

$$EJ\ Index_{Census\ Tract} = Pollution_{Census\ Tract} \times Population_{Census\ Tract} \quad (1)$$

This EJ index allows us to visualize a map of how environmental burden is distributed across the City of Oakland. To relate this EJ index information with transportation patterns and identify the most vulnerable census tracts to environmental discrimination in the transportation-environment nexus, we look at data related to bus routes across Oakland, and private transportation consumption.

2.3. Public Transportation

To analyze public transportation's association with the air quality information gathered, we use the geographic information files from bus routes in Oakland, collected from AC Transit [68]. To have non-bus routes references to compare against, we use OSMnx python package and collect the city's street network [69].

To determine whether street roads where buses transit tend to exhibit higher pollution levels, we create 50m buffers along both types of streets (bus-transited, non-bus-transited), and perform a spatial join with the cleaned air quality data previously described. For each of the emissions, NO, BC, NO_2, we group the air quality data by whether it falls within the buffer of a bus route or non-bus route street.

After determining whether bus-transited streets tend to be associated with increased pollutant levels, the next step is to identify which routes should be prioritized for further interventions (*e.g.,* transition to zero-emission fleets). This is done by identifying bus routes falling primarily on census tracts with high EJ index values. For every bus route, we overlay the 50-m buffered bus routes over the EJ index distribution map and, for every of the 91 bus routes in Oakland, quantify the percentage of bus route segments that fall within a certain EJ index percentile. We then identify the top 10 bus routes with their highest percentage falling in census tracts with high (i.e., ≥75th percentile) EJ index.

To ensure "greater stakeholder participation and public involvement to receive effective transportation decision making" [28], a proposed solution studied here is the community involvement in the participatory aspect of electrifying these bus routes. One potential idea is to allow the community to be invested in the opportunity-charging modality and serve as resource providers to the electric charging stations. To inform the value of this engagement, we measure the estimated rooftop solar PV potential of the buildings on blocks along the bus routes and their potential electricity yield. Estimates of rooftop solar PV potential are taken from Google Project Sunroof [70]. We identify blocks adjacent to the 10 identified bus routes by taking the set difference between the contour shapefile of Oakland, CA and a minimally buffered drive network shapefile for the city. This renders a map of blocks that, with manual removal of unusually large blocks in QGIS [71], is used to overlay parcel data to identify building outlines [72]. Building centroids are then queried in Google Project Sunroof to estimate the potential electricity generation from rooftop solar PV for each building and grouped by bus route.

2.4. Private Transportation

To identify which census tracts would benefit most from increased accessibility to private electric vehicles, low-income households in the bottom 25th percentile of the median household income of census tracts are first selected.

There are two approaches to address this segment of the population. The first one, largely based on Ref. [47], which provides an in depth report of transportation spending by low-income households in the San Francisco Bay Area, captures the demographics that would benefit most from new EV adoption incentive programs, who would likely be described as those with high percentage of zero vehicle ownership, reliant on public assistance income, with high unemployment rates, low expenditure on transportation, and users of alternative modes of transportation to work (*e.g.,* public, bike, walking). The selected indicators that reflect this are: *% unemployment; % of households with public assistance income; % of employed people who take public transportation to work; % of employed people who bicycle to work; % of employed people who walk to work*; and *total transportation expenditures (household average)*. This data is obtained from Ref. [67] at the census tract level for Oakland.

For each indicator, the data is normalized to produce percentile values, which are equally weighted and averaged. The final decision layer for the first approach helps identify tracts for focal efforts on EV adoption incentives.

The second approach identifies census tracts where private vehicle owners would benefit most from trade-in EV adoption incentive programs. Based on Ref. [47] we construct this approach and posit that those regions can be identified by locating segments with high percentage of ownership of 1 vehicle and which also tend to either drive alone or carpool to work; are reliant on public assistance income; have relatively high unemployment rates; as well as have high expenditures on gas, insurance, and transportation overall.

The data to reflect these characteristics is obtained from [67] at the census tract level for Oakland in 2019, using the indicators: *% unemployment; % total households with public assistance income; % employment, car, truck, van to work alone; % employment, car, truck, van to work carpool; expenditures on gasoline and motor oil (household average); transportation expenditures (household average); vehicle insurance expenditures (household average)*; and *% households w/ 1 vehicle*. For each indicator, the data is normalized to produce percentile values, which are then equally weight and averaged.

Lastly, the EJ Index is combined with the private transportation decision layers and visualized as maps for Oakland, CA.

3. Results

The EJ index resolved at a city level for Oakland, CA, is shown in Fig. 1. The values are normalized from 0 to 100, where 100 corresponds to the highest environmental burden related to the transportation sector.

The difference in emissions between streets where buses transit, and those where buses do not is shown in Fig. 2. The left-hand side boxes (light red) show the distribution of air quality measurements that overlap with the 50-meter buffer margin of all bus routes in Oakland. The right-hand side boxes (purple) show the distribution of the air quality measurements that overlap with the 50-meter buffer margin of all streets in Oakland that do not correspond to a bus route. For bus routes, BC levels over the recorded period of time have a mean value of 0.61 μgm^{-3} and a 75th and 99th percentile value of 0.96 and 2.13 μgm^{-3}, respectively, while routes with no buses transiting show mean values of 0.51 μgm^{-3} and 75th and 99th percentile values of 0.78 and 2.01 μgm^{-3}, respectively. For NO, bus routes show a mean value of 11.30 ppb with 75th/95th percentile values of 13.00 and 74.00 ppb, respectively, while non-bus route streets show a mean value of 5.96 ppb, with 75th/95th percentile values of 3.00 and 63.00 ppb, respectively. Lastly, NO_2 mean values in bus-transited streets are 9.35 ppb with 75th/95th percentile values in the distribution of 17.93 and 37.62 ppb, respectively, while

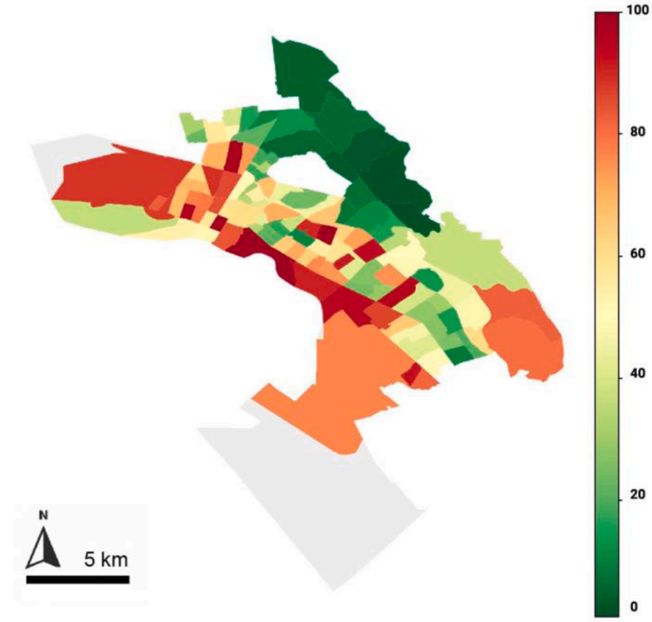

Figure 1. Environmental Justice (EJ) Index of Oakland, CA, containing indicators relevant to transportation and the related health impacts of transportation-induced air pollution.

non-bus transited streets have a mean of 6.81 ppb, with 75th/95th percentile values of 11.69 and 35.35 ppb, respectively. In summary, for all pollutants, the mean, 75th, and 99th percentiles are higher in bus-transited streets.

The top 10 bus routes shown in Fig. 3 (green) represent the bus routes that run through the most disadvantaged communities (≥75th percentile of the EJ index). These bus routes, identified through the multi-layer criteria, are overlaid on all the bus routes of Oakland, CA (grey), and individually disaggregated (Fig. S1).

The street blocks adjacent to the bus routes highlighted in Fig. 3 are shown in Fig. 4a. Each parcel on the block contains the corresponding building centroid(s) selected, as denoted in Fig 4b. These buildings are considered in the calculation of electricity generation via rooftop solar PV to power opportunity-charging buses infrastructure.

In Fig. 5, a histogram representing the bus route's spread across the EJ index is produced for each of the top 10 bus routes. The *y*-axis of each histogram bar represents the fraction of the bus route length that lies in the corresponding EJ index percentile (*x*-axis). The *x*-axis values are normalized from 0 to 100, where 100 corresponds to the highest environmental burden related to the transportation sector. Note: There were segments of the bus route lying outside of the EJ index, so the fraction of the bus route (*y*-axis) is calculated over the total bus route length lying within the EJ index, rather than the entire bus route length.

Fig. 6 shows the two private transportation EV incentive decision layers. Both decision layers are narrowed down to the census tracts in the bottom 25th percentile of median household income in the City of Oakland. Fig. 6a represents the "new EV incentives" decision layer to identify low-income households that likely do not own vehicles and rely primarily on public transportation as a means of commuting. Fig 6b. represents the "trade-in EV incentives" decision layer to identify low-income households that likely own a vehicle but spend a large proportion of their income on vehicle ownership-related expenses. The values are normalized from 0 to 1.0, where 1.0 indicates the census tract are most likely in need of intervention via the corresponding private transportation EV incentives.

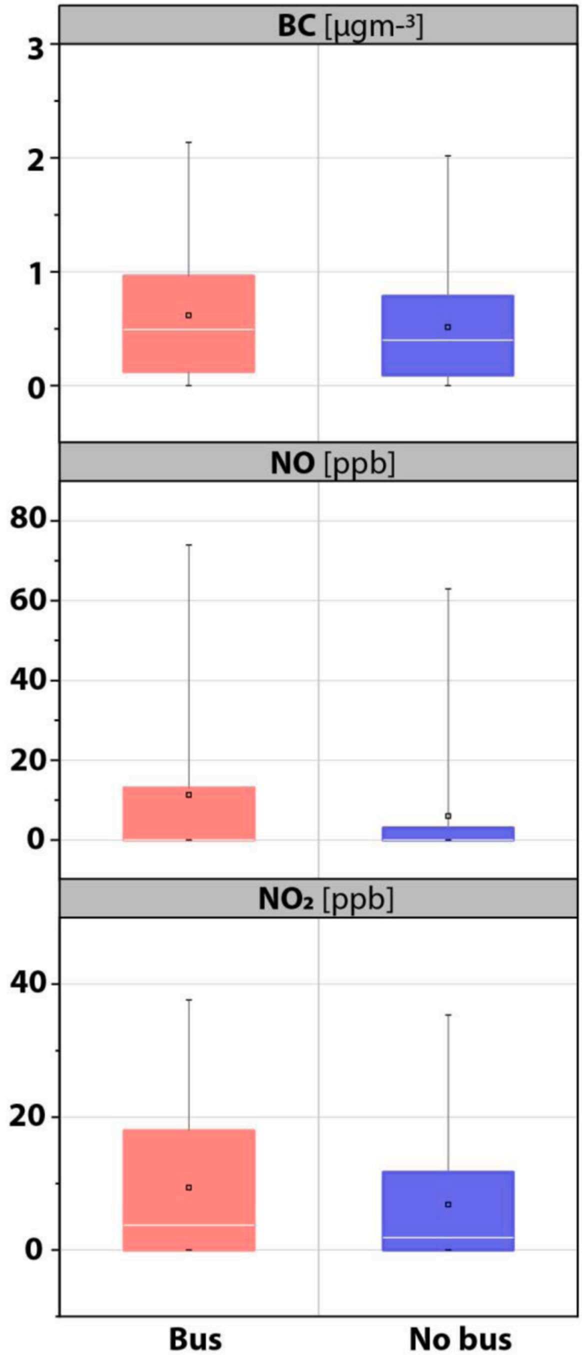

Figure 2. Box plots distributions of BC, NO, and NO_2 concentrations grouped by streets with bus routes (light red) and non-bus routes (purple), respectively.

4. Discussion

The modified index herein presented aims to refine some of the metrics used in the CalEnviroScreen tool with additional information at high spatial granularity, and couple it with spatially resolved information in mobility to uncover areas of opportunity in support of the infrastructure development in clean transportation.

Akin to Ref. [61], we have modified the environmental justice index to focus at a city level and on transportation-related variables only. These modifications are intended to support local decision makers in assessing their jurisdictions with a re-calibrated suite of indicators.

We intend to provide 2 use cases directed at different modes of transportation: public transportation from buses, and private-vehicle ownership. In both cases we utilize different metrics reported in literature as drivers for inclusion, or lack thereof.

4.1. Identifying Public Transportation Bus Routes for Intervention

The mean and median concentration of airborne pollutants measured on streets where buses transit is higher than that of streets without bus routes, as shown in Fig. 2. An approach to mitigate this captured detrimental impact is to convert existing bus fleets into zero-emission ones, coupling this with cleaner electricity generation options. As cities like Oakland embark on programs to transform their transportation systems, areas labeled with higher incidence of environmental injustice should be prioritized.

Of all the bus routes operating in Oakland, the 10 routes presented have their highest proportion falling in census tracts with an EJ index value $\geq$75%. This procedure helps identify the bus routes covering the most environmentally burdened communities.

Our findings show that the bus routes that most require intervention tend to cluster in West Oakland and are in proximity to roads typically associated with heavy traffic, such as highways and major streets (Fig. S4).

The top bus routes highlighted denote a strong association with air pollution in proximate, disadvantaged, neighborhoods and in many cases, major arterial roads and highways, which as shown in Ref. [62], are major sources of air pollution. Some of these bus routes, which coincide with the highway placements, further contribute to a more multifaceted root problem with potential confounding factors at play including a history of housing segregation and the blocking of capital wealth accumulation, unfair or even discriminatory urban planning, changes in transportation patterns, and other structural causes of spatial inequality.

Despite there being many bus routes in the North East region of Oakland, none of the top bus routes cross this region. Comparing the North East Districts 1 and 4 and the West Oakland Districts of 2, 3, and 7 (Fig. S3), West Oakland has a lower median household income of $72,000 or less, whereas North East Oakland has a median household income of greater than $100,000 (Table S1, Fig. S3). The top bus routes (Fig. 3) and the EJ index (Fig. 1) suggest that these latter regions suffer less from the burden of transportation and pollution. Thus, to address the environmental justice issue at hand, interventions to provide better resources to the lower-income, more environmentally burdened West districts of Oakland should be prioritized.

In District 3, West Oakland, lies the entrance to the Bay Bridge, which is a source of concentrated traffic density and consequentially heightened regional air pollution (Figs. S2). While the electrification of bus routes could ameliorate emissions concentrations in this region, it is important to note that these bus routes are likely to be intercity bus routes simply passing through Oakland to reach neighboring cities, such as San Francisco or Berkeley, or beyond. Notably, the top four bus routes identified in this work — J, FS, L, and LC — are intercity bus routes of this nature (Fig. S1). Since these bus routes only partially overlay with the Oakland EJ index, it is possible that the omitted regions of the bus route lie in less environmentally burdened communities than Fig. 5 would suggest. Thus, for interventions at a city-level, one could either only consider intracity bus routes, or coordinate with neighboring cities.

Lastly, to connect these results with the current policy proposals and their respective findings, the AC Transit Clean Corridors Plan identifies the AC Transit lines serving SB 535 Disadvantaged Communities [73, 63]. However, the results of this paper identify the severity of disadvantage and environmental burden as a gradient, whereas the Clean Corridors plan identifies all bus routes that overlap with the SB 535 Disadvantaged Communities. This gradient can allow for a more thorough understanding of which bus routes are more relevant to electrify by ranking each by the distribution of the route across disadvantaged communities.

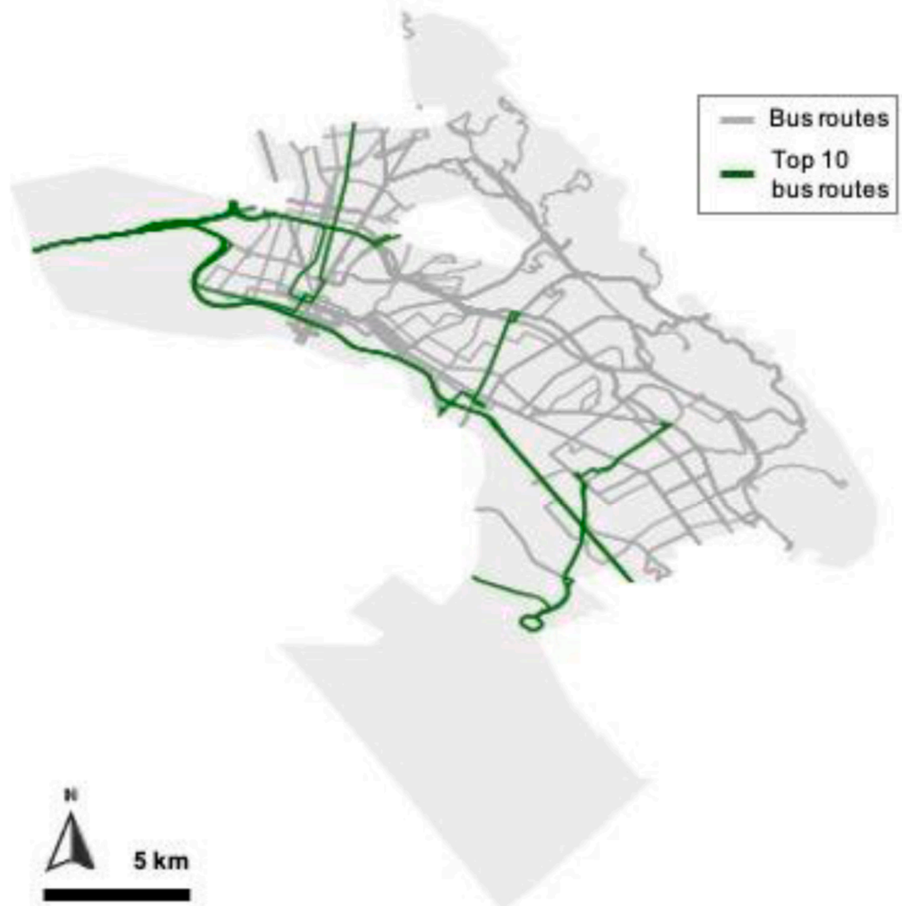

Figure 3. Selection of 10 bus routes with the highest EJ index/burden coverage percentiles in Oakland, CA.

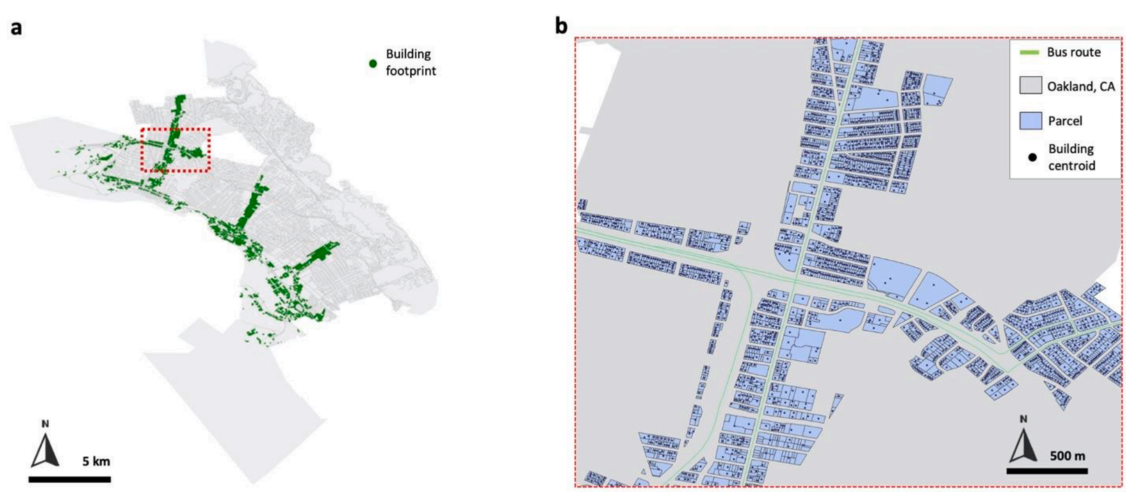

Figure 4. Buildings on street blocks adjacent to top-10 bus routes selected. Green lines indicate the top-10 bus routes, blue outlines are street blocks or parcels, and points are the centroids for the identified street blocks or parcels.

While the metric of ≥75% EJ index value selected as a threshold renders a manageable number of bus routes to study in more depth, the value can be adjusted based on the needs and financial capacity of the city to incorporate a wider pool. The intention is to provide a socio-environmental prioritization framework that supports other frameworks (e.g., technoeconomic, demand-coverage, grid impact analyses) in the evaluation of replacing existing fossil-fueled buses with zero-emission powered ones.

4.2. Operationalizing Equity through Citizen Participation

There are many equally important prongs in which equity can be reflected in transportation justice, as previously stated.

In the context of this work, social equity could be rationalized as the opportunity to have accessible, low cost, and clean transportation means. More specifically in our work, we conceive an example (out of many) in the form of financial and logistic support for and access to

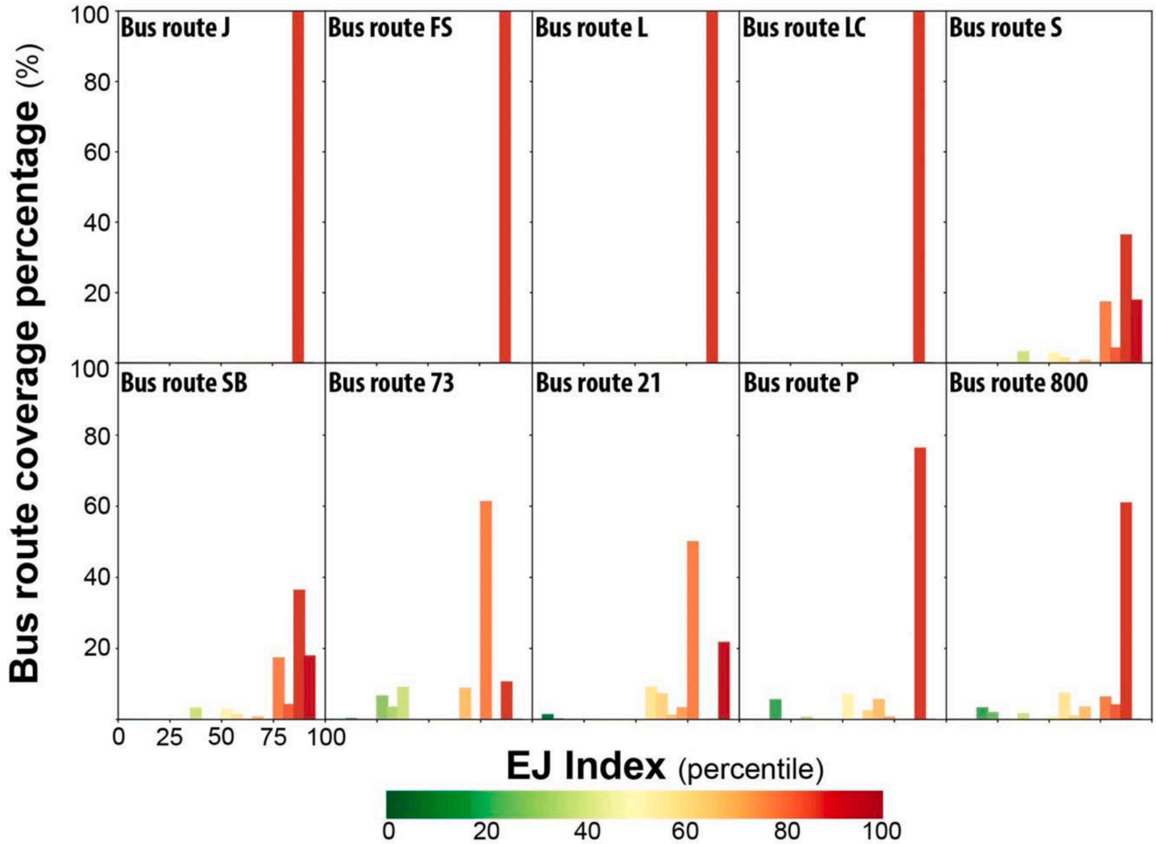

Figure 5. Distribution of bus routes by EJ index coverage. The fraction of the bus route that falls on census tracts in a given EJ index value (x-axis) is represented by the y-axis on each box.

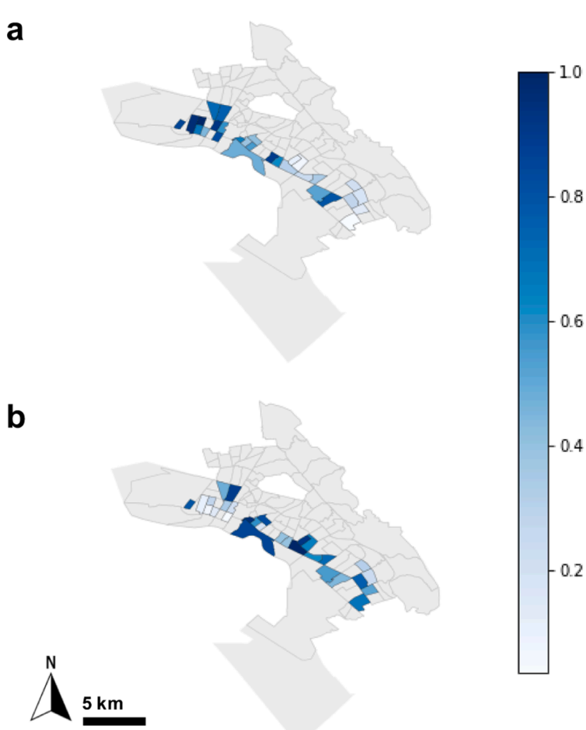

Figure 6. (a) Private transportation "new EV incentives" decision layer, and (b) private transportation "trade-in EV incentives" decision layer. Range is from 0.0 (low priority) to 1.0 (high priority).

clean, affordable private transportation.

In the same logical construction, geographic equity would be reflected in equitable and affordable access to zero-emissions means of public transportation, and adequate accessibility to cover the basic needs (e.g., job, health care services, food).

Procedural equity, achieved via fair community engagement in the decision process, could be strengthened by allowing the community to participate in the powering of the zero-emission buses (e.g., electric). One way of offering a mean of community engagement to achieve environmental justice and ensuring the electric buses are powered by clean energy sources is by (*a*) supporting the installation of solar rooftop PV systems, which could then (*b*) allow those households along the most environmentally burdened bus routes to sell (a share of their) electricity to power the clean buses. Beyond the participatory nature of this approach, it also constitutes a step towards cleaning the energy mix.

Incentives to make rooftop solar installation affordable and allowing households to sell their energy to power the bus routes allows these disadvantaged households to have direct influence on the transportation systems that affect their communities. For the blocks adjacent to the top 10 environmentally burdened Oakland bus routes identified in this paper, the estimated solar rooftop capacity is 303 MW, which, at an estimated 1230 kWh/kW threshold value as reported in Ref. [74], would produce 373 GWh/year. To put into context, some operational studies report an average consumption of 20kWh per bus per charge and over the course of 13–20 charges a day summing up to 260–400 kWh/day [75] or 0.09–0.14 GWh/year (with values varying depending on the bus and charging configurations, bus size, charging and driving cycles, route demand, and other weather and topographic characteristics).

In the same vein of public transportation, it is worth noting that historically, transportation boards and commissions for disadvantaged communities of color –where residents are described as "captive riders" dependent on public transport for mobility–, are disproportionally represented by suburban residents, who historically allocate funding in favor of "discretionary riders" [28]. This asymmetric representation calls for public participation in the proposition and implementation of policies to ensure environmental justice is a central element in transportation infrastructure development.

More explicitly, the approach is an attempt to reflect a community-owned and community-driven project, where participation from block residents can be organized and incorporated in the energy charging phase of the project by co-generating electricity via solar PV. While this concept constitutes one of many approaches in which residents can be involved (in fact, other approaches better suited might exist), it is conceived out of an existing project initiative that is building resilient and participatory communities in Oakland, such as the EcoBlock project [76], and which can be leveraged and expanded to address this intersectionality.

4.3. Identifying Areas for Private Transportation Interventions

Following two decision layers are produced to identify which census tracts would benefit from a prioritized access of EVs based on the findings of Ref. [47] and discussion in data and methods. The first decision layer identifies low-income households that would benefit most from incentives to adopt new EVs, which prioritizes census tracts where households likely own zero vehicles, rely on public transportation to get to work, face employment barriers, and spend a small portion of their income on transportation. The second decision layer identifies low-income households that would benefit most from incentives to trade in existing traditional internal combustion engine (ICE) vehicles for EVs, which prioritizes census tracts where households likely own one vehicle as a result of "forced car ownership", rely on public transportation to get to work, face employment barriers, and spend a larger portion of their income on transportation. Any policy decisions extended from this framework must be appropriate according to these demographic indicators.

The impact of private vehicle in terms of job opportunities and access to amenities has been documented in literature [77,50,52,43]. While at a longer time frame there is a push to transition to car-less urban environments, the current spatial layout of cities and housing still requires a personal reliable mean of transportation as would be a private vehicle.

Our findings, as illustrated in Fig. 6, show that the regions of the city to prioritize either type of private EV incentive lie in the West and South Oakland Districts of 2, 3, 5, 6, and 7, and exclude the higher income Districts 1 and 4 (Figs. S2–S3). As mentioned in previous sections, West Oakland has lower median household income and a larger population of marginalized racial groups than North East Oakland. West Oakland includes Chinatown and Downtown Oakland and East Oakland primarily has higher income residential neighborhoods in the hills of Oakland (Figs. S2–S3).

This paper identifies the census tracts in the lowest quartile of median household income in Oakland, but surprisingly does not entirely coincide with the highest EJ index regions of Oakland. There are many more factors than income at play in the calculation of the EJ index. The intention of keeping the calculation of the private transportation decision layers as a separate process from the EJ index was to overlay the decision layers over the EJ index to identify the census tracts that would simultaneously financially and environmentally benefit from targeted incentives.

For the "new EV incentives" decision layer in Fig. 6a, the region to prioritize policy intervention is the West region of Oakland in Districts 2 and 3, which includes Downtown and Chinatown (Figs. S2–S3). However, this could conflict with the caveat of "discretionary" or "choice" public transport ridership, where residents prefer to not own vehicles due to adequate connectivity from public transportation or alternate modes of transportation such as walking, biking, scooters, and ride-hailing [78]. The objective of giving these incentives is to provide "captive" public transport riders with a wider and more independent option for mobility [78]. Additional multidimensional data and surveying beyond the binary decision criteria used in this paper are needed to decouple captive and discretionary riders.

For the "trade-in EV incentives" decision layer in Fig. 6b, the region to be prioritized the least is the Downtown and Chinatown regions of Oakland in District 2 and 3 (Figs. S2–S3). This is likely due to the fact that there is low vehicle ownership in that region due to high availability of alternative modes of transport and dense housing that is discouraging of car ownership with difficult parking access.

4.4. Opportunities and Challenges in Current Policies in Oakland

The city of Oakland has kicked off the Zero Emission Vehicle Action Plan in November 2019 to be completed in early spring 2022 to build a clean and equitable transportation system in Oakland [79]. This plan outlines the steps to transportation electrification that the city has governance over, such as building infrastructure for EV charging stations in multi-unit buildings and curbside charging, electrifying medium and heavy duty fleets, and increasing availability of shared electric bikes and scooters [79]. As for public transportation electrification, bus routes in Oakland are governed by Alameda-Contra Costa Transit District (AC Transit), who have their own mandates to equitably decarbonize their fleets [31]. The implementation of transportation electrification as a whole can be challenging with separate governing bodies with different authorities and jurisdiction. While it is not under Oakland's jurisdiction to decarbonize AC Transit bus routes, this framework could support conversations and routes prioritization as a means of overlapping environmental justice projects in their sustainable transportation plans. Furthermore, this framework has been segmented to address private transportation and public transportation electrification as separate processes to alleviate such difficulties in governance.

4.5. Public Transportation Policies

The California Air and Resources Board established a new rule, the Advanced Clean Transit regulation, which mandates public transit fleets be entirely emissions free by 2040 [73]. As such, this has been reflected in concrete actions within the City of Oakland, and as of September 2019, AC Transit initiated the Division 4 (D4) modifications to accommodate zero emission buses [31]. These modifications follow the recommendations of the "Clean Corridor Plan" which identify corridors designated as Disadvantaged Communities by the State of California through SB 535 [73,80].

The EJ index and top bus routes presented in this paper approximately match the SB 535 Disadvantaged Communities. Additionally, the gradient nature of the spatial layout we present offers additional granularity in understanding which subset of the disadvantaged communities should be prioritized the most in public transportation policies.

This framework also allows the Clean Corridors program to engage the proximate communities to generate solar PV to electrify the bus routes that affect them the most. Currently, the Clean Corridors program concentrates their electric charging stations to one lot connected to the grid designated in Ref. [31], which lies in District 5 Fruitvale/San Antonio (Fig. S2). Using the approach of solar PV participation allows environmentally burdened households to take a stake in their achieving of environmental justice.

4.6. Private transportation policies

The framework described in this paper produces two decision layers to identify which census tracts would benefit from increased accessibility of EVs based on the findings of Ref. [47] and discussion in data and methods. The first decision layer identifies low-income households that would benefit most from incentives to adopt new EVs, which prioritizes census tracts where households likely own zero vehicles, rely on public transportation to get to work, face employment barriers, and spend a small portion of their income on transportation. The second decision layer identifies low-income households that would benefit most from incentives to trade in existing traditional ICE vehicles for EVs, which prioritizes census tracts where households likely own one vehicle as a result of "forced car ownership", rely on public transportation to get to work, face employment barriers, and spend a larger portion of their income on transportation. Any policy decisions extended from this framework must be appropriate according to these demographic indicators.

4.6.1. *Incentives*

The state of California has set the goal of putting 1.5 million "Zero Emission Vehicles" (ZEVs) on the road by 2025 to reduce transportation related emissions, resulting in the emergence of generous subsidies and tax credits [23].

Due to cost barriers and these blanket subsidies, low-income households remain unable to reap the environmental and health benefits of owning an EV [23]. To accelerate mass market adoption of EVs as well as prevent increasing disparity in the distribution of environmental burdens and benefits, future policy decisions must increase accessibility of EVs to low-income households [22].

Incentives have increased EV sales and propelled the start of the industry, however they have been primarily redeemed by high income households, with 79% of electric vehicle rebates being claimed by households with incomes greater than $100k a year and 99% of electric vehicle rebates being claimed by households with incomes greater than $50k a year [25,81]. Despite active effort from policy reform to make the incentives more equitable in recent years, income brackets of <$100k (the bottom three quartiles of income) comprise <30% of ZEV rebates redeemed [82,83]. As a comparison, in Oakland, the median household income is $68,442 [84] and the region selected in the private transportation decision layers are in the bottom quartile of median household income, having a household income of $44,315 or below.

As stated in Ref. [82] on the California's Clean Vehicle Rebate Program (CVRP), income caps can reduce the occurrence of higher income price-insensitive buyers redeeming ZEV incentives, without decreasing overall ZEV adoption rates.

4.6.2. *Rebates and Trade-in EV Programs*

California effectively makes EV rebates and grants more accessible to low-income households, yet there is still more that needs to be done to increase adoption of EVs in low income-households.

Coupled with income caps, increased rebates for low income consumers have improved equitability in California's ZEV market [82], with still room to improve. CVRP offers increased rebate levels for low-and moderate-income consumers with income falling under 300 percent of the federal poverty level [85]. For example, a married couple earning less than $51,720 could redeem the standard rebate amount increased by $2,500.

There are also programs that offer grants in place of rebates for low income EV consumers, such as the Clean Vehicle Assistance Program, which may alleviate the strain of upfront cost barriers to purchasing EVs. As stated in Ref. [82], even more granularly CVRP incentives that use income brackets could be useful, and furthermore, we posit that if complemented with the indicator presented in this contribution, can represent a more holistic picture considering further socio-environmental aspects.

In the case of forced car ownership in low-income households, buying an EV regardless of redeemable rebates would financially burden a household even further. Thus, it is important to offer trade-in EV programs that allows low-income households to trade in currently owned ICE vehicles with EVs. Furthermore, as stated in Ref. [82], as the market evolves and expands, incentives that can reach new groups as the early-adopter market of ZEVs becomes saturated, will require identifying as best as possible these groups. This issue can be addressed in great part from the framework laid out in this paper.

4.6.3. *Investing in EV Charging Infrastructure*

In addition to the financial barrier of obtaining an electric vehicle, the availability of charging points for EVs is surveyed to be the second greatest impediment in adopting an EV [21]. As described in Ref. [61], installing charging infrastructure requires explicit effort to ensure an equitable rollout, hence the installation of charging stations must prioritize disadvantaged communities and coincide with the increased outreach of ZEV incentives to the different segments of the population, for example, as is described in this framework.

4.6.4. *Shared Electric Mobility*

Alternative modes of transport, such as one-way electric car-sharing services (ECS), are also considered a promising solution for sustainable passenger mobility [86]. ECS offer a means of traveling via a personal EV, at an at-need basis, without the high upfront cost barrier of owning a personal EV. However, to incentivize the adoption of ECS, further work to develop a more integrated design approach, involving changes in users' lifestyle patterns and coordination with decision makers in housing, utilities, workplaces, shopping centers, to name a few, is needed for alternatives to become competitive with the notion of the car [87]. Access to an affordable, personal means of transportation has implications beyond mobility, but also for safety. This has been highlighted during the COVID-19 pandemic, during which public transport ridership dramatically decreased due to the unease of traveling with strangers [88]. There is opportunity for further research on overcoming the challenges of integrating ECS to adapt to user behavior and lifestyles and on the potential for ECS to offer an equitable alternative to the high upfront cost of electric vehicle ownership.

5. Limitations and Future Work

The relationship between transportation spending characteristics by low-income households and economic mobility is multifaceted and thus highly debated. Due to this multifaceted nature, it is difficult to capture the full picture with data in the form of abstracted, binary indicators. The construction of the private transportation decision layers was simplified to accommodate the data available, but the intricacies that have been abstracted away are discussed below.

The first area of uncertainty is the issue of the cost barrier of car ownership. While it is clear that high car ownership and high household transportation expenses correspond to high income households, it can be difficult to differentiate the income level of a household if they own one or zero cars. Car ownership can place a significant financial burden on low income families in cases of "forced car ownership," where families must buy a car for the sake of economic and social mobility even if it is a financially burdensome choice [89,90]. For a household with zero cars, the household may live in a neighborhood highly connected by transit and voluntarily chooses not to buy a car or the household simply may not be able to afford one. These forms of public transit ridership are distinguished by the terms "discretionary" ridership and "captive" ridership [28].

Evidence from Ref. [47] shows find that the proportion of income spent on transportation by low-income households varies drastically depending on whether the household owns a car or not. Thus, the transportation expenditure indicator cannot be comprehensively assessed without knowing information on each corresponding household's car ownership. With the data at the granularity of a census tract, the interdependence of these indicators at a household level is unknown. In lieu of requiring this interdependent data, this paper separated these patterns into two distinct private transportation decision layers to prioritize census tracts with a high percentage of households owning zero cars and spending proportionally less on transportation with respect to their income and those with a high percentage of households owning one car and spending a larger proportion of their income on transportation. This is an imperfect means of identifying which households would benefit most from the EV incentives but offers a general guideline to identify regional transportation consumption patterns. Targeted surveying can help build a more cohesive representation or model of this pattern.

Additionally, due to sparsity of data, some relevant indicators were not included. The Vital Signs from the Metropolitan Transportation Commission provided commute time at the desired granularity of census tracts but did not have a complete dataset for all of Oakland differentiated by mode of transport. Although it provides a complete dataset of overall commute time, this information is not informative given that the distance traveled, and the time spent traveling are highly dependent on mode of transport. Furthermore, low-income households are found to have longer commute times for shorter travel distances as a result of higher dependence on public transport [37]. A full dataset differentiated by mode of transport has potential to offer insight at even higher granularity on where to offer incentives. As datasets become increasingly thorough, future work could build on the framework built in this paper using newly available data.

With more recent dataset or a source of consistently flowing granular air quality data, regulatory bodies could improve data-informed decisions laid out in this framework, real-time.

Lastly, to achieve procedural equity, community engagement is required beyond the mapping efforts, and their concerns, fears, and objections need to be listened to and considered in developing new policies. In that spirit, future interdisciplinary work will center on the construction of an open and iterative dialogue with the analyzed communities to shape a fair decision-making process for any planned intervention.

6. Conclusions

In this contribution we develop a framework that allows policy makers to prioritize private EV incentives and execute public electric bus projects with environmental justice and economic mobility in mind. This framework is applied to the City of Oakland and tailors recommendations according to the unique traits of Oakland's geography and history.

In general, the variables utilized in the index and subsequent open-access decision layers highlight the poor environmental conditions to which segments of the population are exposed.

Capturing patterns to differentiate scenarios of forced or voluntary car ownership, as well as captive or discretionary public transport ridership, requires additional data to understand intent behind consumer choices.

As cities aim to eventually phase out private vehicle ownership by exploring innovative alternative mobility solutions, such as shared bikes, scooters, and rooftop solar to interact with storage and EVs, this framework should be adjusted to ensure equity in the introduction of these added modes of transport and technologies. Consequentially, personal EVs will also be subject to this gradual digression from private vehicle ownership. However, as such programs are planned out, personal EV incentives provide an interim solution for BIPOC communities enduring environmental and transportation injustice.

Lastly, in a COVID-19 world, additional opportunities for transport are needed which also involve scooters, biking, and walking. Long-term exposure to high concentrations to vehicle emissions increase risk of death from COVID-19, which worsens and expedites the risk of mortality from environmental injustice in transportation-related pollution [91]. Public transportation, amidst this pandemic, has undergone numerous changes to ensure public health safety for passengers. Studies have shown that public transport ridership has not been shown to increase COVID-19 cases with proper precautionary measures such as social distancing, increased air circulation, mandatory face coverings [92]. However, the uneasiness of shared public spaces during the COVID-19 lockdown resulted in up to an 80-90% decrease in public transport ridership, globally, leading to significant improvements to air quality due to the reduction of public transportation operation [88, 93]. The aversion to public transport during COVID-19 has resulted in the increased uptake and encouragement of outdoor, private modes of transport such as bicycling and walking [94]. Programs such as Oakland Slow Streets facilitate the soft street closures of local corridors to allow for physically distant activities such as biking and walking [95]. COVID-19 has also drastically shifted the global workforce, requiring businesses to rapidly digitize and shift to remote workflows [96]. Consequentially, the accelerating upward trend of remote work will likely impact commute patterns in unforeseen ways. The pandemic has revealed the centrality of transportation to people's livelihood and the consequential changes to transportation systems must adapt to new challenges while simultaneously prioritizing environmental justice and equity.

Declaration of Competing Interest

The authors declare no competing interests.

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Supplemental Materials

Below, in Fig. S1, are the individual disaggregated maps of the top 10 bus routes that are represented in overlaid format in Fig. 3. Out of all the bus routes in Oakland, CA, these are the bus routes with the largest fraction of the route falling in disadvantaged communities (census tracts with an EJ Index percentile of 75 or greater). An important note is that before evaluating this fraction, each bus route is cropped to fit within the outline of Oakland, CA. Thus, these bus routes include intercity bus routes, for which the part of the bus routes external to Oakland are not evaluated for their EJ Index percentile.

Fig. S2, displays the Oakland City District outlines along with their official corresponding names and numbers.

Fig. S4, displays the average median household income aggregated by mean over each Oakland City District, from the median household income of each census tract. Notably, the income for the northern Districts 1 and 4 have substantially higher income brackets, with an average income of over $100k, and the western Districts have income brackets below $70k.

Table S1 displays the exact values of Fig. S3. The median household income in District 1: North Oakland ($104k) and District 4: Central Oakland ($105k), have income notably higher than District 3: Western Oakland ($61k), District 5: Fruitvale/San Antonio ($61k), and District 7: Elmhurst ($62k).

Below, in Fig. S4, is a map of AC Transit route 800, which runs adjacent to large highways. By electrifying the bus routes that run alongside these high traffic corridors, cities can lighten the environmental burden on neighboring communities affected by such concentrated vehicle emissions.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2021.103179.

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