Environmental Science & Technology

pubs.acs.org/est

Policy Analysis

# Mapping Opportunities for Transportation Electrification to Address Social Marginalization and Air Pollution Challenges in Greater Mexico City

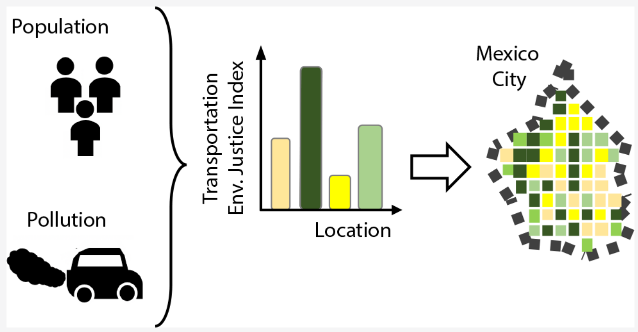
James Adam Mahady,* Claudia Octaviano, Oscar Sebastian Araiza Bolaños, Erick Rosas López, Daniel M. Kammen, and Sergio Castellanos*

Cite This: https://dx.doi.org/10.1021/acs.est.9b06148

Read Online



**ABSTRACT:** Amid climate change and public health concerns, world economies are seeking to reduce the greenhouse gas emissions and local air pollution from transportation. Population growth in cities worldwide will further increase demand for clean and affordable transportation. We propose a city-specific environmental justice mapping index, inspired by a similar index used in California, that highlights promising areas for clean transportation interventions in Greater Mexico City to reduce greenhouse gas emissions and local pollution. This novel approach leverages highly spatially resolved population, pollution, and transportation data. The proposed index score is designed as an open source, updateable point of orientation for decisionmakers as they consider investment in transportation electrification from the standpoint of overlapping atmospheric pollution and social vulnerability.






## I. INTRODUCTION

Amid increasing concerns related to climate change and public health, world economies are swiftly drafting policies to reduce the carbon emissions and local air pollution related to their economic activity. Energy and transportation are the top two sectors responsible for local air and greenhouse gas pollution worldwide.[1] Populations will migrate toward cities in the coming decades in parallel with these policy rollouts. More than 68% of the 9.8 billion people on the planet in 2050 are predicted to be living in large and highly dense urban areas.[2] This significant urban influx raises challenges for decisionmakers to improve urban livability, including access to safe, clean, and affordable mobility.

In particular, a fully electrified transportation sector represents an attractive option that both provides immediate air quality improvements by zeroing out tailpipe airborne pollutants and, when coupled with a decarbonized power sector, provides an environmentally conscious approach that aligns with the urgent need for action on climate and public health policy.[3,4] To this end, federal, regional, and city-level policymakers worldwide are endeavoring to electrify public transport and incentivize light-duty electric vehicle (EV) adoption. Policies to catalyze the transition from internal combustion to zero-tailpipe-emission substitutes are often similar to renewable energy technology incentives.[5] EV incentives include point-of-sale tax credits, import tax exemptions, and preferential roadway access.[6]

Given that EV deployment remains incipient, jurisdictions are experimenting with targeted infrastructure rollout to support uptake in parallel with vehicle incentives (e.g., public charging stations, transit routes designed for electric buses, strategic electric distribution grid system upgrades). This nascent stage of targeted investment is a tremendous opportunity for jurisdictions to make environmental justice (EJ) a priority in transportation policy and regulation planning. Investments in clean transportation modes, including EVs, have the potential to reduce atmospheric pollution in vulnerable communities, especially those located near congested streets and highways.[7] The relationship between environmental and social injustices has been analyzed from local and global perspectives, and through the lens of different fields such as public health,[8] engineering,[9] and public policy.[10] California, one of the first U.S. states to codify EJ in statute, defines EJ principles as “fairness, regardless of race, color, national origin or income, in the development of laws and regulations that affect every community’s natural surroundings, and the places people live, work, play and learn”.[11] Addressing

**Received:** October 11, 2019
**Revised:** January 3, 2020
**Accepted:** January 7, 2020
**Published:** January 7, 2020

such injustices, however, necessitates locally contextualized approaches,[12] and increased emphasis on policy design and evaluations that provide information to improve strategic planning.[13]

An example of a tool that is helpful for enabling such strategic planning is the State of California's Environmental Protection Agency's CalEnviroScreen EJ mapping tool,[14,15] which generates a geographical EJ burden index based on 19 indicators of population vulnerability and pollution burdens by census tract. This tool is a result of California EJ legislation, solidified by the passing of Senate Bill 535[17] in 2012 and the subsequent passing of AB 617[18] in 2017. These pieces of legislation clarify the importance of EJ for the investment of greenhouse gas credit program funds, mandating specific geographic targeting of resources toward disadvantaged communities who face burdens of environmental pollution and social marginalization.[19] Tools like CalEnviroScreen serve as a basis for combining social and pollution indicators and prioritizing investments with the potential to address them holistically.

However, we posit that modifications to an index like CalEnviroScreen are further required to tailor solutions to specific sectors, such as transportation. For example, elements such as nonatmospheric pollution indicators (e.g., proximity to hazardous waste generators, contaminated water bodies, etc.) are not associated with vehicle tailpipe emissions and thus mostly inapplicable for the vehicle electrification lens.

Spatial aggregation presents another challenge. Part of this challenge stems from homogenizing data throughout a jurisdiction. We posit that city and subregional governments tend to possess more disaggregated data on their population and urban landscape than federal or state entities. They are thus better positioned to implement transportation policy that seeks to address EJ concerns within their jurisdiction. Regional data aggregation may be too coarse for planning transportation interventions, which can vary from street to street. Furthermore, stark sociodemographic variations can also occur at finer spatial resolutions, which can be challenging to capture.[20]

In this contribution, we present a city-specific EJ index, inspired by ref 14. Our proposed index differs from ref 14 in that it is more spatially refined to better suit cities, and uses large volumes of transportation-related data to improve decision making on clean transportation interventions. We leverage highly spatially resolved population and pollution data, and both spatial and temporal traffic data. We explore the atmospheric pollution−marginalization nexus through the lens of potential public investment in transportation electrification as a pathway to confront these twin challenges. The proposed index is only indicative of areas deserving attention.

We focus our tool deployment in Greater Mexico City, whose urban center was ranked as the city with the worst traffic in the world in 2017.[21] It is also one of the world's largest metropolitan areas, with a population of 8.9 million in Mexico City proper (Ciudad de México, CDMX),[22] and 21 million in Greater Mexico City.[23]

Greater Mexico City suffers from high levels of atmospheric pollution. In 2016, none of the ozone and particulate matter (PM) monitoring stations in CDMX complied with minimum national air quality standards. Acute and prolonged exposure to these pollutants is damaging to respiratory and cardiac systems and affects the daily lives and livelihoods of those exposed. Internal combustion vehicles, especially heavy-duty, are responsible for the majority of greenhouse gas pollution, particulate matter pollution and a significant portion of the ozone pollution in Greater Mexico City.[24] Therefore, meaningful local criteria and greenhouse gas emissions reductions can be achieved by replacing internal combustion vehicles (which represent nearly all vehicles on the road) with EVs.[25] The atmospheric pollution that investment in EVs can help to reduce is often unequally distributed across geographies, especially in congested urban areas.[26]

Although Greater Mexico City and California greenhouse gas emissions reduction regulations and goals differ, the governments in both areas are firmly committed to reducing transportation emissions in the near term.[17,27,28] Especially for Mexico City proper, jurisdictional greenhouse gas commitments are likely to catalyze the types of investment in clean transportation that the proposed tool could help to guide.[23] California's CalEnviroScreen tool grew from a need to define "disadvantaged communities" that were soon to benefit from billions of dollars of greenhouse gas emissions reduction funding, which the state would invest directly in the most disadvantaged communities.[29]

For Greater Mexico City, the proposed index instead intends to serve as a point of reference for informing geographic focus of existing and future programs, such as the city's commitment to purchasing only zero-emission buses for its fleet from 2025[30] and its interest in public transportation electrification under its Strategic Mobility Strategy.[23] In Mexico City proper, vehicles are responsible for 53% of $PM_{10}$, 56% of $PM_{2.5}$, 86% of $NO_x$, 86% of CO, and 17% of VOC emissions from all sources.[24] Within transportation emissions, buses alone are responsible for 22% of $PM_{10}$, 32% of $PM_{2.5}$, and 23% of $NO_x$ emissions.[24] With these dynamics in mind, we maintain an electric transportation focus, however our proposed index is agnostic to policy intervention approach and low-emission technology pathways.

The proposed methodology, herein applied to Greater Mexico City, can be adapted for use in other regions and cities as well.

## II. MATERIALS AND METHODS

**Geographical Analysis Unit.** Akin to ref 14, we create two indicator groups: pollution and population. Within each group, each indicator represents a percentile score associated with a basic geostatistical area (área geoestadística básica, AGEB). AGEBs are defined by Mexico's National Institute of Statistics, Geography and Computing (Instituto Nacional de Estadística, Geografía e Informática; INEGI) as "geographical areas occupied by a group of blocks perfectly delimited by streets, avenues, sidewalks, or any other type of easily identified terrain feature and whose use of land is principally residential, industrial, service oriented, commercial, etc. AGEBs are only assigned to municipal seats and interior areas of urban zones with a minimum population of 2500 inhabitants.[31]"

Greater Mexico City is geographically defined in this analysis as the population living in a highly dense and connected continuum of urban AGEBs that encompass communities in the states of Hidalgo, Mexico City, and Mexico. The index coverage area is identical to the extent of Mexico's National Population Council's (Consejo Nacional de Población, CONAPO) urban marginalization index for Greater Mexico City.[32] Federal, regional and local decisionmakers use this index and its geographical delineation to inform transportation and development strategies, such as CDMX's 2019 Strategic


https://dx.doi.org/10.1021/acs.est.9b06148
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Mobility Plan (Plan Estratégico de Movilidad de la Ciudad de México 2019).[23] We used QGIS, a free and open-source geographic information system to generate our figures and conduct geographical analyses.[33]

**Pollution Indicators.** The chosen pollution indicators focus on exposure to atmospheric pollution directly related to local transportation modes. They are particle matter (PM) $PM_{2.5}$, $PM_{10}$,[34] ozone,[35] and traffic intensity.[36]

Data for ozone, and particulate matter—both coarse ($PM_{10}$) and fine ($PM_{2.5}$)—are from Mexico's National Institute for Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático, INECC) through their National Air Quality Information System (Sistema Nacional de Información de Calidad del Aire, SINAICA).[37] Data is collected from 26 monitoring station locations for $PM_{10}$, 20 monitoring station locations for $PM_{2.5}$ and 36 monitoring station locations for ozone. We use inverse distance weighting[38] to interpolate between monitoring stations and construct a continuous mesh that translates into a percentile value for each AGEB.

Mexico's Health Secretary (Secretaría de Salud) sets air quality standards[39] and INECC manages the national system for air quality monitoring and evaluation (the SINAICA system aggregates information generated by local authorities). For every day of the calendar year each monitoring station receives a rating of "good," "normal", or "bad" for each criteria pollutant ($PM_{2.5}$, $PM_{10}$, and ozone), as seen in Table 1. Ratings for $PM_{2.5}$ and $PM_{10}$ are based on a 24-h average, whereas ozone's rating is based on a day's highest average hour. Table 1 displays the ranges for good, normal, and bad air quality days for each criteria pollutant. A bracket indicates that the number is included in the range; parentheses indicates it is excluded. In order to be considered valid, a given day's rating must include information from at least 75% of the hours in the day.[40]

**Table 1. Air Quality Indicator Levels and Their Density Range Per Level for $PM_{10}$ ($\mu g/m^3$), $PM_{2.5}$ ($\mu g/m^3$), and Ozone (ppm)**

| air quality indicator | $PM_{10}$ ($\mu g/m^3$) | $PM_{2.5}$ ($\mu g/m^3$) | ozone (ppm) |
|---|---|---|---|
| good | (0 to 37.5] | (0 to 22.5] | (0 to 0.0475] |
| normal | (37.5 to 75] | (22.5 to 45] | (0.0475 to 0.095] |
| bad | >75 | >45 | >0.095 |

We construct ozone, $PM_{10}$, and $PM_{2.5}$ indicators by counting the number of "bad" air quality days over all days measured. The collected data corresponds to a 2013–2015, three-year annual average.

We generate the traffic intensity indicator by aggregating number and intensity of traffic jams at a street-segment level, and acquired on multiple street segments over the course of 6 months at a 1 min resolution.[41] These jams are binned into five equal-interval categories that are created by comparing the measured velocity vs a free flow speed. Level 1 traffic jam corresponds to a 20% decrease in baseline speed, and increases systematically until reaching level 5, which corresponds to near stoppage. Results are presented in a mesh of 500 × 500 equidistant blocks that cover the entire region of study. Counts are then aggregated at a block level and attributed to the AGEBs that intersect with each block. While traffic intensity is correlated with the other pollution indicators, we add it to the proposed index to capture the more localized effects of atmospheric pollution from vehicle traffic.[36,42]

**Population Indicators.** Population indicators illustrate social dimension of the Greater Mexico City and, coupled with the pollution indicators, highlight areas where transportation interventions—whether by expanding clean multimodal transportation, electrifying public transportation fleets, or a combination of these or other options—could improve access to economic opportunity for marginalized groups (e.g., those with lower social development index scores,[14] indigenous communities, etc.) while also providing air quality benefits.

To take social marginalization into account in the index, we include indicators related to poverty, race and differently abled individuals.

As an indicator of relative levels of poverty, we apply Mexico's CONAPO 2010 Index of Urban Marginalization (Índice de Marginación Urbana 2010, IMU). The IMU uses data from Mexico's 2010 census to generate an indicator that defines the level of social marginalization for each of the approximately 5200 AGEBs in Greater Mexico City.[14] The marginalization indicator is based on household access to education, public sanitation services, healthcare, electricity, running water, and refrigeration.[43] To incorporate a racial marginalization component, we use Mexico 2010 census data on the share of population three years of age and older that speaks an indigenous language.[44] Indigenous communities have faced discrimination in Mexico for hundreds of years.[45]

Age groups particularly vulnerable to air pollution impacts are considered in the index by quantifying the share of population of a given AGEB made up of individuals under six years of age, and sixty-five years of age and older.[46,47] Asthmatics, also especially vulnerable to air pollution, are included in the index as number of asthma cases recorded at public hospitals in Greater Mexico City from 2014 to 2016.[48,49] At present the geographical residence of individual asthma cases are only available at a less granular municipality (alcaldías/municipios), rather than more granular AGEB, level.

Finally, we include the share of the population of each AGEB with limited mobility (difficulty walking or moving autonomously) as recorded in the Mexico 2010 census.[44] This indicator is included to consider areas with higher concentrations of differently abled individuals who often stand to benefit a great deal from improved access to transportation in terms of physical, economic and social mobility.[50]

**Spatially Resolving the Index at an AGEB Level.** This index applies ref 15 method of calculating percentile rankings for each of the average percentiles of each of the pollution indicators and population indicators, respectively, and subsequently multiplying these to reach the final score for each of the AGEBs.[51] These scores are then ranked to generate percentage rankings for each of the AGEBs and are mapped by color gradient for easy visual inspection. eq 1 below denotes the calculation for the score

$$\text{Index}_{\text{AGEB}} = \text{pollution}_{\text{AGEB}} \times \text{population}_{\text{AGEB}} \quad (1)$$

where $\text{Index}_{\text{AGEB}}$ is the final index score percentile, obtained by multiplying the pollution indicator percentile, $\text{pollution}_{\text{AGEB}}$, by the population indicator percentile, $\text{population}_{\text{AGEB}}$, all resolved at an AGEB level. AGEBs that do not have a value due to lack of data are omitted and the $\text{Index}_{\text{AGEB}}$ is computed with the remaining available indicators. The accompanying index spreadsheet can be found in the Supporting Information.


https://dx.doi.org/10.1021/acs.est.9b06148
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

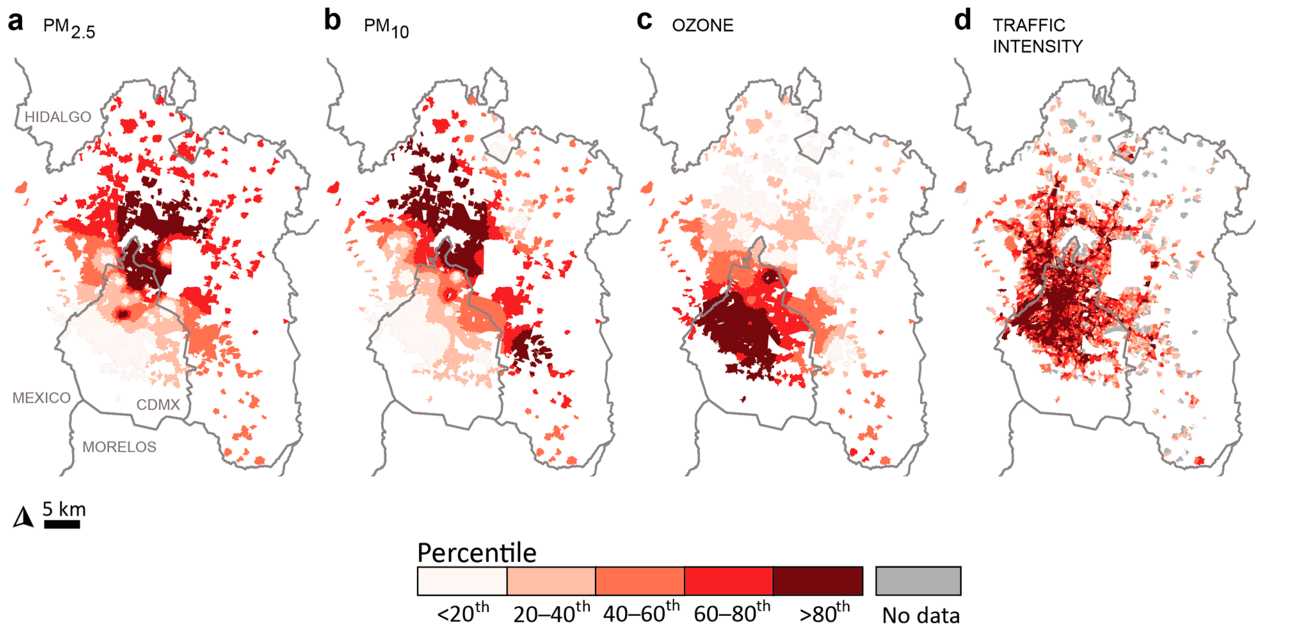



**Figure 1.** Geographical distribution of pollution indicators scaled in percentile for (a) $PM_{2.5}$, (b) $PM_{10}$, (c) ozone, and (d) traffic intensity. State boundary and AGEB shapefile source: INEGI.

## RESULTS

The first set of maps in Figure 1 on the preceding page show pollution indicators for $PM_{2.5}$, $PM_{10}$, ozone, and traffic intensity. The darker the shade of red, the more intense the pollution burden for a given AGEB. AGEBs without data are greyed out.

The maps in Figure 2 show indicators for vulnerability to pollution: (a) asthma and (d) particularly sensitive age groups; social marginalization: (f) index of urban marginalization, and (b) indigenous population; (e) individuals with limited mobility, and (c) population density. Darker shades of green indicate higher rates of vulnerability, social marginalization and individuals with limited mobility. Darker shades of green also indicate higher levels of population density, which is included to incorporate the varying population densities of each AGEB into the overall index.

Figure 3 maps show aggregate pollution (in red, Figure 3a) and population (in green, Figure 3b) burdens. They display unweighted averages of all the indicators mapped above. The darker shades indicate a greater pollution burden and population vulnerability.

Figure 4 is an EJ-oriented index using an unweighted average of pollution and population indicators from Figure 3. Less burdened AGEBs appear in yellow, and more burdened AGEBs appear in dark blue.

## DISCUSSION

The proposed index score aims to generate a quantifiable metric that is intentionally simple in its calculation and therefore relatively straightforward to disaggregate. It is designed to serve as a point of orientation for decisionmakers as they consider investment in transportation electrification from the standpoint of overlapping EJ-relevant concerns of atmospheric pollution and social vulnerability.

The aggregate map in Figure 4 highlights areas of the city where investment in transportation electrification may be a good fit for addressing EJ concerns. Eastern and northeastern areas of CDMX, adjacent areas in the State of Mexico, and AGEBs around the urban periphery appear in dark blue, corresponding to high burden AGEBs.

**Linking Variables and Prioritizing Interventions.** Mexico's constitution states the right of all persons to "an environment suitable for their development and wellbeing",[52] creating a clear statutory basis for environmentally minded social development policies at both federal and municipal levels. In fact, Mexico is currently prioritizing social and environmental dimensions of energy and climate policy and therefore this type of data-intensive and multidimensional index is of crucial importance for decision making.

For example, CDMX is constructing a cable car system to serve marginalized communities in the northern parts of the city.[53] The city is also planning to invest in a zero-emission bus-rapid transit line to serve low- and middle-income communities in the eastern CDMX municipality of Iztapalapa.[54] The CDMX *Strategic Mobility Plan 2019* prioritizes serving marginalized communities in CDMX (as identified by the IMU) and sheds a favorable light on transportation electrification investment. However, it does not explicitly link marginalized communities with other relevant variables such as atmospheric pollution.

Another example of regions the government identified for social-marginalization oriented intervention appears in Figure 5. In this case, the federal government's *25 prioridades*—25 priority areas—includes a focus on "urban development" in several marginalized municipalities in Greater Mexico City (Chimalhuacán, Chalco, Valle de Chalco, and Ecatepec), outlined in red. The current approach fails to expressly mention atmospheric pollution, additional aspects of marginalization (e.g., vulnerable age groups, indigenous communities, etc.), and preferred types of projects or programs to spur urban development.[55] As Figure 5 suggests, focusing only on these priority regions misses a large number of AGEBs across Greater Mexico City with high atmospheric and social marginalization burden (shown in dark blue). We posit that the proposed disaggregated index can be valuable for use both outside of and within priority investment areas. For example, in


https://dx.doi.org/10.1021/acs.est.9b06148
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

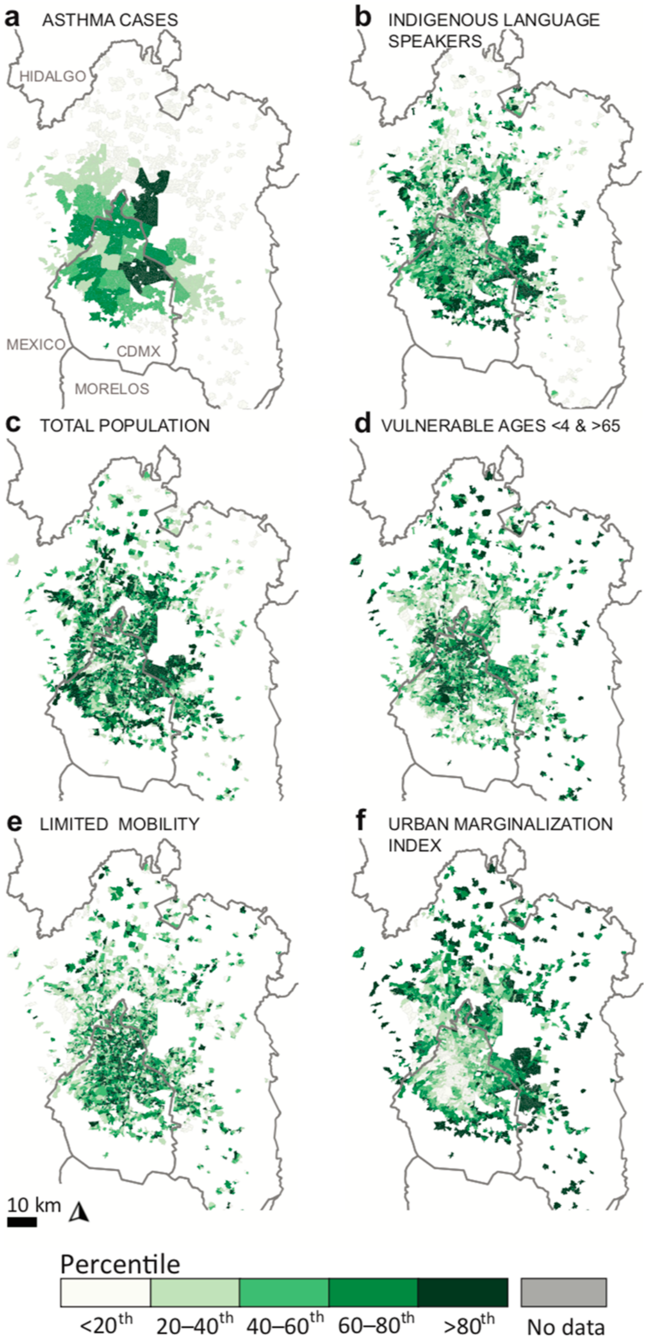



**Figure 2.** Geographical distribution of population indicators scaled in percentile for (a) asthma cases, (b) indigenous language speakers, (c) total population, (d) vulnerable ages (between 0 and 4 and 65+ years), (e) limited mobility, and (f) urban marginalization index. State boundary and AGEB shapefile source: INEGI.

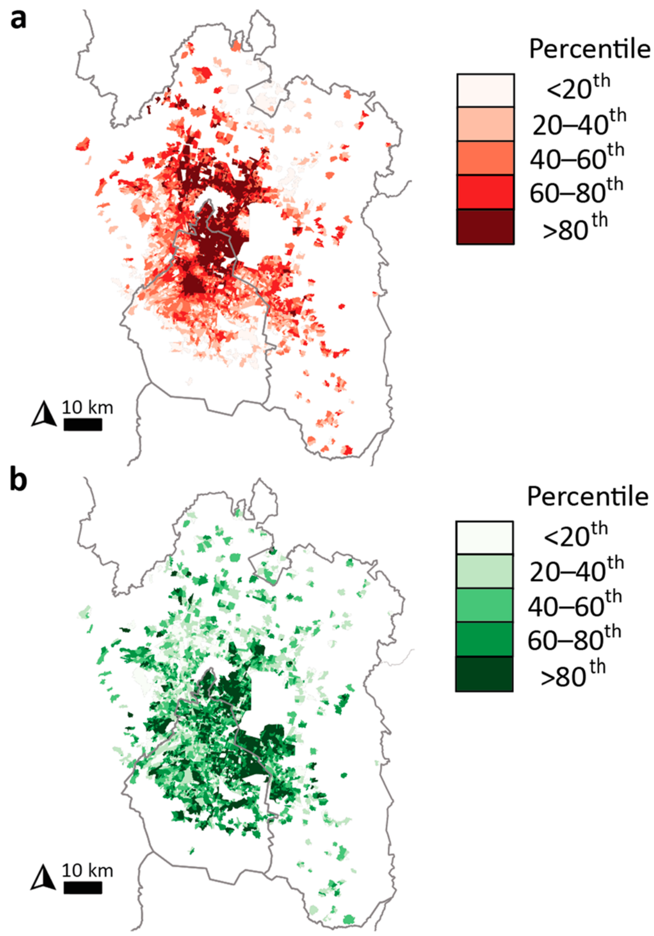



**Figure 3.** Aggregated index scaled by percentiles for (a) pollution, and (b) population, where lighter shades show low burden and dark colored regions denote AGEBs with higher burden. State boundary and AGEB shapefile source: INEGI.

Figure 5, decisionmakers can clearly identify a small selection of AGEBs to target within Chalco and Valle de Chalco (lower-right municipalities bounded in red) with high levels of pollution and social marginalization, while simultaneously expanding resources to benefit those high-burden AGEBs clustered in Ecatepec and Chimalhuacán (middle and upper regions bounded in red). In other words, this holistic visual index can be used to prioritize transportation interventions that address atmospheric pollution and social marginalization both within and outside of areas that the government has prioritized for development investment.

While Figures 4 and 5 illustrate an EJ-oriented ranking that takes things one step further and directly links environmental and social policy areas through the lens of cleaner transportation, the decision of a specific transportation intervention will ultimately reside with the decisionmakers at a city, municipality and metro area level. For example, a U.S. Federal Highway Administration Environmental Justice Reference guide includes "solicit[ing] input from potentially impacted minority and low-income populations" as a key data collection and analysis question to consider in its *Environmental Justice Toolkit*.[56]

**Example of EJ-Transportation Index Application: EV Charging Density by AGEB Index Values.** Figure 6 is an example of an application of the index that examines AGEB-level pollution and marginalization burdens of existing electric vehicle charging locations deployed in Greater Mexico City as of spring 2019.[57] The chart shows how many charging locations fall within a given AGEB on the vertical axis, compared against the index value on the horizontal axis. Recall that the greater the index percentile, the higher the environmental and population marginalization faced by individuals in that AGEB.

The overall trendline (in dark red) in Figure 6 is downward sloping but does not suggest a significant relationship across the entire charging station data set. However, the highest charging station density (5−7 per AGEB) appears in AGEBs


https://dx.doi.org/10.1021/acs.est.9b06148
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

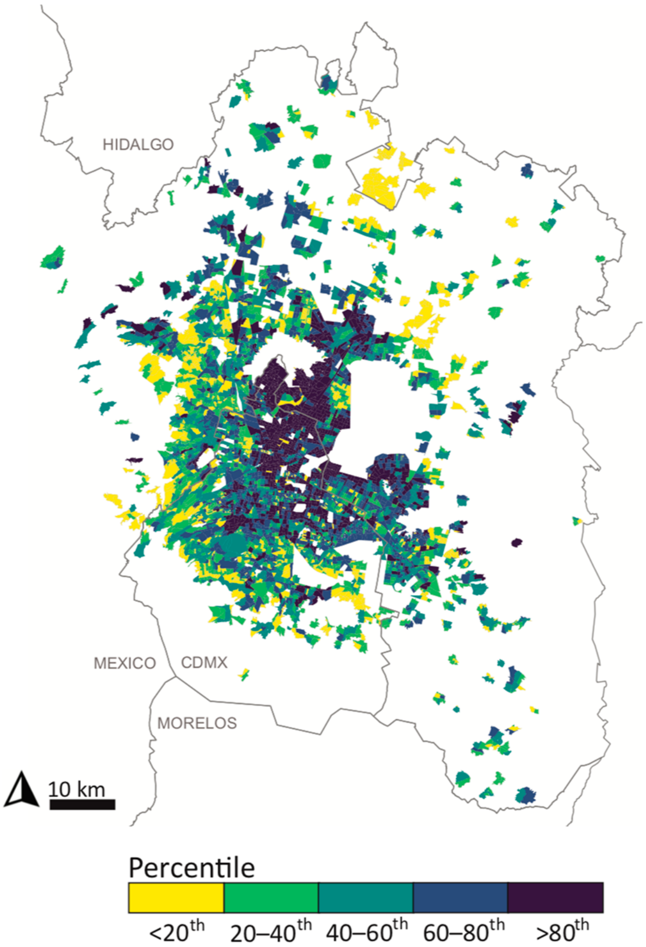



**Figure 4.** Final aggregated index that contains all variables equally weighed for Greater Mexico City, where lighter yellow shows low burden and dark purple colored regions denote AGEBs with higher burden. State boundary and AGEB shapefile source: INEGI.

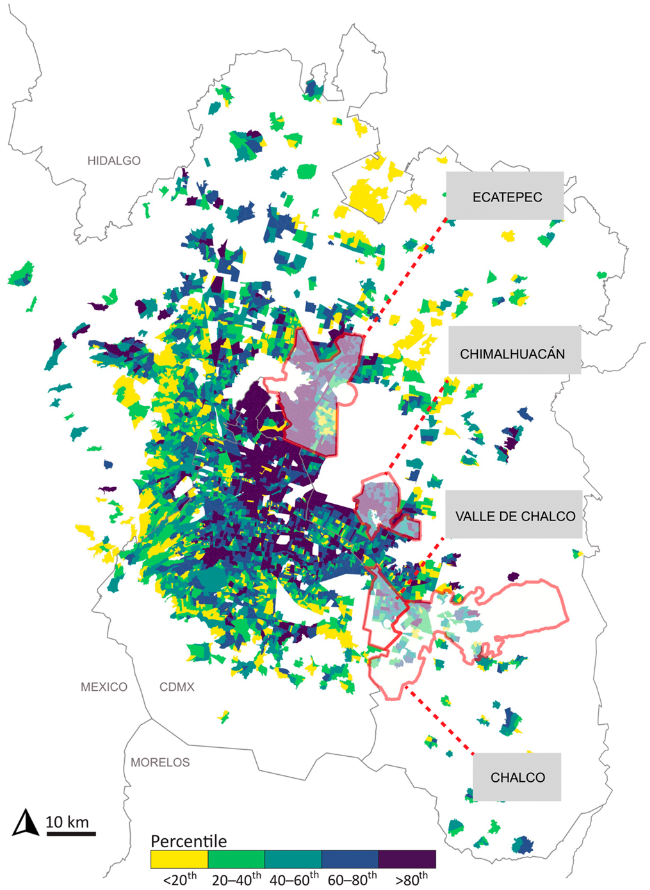



**Figure 5.** Areas that the federal government has prioritized for investment in social development (red polygons) (ref 50) overlaid against the final aggregated index, as shown in Figure 4. State boundary and AGEB shapefile source: INEGI.

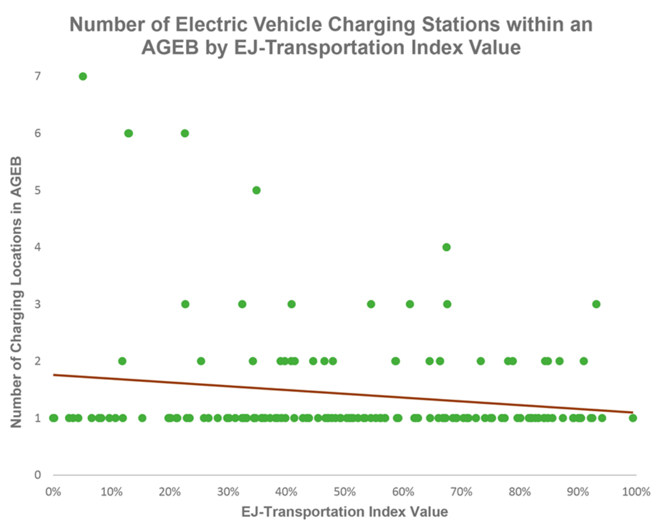



**Figure 6.** Number of electric vehicle charging stations per AGEB across AGEBs with indexed values throughout Greater Mexico City. A linear fit (dark red) is performed to show general trend of installation per burden index.

with a lower environmental and population marginalization value. The use of the proposed index shows that better-off areas with more access to services and cleaner air are some of the first to demand (or to be supplied) with electric vehicle charging infrastructure. This chart suggests that as demand for EVs grows, there is an opportunity to more evenly distribute investments in EV charging infrastructure density across EJ-Transportation Index levels. While charging station installations per se might not directly result in local and greenhouse gas pollution reductions, they may bring other tangible associated improvements to the surrounding community's physical environment (e.g., improvements to paved surfaces) and access to key services (e.g., electrical grid infrastructure). Charging stations are therefore considered an integral piece of the larger transition to a cleaner transportation paradigm and, under that context, are relevant as an example of an application for the proposed tool.

The applications like the spatial analysis in Figure 6 attempt to frame the pollution-marginalization linkage in a clear and direct manner so that the rationale is tangible and easily assessed.

This index represents a first step toward crafting an open-source, transparent tool for linking these twin challenges and facilitating prioritization of transportation investment in marginalized areas suffering from poor air quality. Our framework overlaps challenges of pollution and marginalization to be understood in the context of transportation electrification policy design. Although city and regional transportation policy design takes marginalization into account, it does not currently


https://dx.doi.org/10.1021/acs.est.9b06148
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

prioritize transportation electrification as a tool for addressing the poor air quality in many marginalized areas. The proposed index addresses these twin challenges through targeted investment in programs such as transportation electrification and tailors the underlying EJ-oriented index to the Greater Mexico City context.

More sophisticated assessments can be implemented at any one variable to improve the overall index scoring quality. For example, dispersion analysis could better provide an understanding of the pollutants spatial and temporal evolution. To complement this, analyses of modality and timing of population movement through heavily polluted areas are required to more precisely understand where and when populations are most impacted by pollution. Similarly, pollution indicators could be weighted to reflect their differing health impacts per guidance from local public health agencies. Following the 2020 census, the population indicator could be updated to reflect the latest changes in marginalization and vulnerability.

City data collection and publication efforts could be improved to strengthen indicators presented herein. For example, private and public hospitals could gather and report asthma data at high resolution to improve the current data set that only includes cases at public hospitals. The advent of new low-cost sensing technologies also offers opportunities for more granular analysis of pollution impacts.

In the context of Greater Mexico City, the results may be conservative due to a lack in some segments of the population in reporting their age (hence, underreporting vulnerable aged population). The environmental exposure dynamic uses "Bad Days" as defined by Mexican environmental regulations. Since the index only uses % of "Bad Days" and does not consider or weight "Normal Days" in terms of the impacts of ozone and PM on health. This means that it may understate the nonzero effects that a "Normal Day" likely has on sensitive groups in the population (e.g., individuals with compromised cardiac and respiratory systems and individuals suffering from asthma).

Moving forward, this index can be expanded to other cities contending with marginalization and air pollution challenges and even serve as a vehicle for collaborative policy design and implementation in cities. This could be particularly relevant for border cities that may differ demographically but likely share—to a large extent—pollution externalities and transit corridor infrastructure.[16]

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b06148.

Proposed Atmospheric Pollution and Social Marginalization Index, Spreadsheet containing the proposed index's underlying information and methodologies, EJIndexGreaterMexicoCity_2019.xlsx (XLSX)

## ■ AUTHOR INFORMATION


### Corresponding Authors

**James Adam Mahady** – *California Institute for Energy and Environment, University of California at Berkeley, Berkeley, California 94720, United States;* orcid.org/0000-0002-8323-5213; Phone: +1 (206) 218-9535; Email: james_mahady@berkeley.edu

**Sergio Castellanos** – *California Institute for Energy and Environment and Energy and Resources Group, University of California at Berkeley, Berkeley, California 94720, United States*; Email: sergioc@berkeley.edu

### Authors

**Claudia Octaviano** – *Coordinación General de Mitigación del Cambio Climático, Instituto Nacional de Ecología y Cambio Climático, Ciudad de México, Mexico 14210, United States*

**Oscar Sebastian Araiza Bolaños** – *Coordinación General de Mitigación del Cambio Climático, Instituto Nacional de Ecología y Cambio Climático, Ciudad de México, Mexico 14210, United States*

**Erick Rosas López** – *Coordinación General de Mitigación del Cambio Climático, Instituto Nacional de Ecología y Cambio Climático, Ciudad de México, Mexico 14210, United States*

**Daniel M. Kammen** – *Energy and Resources Group, University of California at Berkeley, Berkeley, California 94720, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.9b06148


### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

We thank Alex Gao and Pedro Sánchez for their support with data processing and visualization. We are grateful to the INECC team: Ana María Contreras, Adolfo Contreras, Ulises Ruiz,and Gabriela Mariscal. We thank Hector Cárdenas at UC Berkeley for his insightful discussions of the material, and the World Resources Institute in Mexico City for providing valuable feedback. The authors thank Waze and their Connected Citizens Program for providing data and their support in disseminating case scenarios for our use. The authors also appreciate the United Nations Global Pulse Initiative's support with data access. J.M. greatly appreciates the financial support of UC Berkeley's Center for Latin American Studies through the Tinker Summer Research Grant as well as the UCLA Blum Center on Poverty and Health in Latin America Summer Scholars Program. S.C. and J.M. thank Tec de Monterrey and the Binational Laboratory on Smart Sustainable Energy Management and Technology Training program funded by CONACYT-SENER's FSE. D.K. gratefully acknowledges support from the U.S. National Science Foundation CyberSEES program (Grant No. 1539585), and both the Karsten and Zaffaroni Family Foundations. D.K. also thanks the California Energy Commission for support (EPC-15-078).

## ■ REFERENCES

(1) European Environment Agency. Sectoral greenhouse gas emissions by IPCC sector https://www.eea.europa.eu/data-and-maps/daviz/change-of-co2-eq-emissions-2 (accessed March 17, 2019).

(2) United Nations. 68% of the world population projected to live in urban areas by 2050, says UN https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed March 17, 2019).

(3) Anderson, C. M.; Kissel, K. A.; Field, C. B.; Mach, K. J. Climate Change Mitigation, Air Pollution, and Environmental Justice in California. *Environ. Sci. Technol.* **2018**, *52* (18), 10829–10838.

(4) Steinberg, D.; Bielen, D.; Eichman, J.; Eurek, K.; Logan, J.; Mai, T.; McMillan, C.; Parker, A.; Vimmerstedt, L.; Wilson, E.

Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization. *Renew. Energy* **2017**, *53*, 31.
(5) Mints, P. The History and Future of Incentives and the Photovoltaic Industry and How Demand Is Driven. *Prog. Photovoltaics* **2012**, *20* (6), 711−716.
(6) Hall, D.; Cui, H.; Lutsey, N. *Electric Vehicle Capitals of the World: What Markets Are Leading the Transition to Electric?*; International Council on Clean Transportation, 2017.
(7) Kragh, B. C.; Nelson, C.; Groudine, C. *Environmental Justice: The New Normal for Transportation*; U.S. Federal Highway Administration Public Roads, 2016, *79*(5), p 4.
(8) Nardone, A.; Thakur, J.; Balmes, J. R. *Historic Redlining and Asthma Exacerbations Across Eight Cities of California: A Foray into How Historic Maps Are Associated with Asthma Risk*; Dallas, TX, 2019.
(9) Ji, S.; Cherry, C. R.; Zhou, W.; Sawhney, R.; Wu, Y.; Cai, S.; Wang, S.; Marshall, J. D. Environmental Justice Aspects of Exposure to PM2.5 Emissions from Electric Vehicle Use in China. *Environ. Sci. Technol.* **2015**, *49* (24), 13912−13920.
(10) Helme, N.; Davis, S.; Reed, S.; Helme, N. G.; Levinson, M.; Wooley, D. *Advancing Environmental Justice: A New State Regulatory Framework to Abate Community-Level Air Pollution Hotspots and Improve Health Outcomes*; Goldman School of Public Policy, Center for Environmental Public Policy: Berkeley, CA, 2017; p 37.
(11) California Environmental Protection Agency. Environmental Justice Program https://calepa.ca.gov/envjustice/ (accessed June 13, 2019).
(12) David Carruthers. *Environmental Justice in Latin America: Problems, Promise and Practice*; The MIT Press, 2008.
(13) Institute for Transportation and Development Policy. Sustainable mobility: how does your city measure up? https://naindicators.itdp.org/ (accessed March 12, 2019).
(14) Rodríguez, M.; Zeise, L. *CalEnviroScreen 3.0: Update to the California Communities Environmental Health Screening Tool (Poverty)*; **2017**.
(15) California Environmental Protection Agency. *CalEnviroScreen 3.0*, **2017**.
(16) Morello-Frosch, R.; Pastor, M.; Porras, C.; Sadd, J. Environmental Justice and Regional Inequality in Southern California: Implications for Future Research. *Environ. Health Perspect.* **2002**, *110* (suppl 2), 149−154.
(17) Bill Text - SB-535 California Global Warming Solutions Act of 2006: Greenhouse Gas Reduction Fund. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201120120SB535 (accessed November 26, 2018).
(18) State of California Legislature. Bill Text - AB-617 Nonvehicular air pollution: criteria air pollutants and toxic air contaminants. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB617 (accessed November 26, 2018).
(19) Colleen, C.; DeShazo, J. R. *Investment Justice Through the Greenhouse Gas Reduction Fund: Implementing SB 535 and Advancing Climate Action in Disadvantaged Communities*, **2014**.
(20) Banzhaf, S.; Ma, L.; Timmins, C. Environmental Justice: The Economics of Race, Place, and Pollution. *J. Econ. Perspect.* **2019**, *33* (1), 185−208.
(21) TomTom. Full ranking, TomTom Traffic Index https://www.tomtom.com/en_gb/trafficindex/list?citySize=LARGE&continent=ALL&country=ALL (accessed March 12, 2019).
(22) Index Mundi. Mexico Demographics Profile 2018 https://www.indexmundi.com/mexico/demographics_profile.html (accessed Mar 17, 2019).
(23) Secretaría de Movilidad. *Plan Estratégico de Movilidad de La Ciudad de México 2019; Strategy*; Gobierno de la Ciudad de México, 2019.
(24) Secretaría del Medio Ambiente de la Ciudad de México, D. B. C. *Inventario de Emisiones de la Ciudad de México 2016; Dirección General de Gestión de la Calidad del Aire*; Dirección de Monitoreo Atmosférico.: Ciudad de México, 2018.
(25) Castellanos, S. Big Data Brings Cleaner Air and Better Transportation to Mexico https://datamakespossible.westerndigital.com/cleaner-air-better-transportation-mexico/ (accessed June 13, 2019).
(26) Marshall, J. D.; Swor, K. R.; Nguyen, N. P. Prioritizing Environmental Justice and Equality: Diesel Emissions in Southern California. *Environ. Sci. Technol.* **2014**, *48* (7), 4063−4068.
(27) State of California Legislature. *California Renewables Portfolio Standard Program: Emissions of Greenhouse Gases*, **2018**; Vol. *SB 100*.
(28) Distrito Federal de México. *Programa de Acción Climática: Ciudad de México 2014−2020*; Centro Mario Molina para Estudios Estratégicos sobre Energía y Medio Ambiente, June 2014.
(29) Truong, V. Addressing Poverty and Pollution: California's SB 535 Greenhouse Gas Reduction Fund. *Harv. Civ. Rights 49* 37; p 514.
(30) C40 Cities Finance Facility. C40: Green and Healthy Streets https://www.c40.org/other/green-and-healthy-streets (accessed September 19, 2019).
(31) Consejo Nacional de Evaluación de la Política de Desarrollo Social. Rezago Social a Nivel Zonas Urbanas https://www.coneval.org.mx/Medicion/IRS/Paginas/Rezago_social_AGEB_2010.aspx (accessed March 26, 2019).
(32) Instituto Nacional de Estadística, Geografía e Informática. Grado de marginación urbana por AGEB, Zona Metropolitana del Valle de México, 2010, 2011.
(33) QGIS Development Team. *QGIS Geographic Information System*; Open Source Geospatial Foundation Project, 2019. http://qgis.osgeo.org/.
(34) USEPA. Health and Environmental Effects of Particulate Matter (PM) https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm (accessed April 6, 2019).
(35) US EPA, O. Health Effects of Ozone Pollution https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution (accessed April 6, 2019).
(36) Zhang, K.; Batterman, S. Air Pollution and Health Risks Due to Vehicle Traffic. *Sci. Total Environ.* **2013**, *450*, 307−316.
(37) Instituto Nacional de Ecología y Cambio Climático. Sistema Nacional de Información de la Calidad del Aire https://sinaica.inecc.gob.mx/ (accessed March 26, 2019).
(38) de Mesnard, L. Pollution Models and Inverse Distance Weighting: Some Critical Remarks. *Comput. Geosci.* **2013**, *52*, 459−469.
(39) Secretaría de Salud. Normas Oficiales Mexicanas (NOM) de Calidad del Aire Ambiente http://www.gob.mx/cofepris/acciones-y-programas/4-normas-oficiales-mexicanas-nom-de-calidad-del-aire-ambiente (accessed March 18, 2019).
(40) Instituto Nacional de Ecología y Cambio Climático. *Informe Nacional de Calidad del Aire, 2016*; Instituto Nacional de Ecología y Cámbio Climático, Coordinación General de Contaminación y Salud Ambiental, Dirección de Investigación sobre la Calidad del Aire y los Contaminantes Climáticos: Mexico City, 2017.
(41) Waze. Free Driving Directions, Traffic Reports & GPS Navigation App by Waze https://www.waze.com/ (accessed April 6, 2019).
(42) Apte, J. S.; Messier, K. P.; Gani, S.; Brauer, M.; Kirchstetter, T. W.; Lunden, M. M.; Marshall, J. D.; Portier, C. J.; Vermeulen, R. C. H.; Hamburg, S. P. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. *Environ. Sci. Technol.* **2017**, *51* (12), 6999−7008.
(43) Consejo Nacional de Población. Capítulo 1, Marginación Urbana 2010 http://www.conapo.gob.mx/es/CONAPO/Capitulo_1_Marginacion_Urbana_2010 (accessed May 5, 2019).
(44) Instituto Nacional de Estadística, Geografía e Informática. Censo de Población y Vivienda 2010 https://www.inegi.org.mx/programas/ccpv/2010/ (accessed June 5, 2019).
(45) Bello, M. A.; Rangel, M. Equity and Exclusion in Latin America and the Caribbean: The Case of Indigenous and Afro-Descendant Peoples. *CEPAL Rev.* **2002**, *76*.39
(46) Malig, B. Air Pollution and Children's Health - A Fact Sheet by OEHHA and the American Lung Association https://oehha.ca.gov/


https://dx.doi.org/10.1021/acs.est.9b06148
*Environ. Sci. Technol.* XXXX, XXX, XXX−XXX

air/air-pollution-and-childrens-health-fact-sheet-oehha-and-american-lung-association (accessed June 4, 2019).
(47) Air Pollution and Mortality in the Medicare Population, *NEJM* https://www.nejm.org/doi/full/10.1056/NEJMoa1702747?query=featured_home (accessed April 6, 2019).
(48) Secretaría de Salud. Egresos Hospitalarios http://www.dgis.salud.gob.mx/contenidos/basesdedatos/da_egresoshosp_gobmx.html (accessed March 17, 2019).
(49) California Environmental Protection Agency Office of Environmental Health Hazard Assessment. Asthma https://oehha.ca.gov/calenviroscreen/indicator/asthma (accessed June 4, **2019**); p 2.
(50) World Bank. For Persons with Disabilities, Accessible Transport Provides Pathways to Opportunity http://www.worldbank.org/en/news/feature/2015/12/03/for-persons-with-disabilities-accessible-transport-provides-pathways-to-opportunity (accessed June 5, 2019).
(51) California Environmental Protection Agency Office of Environmental Health Hazard Assessment. CalEnviroScreen: Scoring & Model https://oehha.ca.gov/calenviroscreen/scoring-model (accessed April 6, 2019).
(52) Secretaría de Gobernación. Decreto por el que se declara la adición de un párrafo quinto al artículo 4o. Constitucional y se reforma el párrafo primero del artículo 25 de la Constitución Política de los Estados Unidos Mexicanos, **1999**.
(53) Forbes Staff. *Las Cuatro Líneas de Cablebús Que La CDMX Tendrá En Los Próximos Años*; Forbes México: Mexico City, February 7, 2019.
(54) C40 Cities Finance Facility. Mexico City - Eje 8,https://c40cff.org/projects/mexico-city-eje-8 (accessed May 6, 2019).
(55) Ramirez, M. Los 25 programas prioritarios de AMLO https://dnf.com.mx/index.php/2018/08/06/los-25-programas-prioritarios-de-amlo/ (accessed March 17, 2019).
(56) *Federal Highway Administration Environmental Justice Reference Guide*; US Federal Agency Report; US Federal Highway Administration, 2015; p 82.
(57) Instituto Nacional de Ecología y Cambio Climático. Internal Database: Electric Vehicle Charging Locations. April **2019**.


https://dx.doi.org/10.1021/acs.est.9b06148
*Environ. Sci. Technol.* XXXX, XXX, XXX−XXX