CHAPTER 7

Measuring Electric Vehicle Infrastructure Among Cities: A Multidimensional Approach

Z. Justin Ren, PhD and John P. Helveston, PhD

7.1 Introduction

Urban areas across the world are leading Electric Vehicle (EV) adoption, with over 40% of the world's EVs concentrated in just 20 cities. EV adoption is transforming cities' mobility and energy systems, and in particular EV charging infrastructure. While earlier literature considered the effects and implications of national- and state-level EV policies, few studies have focused on helping city-level decision-makers prepare for future EV adoption. This chapter quantifies the various dimensions of a city's readiness in meeting demand for EV charging infrastructure. A multidimensional framework is proposed, comparing what influences infrastructure investment decisions in different cities around the world. That index then prompts a discussion about what policymakers can learn from such a framework to contribute to better EV infrastructure decisions by cities.

Along with much other evidence, the case studies in this volume indicate that accelerated adoption of electric vehicles (EVs) will require a substantial increase in the buildout of EV charging infrastructure.[240] However, EV adoption rates vary substantially among different cities around the world, due to idiosyncrasies that support varying EV adoption rates and levels of available charging

240 National Renewable Energy Laboratory (NREL), *National Plug-In Electric Vehicle Infrastructure Analysis*, 2017, Available at: https://www.nrel.gov/docs/fy17osti/69031.pdf; China's National Development and Reform Commission (NDRC), *Guidelines for accelerating the plug-in electric vehicle charging infrastructure deployment*, 2015, Available at: http://www.ndrc.gov.cn/zcfb/zcfbtz/201511/W020151117576336784393.pdf.

infrastructure. For example, greater levels of public charging infrastructure will be required to support greater EV adoption in cities like Beijing, where most residents live in high-rise apartments with limited dedicated parking. By contrast, in cities like Austin, Texas, most residents have at least one dedicated parking space at their home, where charging can occur.[241]

In addition, while EV adoption is frequently studied at the national level[242] and state level,[243] cities remain the spearhead for large portions of global EV adoption. As of November 2017, 40% of all EVs in the world were concentrated in just 20 cities.[244] The advent of increased EV adoption in urban centers is requiring city policymakers to consider important structural changes to city infrastructure systems, particularly in EV charging infrastructure. Indeed, examining city-level adoption rather than national or regional adoption has important implications for ensuring adequate infrastructure planning and implementation.

This chapter uses the metropolitan area as a unit of analysis in order to characterize how different factors are associated with EV adoption in select cities. By focusing on the city level, we aim to help city planners and policymakers understand what drives EV infrastructure needs in their own localities and devise appropriate policies accordingly. In particular, we identify a series of city-specific drivers underlying residents' decision to adopt EVs. Then we propose a multivariate framework that incorporates those drivers in order to measure a city's readiness to adopt an EV public charging infrastructure. The framework can be depicted visually and possibly aggregated into a single number. Therefore, the framework has the potential to help city policymakers look at peer

241 Hall, D., Cui, H. and Lutsey, N., *Electric vehicle capitals of the world: What markets are leading the transition to electric?*, 2018, ICCT, Available at: https://www.theicct.org/sites/default/files/publications/EV_Capitals_2018_final_20181029.pdf.

242 Helveston, J. P., Liu, Y., Feit, E. M., Fuchs, E. R. H., Klampfl, E. and Michalek, J. J., *Will subsides drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China*, 2015, Transportation Research Part A: Policy and Practice, 73, 96–112, Available at: https://www.sciencedirect.com/science/article/pii/S0965856415000038; Rietmann, N., and Lieven, T., *How policy measures succeeded to promote electric mobility—Worldwide review and outlook*, 2019, Journal of Cleaner Production, 206, 66–75, Available at: https://www.sciencedirect.com/science/article/pii/S0959652618328415.

243 Jenn, A., Azevedo, I. L., & Ferreira, P., *The impact of federal incentives on the adoption of hybrid electric vehicles in the United States*, 2013, Energy Economics, 40, 936–342, Available at: https://www.sciencedirect.com/science/article/pii/S0140988313001709; Jenn, A., Springel, K., and Gopal, A. R., *Effectiveness of electric vehicle incentives in the United States*, July 2017, Energy Policy, 119, 349–356, Available at: https://www.sciencedirect.com/science/article/pii/S0301421518302891.

244 Ibid., Hall, D., Cui, H., & Lutsey, N.

cities to better understand their own barriers to accelerating the electrification of their transportation sector.

The rest of the chapter is organized as follows: First, relevant background information is discussed. Then we present a multifaceted framework that measures a city's EV public infrastructure readiness by analyzing the real-world data that have been collected and compiled. A discussion of findings from this application follows. The chapter concludes with suggestions to practitioners and thoughts on future directions for research.

7.2 Background

The transportation sector is now the largest contributor to anthropogenic carbon (CO_2) emissions in the United States.[245] As a result, vehicle electrification is perceived as one of the most significant ways to reduce air pollution and CO_2 emissions in the United States.[246] Accelerated EV adoption is also perceived as one of the most significant sources of new electricity demand for the energy sector.[247]

Meeting this electricity demand will require substantial increases in charging infrastructure. A study by the National Renewable Energy Laboratory (NREL) estimates that approximately 600,000 nonresidential Level 2 chargers (240 V and 12–80 A) and 25,000 DC fast chargers (up to 500 V and 125 A) would be necessary to satisfy charging demand from an anticipated 15 million EVs on the road in 2030, which would make up just 5% of the total number of vehicles in the United States.[248] China's National Development and Reform Commission (NDRC) issued similarly large estimates of increased vehicle electrification in China with its plan to build 12,000 charging stations and more than 4.8 million chargers nationwide by 2020.[249] In Norway—the world leader in EV adoption by percentage of new vehicle sales—approximately 100,000 EVs (3% of all vehicles) in operation are supported by a network of 4,400 Level

245 US EPA, *Fast Facts on Transportation Greenhouse Gas Emissions*, 2018, Available at: https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.
246 Sperling, D., *Three Revolutions: Steering Automated, Shared, and Electric Vehicles to a Better Future*, 2018, (Washington DC: Island Press).
247 Fox-Penner, P., Gorman, W. and Hatch, J., *Long-term U.S. transportation electricity use considering the effect of autonomous-vehicles: Estimates & policy observations*, Feb. 2018, *Energy Policy*, 122, 203–213.
248 NREL, *National Plug-In Electric Vehicle Infrastructure Analysis*, 2017.
249 NDRC, *Guidelines for accelerating the plug-in electric vehicle charging infrastructure deployment*, 2015.

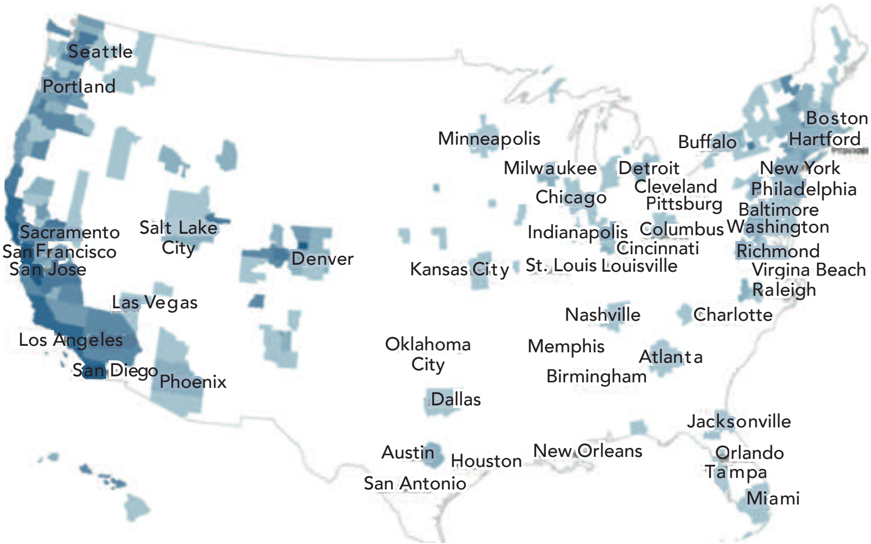
1 chargers (120 V and 16 A) and 2,700 Level 2 chargers,[250] which is roughly 14 EVs per Level 1 and Level 2 charger combined.

Based on national-level data and analyses, increased charging infrastructure will clearly be necessary even for modest increases in the number of EVs on the road. However, prior work also shows high levels of heterogeneity in city-level rates of EV adoption. While many cities across the world have virtually no EVs on the road, other cities, such as Oslo and Bergen in Norway, are rapidly adopting EVs, which represented more than 33% of vehicle sales in 2016.[251] In larger cities such as Los Angeles and Shanghai, EV sales made up just 4% and 6% of 2016 sales, respectively. However, given the size of their markets, both Los Angeles and Shanghai already have approximately 100,000 EVs on the road—close to the total number in all of Norway.[252] As an illustration of this variation in EV adoption, consider the EV adoption rates in the United States shown in Figure 7.1.[253]

State-level EV policies that incentivize EV adoption are clearly visible in the Figure. For example, many cities in California have higher adoption than cities in other states, and California has had comparatively stronger policies to support greater EV adoption, such as the "Zero-Emission Vehicle" (ZEV) mandate, which requires that a minimal percentage of an automaker's statewide sales must be vehicles that produce no tailpipe emissions. However, the large variance in EV adoption across cities cannot be explained solely by national- or state-level policies or incentives. For example, EV shares across different metropolitan areas within the state of California are quite different even though, as a whole, the state accounts for the largest portion of EV sales in the United States. These trends suggest that cities play an important role in EV adoption around the world; also, that different cities may require different quantities and types of EV infrastructure to support their respective rates of EV adoption. (Refer to Chapter 8 and 9 in this work for more discussion on cities' role in EV adoption.)

250 Ibid., Lorentzen, E., Haugneland, P., Bu, C., and Hauge, E.
251 Ibid., Hall, D., Cui, H., & Lutsey, N.
252 Ibid., Hall, D., Cui, H., & Lutsey, N.
253 Slowik, P., and Lutsey, N., *The Continued Transition to Electric Vehicles in U.S. Cities*, 2018, ICCT, Available at: https://www.theicct.org/sites/default/files/publications/Transition_EV_US_Cities_20180724.pdf.

FIGURE 7.1 Electric Vehicle Share of New 2017 Vehicle Registrations by Metropolitan Area[254]



Electric vehicle share of new 2017 vehicle registrations by metropolitan area.

0%–0.5% 0.5%–1% 1%–1.5% 1.5%–2% 2%–3% 3%–4% 4%–5%

While prior literature has examined ways different policies spur increased EV adoption at the national level[255] and state level,[256] less work has been done comparing features associated with city-level EV adoption. In this chapter, we compare important characteristics of different cities around the world that support the infrastructure needs of increased EV adoption. Given the idiosyncrasies of cities worldwide, cities might need vastly different charging infrastructures to support a given number or percentage of EVs. The framework proposed here highlights the various influencing factors of a city, such as its EV-related incen-

254 *The Continued Transition to Electric Vehicles in US Cities*, 2018, ICCT. New Vehicle registration data from IHS Automotive.

255 Helveston, J. P., Liu, Y., Feit, E. M., Fuchs, E. R. H., Klampfl, E. and Michalek, J. J., *Will subsides drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China*, 2015, Transportation Research Part A: Policy and Practice, 73, 96–112; and Rietmann, N., and Lieven, T., *How policy measures succeeded to promote electric mobility—Worldwide review and outlook*, 2019, Journal of Cleaner Production, 206, pages 66–75.

256 Jenn, A., Azevedo, I. L. and Ferreira, P., *The impact of federal incentives on the adoption of hybrid electric vehicles in the United States*, 2013, Energy Economics, 40, 936–342, Available at: https://www.sciencedirect.com/science/article/pii/S0140988313001709; Jenn, A., Springel, K., and Gopal, A. R., *Effectiveness of electric vehicle incentives in the United States*, 2018, Energy Policy, 119, 349–356, Available at: https://www.sciencedirect.com/science/article/pii/S0301421518302891.

tives, public transit, traveling distance, housing types, workplace charging, and air pollution. By comparing those factors side-by-side across cities, city planners can benefit from:

1. Gaining a global look at the various dimensions of a city's ecosystem that relate to EV adoption, such as housing, commuter behavior, and air quality. For example, a city with particularly poor air quality caused by heavy use of Internal Combustion Engine (ICE) vehicles may have an added incentive to deploy more EV infrastructure in order to encourage faster EV adoption.
2. Learning how their own cities stack up against peer cities, but more important, what causes the difference. A city can also identify its peer-comparable cities to deepen its comparison and learning.
3. Helping guide their investment decisions related to EV public infrastructure based on their local environment. For example, a city that finds itself low on both home charging and workplace charging may start to think of ways to increase public infrastructure deployment to increase its EV impact.

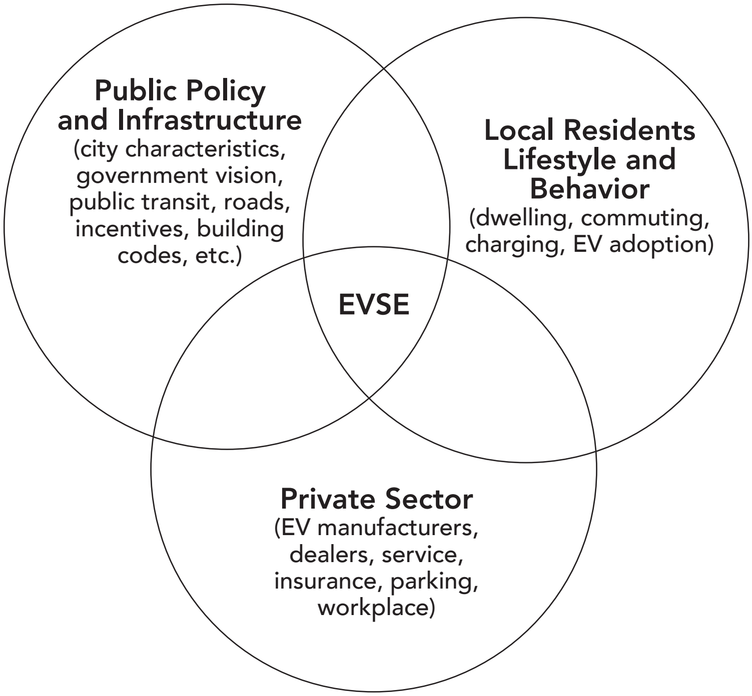
Next, the framework to measure a city's EV impact as a system is presented.

7.3 Framework

The goal is to develop a quantitative and visual framework to measure and compare major factors related to EV infrastructure on different cities. The framework is referred to as a city's "EV Infrastructure Graph" (EVIG) 1.0.

In measuring the EVIG of a city, it is important to take a holistic view and consider a variety of factors that affect the city's EV adoption rate and the associated public charging needs, keeping in mind that the same adoption rate in two different cities may require vastly different infrastructure needs. EVs are part of a complex urban ecosystem with multiple subsystems, each of which EV would interact with. The following figure provides a simple illustration.

FIGURE 7.2 EV as Part of a City Ecosystem[257]



As shown in the figure, EV is at the intersection of multiple systems: EV supply chains, public policy and infrastructure, and consumers. Therefore, any meaningful attempt to measure a city's EV infrastructure must incorporate major factors in those systems. The figure makes it clear that, for a city planner, deepening the impact of EVs is not only about installing more public chargers. Instead, it should be viewed in the context of a city's inherent characteristics, linked to its history, infrastructure, culture, demographics, and people.

Summarizing how all the variables above relate to a city's EV impact is not easy. Ahead, some major factors included in the multidimensional framework are discussed.

257 Source: Authors.

7.3.1 EV Incentives and EV Market Share

Incentives related to EV ownership are probably the most direct driver of EV adoption, as well as the most deeply researched aspect of EV adoption literature.[258] There are two main types of incentives:

- **Monetary incentives offered to a city's residents for owning an EV.** These include rebates, deductions in taxes, tolls, and fees at all levels (national, state, and local). The stronger such monetary incentives are for a city, the greater EV demand there will be, and consequently, the greater the needs for public charging infrastructure. Various nations have implemented such direct financial incentives, from the $7,500 tax credit in the United States to the 50% exemption from value added tax (VAT) and purchase tax in Norway. In addition, many states or local municipalities adopt their own incentives to encourage EV purchase.
- **Traffic regulation and nonmonetary incentives offered for owning an EV.** This category includes HOV lane access (e.g, Norway, and California in the United States), priority registration (or restriction on ICE vehicles, which is being implemented in major cities in China). Similar to monetary incentives, they are expected to spur EV demand and, in turn, public charging infrastructure. Following Rietmann and Lieve,[259] this category is called Traffic Regulation and Incentives.
- **Local EV market share.** An EV market share measure is included in the framework because market ownership of EVs provides a baseline to measure the potential impact of EV charging infrastructure. The dynamics between EV market share and charging infrastructure are bidirectional and subject to other factors. However, given a fixed amount of EV charging infrastructure, the higher a city's EV market share is, the higher the use of charging infrastructure and overall impact.

7.3.2 EV Charging Infrastructure: Home Charging and Workplace Charging

Imagine an EV that has been purchased by a typical consumer. In its whole lifespan of use, where would this EV spend its time, and how long? Of course, a precise answer will depend on the lifestyle of its owners, but assume a typical consumer is one who drives to work, where he/she spends 40 hours a week, goes to home every night, and does most leisure activities on weekends. In that case, it is not farfetched to conclude that this owner's EV will spend about half

258 Ibid., Jenn, A., Azevedo, I. L. and Ferreira, P.; Ibid, Jenn, A., Springel, K., & Gopal, A. R.; Ibid., Slowik, P., and Lutsey, N., 2017.

259 Ibid., Rietmann, N., and Lieven, T.

of its time in its owner's home (roughly 12 hours a day, or 84 hours a week). The rest of the time (about 168 hours a week – 84 hours at a week at home – 40 hours at work = 44 hours a week) this EV will be somewhere traveling or parked elsewhere (sometimes public roads or in parking facilities). Public charging needs are derived from this last bucket of time. This EV's time is divided as shown in Figure 7.3.

FIGURE 7.3 Where Does an EV Spend Its Time? A Typical EV Driven to Work Five Days a Week and Spending Every Night at Home

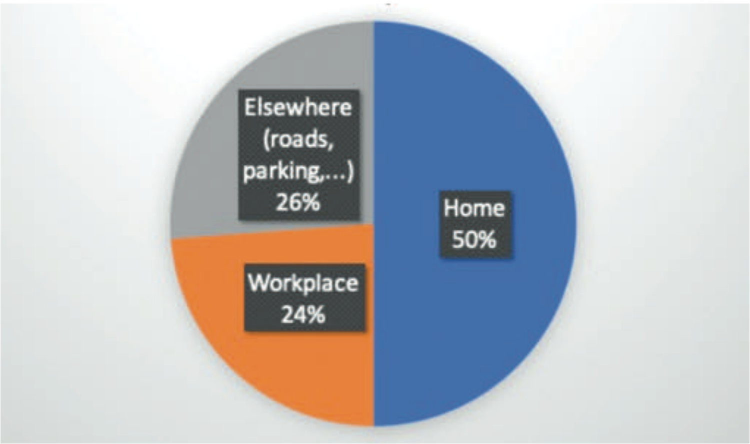


Figure 7.3 highlights the fact that there are three major destinations for EV charging: home, workplace, and other parking facilities. Public charging infrastructure falls into the last category. Note that such infrastructure concerns are unique to EVs. Refueling for ICE vehicles happens at one type of facility: gas stations. EVs need electricity, so it matters where they can get recharged.

If total charging needs are constant, public charging needs can be viewed as a substitute to home and workplace charging. (In the longer run, however, higher availability of home charging can spur more EV adoption, which creates total higher charging needs and, in turn, higher demand for public charging. So, home charging complements public charging in the long term.) A city that has a very strong home charging base or workplace charging infrastructure may not need as many pubic charging facilities as a comparable city that has the same total EV battery volume but less access to charging at home or at a workplace. The reverse is also true: a city with extremely accessible public charging can focus less on private charging demand, whether it be for charging at home or at work. Therefore, it is measured as follows:

- **Availability of home charging.** Home charging is an important part of EV infrastructure, as most privately owned EVs will spend the majority of their time in private homes and/or garages. When an EV owner is able to charge his/her EV at home, it reduces need for public charging facilities. However, a city that has 100% home charging for EV owners will still need some public charging. But a city or town with less home charging infrastructure for EV owners (a densely populated urban center versus a town dominated by single-family houses, for example) will face more demand pressure for EV chargers on public roads and at other facilities.
- **Availability of workplace charging.** Similar to home charging, workplace charging provides another important base for EVs. A few states in the United States and some cities are making great strides in expanding workplace charging. For example, in California almost 50% of all EVs reportedly have access to workplace charging, which may help explain why California has the highest EV adoption rate in the United States.[260]

Workplace charging is also strategically important in the transition to clean energy and grid planning. After all, most workplace charging happens during the day, thereby taking advantage of abundant solar, low wholesale power prices, and available system capacity. It can also raise EV awareness and alleviate range anxiety, thereby boosting EV adoption.[261] This means that workplace charging is not merely a substitute to public charging in the short term, but it can be complementary in the long run. As with home charging, availability of workplace charging may have a positive effect on EV ownership. That is, people may be more likely to consider buying an EV if they can actually charge their EVs at work. But again, the focus here is on the effects of substituting workplace charging with public charging by fixing total EV demand as constant.

7.3.3 Mobility Behavior of Residents

EV adoption and EV charging needs are a direct function of how their owners use their vehicles, so the extent of vehicle usage in a city must be measured. A city with a greater distance driven by EV calls for more public charging infrastructure, compared to one in which driving distances are shorter with less driving, *ceteris paribus*. We view two factors as having the largest effect on a

260 California Air Resources Board (CARB), *California's Advanced Clean Cars Midterm Review: Appendix B: Consumer Acceptance of ZEVs and PHEVs*, 2017, Available at: https://www.arb.ca.gov/msprog/acc/mtr/appendix_b.pdf.

261 O'Connor, P. and Jacobs, M., *Charging Smart: Drivers and Utilities Can Both Benefit from Well-Integrated Electric Vehicles and Clean Energy*, 2017, Available at: https://www.ucsusa.org/clean-vehicles/electric-vehicles/smart-charging.

locality's public charging needs: average daily driving distance and availability of public transportation.

- **Travel distance.** To measure the impact of EV and EV infrastructures across cities, a benchmark for vehicle usage should be established for the following reasons. First of all, a city whose residents drive more miles each day has a higher potential for EV adoption than a comparable one in which driving is less routine. Second, an EV's charging frequency is linked to its usage. The farther an EV travels on a regular basis, the more frequently it needs to be charged. On a city level, the farther the distances its residents drive their EVs, the more public charging infrastructure the city needs.
- **Availability of public transportation.** The link between public transportation and public EV infrastructure may not be obvious, but it is actually a strong one. If a city has very comprehensive and readily available public transportation, then its residents are less likely to need to own private cars, including EVs, and the demand for EV public charging infrastructure is reduced. Put another way, consider two cities, one of which has a strong public transportation network while the other does not; otherwise, they are similar in every aspect. This framework will assign a higher value to the latter (the city with less public transportation), and a lower value to the former (the city with more public transportation).

It should be noted that some cities are actively pursuing electrifying their public transportation fleets such as buses or trams. Since the focus here is on personal EV ownership, our definition of public charging infrastructure does not include charging stations built specifically for those public transportation vehicles.

7.3.4 Environment Impact

The focus here is on measuring a locality's potential relation between its EV infrastructure and its local environment. The connection is not direct—installing EV charging infrastructure will not directly improve the environment. In addition, from a value chain perspective, just replacing ICEs with EVs does not necessarily reduce a city's carbon footprint or pollution because generating electricity or producing the EV can cause carbon emission and pollution elsewhere in the supply chain.[262] However, we would like to establish a link between the EV infrastructure and the environment for two reasons.

First, as discussed in the section on home and workplace charging, EV public infrastructure can stimulate EV demand, which in turn can reduce gasoline

262 Nealer, R. and Hendrickson, T. P., *Review of Recent Lifecycle Assessments of Energy and Greenhouse Gas Emissions for Electric Vehicles*, 2015, Current Sustainable/Renewable Energy Reports, 2(3), 66–73, Available at: https://link.springer.com/article/10.1007/s40518-015-0033-x.

consumption and greenhouse gas and other pollutants. Second, building an environment benchmark in the framework can reflect how urgently a city wants to increase its decarbonization efforts. A city with heavy pollution from transportation has a greater need for EV adoption. For these reasons, we include an air-quality measure in our framework.

7.4 Data and Measurement

In this section, the multiple aforementioned measures are incorporated into an operational framework. Here, the measurement of each dimension, and where such data were obtained, is discussed. Next, the multiple dimensions of data were converted into one common scale. Last, the results are presented in a multidimensional matrix and methods to aggregate into a single-number index are proposed.

7.4.1 Measurement and Data Sources

Measuring each of the dimensions depends on state-of-the-art research literature as well as our own primary research and data collection. Below, we detail how we measure and collect data on each dimension.

Monetary incentives offered to a city's residents for owning an EV. Because monetary incentives are quantifiable, it is relatively straightforward to summarize all the incentives available in a locality. Some difficulty does arise when such incentives depend on vehicle characteristics such as battery type, capacity, weight, or value. One could take averages or pick their modal values. Another issue is how to compare incentives in different currency denominations. Here, most research literature converts them to US dollars. Such an approach is valid because EV manufacturers in general align their EV out-of-factory prices across different markets (excluding tariffs and taxes). Data were compiled from various public sources on monetary incentives given to EVs in each market.

The last issue to consider is which statistics should be used in across-city comparisons: ratios themselves, rank data, or percentile. However, to provide a uniformed numeric scale across all dimensions, we adopt decile measurement. Decile information is convenient and easy to understand: A data point of smallest value that falls into the first decile would get a value of 1, while the largest value would belong to the 10th decile and get a value of 10.

Using decile information also implies that a city's ranking is a relative measure that will depend on which other cities it is being compared to. It is appropriate in this setting because our goal is to compare side-by-side how cities differ in their potential to meet their EV demand. Table 7.1 shows incentive ratios at selected cities around the world.

TABLE 7.1 Incentive Ratios

	Monetary Incentives (USD)	Decile
Beijing, China	6,000	1
Oslo, Norway	25,000	10
Los Angeles, USA	12,000	6
Portland, USA	10,500	3
Boston, USA	12,500	8

Traffic regulation and nonmonetary incentives offered to own an EV. Compared to monetary incentives, nonmonetary incentives are more difficult to gauge and compare. However, prior research has demonstrated that it is possible and such comparison can generate meaningful results (e.g., Slowik and Lutsey 2017, Rietmann et al. 2018).[263] Similar to the evaluation scheme proposed by Rietmann et al. 2018, each cities' nonmonetary incentives are reviewed and a three-point weighting method that maps the strength of each locality's nonmonetary incentives is put into a numeric scale from 1 to 3, with 1 being nonexistent and 3 being the strongest. Finally, this is converted into deciles, which is the common numeric scale for all measures. Table 7.2 contains numeric mapping of nonmonetary incentives at selected cities around the world.

TABLE 7.2 Nonmonetary Incentives

	Nonmonetary Incentives (USD)	Decile
Beijing, China	2	8
Oslo, Norway	3	10
Los Angeles, USA	3	6
Portland, USA	1	3
Boston, USA	1	3

263 Ibid., Hall, D., Cui, H., and Lutsey, N.; Ibid, Rietmann, N., and Lieven, T.

Home charging potential. As a first step, the percentage of a city's households with private parking space is used to gauge the potential of home charging. Such data can be obtained from the US census for US cities, and through various other sources for international cities (for example, for Norway cities we obtain information through data published on Statistics Norway website[264]). This percentage is an upper bound on how much private charging a city can contain. As an example, if 63% of a city's dwellings have a garage or carport, private charging can be installed in at most 63% of its houses or apartments. Then, the above percentages are converted into deciles. Table 7.3 summarizes such a metric for selected cities.

TABLE 7.3 Home Charging Potential

	Home Charging Potential	Decile
Beijing, China	30%	2
Oslo, Norway	52%	6
Los Angeles, USA	80%	10
Portland, USA	72%	8
Boston, USA	43%	3

Workplace charging. For workplace charging, a different approach is used because no data are available on workplace parking across all cities to gauge its potential for charging. Instead, the status quo is looked at by obtaining the number of workplace-charging-points per million population in a city. Such information for major cities is available from research by third-party sources such as International Center for Clean Transportation (ICCT). For other cities, data were obtained through ad hoc researches. In a few cases, estimates are relied upon, and these are clearly marked as such. Table 7.4 shows these metrics for selected cities.

264 Statistics Norway website: https://www.ssb.no/en/statbank/.

TABLE 7.4 Workplace Charging

	Home Charging Potential	Decile
Beijing, China	325	10
Oslo, Norway	206*	8
Los Angeles, USA	33	3
Portland, USA	90	6
Boston, USA	25	1

*Unable to obtain data on workplace chargers in Oslo so it is assumed that 25% of all chargers in the city are workplace chargers.

Vehicle usage. Total Daily Vehicle Miles of Travel (DVMT) is used to capture vehicle usage. For that, first the DVMT per capita that has been consistently measured for major US urbanized area is used. In particular, a dataset maintained by the US Department of Transportation, which can be found at https://www.transportation.gov/mission/health/transportation-and-health-tool-data-excel, contains vehicle miles traveled per capita for major urban areas in the United States. For cities outside the United States, ad hoc searches were conducted and compiled into the same scale. Then, the resulting data were multiplied by city population to obtain the total DVMT of each city. Finally, these numbers were used to compute deciles for each city in the sample.

Table 7.5 contains these metrics for selected cities.

Substitutability of public transportation. Multiple measures can gauge a city's public transportation infrastructure, such as public transportation miles per capita, or coverage area of public transportation. But the preferred measure is percentage of commuters who use public transit, because it is an outcome measure (i.e., commuter choice) which is a function of the state of public transportation infrastructure. In other words, if a city has a high percentage of public transit users, it has less need for private cars, including EVs. In turn, that city has less demand for public charging for EVs than does another city that has a lower percentage of public transit users, ceteris paribus.

Such commuter choice data are available for most cities from multiple organizations (for example, https://alltransit.cnt.org/metrics/), Or, for US cities, the aforementioned Transportation and Health Tool dataset is available from the US Department of Transportation. After obtaining those data for cities, the complementary percentages are taken, and their deciles are computed. Table 7.6 contains these metrics for selected cities.

TABLE 7.5 Vehicle Usage[265]

	DVMT Per Capita	City Population (metro area)	Total DVMT (in million miles)	Decile
Beijing, China	325	40,000,000	1,600,000,000	10
Oslo, Norway	206*	1,710,000	16,758,000	1
Los Angeles, USA	33	13,000,000	289,900,000	8
Portland, USA	90	2,389,228	44,917,486	6
Boston, USA	25	4,628,910	103,687,584	3

TABLE 7.6 Substitutability of Public Transportation

	Substitutability of Public Transportation	Decile
Beijing, China	35%	1
Oslo, Norway	65%	6
Los Angeles, USA	88%	10
Portland, USA	87%	8
Boston, USA	65%	3

Environmental impact. In order to measure the potential effect of EV adoption on a city's environment, air quality was selected, since it is the effect most closely related to cities and transportation. In particular, the internationally-adopted PM2.5 measure was used, which describes concentration of fine inhalable particles with diameters that are 2.5 micrometers and smaller. Such data are available for practically all major cities around the world.

265 In the DVMT per capital column, reference for Beijing is Wang, M. and He, D., *Projection of Chinese Motor Vehicle Growth, Oil Demand, and CO2 Emissions through 2050*, 2006, Argonne National Laboratory. For DVMT per capital for Oslo, see country level data from http://internationalcomparisons.org/environment/transportation.html.

However, not all city air pollution is caused by transportation. Other major sources include industry and residential use of fuels of various sources. Also, cities around the world differ in the proportion of transportation in their total energy consumption. To control for such differences, the PM2.5 measure is multiplied by the percentage of transportation in a locality's total energy consumption. Table 7.7 provides these metrics for selected cities.

TABLE 7.7 ENVIRONMENTAL IMPACT

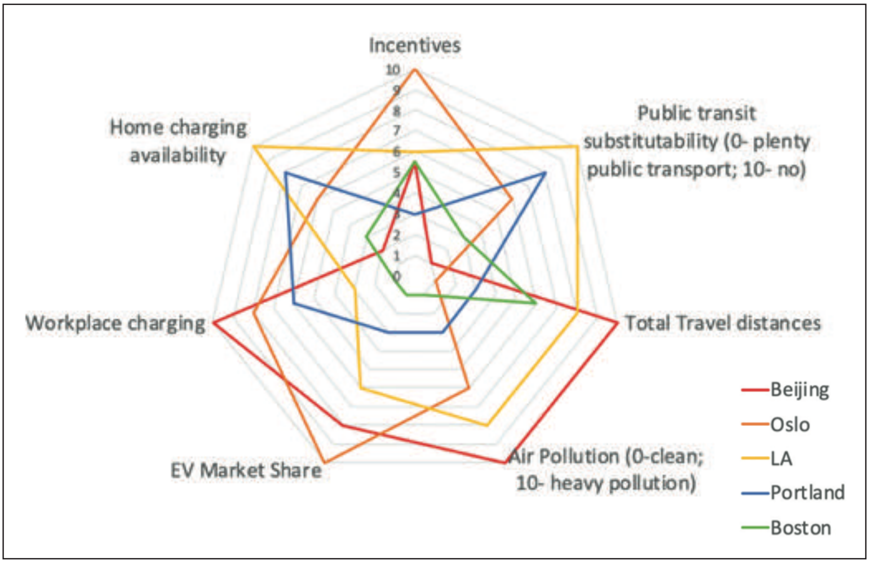
	Environmental Impact	Decile
Beijing, China	12.8%	10
Oslo, Norway	2.5%	6
Los Angeles, USA	4.5%	8
Portland, USA	2.5%	3
Boston, USA	2.5%	3

7.5 Application of a Multidimensional Comparison Framework

Having collected data for all the above variables, the next step is to assemble them into a visual framework.

The key idea is to present all the dimensions on one single graph. The tool chosen is called a radar chart. Using the data compiled for Beijing, Oslo, Los Angeles, Portland, and Boston, their EV public infrastructure impact comparison is as follows:

FIGURE 7.4 Multidimensional EV Infrastructure Graph (EVIG) 1.0: An Application[266]



In the radar chart, each city is represented by a polygon with colored sides. Each polygon has seven vertices, each representing one dimension of impact measurement. The position of each vertex is determined by the decile value of each dimension that we have compiled above. The higher the value, the farther the vertex is from the center. For example, the city of Oslo has a value of 10 in the incentives dimension. Hence, its vertex on that dimension is the highest and farthest from the center.

As we can see, each city has a unique shape due to differences in each of those dimensions. This is important because the graph tells us that even though each city would like to have maximum impact from additional EVSE, it should follow its own path, in keeping with its unique infrastructure, people, and economic conditions.

As an aggregate measure, the overall impact from additional EVSE in each city could be measured by the total area of each polygon. The larger area of a polygon, the greater the overall impact of more EVSE of the city the polygon represents. We can visually see that polygons for Beijing and Los Angeles have the greatest area, the one for Oslo is in the middle, while the polygons for Portland and Boston are smallest. (It is also important to note that this

266 Source: By authors.

comparison is entirely relative because all statistics are deciles, and thus highly dependent upon data from the underlying comparison cities.) Based on this metric, three groups of potential impact seem to exist: high-impact cities (Beijing and Los Angeles), medium-impact cities (Oslo), and low-impact cities (Portland and Boston).

Beijing. Even though it is somewhat unsurprising that Beijing scores high on the overall impact, it is interesting to see what the specific underlying main drivers are: air quality, travel distances, workplace charging, and EV market share. The connection between air quality and EV adoption is obvious. Beijing has the worst air quality among all cities. More EV infrastructure will encourage EV adoption, which could meaningfully reduce pollution from driving gasoline-powered cars and improve air quality. In addition, daily driving distances in Beijing are the highest in the world. To alleviate range anxiety, which has been identified as one of the main obstacles of EV adoption in Beijing, it is critical that the city deploy more public chargers along main commuter routes. (See Chapter 4 for details on how Beijing is aggressively embarking on such an initiative.)

Compared to other cities, Beijing does not have plentiful home charging infrastructure, but its city government has installed many workplace chargers. This suggests that the city could expand its EV impact if it can find creative ways to increase home charging availability.

Beijing's EV incentives are only average among its peers, suggesting that it could amplify EV impact by increasing its incentives. Finally, it is worth noting that Beijing has a good public transportation system, which serves as an effective substitute for personal vehicles.

Los Angeles. Compared to Beijing, Los Angeles ranks almost as high on overall EV impact but its profile is somewhat different.

Los Angeles has significant air pollution, which calls for more EV use and less ICE use. LA residents also drive longer distances than residents of most other cities, such as Portland or Oslo, which further necessitates public charging infrastructure deployment. But what really makes LA stand out from Beijing in this index is its lack of an extensive public transportation system. Therefore, aside from huge capital expenditure to develop a public transit system, one sensible policy recommendation would be to spend more on EV charging infrastructure.

Los Angeles has a high home charging potential because almost 80% of single-family dwellings have parking, but it has fewer workplace chargers. So, to increase the impact of EVs, one strategy might be to push for city regulations regarding EV charging readiness in single-family homes as well as at workplaces.

Another interesting point that is not so apparent in the EVIG graph is that research has shown that HOV access has been a quite powerful incentive for LA residents to buy EVs.[267] The City of Los Angeles has very high traffic congestion,[268] but the State of California allows advanced clean energy vehicle to use HOV lane as an incentive. In fact this incentive turns out to be working too well: clean energy vehicles are clogging some HOV lanes, and the State of California had to revoke access for a number of EV owners.[269]

Oslo. Despite the fact Oslo has the most incentives for EVs, our framework puts Oslo behind Beijing and Los Angeles for several reasons. First of all, its residents do not drive as far each day as the residents of other cities (in fact, its daily driving distances are the shortest among the five in our comparison group). Also, it boasts an extensive and convenient public transportation system. Last, its air quality is relatively good. For all of those reasons, the impact of further EV infrastructure deployment is limited. Nevertheless, Oslo is still relatively high on EV impact because it has a high EV market share and high charging availability at homes and workplaces. However, the workplace charging estimate may not be accurate.

Boston. Our framework puts Boston among the low-impact cities. Its EV penetration is low, but so is its air pollution. It also has a heavily used public transit system. Boston residents actually drive farther than residents of other cities (Boston's distances are second only to Beijing's, and even higher than Los Angeles's). However, because its population is medium-sized, its total driving distances fall into the medium range among cities in our sample. In addition, its home charging infrastructure is relatively scarce because the city is small and densely populated, and many of its residents do not have dedicated parking.

Currently, Boston requires that five percent of its parking be equipped with EV chargers, and an additional 10% be EV-ready for new buildings in parts of the city. To accelerate its EV impact, the city could, among other things, consider more aggressive pubic charging infrastructure deployment and more progressive construction codes on residential and commercial building. Doing so would increase EV adoption and charging infrastructure in all homes, workplaces, and public places.

---

267 Tal, G. and Nicholas, M.A., *Evaluating the Impact of High Occupancy Vehicle Lane Access on Plug-in Vehicles in California*, n.d., UC Davis Institute of Transportation Studies, Available at: https://policyinstitute.ucdavis.edu/files/HOV_April_2014_Final3.pdf.

268 See various city rankings. For example: https://www.tomtom.com/en_gb/trafficindex/list?citySize=LARGE&continent=ALL&country=ALL.

269 Newberry, L., *Anger in California's carpool lanes as more than 200,000 drivers are set to lose decals*, Sept. 17, 2018, Los Angeles Times, Available at: https://www.latimes.com/local/california/la-me-ln-clean-air-car-decals-20180917-story.html.

Portland. Portland is considered medium to low in terms of EV impact. Its EV incentives are not as strong as those of other cities, but it has ample workplace and home charging capabilities. It has good air quality, and its residents do not drive as far as residents of other cities.

Portland is an interesting case because it has a comprehensive public transit system. However, that system's usage is low, suggesting that it has potential to increase ridership. City planners should consider that when they seek to reduce Portland's dependence on ICE vehicles.

7.6 Extension and Conclusions

Cities play a pivotal role in reducing carbon emissions and global warming. In that role, EVs are at the center of efforts to decarbonize transportation and reduce cities' carbon footprint.

This chapter proposed a system-wide framework for cities to evaluate ways their infrastructure, economic conditions, and residents' behavior relate to EV adoption and EV usage. We use a multidimensional chart to provide visuals of the overall impact EVs could have on a city based on identified factors such as EV incentives, home charging potential, workplace charging, public transportation, total driving distance, and air pollution. Ideally, city planners can use this to form ideas about how their cities can most effectively reduce carbon emission caused by transportation.

Future work will focus on refining and extending this framework in several directions. For one, those factors that we identify are interconnected and their dynamics are complex. For example, public transportation is directly linked to EV adoption, but it is also indirectly related through total driving distance. Similarly, EV incentives may directly affect purchase decisions but may also affect home or workplace charging, depending on incentives. The framework can be further extended to model such interactions. With available data, quantitative assessment of the impact of each factor could be done. Collaborating with cities to further implement and test this work is of particular interest.