Future Mobility Calculator:

An electric mobility infrastructure assessment tool technical note

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Abstract

Mass electrification within the transport sector presents an opportunity to simultaneously reduce tailpipe emissions by switching propulsion technologies and to improve the electrical grid. Fully realizing the potential that electric vehicles (EV) offer requires a robust roadmap for infrastructure development and investment to ensure deployment is cost effective and resource efficient. To help quantify the infrastructure and investment needed for EV adoption for urban passenger mobility and its associated benefits, this paper introduces the Future Mobility Calculator (FMC). Developed by WRI and Siemens in collaboration with the Coalition for Urban Transitions, the FMC is an Excel-based tool that—for a given range of city-specific inputs and a projected rate of transport electrification—identifies the quantity and cost of infrastructure required for EV adoption through 2050. The tool also estimates the potential social benefits associated with a reduction in emissions that would result from electrification and modal shifts. The FMC does not provide a comparative cost-benefit analysis between scenarios but is rather designed to estimate impacts of a designated EV uptake scenario developed by the user given a set of inputs and assumptions. The FMC is intended to be used by modelers to support city planners, transit agencies, city policy makers, utilities, and charge point operators. The FMC aims to help cities make informed decisions and plan accordingly for the future of their mobility and energy systems. This technical note details the structure, methodology and assumptions (listed separately under each section) of the FMC.

Abbreviations and Acronyms

- EV = Battery electric vehicle
- PHEV = Plug-in hybrid electric vehicle
- ICE = Internal combustion engine
- VKT = Vehicle kilometers traveled
- LDV = Light duty vehicle
- HDV = Heavy duty vehicle

1 Introduction

1.1 Background

As urban centers continue to grow, so will the share of global emissions they produce linked to an expanding transport sector and increased electricity consumption. In 2019, transportation accounted for 24 percent of global CO2 emissions (IEA 2020) and is the fastest growing emissions sector (Wang and Ge 2019), with road vehicles accounting for nearly three-quarters of all transport CO2 emissions. Electrification within the transport sector presents a solution to help mitigate potential emissions associated with the growth of cities by reducing tailpipe emissions and improving grid functionality and sustainability through smart charging.

While the promise of EVs for emissions reductions and reduced operational costs are attractive, uptake of the technology at scale will require the development of a robust vehicle adoption pathway and charging infrastructure network. To help facilitate planning, this paper introduces the Future Mobility Calculator (FMC). Developed by WRI and Siemens in collaboration with the Coalition for Urban Transitions, the FMC focuses on the urban infrastructure needed for successful EV and charging station rollout and the costs and social benefits associated with that investment. Understanding the appropriate quantity and type of charging stations to install, the increased electricity demand from EVs, and the cost (and social benefits) of vehicle and infrastructure deployment are crucial for effective resource management, decision making, and building political support for electrification. The FMC aims to help cities make informed decisions and plan accordingly for the future of their mobility and energy systems.

The term "EVs" can refer to few different vehicle technologies including battery EVs (fully electric), plug-in hybrid EVs (battery and petrol), and fuel cell vehicles (hydrogen fuel). While plug-in hybrid and fuel cell vehicles are an important part of the shift to sustainable transport, the FMC considers the adoption of battery EVs only, any reference to "EV" or "EVs" in this paper refers exclusively to fully electric battery EVs.

1.2 Tool Overview

The FMC is an Excel-based tool that, for a given range of city-specific inputs (general city data, mobility data, charging infrastructure data, and cost data) and a projected electric transport uptake scenario for 2035 and 2050, identifies the quantity and cost of infrastructure required. It also quantifies some of emissions benefits that would result from an investment in electric transport infrastructure, based on input data and listed assumptions. The FMC is not intended to provide a direct comparative cost-benefit analysis against other propulsion technologies such as diesel, hydrogen or CNG. These types of comparisons are addressed in other literature and tools (UChicago Argonne, LLC 2019; Cooper et al. 2019a). Instead, the main purpose of the tool is to estimate the costs, requirements, and some of the key benefits of defined electrification scenarios, which are needed to effectively plan for future EV use.

The FMC is designed to provide a city-specific analysis, informed by the city-specific inputs entered by the user. When user inputs are not available, the tool provides defaults. These defaults vary based on the typology of the city, but they represent broad and generic estimations. The less default inputs that are needed, the more the calculator outputs will reflect the reality of the city. Likewise, the user should take care to match the geographic scope of all data. Users are encouraged to manually enter as many city-specific inputs as they are able and to avoid mixing with regional data to the extent possible.

The FMC is designed to accommodate inputs for four modes of motorized transit: private car, private two-wheeler, public bus, and shared fleet vehicle. This tool is designed for fully battery electric vehicles and not for plug-in hybrid electric vehicles (PHEVs) or hydrogen fuel cell vehicles. Users may include PHEVs in their total EV count, but the vehicle specifications included in the tool are tailored to the attributes of battery electric vehicles. Since the tool is designed specifically to plan for electric vehicles (and not to provide guidance on other topics related to general mobility planning), the tool does not analyze non-motorized transportation. The user designates a desired future transport electrification scenario for the years 2035 and 2050.

The FMC incorporates a transparent interface allowing the user to view inputs and calculations as well as integrate their own data, allowing complete customization for the city in question. The tool is open-sourced, and users can change any desired default assumptions, in addition to the suggested city-specific inputs. For example, the user can change the default emission factors, default assumption for battery efficiency loss in hot or cold climates, or any other default assumption in the tool.

When city-specific data is not available, the tool is programmed with over 500 default data points, which help fill gaps in the user's data. These default inputs are sourced from work done by a range of institutions including the IPCC, World Bank, C40, IEA, IRENA, US EPA, UNEP, and ICCT among others. Inputs are based on present day and projected values as well as assumptions inferred based on trends. Based on the city's population density and economy, these default inputs are sourced from four pre-loaded city typologies: (1) emerging economy – high density, (2) developed economy – low density, (3) developed economy – high density, and (4) emerging economy – low density. While no planning tool can provide complete scenarios with absolute certainty, the FMC uses these different city typologies to source specific default inputs which are intended to be most applicable to the city in question.

The FMC is specifically designed to conduct city-level analysis, but the geographic extent of the city's analysis can be modified depending on how the user defines a city's limits in the inputs. Using the city-specific inputs entered by the user in conjunction with default inputs, the tool estimates the emission reductions, number of necessary EV purchases, electricity consumption, and required number and type of EV charging stations.

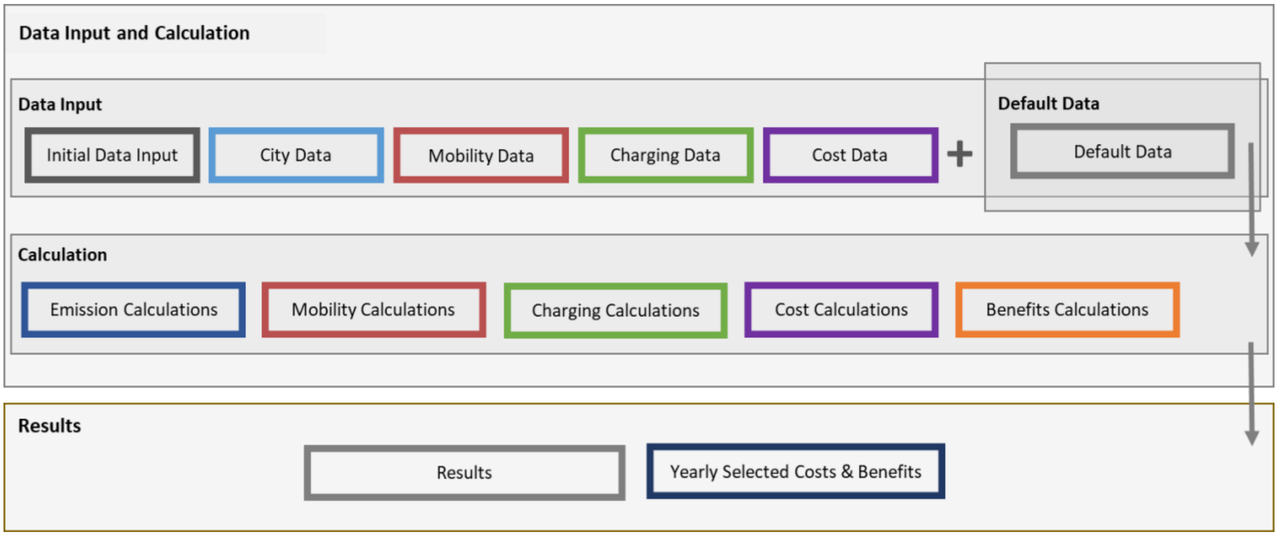
1.3 Tool Structure

The FMC is an excel-based tool developed around three primary operational sections:

- Data input tabs: Initial Data Input, city, mobility, charging, and cost.
- Calculation tabs: Mobility, charging, cost, emissions, and benefits.
- Results tabs: Results and Yearly Selected Costs-Benefits

The general informational flow within the tab is broken down visually in Figure 1. Building on basic city information from Initial Data Input, user inputs in the remaining data input tabs combined with default data are used in Calculation tabs to produce outcomes in the Results. A complete list of the tabs included in the FMC is shown in Table 1.

Figure 1. General view of the FMC structure and informational flow



Note: Figure 1 depicts each of the different tool sections: Data Input, Calculation and Results. Starting with basic city information collected in Initial Data Entry, user inputs from Data Input tabs combined with Default Data feed into Calculation tabs. The calculated outcomes are displayed in Results tabs. This figure does not depict every tab included in the FMC, please see Table 1 for a complete list. Source: WRI

Tab Type	Tab Name					
Information tabs	Start Overview Glossary Sources					
Tool configuration tabs	Initial Data Entry User Typology Selection					
	Tool Section					
	City	Mobility	Charging	Cost	Emissions	Benefits
Data input tabs	City Data	Mobility Data	Charging Data	Cost Data		
Default input tabs	City Default	Mobility Default	Charging Default	Cost Default		Benefits Default
Calculation tabs		Mobility Calc	Charging Calc	Cost Calc Cost Calc 1-Vehicle Uptake Cost Calc 2-Vehicle Investment Cost Calc 3-Vehcile Maintenance	Emissions Calc	Benefits Calc Benefits Calc 1-Emissions

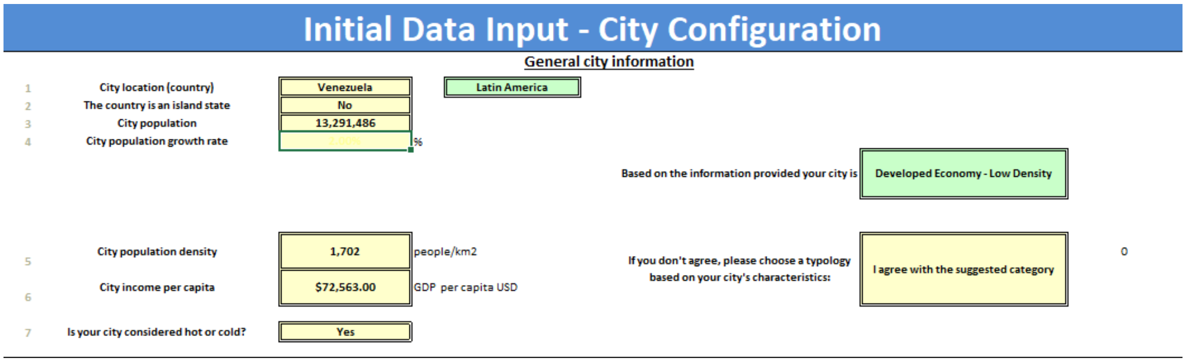
				Cost Calc 4-Charger Uptake Cost Calc 5-Charger Monetization Cost Calc 6-Electricity		
Results tabs	Results Yearly Selected Costs and Benefits					

Table 1. A breakdown of all tabs included in the FMC

Note: Tabs are divided by Tab Type and Tab Name. Data input, Default input, and Calculation tabs are further separated by the Tool Section they are associated with. Note that some sections of the tool such as Emissions, only have a Calculation tab, where inputs for those calculations are sourced from other sections of the tool. Similarly, the City section does not have a calculation tab, where City inputs feed into other calculation sheets, but the City section does not have a calculation tab of its own. Source: WRI

1.3.1 Main Configuration

Figure 2. Screenshot of the Initial Data Entry tab, where users input basic city information and define a city typology.



Initial Data Input - City Configuration

General city information

1 City location (country) Venezuela Latin America
2 The country is an island state No
3 City population 13,291,486
4 City population growth rate 2.00% %

Based on the information provided your city is Developed Economy - Low Density

5 City population density 1,702 people/km2
6 City income per capita $72,563.00 GDP per capita USD

If you don't agree, please choose a typology based on your city's characteristics: I agree with the suggested category 0

7 Is your city considered hot or cold? Yes

Source: WRI

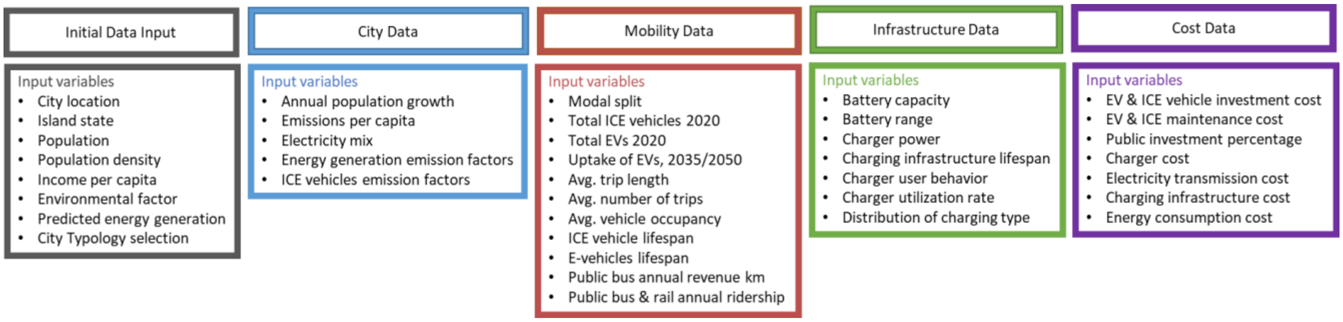
The Initial Data Entry tab gathers basic city attributes and establishes the City Typology associated with the city under analysis. For information on how these typologies were chosen, see Annex 1. The selected City Typology will inform the Default Inputs used throughout the tool. Inputs for Initial Data Entry can be seen in Figure 2. Current and future electricity generation is designated as moderate, low-carbon, or dirty, depending on the mix of electricity generation sources input by the user. The ranges for these three categories are defined in Table 2. This tab also includes an option to indicate if your city experiences temperature extremes, which can impact battery performance.

1.3.2 Data Input and Calculation

Data Input tabs are where the user enters the bulk of the city's data used in the tool. Associated with each Data Input tab is a Default Data tab, which houses the City Typology default information. The inputs for each of the Data Input tabs are listed visually in Figure 3. Given that the FMC is a long-term planning tool, the inputs for the default data tab should reference overall trends over the long-term. Short- and medium-term influences, such as the impact of COVID-19 or other topical issues, are not intended to be reflected by this tool.

Calculation tabs utilize the values from Data Input tabs to draw out relationships in the data and produce tool outputs. Outputs from one Calculation tab are often utilized in another Calculation tab to help produce results.

Figure 3. Visual breakdown of the inputs included in the Data Input tabs

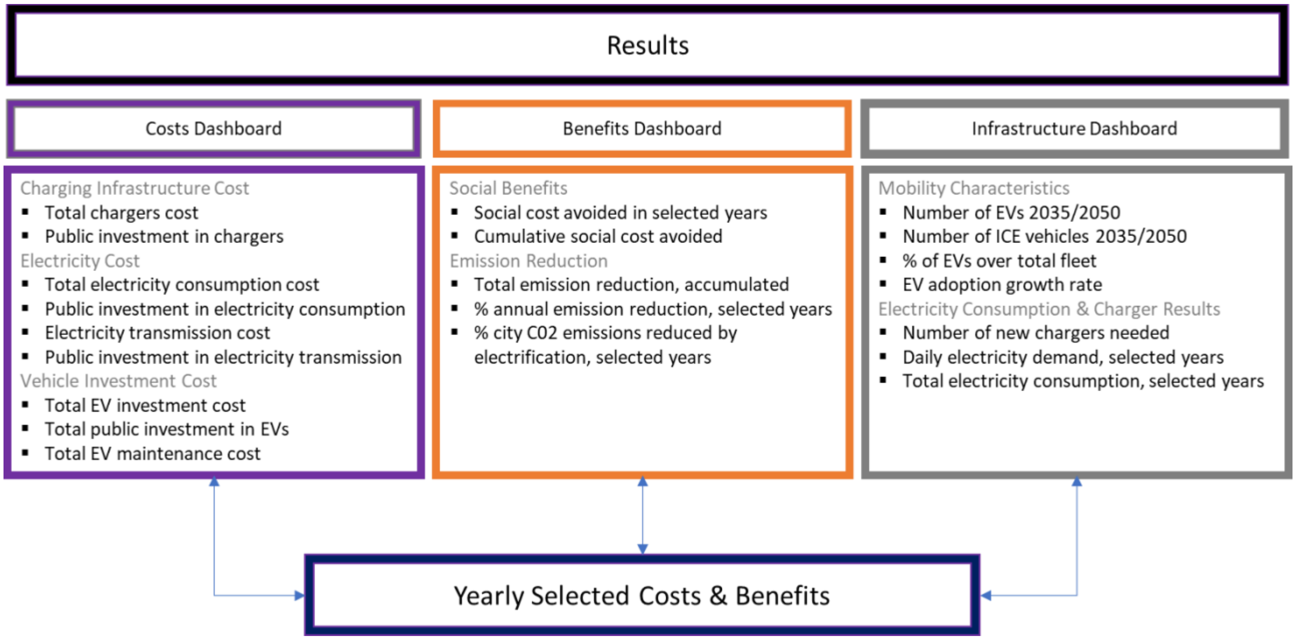


Note: Input definitions and their utility within the tool are detailed in the Methodology. Source: WRI

1.3.3 Results Tabs

Results tabs display the outputs produced with in the Calculation tabs. The outputs for each of the Results tabs are listed visually in Figure 4.

Figure 4. Visual breakdown of the results included in the FMC



Note: Results and associated calculations are described in the Methodology section. Source: WRI

1.3.4 Limitations

Although the FMC provides a robust calculation framework, it faces some limitations:

- Accuracy of the outputs will significantly depend on the degree and accuracy of city-specific inputs from the user. Default data is provided to help fill out potential gaps in the user's data input and is based on comparative assumptions from existing literature.
- Some data inputs have more weight than others. The FMC analysis is built around several key inputs including, population growth rate, 2020 vehicle population, modal split, average vehicle occupancy rate, trip length, charger power, and monetary input values included in the Cost Data. Users should pay particular attention to the accuracy of these key central inputs.

- The term "EVs" can refer to few different vehicle technologies including battery EVs (fully electric), plug-in hybrid EVs (battery and petrol), and fuel cell vehicles (hydrogen fuel). While plug-in hybrid and fuel cell vehicles are an important part of the shift to sustainable transport, the FMC considers the adoption of battery EVs only, any reference to "EV" or "EVs" in this paper refers exclusively to fully electric battery EVs.
- The FMC uses 2020 as a baseline year for analysis. Short- and medium-term influences, such as the impact of COVID-19 or other topical issues, are not intended to be reflected by this tool.
- The FMC produces estimates of the quantity and cost of infrastructure associated with EV uptake scenarios built by the user. These estimates can be used to compare different EV uptake scenarios. The outcomes produced in different scenarios are not intended to show which outcomes are more or less likely to occur.
- In all annual ridership calculations, the authors assume the default number of days as 365.
- The tool is not intended to help cities decide which propulsion systems would be best for their fleets. These types of comparisons are addressed in other literature and tools, including recent work produced by WRI (Cooper et al. 2019a). Rather, this tool is designed to provide estimates of the energy and infrastructure needs for a given electrification scenario and an analysis of the associated costs and some social benefits.
- The emission factors estimations in this tool are related only to tailpipe and electricity generation, as the ones coming from suspended material due to vehicle operation, such as vehicle braking and tire friction, are not considered in this version of the FMC.
- In its analysis the FMC focuses on a limited number of transport modes including private cars, private two-wheelers, shared fleets (cars), and public buses and rail.
- In terms of electricity generation, when users define their future electricity generation mix, the FMC does not account for the infrastructure requirements and costs associated with increasing the share of renewable generation on the grid. When calculating the daily electricity load the grid will experience from EV adoption, the tool it is assumed the charging load will be distributed equally over the course of the day (24 hours). The location and duration of EV charging occurring during the day is a major determinant of the upgrades which will be required (or could be offset) to power distribution and generation infrastructure. The tool also does not consider smart charging or any vehicle-to-grid integration, which will likely impact the use of charging ports.

- The social benefits included in the tool do not measure or account for the value of time of residents in the city.
- While the costs associated with health impacts are incorporated into the social cost values linked to pollutants in the tool, there are several health and social impacts associated with air pollution (such as organ damage and lower reproductive rates) that the tool does not currently capture.
- This tool does not include scenarios for electrifying trucks and urban goods transportation.
- The tool also does not consider how new technologies such as autonomous vehicles would impact the electrification process.
- When the authors refer to 'modal split', they refer only the split between motorised options only.

2 Tool Methodology & Configuration

2.1 Tool Configuration

Tool configuration and establishing the City Type occur within the Initial Data Entry tab. This section will describe the different city typologies and other parameters that calibrate the FMC to determine which default inputs will be used to fill in unknown data. For information on how these typologies were chosen, see Annex 1. For more reliable results, it is highly recommended that users input city-specific information (cells in yellow) about the city being analyzed instead of relying on default data.

2.1.1 City Configuration (Input sheet—Initial Data Entry tab)

This is the main configuration tab where users define and determine key attributes of the city under analysis. User inputs and selections in this tab will impact assumptions and calculations throughout the tool, to best reflect the city under analysis. There are four key selections that are impacted by this:

- **City Typology Selection** – Based on inputs for population density and income per capita, the tool will determine the most appropriate City Type and associated default inputs for the city (see Annex 1 for definition of City Types). The City Type can also be manually selected by the user.
- **Projected electricity generation mix** – This informs the user whether the electricity generation in their city will be considered dirty, moderate, or low-carbon based on user assumptions made for the city's projected low-carbon electricity generation. Please refer to City Section (below) for benchmarking default data assumptions. For reliable results, it is preferred to have city-specific inputs from the user based on the city being analyzed. This information will likely be made available by local utility companies or at the system operator level (regional or national, especially for future projections).
- **Island State** – This determines whether the city is on an isolated island or not. We have defined an isolated island as one which needs to import most of its electricity. This impacts electricity infrastructure and transmission costs.
- **Environmental Factor** – Determines if a city's climate will have an impact on EV performance. Users may select if their city is considered hot (summer monthly average above 35C during the hottest month of the summer) and/or cold (monthly average

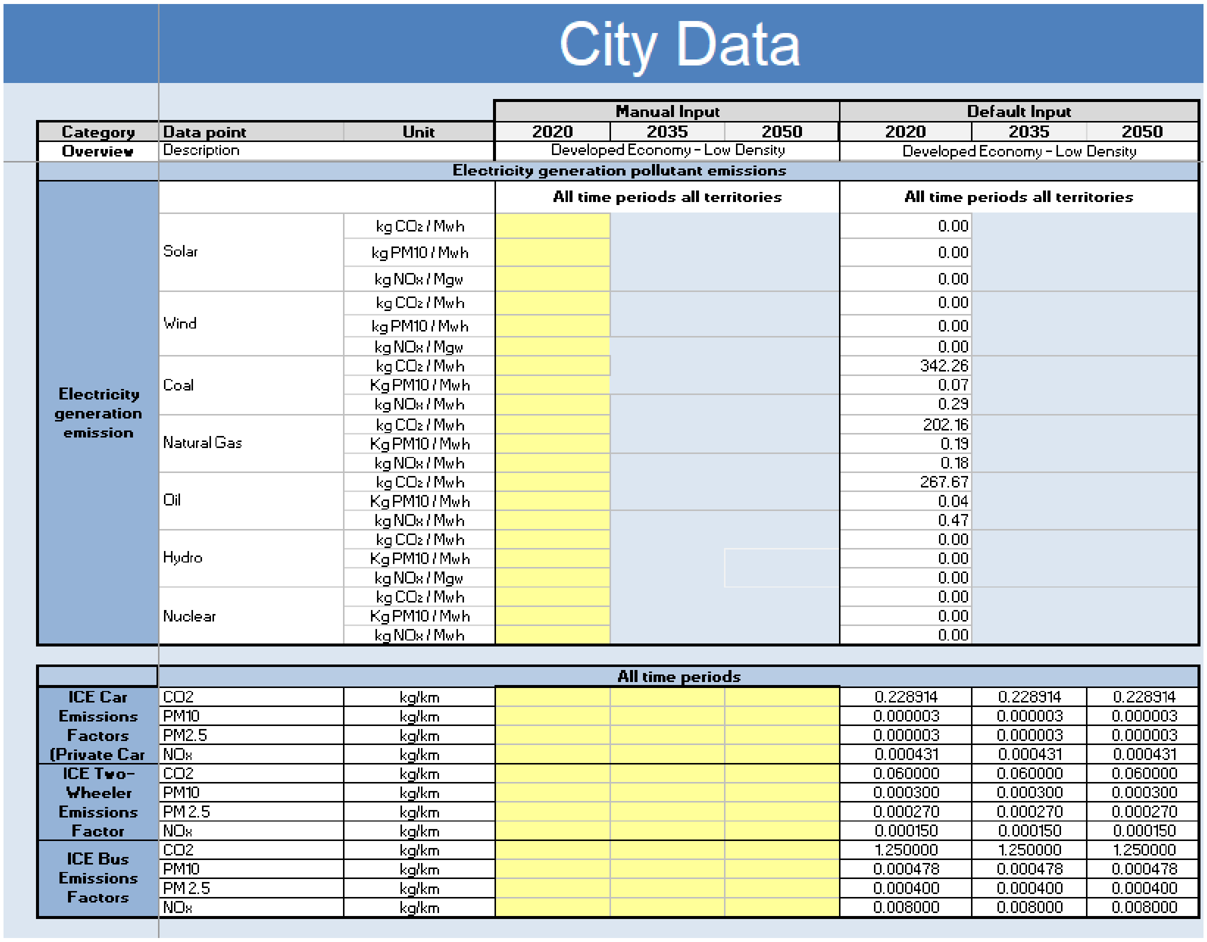
below -6C during the coldest month of the winter) (Motoaki, Yi, and Salisbury 2018; Hawkins 2019). If these attributes are present in a city, the tool will account for its impacts on additional battery use for climate control within the vehicle and impacts on battery performance.

2.2 Data Input and Calculation Sheets

2.2.1 City

This section comprises of the variables that depend on the physical, social and economic characteristics of the city. While the City Data tab does not correspond to “City Calculations,” as is the case with other tabs, these inputs are used throughout all of the calculations and are key inputs for the emissions and benefits calculations. It is dedicated to a range of city attributes and variables related to population and land use, electricity consumption mix, health information, electricity generation, and mobility emissions factors. While default inputs are present in the tool (based on assumptions listed below), as shown in Figure 5, city-specific inputs entered in the yellow cells for each attribute are preferred.

Figure 5. Screenshot of the City Data tab, where users input general city information



City Data

			Manual Input			Default Input		
Category	**Data point**	**Unit**	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**
Overview	Description		Developed Economy - Low Density			Developed Economy - Low Density		
	Electricity generation pollutant emissions							
Electricity generation emission			**All time periods all territories**			**All time periods all territories**		
	Solar	kg CO_2 / Mwh				0.00		
		kg PM10 / Mwh				0.00		
		kg NOx / Mgw				0.00		
	Wind	kg CO_2 / Mwh				0.00		
		kg PM10 / Mwh				0.00		
		kg NOx / Mgw				0.00		
	Coal	kg CO_2 / Mwh				342.26		
		Kg PM10 / Mwh				0.07		
		kg NOx / Mwh				0.29		
	Natural Gas	kg CO_2 / Mwh				202.16		
		Kg PM10 / Mwh				0.19		
		kg NOx / Mwh				0.18		
	Oil	kg CO_2 / Mwh				267.67		
		Kg PM10 / Mwh				0.04		
		kg NOx / Mwh				0.47		
	Hydro	kg CO_2 / Mwh				0.00		
		Kg PM10 / Mwh				0.00		
		kg NOx / Mgw				0.00		
	Nuclear	kg CO_2 / Mwh				0.00		
		Kg PM10 / Mwh				0.00		
		kg NOx / Mwh				0.00		
	All time periods							
ICE Car Emissions Factors (Private Car	CO2	kg/km				0.228914	0.228914	0.228914
	PM10	kg/km				0.000003	0.000003	0.000003
	PM2.5	kg/km				0.000003	0.000003	0.000003
	NOx	kg/km				0.000431	0.000431	0.000431
ICE Two-Wheeler Emissions Factor	CO2	kg/km				0.060000	0.060000	0.060000
	PM10	kg/km				0.000300	0.000300	0.000300
	PM 2.5	kg/km				0.000270	0.000270	0.000270
	NOx	kg/km				0.000150	0.000150	0.000150
ICE Bus Emissions Factors	CO2	kg/km				1.250000	1.250000	1.250000
	PM10	kg/km				0.000478	0.000478	0.000478
	PM 2.5	kg/km				0.000400	0.000400	0.000400
	NOx	kg/km				0.008000	0.008000	0.008000

Note: The data sheet includes cells for both city-specific user input (preferred) and pre-loaded default inputs based on the previously designated city typology. Source: WRI

Input (Data input sheet - 'City Data')

- **Population** (number of people): This contains the population of the city in 2020.
- **Average annual population growth rate, today-2050** (percentage): The average rate at which the population grows every year. This percentage is sensitive, and the user input will have a significant impact on results.
- **Population Density** (residents/km^2): The density is based on the number of residents within the defined municipal area of the city. This is an input from the "Initial Data Input."
- **Emissions per capita** (MTCO2/year): The annual regional median per capita emissions, BASIC, GHG emissions from stationary electricity, transportation and waste ("C40 : Greenhouse Gas Protocol for Cities Interactive Dashboard" n.d.)
- **Electricity mix** (percentage of electricity generated in MWh from each source): The electricity mix of the grid currently available in the selected city and expected or desired mix in the future. The final results will vary depending on whether the user inputs expected or desired mix.
- **Electricity generation emissions** (kg/MWh per each generation source): List of emission factors for electricity generation pollutants - CO_2, PM_{10}, and NO_x emissions based on fuel type.
- **ICE vehicles emission factors**; (kg/km): List of emission factors for ICE combustion engine pollutants - CO_2 PM_{10}, and NO_x emissions based on vehicle mode.

City General Default Input Assumptions (Default input – 'City Default')

- **Population**: The default average annual population growth rate from 2020-2050 is 2.3% for emerging economies and 0.5% for developed economies based on (United Nations, Department of Economic and Social Affairs, and Population Division 2019)
- **Average annual population growth rate, today-2050** (percentage): The average rate at which the population grows every year. These rates are based on the World Urbanization Prospects 2018 projections that incorporate data from 1950 and project out to 2050 (United Nations 2019).
- **Population Density** (residents/km^2): The density is based on the number of residents within the defined municipal area of the city. This is an input from the "Initial Data Input."
- **Climate information**: By default, "Hot" is considered above 35C (95F) while "Cold" is considered below -6C (20F).
- **Emission per capita**: Based on the city location, the default regional median per capita emissions per year is sourced from ("C40 : Greenhouse Gas Protocol for Cities Interactive Dashboard" n.d.)
- **Electricity mix**: The city is categorized as Dirty, Moderate, or Low-Carbon based on current and projected electricity mix data input from the user. It is assumed that the electricity on the grid will get cleaner with time. The tool provides analysis of different potential future scenarios, not business as usual projections.

Table 2. The percentage of low or zero carbon electricity generation associated with each electricity mix type included in the FMC.

Electricity Mix	2020	2035	2050
Dirty	12%	29%	55%
Moderate	25%	55%	85%
Low-Carbon	65%	95%	100%

Source: Authors assumption, estimated based on (Kennedy, Stewart, and Westphal 2019)

- **Electricity generation emissions**: The default Emission factors for coal, natural gas, and oil are sourced from IPCC 2006 Emission Factors, (Mawdsley et al., n.d.) and (Comission for Environmental Cooperation 2015). These are global averages. By default, the electricity generation emission factors only consider in-site generation and not life-cycle value. It is assumed that the following electricity generation types have zero pollutant emission factors: Solar, Wind, Hydro and Nuclear.
- **ICE vehicles emission factors**: The default emission factors by pollutant and vehicle type are sourced from (Yang and Bandivadekar, n.d.), (UNEP 2018), (Song 2017), (Victoria Transport Policy Institute 2018), and (Cooper et al. 2019b). All shared fleet vehicles are assumed to have the same emission factors as private cars.

2.2.2 Mobility

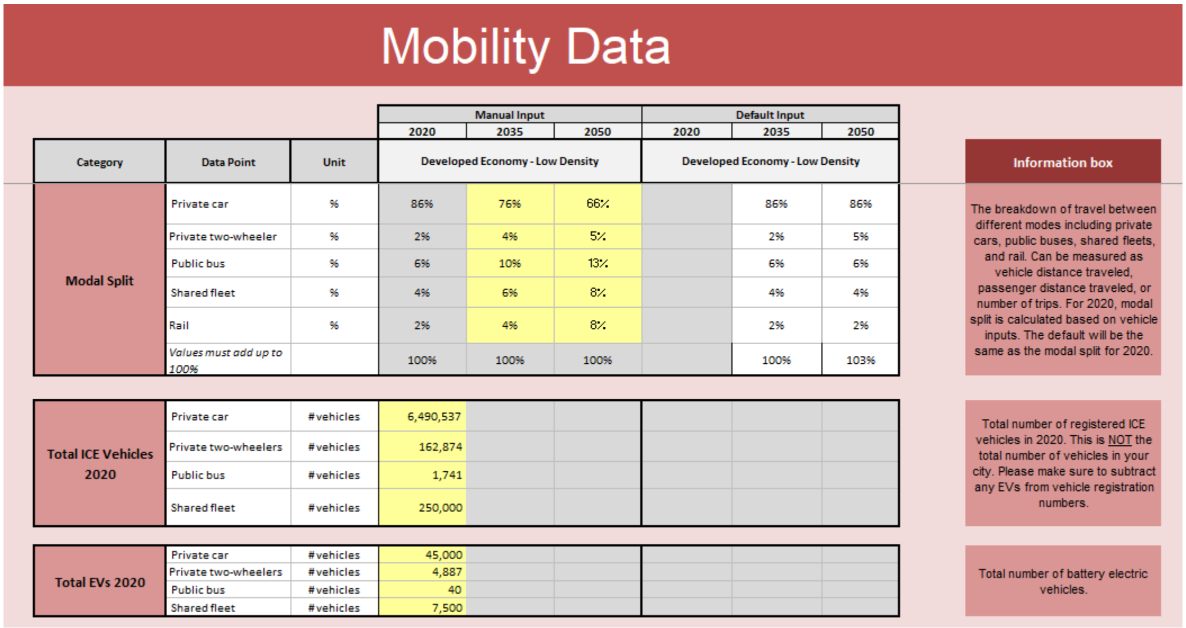
In this section the user is provided with the ability to explore different future scenarios by defining future modal split and EV uptake into 2035 and 2050. For the year 2020, tool users input the total number of vehicles (ICE and EV) operating in the city; these inputs used to define the city's average daily VKT and the projected vehicle populations in the city for 2035 and 2050.

Within the tool there are five vehicle modes considered:

- **Private cars**: owned and used by private residents or households.
- **Private two-wheelers**: privately owned and operated motorized two-wheeled vehicles, does not include human-powered bicycles.
- **Shared fleets**: owned by businesses or cities (public) and used for taxi services, on-demand rides, ridesharing, or car rentals. In the FMC, shared fleets are classified as cars. Generally, they are the same size as private cars, but with higher utilization rates.
- **Public buses**: part of the city public transit system
- **Rail**: includes subway, light rail, tram, cable-car, regional train, etc.

Figure 6. Screenshot of the Mobility Data tab, where users input general city information.

The data sheet includes cells for both city-specific user input (preferred) and pre-loaded default inputs based on the previously designated city typology. Source: WRI



Mobility Data

			Manual Input			Default Input			
			2020	2035	2050	2020	2035	2050	
Category	Data Point	Unit	Developed Economy - Low Density			Developed Economy - Low Density			Information box
Modal Split	Private car	%	86%	76%	66%		86%	86%	The breakdown of travel between different modes including private cars, public buses, shared fleets, and rail. Can be measured as vehicle distance traveled, passenger distance traveled, or number of trips. For 2020, modal split is calculated based on vehicle inputs. The default will be the same as the modal split for 2020.
	Private two-wheeler	%	2%	4%	5%		2%	5%	
	Public bus	%	6%	10%	13%		6%	6%	
	Shared fleet	%	4%	6%	8%		4%	4%	
	Rail	%	2%	4%	8%		2%	2%	
	Values must add up to 100%		100%	100%	100%		100%	103%	
Total ICE Vehicles 2020	Private car	#vehicles	6,490,537						Total number of registered ICE vehicles in 2020. This is NOT the total number of vehicles in your city. Please make sure to subtract any EVs from vehicle registration numbers.
	Private two-wheelers	#vehicles	162,874						
	Public bus	#vehicles	1,741						
	Shared fleet	#vehicles	250,000						
Total EVs 2020	Private car	#vehicles	45,000						Total number of battery electric vehicles.
	Private two-wheelers	#vehicles	4,887						
	Public bus	#vehicles	40						
	Shared fleet	#vehicles	7,500						

Mobility Input (Data input sheet - 'Mobility Data'; Default information – 'Mobility Default')

- **Modal split, 2035 and 2050** (% motorized vehicle utilization by mode): The breakdown of travel between different modes including private cars, public buses, shared fleets, and rail. While modal split can be measured in a variety of ways (such as vehicle distance traveled, passenger distance traveled, or number of trips for the years 2035 and 2050), in this tool we calculate modal split by the percentage breakdown of commuters' predominant (i.e., longest distance) mode. For 2020, the modal split is calculated based on the total number of vehicles input by the user, and by the ridership information provided by the user for public transportation. User input can have a significant impact on the vehicle numbers in the future. Users should keep modal split measurements the same across all sources.
- **Total ICE vehicles 2020** (no. of vehicles): For each mode, the total number of registered ICE vehicles operating within a city for 2020. If possible, this input should be sourced from vehicle registrations. This is NOT the total number of vehicles in a city. If using a value that is the total number of vehicles in a city, please subtract out the number of EVs in the city. Additionally, please ensure shared vehicles, taxis and transportation network company (TNC) vehicles, are counted separately from the total number of total private vehicles. As with EVs, TNCs will likely need to be subtracted from the total number of registered vehicles given that they are not registered separately. Despite the fact that many TNC drivers operate on multiple platforms, all TNC vehicle numbers should be counted as individual drivers because it is not public knowledge which drivers have dual-registrations. Almost all calculations are based off registered vehicle numbers in some way, so users should be careful when inputting these numbers. For private vehicles, if available, user can input only the number of ICE vehicles which are used on a daily basis (not all of the registered vehicles), if they (1) also input this information for EVs, and (2) use an average occupancy per vehicle (see below) which only includes vehicles used daily.

- **Total EVs 2020** (no. of vehicles): For each mode, the total number of registered EVs (fully battery electric vehicles) operating in a city for 2020. This input should be sourced from vehicle registrations. This tool is designed for fully battery electric vehicles and not for plug-in hybrid electric vehicles (PHEVs). For private vehicles, if available, user can input only the number of EVs which are used on a daily basis (not all of the registered vehicles), if they (1) also input this information for ICE vehicles, and (2) use an average occupancy per vehicle (see below) which only includes vehicles used daily.
- **Uptake of EVs, 2035 and 2050** (% EVs): For each mode, the percentage of total vehicles targeted to be electric in a city for the years 2035 and 2050. These numbers are based on the goals put forward by the city. For 2020, this value is already calculated from the values input for "Total ICE vehicles 2020" and "Total EVs 2020."
- **Average trip length** (km/trip): For all modes excluding public bus and rail, the average distance traveled per trip taken by a vehicle. For buses, this is average trip length. The average trip length will have a significant impact on the charging infrastructure outputs.
- **Average number of trips per day per vehicle** (trips/day): For all modes excluding public bus and rail, the average quantity of trips taken per day per vehicle. These data are commonly collected in household travel surveys.
- **Average occupancy per registered vehicle** (passengers/vehicle): For all modes excluding public bus and rail, the average number of users in a vehicle. This number includes the average across all registered vehicles, including those which are not used daily. This number is a standard metric of shared mobility vehicles. For private cars and two-wheelers, this number can be estimated by taking the average occupancy for a vehicle on the road (a metric commonly kept by cities) and reducing it by the percentage of vehicles which are not used for everyday travel (this can be estimated based on the percentage of households with 3 or more vehicles, which is a common metric recorded in household travel surveys). Alternatively, users can also input the average occupancy per vehicle on the road, if they input the number of vehicles used daily above (as opposed to inputting the total number of registered vehicles above). This number is highly sensitive. Changing occupancy from 1 passenger to 2 passengers can cut the number of total vehicles in half.
- **Average lifespan of ICE vehicles** (years): For all modes excluding rail, the average vehicle lifespan of an ICE vehicle.
- **Average lifespan of e-vehicles** (years): For all modes excluding rail, the average vehicle lifespan of an EV.
- **Public bus annual vehicle revenue kilometers, 2020** (km): For public buses only. This information is typically provided in annual reports from the local transit agency. If a region has several agencies, use information from an aggregated source (preferred, such as from a regional planning entity) or from the largest agency in the region (if necessary). Ideally, this information would represent just revenue miles traveled, but total VKT will suffice. This information may be given on a per-bus basis; if so, use that information to calculate the total annual VKT for all buses together.
- **Public bus and rail annual ridership, 2020** (no. of riders): For both public buses and rail, the annual ridership numbers on that transit system. This information is typically provided in annual reports from the local transit agency. If a region has several agencies, use information from an aggregated source (preferred, such as from a regional planning

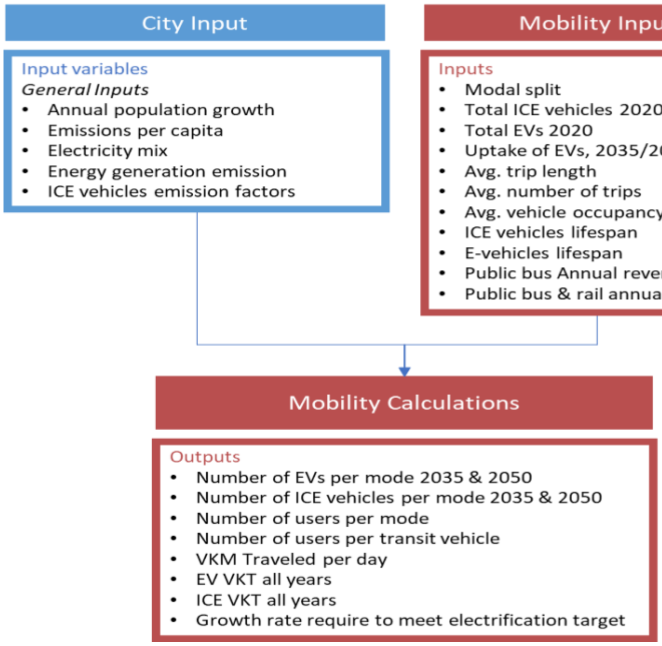
- entity) or from the largest agency in the region (if necessary). Ideally this information will include linked trips as one rider, but unlinked trip data will suffice as well.
- Average annual population growth rate, today-2050 (%): From City Input.

Mobility Default Input Assumptions

- **Modal split, 2035 and 2050**: The default modal split for 2035 and 2050 is automatically filled in with the same modal split that is calculated in 2020 based on the vehicle numbers. If users want to change their modal split, they will need to manually input their own projections. If mode split is manually entered, it should be broken down by the predominant mode (i.e., the mode used for the longest distance) for each user of multimodal trips.
- **Uptake of EVs, 2035 and 2050**: The default uptake of EVs is based on U.S. market share indications from the Edison Electric Institute's EV Sales 2019 report and mode share projections from the IEA's 2018 Global EV Outlook report (Edison Electric Institute 2019; IEA 2018)
- **Average trip length**: By default, EVs and ICE vehicles have the same unit distance traveled, and they are the only two types of engines (for simplification purposes). While EV drivers have been found to travel less miles than ICE drivers, it assumed that ICE vehicles and EVs have the same average trip length and number of trips per day and the same VKT for each mode (Boston and Werthman 2016). For shared fleets, the default trip length only accounts for distance traveled with a passenger in the vehicle. Deadheading, drivers traveling without passengers, is not taken into account.
- **Average number of trips per day per vehicle**: The average number of trips per day is calculated based on the CURB database from (The World Bank 2016). Private cars and private two-wheelers are assumed to have the same number of trips per day. Literature reveals that the number of trips taken by an individual correlates with economic activity (Blumenberg et al. 2012; Litman 2020). Therefore, the number of trips is assumed higher in developed economies than in emerging economies. Determining the difference between high-income and low-income trips per day is an imperfect science, and a simple binary variable is used between these two income levels, based on author's assumptions. Literature is inconsistent on whether future trends will dictate more or less trips per person. Therefore, the average number of trips are expected to remain constant between the different years.
- **Average occupancy per registered vehicle**: In general, shared fleets have higher occupancy rates than private vehicles (UNEP 2018; Schaller 2018). Private cars are assumed to have lower occupancy than other modes (UNEP 2018; Schaller 2018). Private vehicle occupancy is based on national data in the US, which is then reduced by 24% to account for all registered vehicles (not just occupancy of vehicles on the road. The 24% reduction is based on the 24% of US households that have three or more vehicles (Center for Sustainable Systems 2019). The default inputs do not change overtime.
- **Average lifespan of ICE vehicles**: The default average lifespan for all modes does not change over time or by economy type. The average lifespans come from the following reports: IAEE Report 2014, Nationwide Insurance 2017, US DoT.

- **Average lifespan of e-vehicles**: The default average lifespan for all modes does not change over time. The average lifespans come from the following reports: (US DOE n.d.), BYD Warranty, UNEP 2018.
- Public bus annual vehicle revenue kilometers, 2020: No default alternative listed in the tool.
- **Public bus and rail annual ridership, 2020**: No default alternative listed in the tool.

Figure 7. Mobility calculations use information from the City Input and Mobility Input tabs



Note: Outputs produced in the Mobility Calculations sheet are used in all other FMC calculation sheets.

Mobility Calculations (Calculation sheet - 'Mobility Calc')

1. Number of vehicles per mode (V)

Number of vehicles per mode will be a required input for each mode for 2020, but the tool will calculate these figures for 2035 and 2050. Also, not all private cars and private two-wheelers are expected to be used every day, so a utilization factor will be applied to these modes to calculate their use in 2020.

a. Number of vehicles per mode in 2020
    a. For all modes: These data are required inputs.
b. Number of vehicles per mode in 2035 and 2050
    a. For private cars, private two-wheelers, and shared fleets:

$$\frac{Users_m}{Average\ Occupancy\ per\ Registered\ Vehicle_m} = \boldsymbol{V_m}$$

    b. For public bus and rail:

$$\frac{Users_m}{UTV_m} = \boldsymbol{V_m}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus, rail)
- Users = people traveling daily per mode (calculations provided below)
- UTV = Users per transit vehicle (calculations provided below)

2. Number of EVs and Number of ICE vehicles (EV_m, ICE_m)

-

a. For 2020: These values are input by the user.
b. For 2035 and 2050:
c. Number EVs:

$$V_m\ \%\ uptake\ of\ EVs_m = \boldsymbol{EV}_m$$

d. Number ICE vehicles:

$$V_m - EV_m = \boldsymbol{ICE_m}$$

Variables

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus, rail)
- V = Number of vehicles per mode

3. Number of users per mode (Users)

Users for each transportation mode is used to calculate and/or incorporate mode-split information.

a. Numbers of users per mode for 2020:
   a. Total:

$$\sum_{m} Users = \boldsymbol{Users_{total}}$$

   b. For private cars, private two-wheelers, and shared fleets:

$$V_m \bullet \, Average\ Occupancy\ per\ Registered\ Vehicle_m = \boldsymbol{Users_m}$$

   c. For public bus and rail:

$$\frac{Annual\ Ridership_m}{365\ days \bullet 2\ rides\ per\ user\ per\ day} = \boldsymbol{Users_m}$$

   d. Number of riders per mode for 2035 and 2050:
      i. Total:

$$Users_{total,2020} \bullet \, (1 + \, Annual\ Population\ Growth\ Rate)^{\wedge\, number\ of\ years} = \boldsymbol{Users_{total}}$$

      ii. For each mode:

$$Users_{total} \bullet \, Mode\ Split_m \quad = \boldsymbol{Users_m}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus, rail)
- V = Number of active vehicles per mode

4. Number of users per transit vehicle (UTV)

The number of riders per transit vehicle is used to calculate the number of transit vehicles in in 2035 and 2050. These numbers are calculated based on 2020 input data.

a. Numbers of users per transit vehicle (applies only for bus and rail):
   - $\frac{Annual\ Ridership_m}{V_m \bullet \, 365 \bullet \, 2\ rides\ per\ user} = \boldsymbol{UTV_m}$

Variables:

- m = vehicle mode (only applies here to bus, rail)
- V = Number of active vehicles per mode

5. Vehicle Kilometers Traveled per Day (VKT)
   -

a. Total:

$$\sum_{m} VKT = \boldsymbol{VKT_{total}}$$

b. For private cars, private two-wheelers, and shared fleets:

$$V_m \bullet \; Average\ Number\ of\ Trips_m \bullet Average\ Trip\ Length_m = \boldsymbol{VKT_m}$$

c. For public bus (VKT for rail is not calculated):

$$V_m \bullet KPV_m \;\; = \boldsymbol{VKT_m}$$

$$\frac{Annual\ Revenue\ Kilometers\ per\ Transit\ System_m}{365 \bullet V_{m,2020}} = \boldsymbol{KPV_m}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus, rail)
- V = Number of vehicles per mode
- KPV = Kilometers per bus per day
- VKT = Daily Vehicle Kilometers Traveled

Mobility Outputs

- Total ICE vehicles per mode 2035 and 2050.
- Total EVs per mode 2035 and 2050.
- Total distance travelled by ICE and EVs per vehicle mode all years.
- Growth rate required of vehicle electrification per mode to achieve the designated EV uptake percentage.

2.2.3 Charging Infrastructure

Electricity consumption calculation and estimation are an important component for calculating a city's charging infrastructure requirements and the emissions associated with vehicle electricity use. For electricity usage, two main variables are considered: 1) VKT and 2) an environmental factor which adjusts that estimate by considering average temperatures of the city, which can impact battery efficiency.

The FMC assumes that EV operators can charge at four different location types:

- **Home**: residential charging setting
- **Work**: charging located at a place of employment
- **Public**: charging locations accessible for public use
- **Depot**: charging locations for fleets, most commonly not accessible to the public

The FMC assumes that there are six different charger types that EVs can use to charge. This is broken down between LDVs and HDVs, each vehicle class is associated with three charger types. Charger power values (kW) listed below should be used as reference values, the terminology used to describe different kW ranges can vary by geography (International Energy Agency 2019).

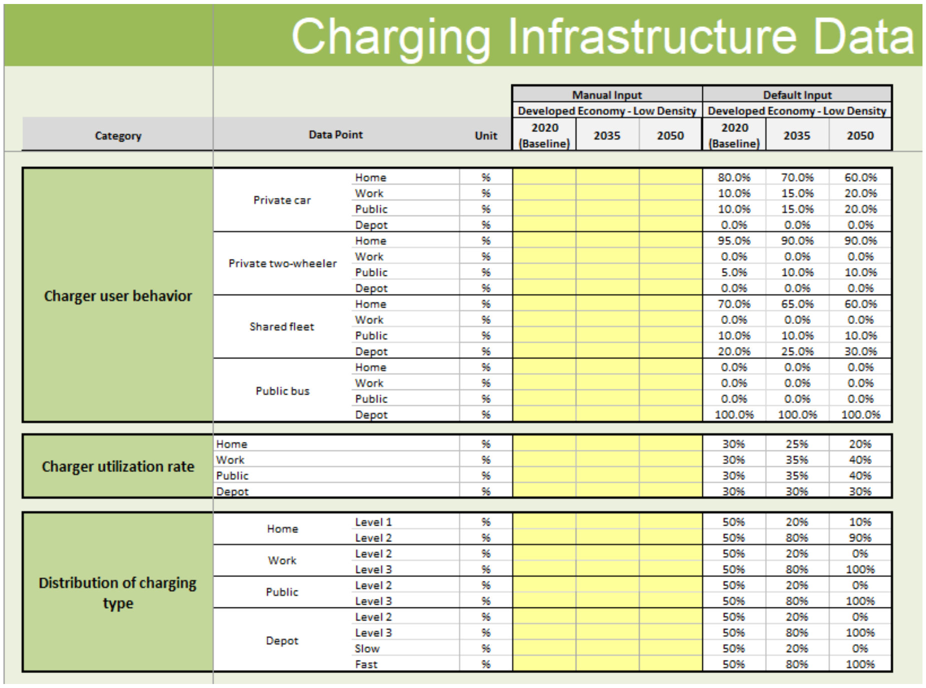
LDV Charging

- Level 1: Most commonly found in home charging settings and facilitated by a wall outlet, either 120V or 240V depending on geography. Charging power is less than 3.7 kW.
- Level 2: Most commonly found in public, private, and work charging settings. Charging power can range between 3.7 kW and 22 kW.
- Level 3: Almost exclusively found in public or depot charging settings. Charging power is above 50 kW, but no greater than 400 kW.

HDV Charging

- Slow chargers: Most commonly found in depot settings. Charging power capabilities can range between 22 kW and 60 kW
- Fast chargers: Most commonly found in depot settings. Charging power capabilities range between 125 kW and 400 kW.

Figure 8. Screenshot of the Charging Infrastructure Data tab, where users input general city information.



Charging Infrastructure Data

Category	Data Point		Unit	Manual Input			Default Input		
				Developed Economy - Low Density			Developed Economy - Low Density		
				2020 (Baseline)	2035	2050	2020 (Baseline)	2035	2050
Charger user behavior	Private car	Home	%				80.0%	70.0%	60.0%
		Work	%				10.0%	15.0%	20.0%
		Public	%				10.0%	15.0%	20.0%
		Depot	%				0.0%	0.0%	0.0%
	Private two-wheeler	Home	%				95.0%	90.0%	90.0%
		Work	%				0.0%	0.0%	0.0%
		Public	%				5.0%	10.0%	10.0%
		Depot	%				0.0%	0.0%	0.0%
	Shared fleet	Home	%				70.0%	65.0%	60.0%
		Work	%				0.0%	0.0%	0.0%
		Public	%				10.0%	10.0%	10.0%
		Depot	%				20.0%	25.0%	30.0%
	Public bus	Home	%				0.0%	0.0%	0.0%
		Work	%				0.0%	0.0%	0.0%
		Public	%				0.0%	0.0%	0.0%
		Depot	%				100.0%	100.0%	100.0%
Charger utilization rate	Home		%				30%	25%	20%
	Work		%				30%	35%	40%
	Public		%				30%	35%	40%
	Depot		%				30%	30%	30%
Distribution of charging type	Home	Level 1	%				50%	20%	10%
		Level 2	%				50%	80%	90%
	Work	Level 2	%				50%	20%	0%
		Level 3	%				50%	80%	100%
	Public	Level 2	%				50%	20%	0%
		Level 3	%				50%	80%	100%
	Depot	Level 2	%				50%	20%	0%
		Level 3	%				50%	80%	100%
		Slow	%				50%	20%	0%
		Fast	%				50%	80%	100%

Note: The data sheet includes cells for both city-specific user input (preferred) and pre-loaded default inputs based on the previously designated city typology. Source: WRI

Charging Infrastructure Input (Data input sheet - 'Charging Data')

- **Battery capacity** (kWh): Average battery capacity available in the city for each vehicle mode in the years 2020, 2035, and 2050.
- **Battery range** (km): Maximum distance each vehicle mode can travel with the battery size defined in the battery capacity input.
- **Charger power** (kW): The average power flow (kW) each EV charger type can supply to a vehicle in your city under normal circumstances. This input is sensitive and has an impact on charger numbers.
- **Charging infrastructure lifespan** (years): Number of years each charger type will continue to function properly assuming regular maintenance and usage habits.
- **Charger user behavior** (by mode, % charging location): Percentage of time during a given day (out of 24 hours) that each mode will utilize each location to charge the vehicle battery. For each vehicle mode, the user behavior at each associated charging setting should add to 100%. Current, expected, or desired charging behavior of EV owners when charging their vehicles can be applied to this variable by the user.
- **Charger utilization rate** (% charging location): Percentage in a given day (out of 24 hours) that a charger will be operating and plugged into a vehicle per charging location (home, work, public, depot charging).
- **Distribution of charging type** (by location, % charger type): The distribution of charging speeds type that exists within a defined charging location type. For each charging setting, the percent of each charging speed present should collectively add to

100 percent. Current, expected or desired available charging infrastructure type/level by location in your city.

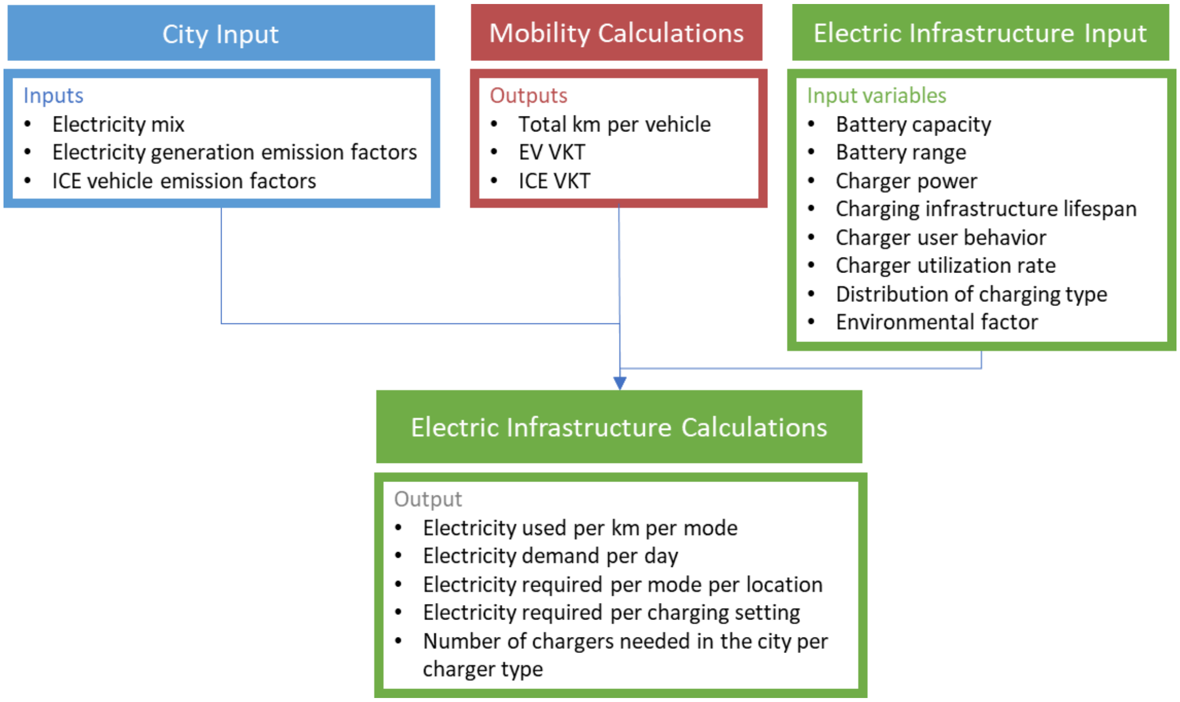
- Environmental factor (percent): Percentage of operational loss and impact to vehicle battery efficiencies due to presence of extreme temperatures. This is determined by the selection made within the tool's "Initial Data Entry" tab.

Charging Infrastructure Default Input Assumptions (Default information – 'Charging Default')

- **Battery range** (km): By default, the battery range is projected to increase over time based on current trends (IEA 2020). Battery range and battery capacity are assumed to increase at similar rates in the default settings.
- **Charger power** (kW): This default input data considers various levels of charging for both light duty vehicles (Level1; Level 2; Level 3) and heavy-duty vehicles (Slow charging; Fast charging) (Nicholas, Lutsey, and Hall 2019; Proterra 2019). Future projections are based on the rationale that charging capacity is projected to increase over time. Therefore, it is assumed that there is a desire to access to faster chargers, so charging power increases over time.
- **Charging infrastructure lifespan** (years): The default input data considers multiple charger settings and for relevant charging levels available within each setting (Smith and Castellano 2015; Chang et al. 2012).
- **Charger user behavior** (by mode, % charging location): The default input data is based on IRENA smart charging projections and trends observed by the US DOE and ICCT (Hall and Lutsey 2020; US DOE n.d.; IRENA 2019). It assumes that vehicles are charged to 100% each time they are plugged in for charging. It also assumes that, through time, home charging for private vehicles will decrease, while work and public charging increase. For shared fleets, home charging is assumed to decrease through time as depot charging increases. For public buses, charging is assumed to always take place in a depot given that opportunity charging is a nascent technology.
- **Charger utilization rate** (% charging location): Based on research done on public charging trends and the speed of chargers, utilization rate is assumed to start at 30% of the day in places that serve private vehicles (home and work). 30% is roughly 8 hours which corresponds to an average workday or an average night (IRENA 2019). The author assumes this percentage will decrease slightly through time (20% by 2050) for home charging based on (1) an increase in charger speed and (2) an increase in public and depot charging, especially for shared fleets (Wolbertus, Van den Hoed, and Maase 2016; Wolbertus et al. 2018). Electricity consumption is also assumed to continue to increase with time (IEA 2019).
- **Distribution of charging type** (by location, % charger type): The default percentages are based on the percentages of each level of charger currently available globally (IEA 2020). Future trends are based on the following:
    - *Home charging* for both level 1 and 2 chargers are assumed to grow in the model at the same rate as private vehicles (electric cars and two-wheelers) initially, however home charging is expected to decrease as the utilization of charging infrastructure in the workplace and public spaces increases (Engel et al. 2018). We are not assuming that buying an EV means you purchased a home charger, so the number of level 1 chargers will likely be lower than the number of private vehicles.

    - In the case of *workplace* chargers, level 2 chargers are expected to grow more rapidly at the beginning due to government incentive programs and then grow steadily. In parallel, level 3 chargers will grow steadily as it is primarily deployed in the public space due to higher installation and operational cost but faster charging speed. As volumes and infrastructure increase, the costs will reduce and make level 3 viable for workplace charging as well.
    - *Public charging* may vary depending on the city type. In cities associated with developed economies, as public investment increases, level 2 chargers will be replaced with level 3 chargers. In emerging economies, we can expect both chargers to be in place simultaneously.
- **Environmental factor** (percent): By default, this factor is assumed to be 1%, meaning that in "hot" or "cold" climates batteries consume 1% more energy (Motoaki, Yi, and Salisbury 2018; Hawkins 2019).

Figure 9. Electric Infrastructure Calculations use input data from City Input and Electric Infrastructure Input sheets and outputs from the Mobility Calculations sheet.



Charging Infrastructure Calculations (Calculation sheet - ‘Charging Calc’)

1. Total daily electricity demand per transit mode.
   a. Electricity used per km by vehicle mode (m): each mode’s kWh of fuel used per km.

$$\frac{Vehicle\ battery\ capactity_m}{Battery\ range_m} = \boldsymbol{Electricity\ used\ per\ km_m\ (kWh/km)}$$

   b. Adjusted electricity used per km by vehicle mode (m), accounting for the Environmental factor.

$$Electricity\ used\ per\ km_m + (Electricity\ used\ per\ km \bullet Environmental\ factor_m) = \boldsymbol{Adjusted\ electricity\ used\ per\ km_m\ (kWh/km)}$$

   c. Daily electricity demand, per transit mode (m).

Total kWh needed for each mode to drive the defined daily km (Mobility Calculation) based on the calculated electricity used per km (Charging Infrastructure Calculation).

$$Adjusted\ electricity\ used\ per\ km_m \bullet\ eVKT_m = \boldsymbol{Electricity\ demand_m\ (kWh/day)}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- eVKT = VKT of electric vehicles (Average Daily VKT from Mobility calculations)

2. Chargers needed in the city.

The quantity of chargers by type (k) needed to support each transit mode’s calculated daily electricity consumption (Charging Infrastructure Calculation). The following calculation is run for each transit mode (m).

   a. Daily electricity demand (kWh) per transit mode (m) by charging location (j)

$$Electricity\ demand_m \bullet Charger\ user\ behavior_m\ (\%_j) = \boldsymbol{Electricity\ required_{m/j}\ (kWh/day)}$$

   b. Electricity required (kWh) per charging setting (j).

$$\textstyle\sum_m Electricity\ required_j\ (kWh/day) = \boldsymbol{Electricity\ required_j}$$

   c. Quantity of chargers needed by type (k), per charging location (j).

This equation assumes that for each charger type at each charging location, those sochargers will be used uniformly throughout the day. The number of chargers needed is a function of the electricity required at charging location (j) and the total power flow (kW) each charger type (k) present at that location can facilitate given its associated charger utilization rate, which is a percentage of 24 hours.

$$\frac{Electricity\ required_j\ \bullet Distribution\ of\ charger\ type_j\ (\%_k)}{Charger\ power_k\ \bullet 24\ hours \bullet Charger\ utilization\ rate\ (\%_j)} = \boldsymbol{Chargers\ needed_{k/j}}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- j = location (home, work, public, depot)
- k = charger type (LDV [Level 1, Level 2, Level 3], HDV [Slow, Fast, Overhead])

Charging Infrastructure Output

1. Total electricity demand for all vehicle modes (m)

$$\sum_{m} Daily\ electricity\ consumption_m$$

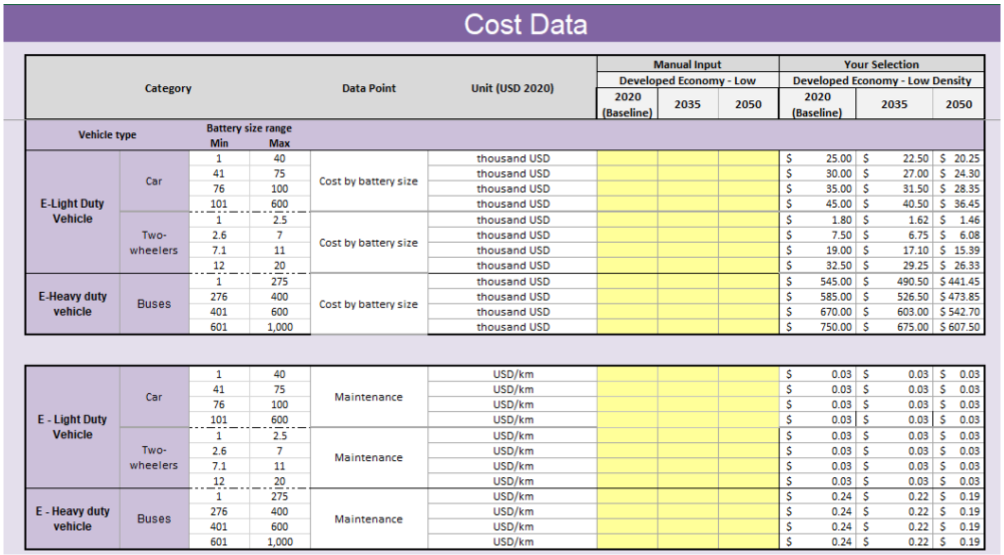
2. Number of chargers per charger type (k)

$$\sum_{j} chargers\ needed_k$$

2.2.3 Cost

This section is focused on estimating cost information of vehicles and chargers, the public investment required for vehicle adoption and infrastructure, the cost of electricity transmission to the charging station and consumption. It does not include potential grid reinforcement or upgrade costs.

Figure 10. Screenshot of the Cost Data tab, where users input cost information for the city.



Cost Data

Category				Data Point	Unit (USD 2020)	Manual Input			Your Selection		
						Developed Economy - Low			Developed Economy - Low Density		
						2020 (Baseline)	2035	2050	2020 (Baseline)	2035	2050
Vehicle type		Battery size range Min	Max								
E-Light Duty Vehicle	Car	1	40	Cost by battery size	thousand USD				$ 25.00	$ 22.50	$ 20.25
		41	75		thousand USD				$ 30.00	$ 27.00	$ 24.30
		76	100		thousand USD				$ 35.00	$ 31.50	$ 28.35
		101	600		thousand USD				$ 45.00	$ 40.50	$ 36.45
	Two-wheelers	1	2.5	Cost by battery size	thousand USD				$ 1.80	$ 1.62	$ 1.46
		2.6	7		thousand USD				$ 7.50	$ 6.75	$ 6.08
		7.1	11		thousand USD				$ 19.00	$ 17.10	$ 15.39
		12	20		thousand USD				$ 32.50	$ 29.25	$ 26.33
E-Heavy duty vehicle	Buses	1	275	Cost by battery size	thousand USD				$ 545.00	$ 490.50	$ 441.45
		276	400		thousand USD				$ 585.00	$ 526.50	$ 473.85
		401	600		thousand USD				$ 670.00	$ 603.00	$ 542.70
		601	1,000		thousand USD				$ 750.00	$ 675.00	$ 607.50
E - Light Duty Vehicle	Car	1	40	Maintenance	USD/km				$ 0.03	$ 0.03	$ 0.03
		41	75		USD/km				$ 0.03	$ 0.03	$ 0.03
		76	100		USD/km				$ 0.03	$ 0.03	$ 0.03
		101	600		USD/km				$ 0.03	$ 0.03	$ 0.03
	Two-wheelers	1	2.5	Maintenance	USD/km				$ 0.03	$ 0.03	$ 0.03
		2.6	7		USD/km				$ 0.03	$ 0.03	$ 0.03
		7.1	11		USD/km				$ 0.03	$ 0.03	$ 0.03
		12	20		USD/km				$ 0.03	$ 0.03	$ 0.03
E - Heavy duty vehicle	Buses	1	275	Maintenance	USD/km				$ 0.24	$ 0.22	$ 0.19
		276	400		USD/km				$ 0.24	$ 0.22	$ 0.19
		401	600		USD/km				$ 0.24	$ 0.22	$ 0.19
		601	1,000		USD/km				$ 0.24	$ 0.22	$ 0.19

Note: The data sheet includes cells for both city-specific user input (preferred) and pre-loaded default inputs based on the previously designated city typology. Source: WRI

Cost Input (Data input sheet - ‘Cost Data’)

All cost numbers should be entered without tax.

- **Average E-Vehicle investment cost by battery size (thousand USD 2020)**: Average cost of vehicle split by vehicle mode and battery size with ranges to customize input from the selected city.

Table 3 – Battery size ranges allow users to input costs that vary by battery size and vehicle modes.

Vehicle mode		Battery size range (kWh)	
		Min	Max
E-Light Duty Vehicle	Car	1	40
		41	75
		76	100
		101	600
	Two-wheelers	1	2.5
		2.6	7
		7.1	11
		12	20
E-Heavy Duty Vehicle	Public buses - depot	1	275
		276	400
		401	600
		601	1,000

- Average cost of vehicle investment for ICE vehicles (thousand USD 2020): Average cost of vehicle, by vehicle mode.
- Average E-Vehicle maintenance cost per vehicle mode per battery size (USD 2020 Cost per km): The average maintenance cost of each vehicle mode per battery size (same as Table 3).
- Average cost of vehicle maintenance for ICE vehicles (USD 2020, Cost per km): Average maintenance cost of vehicle, by vehicle mode.
- **Public investment by investment asset (percentage)**: Public sector investment in the purchase of different vehicles and infrastructure as a percentage of the total cost to consumers. This number has a significant impact on cost results.
    - LDV – Car
    - LDV – Shared vehicle
    - LDV – Two-wheelers
    - HDV – Public bus depot
    - Charging infrastructure
    - Electricity consumption cost
    - Electricity transmission cost
- **Electricity transmission (USD 2020 per charger)**: Average total cost of electricity transmitted to the charging infrastructure.
    - Greenfield (thousand USD 2020 per charger)
    - Greenfield (island state) (thousand USD 2020 per charger)
    - Operation and maintenance (USD 2020 per charger)
- **Charging infrastructure cost (thousand USD 2020)**: Cost of each charger type including installation costs.
- **Electricity consumption cost (USD 2020 per kWh)**: Cost of electricity consumption. This number has a significant impact on the final cost of electricity per vehicle class. Doubling the consumption will roughly double the final electricity cost for all vehicles.

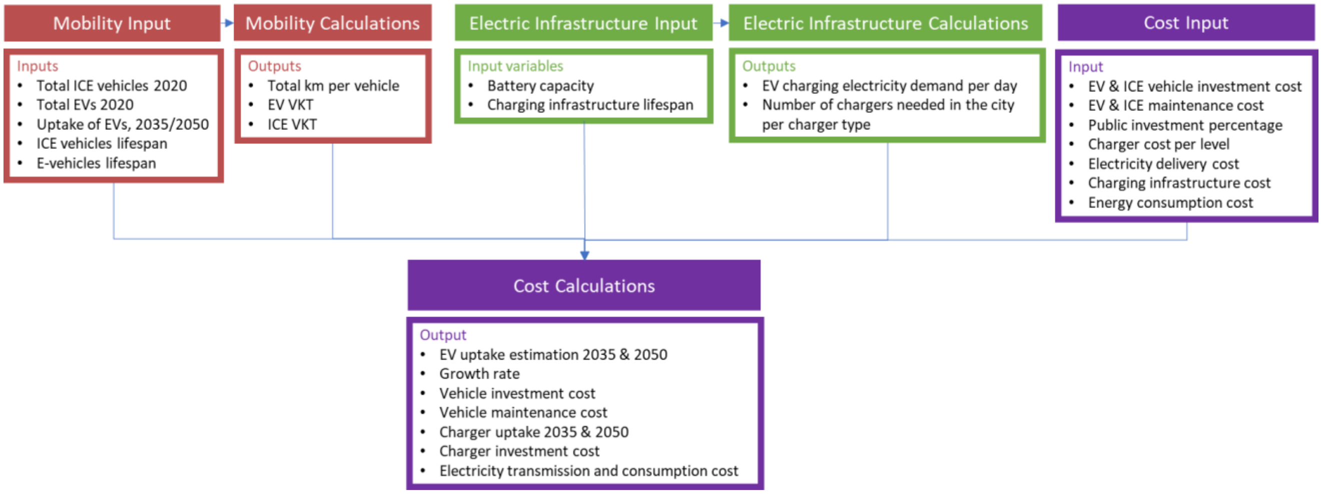
Cost Default Input Assumptions (Default information – 'Cost Default')

All cost default values are in USD 2020 (based on rates in February 2020).

- Average E-Vehicle investment cost by battery size (thousand USD 2020):
    - Default input data for cars is calculated based on estimates from EIA (2017) and IDB (2016).
    - Default input data for two wheelers is calculated based on estimates from Shu (2019); Hinton (2018); Zero Motorcycles; and Muoio (2017).
    - Default input data for buses is calculated based on estimates from Bloomberg New Energy Finance (2018) and Reuters (2017).
    - In real terms, the default input values assume vehicle costs fall at 10% over a 15-year period due to improvements in technology and increase in sales volume.
    - For ease of calculation, the cost of a shared fleet vehicle is assumed to be the same as the cost of a private car.
- Average cost of vehicle investment for ICE vehicles (thousand USD 2020):
    - Default input data for all modes are calculated based on estimates from UNEP (2018).
    - In real terms, the default input values assume vehicle costs fall at 10% over a 15-year period due to improvements in technology and increase in sales volume.
    - For ease of calculation, the cost of a shared fleet vehicle is assumed to be the same as the cost of a private car.
- Average E-Vehicle maintenance cost per vehicle mode per battery size (USD 2020 Cost per km):
    - Default input data for cars is calculated based on estimates from Berman (2018) and Edmunds (2020).
    - Default input data for two wheelers is calculated based on estimates from (UNEP 2018).
    - Default input data for buses is calculated based on estimates from Mickle, Siegel, and Sutton and FTA (2018).
    - The maintenance cost per EV mode is the same, independent of the battery size.
    - Assumed decrease of 50% in EV maintenance cost in developing economies due to cheaper labor compared to developed economies. This is assuming the major portion of the maintenance cost comes from labor based on Antich (2018).
- Average cost of vehicle maintenance for ICE vehicles (USD 2020, Cost per km):
    - Default input data for cars and two wheelers is calculated based on estimates from Lutsey and Nicholas (2018).
    - Default input data for buses is calculated based on estimates from FTA (2018).
- Public investment by investment asset (percentage):
    - The default values assume a 5% public investment per year for a private car in 2020 based on information from this US Energy Information Administration report (EIA 2017). The public investment in shared fleet vehicles and two-wheelers are based on car numbers. For buses, public investment is assumed to be 100%.
    - Public investment for charging infrastructure includes total cost for public chargers and existing policy incentives for private ones (Slowik et al. 2019).

  - Public investment decreases in vehicles by 1% over a 15-year period in developed economies and by 3% over a 15-year period in developing economies as vehicles become cheaper with increased adoption and lower battery prices. The assumptions are based on insights in IEA (2020).
  - Public investment increases in charging infrastructure by 30% over a 30-year period as charging infrastructure increases drastically to overcome barriers to EV adoption, especially as more expensive DC fast charging infrastructure increases in the public and at the workplace (through incentives and subsidies) (Slowik et al. 2019).
  - The public investment in shared fleets is assumed to be double of cars as it includes private and publicly owned fleets. Public investment in shared fleets is the percentage of total cost paid by public institutions to subsidize fleet purchase. Shared fleets are cars owned either publicly (city-owned) or privately (Uber, Lyft, etc.).
- Electricity transmission (USD 2020 per charger):
  - Electricity transmission costs cover the cost of transmission and distribution and are a fixed cost, based on retail electricity bills. Future cost scenarios for 2035 and 2050 are calculated based on impacts from GDP rate increase (Cambridge Econometrics 2018).
  - The electricity transmission cost for islands is assumed to be 10% higher cost due to the isolated nature of island states and added infrastructure to transmit electricity.
  - The tool uses values estimated from Cambridge Econometrics (2018).
  - Electricity transmission costs do not consider Level 1 chargers as they are connected to the existing residential grid infrastructure.
- Charging infrastructure cost (thousand USD 2020):
  - Charging station infrastructure cost decrease by 20% over a 15-year period as volume of infrastructure deployment increases causing manufacturing and installation costs to reduce. It includes cost of each charger type including installation costs (labor, materials, permits) (Agenbroad 2014; Bloomberg New Energy Finance 2018).
- Electricity consumption cost (USD 2020 per kWh):
  - Electricity consumption prices increase at a 10% rate over a 15-year period based on information EuroStat electricity prices for household consumers (Eurostat 2020).

Figure 11. Cost Calculations use input data from Mobility Input, Electric Infrastructure Input, and Cost Input.



Note: Information is also pulled from Mobility Calculations and Electric Infrastructure Calculation sheet outputs.

Cost Calculations (Calculation sheet - 'Cost Calc' compiles inputs calculation sheets below)

1. **Vehicle uptake estimation** (Calculation sheet - 'Cost Calc 1 – Vehicle Uptake')

The desired vehicle numbers for selected years 2020, 2035 and 2050 and vehicle lifespan from the Mobility section are used as input to calculate number of new vehicles to be purchased per year per vehicle mode assuming growing technological adoption and retirement based on lifespan (for EVs only). The calculations are split between 2020-2035 and 2035-2050 to account for different adoption rates.

Annual change of vehicles (Ai) without retirement:

Between 2020-2035:

$$AiEV_m = n * \left(\frac{total\ EV_{2035,m} - \ total\ EV_{2020,m}}{\sum_1^{16} n} \right)$$

$$AiICEV_m = n * \left(\frac{total\ ICE_{2035,m} - \ total\ ICE_{2020,m}}{\sum_1^{16} n} \right)$$

Between 2036-2050:

$$AiEV_m = n * \left(\frac{total\ EV_{2050,m} - \ total\ EV_{2035,m}}{\sum_{17}^{31} n} \right)$$

$$AiICEV_m = n * \left(\frac{total\ ICE_{2035,m} - \ total\ ICE_{2020,m}}{\sum_{17}^{31} n} \right)$$

Retirement for Pre-2020 EV purchases

a. Year of expiration for EVs (nex2020)

$$nex2020_m = \ 2020 + vehicle\ lifespan$$

b. Percentage of EVs retired each year

$$\%\ of\ EV\ retired_m = \frac{1}{EV\ Lifespan_m}$$

c. Number of EVs retired

$$Number\ EV\ Retired_m = \int_1^{nex2020} \left\{ total\ EV_{2020,m} * \%\ EV\ retired_m \right\}$$

For EV purchase between 2020-2035

a. Year of expiration for EVs ($nex2035_m$) = $nex2020_m$ + vehicle lifespan
b. Number of EVs retired = Corresponding $AiEV_m$

For EV purchase between 2035-2050

a. Year of expiration for EVs ($nex2050_m$) = $nex2035_m$ + vehicle lifespan
b. Number of EVs retired = Corresponding $AiEV_m$

Total Necessary New EV purchases

a. Necessary New EV Purchases (NEV_n) = $AiEV_m$ + retired $vehicles_{pre\text{-}2020}$ + retired $vehicles_{2020\text{-}2035}$+ retired $vehicles_{2035\text{-}2050}$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected year number (assuming for 2020, n=1)
- l = vehicle lifespan
- nex = year of expiration of EV
- NEV = necessary new EV purchases
- Ai = annual change of vehicles without retirement

2. **Growth Rate** (Calculation sheet - 'Cost Calc 1 – Vehicle Uptake')

a. $\frac{Total\ EVs - Previous\ EVs}{Previous\ EVs}\ x\ 100 = Growth\ Rate_{n,m}$

3. **Vehicle Investment Cost** (Calculation sheet - 'Cost Calc 2 – Vehicle Investment')

a. Cost of new vehicles per year per vehicle mode (per battery size for EVs).

The vehicle investment cost is estimated based on vehicle mode and the battery size, since the battery is the most important element determining the cost of an e-vehicle. If different battery sizes have been entered in the Charging Infrastructure section, the battery size for 2020 is stated only for 2020, the battery size for 2035 is applied to all the years from 2021 to 2035, and the battery size for 2050 is applied to all the years from 2036 to 2050.

$$Total\ investment\ cost\ per\ year\ (TNEVinvest_n) = \sum_m NEV_n * CEV_{s,n}$$

$$Total\ investment\ cost\ per\ year\ (TICEVinvest_n) = \sum_m TICEV_n * CICEV_n$$

b. Total public investment per year.

It includes the total cost for public fleets (buses, city fleets) and subsidy for private vehicles (cars, two wheelers, shared fleets). For default input assumptions are stated earlier in the section 2.2.4.

$$Total\ public\ investment\ per\ year\ =\ T\ NEV_{n,m} * Pubinvest_{m,n}$$

Variables:

- CEV = Cost of an EV based on battery size
- CICEV = Cost of an ICE vehicle
- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- s = battery size (kWh)
- Pubinvest = public investment percentage for EVs

4. **Vehicle Maintenance Cost** (Calculation sheet - 'Cost Calc 3 – Vehicle Maintenance')
   -
   a. Total km traveled per year per vehicle mode and engine. Number of km traveled for each vehicle mode and engine from the Mobility Data section. The maintenance cost is estimated based on vehicle mode and the battery size, since the battery is the most important element determining the cost of an e-vehicle. It is suggested for the cities, to enter an average maintenance cost of their fleet, given that different cities may have different fleet compositions for each vehicle mode.

$$EV\ maintenance\ cost = \sum_{m}\sum_{n} distance\ traveled * maintenance\ cost_{s}$$

$$ICE\ maintenance\ cost = \sum_{m}\sum_{n} distance\ traveled * maintenance\ cost$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- s = battery size (kWh)

5. **Total number of charging stations** (Calculation sheet - 'Cost Calc 4 – Charger Uptake')

From the Charging Infrastructure section, we retrieve the total number of chargers needed per location per type for 2020, 2035 and 2050, and calculate the number of chargers that need to be purchased per year assuming the number of vehicles increases at a constant rate. The calculations are split between 2020-2035 and 2035-2050 to account for different adoption rates.

New chargers per year (Nc) without retirement:

Between 2020-2035:

$$Nc_k = n * \left(\frac{total\ chargers_{2035,k} - \ total\ chargers_{2020,k}}{\sum_1^{16} n} \right)$$

Between 2036-2050:

$$Nc_k = n * \left(\frac{total\ chargers_{2050,k} - \ total\ chargers_{2035,k}}{\sum_{17}^{31} n} \right)$$

For Pre-2020 charger purchases

a. Year of expiration for chargers (nex2020)

$$nex2020_k = \ 2020 + charger\ lifespan$$

b. Percentage of chargers retired each year

$$\%\ of\ EV\ retired_k = \frac{1}{Charger\ Lifespan_k}$$

c. Number of chargers retired

$$Number\ of\ Chargers\ Retired_k = \int_1^{nex2020} \{total\ Chargers_{2020,k} * \%\ Chargers\ retired_k\}$$

For charger purchase between 2020-2035

a. Year of expiration for chargers ($nex2035_k$) = $nex2020_k$ + charger lifespan
b. Number of chargers retired = Corresponding Nc_k

For charger purchase between 2035-2050

a. Year of expiration for chargers ($nex2050_k$) = $nex2035_k$ + charger lifespan
b. Number of chargers retired = Corresponding Nc_k

Necessary New Charger Purchases (NC_n) = Nc_k + retired $chargers_{pre\text{-}2020}$ + retired $chargers_{2020\text{-}2035}$+ retired $chargers_{2035\text{-}2050}$

Variables:

- n = selected year number (assuming for 2020, n=1)
- k = charger type (LDV [Level 1, Level 2, Level 3], HDV [Slow, Fast, Overhead])
- l = charger lifespan
- nex = year of expiration for chargers
- NC = necessary new charger purchase
- Nc = new chargers per year without retirement

6. **Charger investment cost** (Calculation sheet - 'Cost Calc 5 – Charger Investment')
   -
   a. Total cost for chargers per year

$$total\ investment\ per\ year\ (TChinvest_n) = \sum_k T\ NCh_n * Cch_n$$

   b. Total public investment in chargers per year. This incorporates the charger's public investment percentage (Pubinvest) input in this section. It includes the total cost of public chargers and potential subsidies offered for private ones. For additional details please refer to Cost Assumptions section above.

$$Total\ public\ investment\ per\ year\ = T\ NCh_{n,k} * Pubinvest_{k,n}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- k = charger type (LDV [Level 1, Level 2, Level 3], HDV [Slow, Fast, Overhead])
- Pubinvest = percentage of public investment for charging stations

7. **Electricity transmission and consumption cost** (Calculation sheet - 'Cost Calc 6 – Electricity')
   -
   a. Total electricity transmission cost of the charging station types informed in this section, depending on if it is an island or non-island state

$$T\ CElectrans = \sum_n T\ NCh_{m,s} * CElectrans$$

   b. Total public investment in charger's deployment cost per year. This incorporates the investment percentage (Pubinvest) input in this section

$$Total\ public\ investment\ per\ year\ = T\ CEletrans_n * Pubinvest_n$$

   c. Total Electricity consumption per vehicle mode per year. Using the kWh/day variable from the Charging infrastructure section and the total EVs per vehicle mode from the Mobility section, we calculate the yearly electricity consumption per vehicle.

$$Total\ energy\ consumption_{m,n} = \left(\frac{total\ kwh/day_m}{electric\ vehicle_m}\right) * 365$$

   d. Total cost of electricity consumption per year.

$$Total\ energy\ consumption\ cost = \sum_n Total\ energy\ consumption_m * electricity\ cost$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- k = charger type (LDV [Level 1, Level 2, Level 3], HDV [Slow, Fast, Overhead])
- s = battery size (kWh)

Cost Output

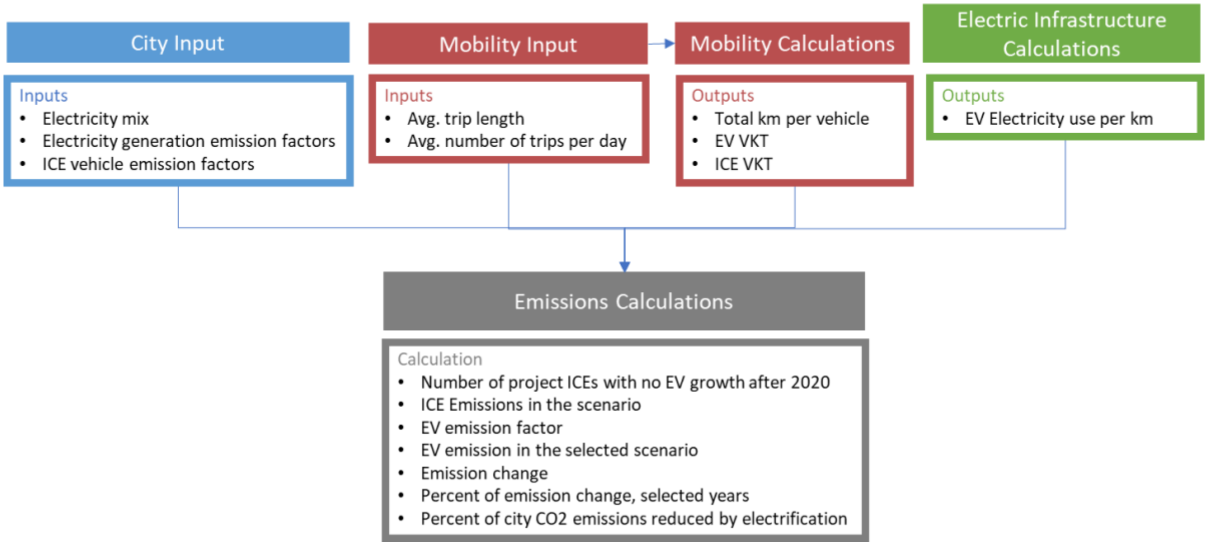
- **Total investment in EVs** (million USD 2020) per vehicle mode per year
- **Total public investment in EVs** (million USD 2020) per vehicle mode per year
- **Total maintenance cost for EVs** (million USD 2020) per vehicle mode per year
- **Total investment in chargers** (million USD 2020) per charger type per year
- **Total public investment in chargers** (million USD 2020) per charger type per year
- **Total electricity transmission cos**t (million USD 2020) per charger type per year
- **Total public investment in electricity** transmission cost (million USD 2020) per charger type per year
- **Total electricity consumption cost** (million USD 2020) per vehicle mode per year
- Total public investment in electricity consumption cost (million USD 2020) per vehicle mode per year

2.2.5 Emissions

For the Emissions Calculations, the tailpipe emission of e-vehicles is 0. The emissions generated by the electricity production for charging are included. The emission factors estimations in this tool are related only to tailpipe and electricity generation. We do not consider emissions from braking and tire friction in this version of the FMC. Additionally, the tool does not account for carbon produced during manufacturing.

Figure 12. Emissions Calculations use input data from City Input and Mobility Input.

Outputs produced in the Mobility Calculations and Electric Infrastructure Calculation sheets are also used.



Emissions Inputs (Data input sheet - 'City Data')

- Average vehicle trips per day: from *Mobility Input*
- Average trip length: from *Mobility Input*
- ICE emissions factor: from *City Input*
- Total km per vehicle mode: from *Mobility Calculations 2*.
- Pollutant emission for electricity generation by source: from *City Input*
- EV distance travelled by vehicle mode: from *Mobility Calculations 2.*

Emissions Assumptions (Default information – 'City Default')

- I ICE vehicle emission factors are taken primarily from US EPA (2008) and Song (2017). Because fuel economy standards (EURO I-V) do not exist in every country, they are not considered in this version of the FMC. The tool assumes that emission factors are constant over time. Users are encouraged to update the data with more geographically or temporally relevant data when inputting their data.
- All low-carbon electricity sources (the tool includes wind, solar, hydro, nuclear) are assumed to have zero emissions for electricity generation.
- We assume shared fleets to have the same emissions factors as private cars.

Emissions Calculations (Calculation sheet - ‘Emissions Calc’, ‘Benefit Calc 1-Emissions’)

1. Number of projected ICEs in a situation where the electrification rate stays at the 2020 electrification rate.

If all vehicles were Internal Combustion Engine (ICE)

$$Baseline\ emissions = ((ICE\ VKT_{m,n} + EV\ VKT_{m,n}) - ((ICE\ VKT_{m,n} + EV\ VKT_{m,n}) \times 2020\ \%\ Electrification))) \times ICE\ Emission\ Factor_{p,n,m}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- p = pollutant (CO_2, PM10, NO_x)

2. ICE emission in the scenario

$$Sc\ ICE = Sc\ ICE\ VKT * ICE_{p,m}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- p = pollutant (CO_2, PM10, NO_x)
- Sc ICE VKT = The number of ICE vehicles remaining after accounting for EV uptake calculated based on Mobility Inputs.
- ICE_p = ICE Vehicle Emissions factor

3. EV emission factor per VKT

$$EV\ Emission\ factor_{f,m} = \sum_{p,m} electricity\ mix * fuel\ emission\ factor_{f,m} * EV\ efficiency_{m,n}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- f = fuel source
- p= pollutant (CO2, PM10, PM2.5, NO_x)

4. EVs emission in the selected scenario

$$Sc\ EV = Sc\ EV\ VKT_{m,n} * EV\ emission\ factor_{f,m}$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- Sc EV VKT = Vehicle kilometers travelled in selected scenario of EV uptake calculated based on Mobility Calculations 2

5. Emission change
   -
     a. $Annual\ pollutant\ emission\ change_p = Baseline\ emissions - (Sc\ ICE + Sc\ EV)$
     b. $Accumulated\ pollutant\ emission\ change_p = \sum_{n,m} annual\ pollutant\ emission\ change$

Variables:

- p = pollutant (CO_2, PM10, PM2.5, NO_x)
- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years

6. Percentage of emission change, selected years

$$Percentage\ of\ annual\ emission\ reduction = \left({}^{Pollutant\ emission\ change}/_{Baseline}\right) * 100$$

7. Percentage of city CO_2 emissions reduced by electrification

$$Percentage\ of\ annual\ reduction = \left({}^{CO_2\ emission\ change}/_{(Population\ _n \times Emissions\ per\ capita)}\right) * 100$$

-
  - n = selected years

Emissions Output

- Total emission reduction kg/year per pollutant
- Percentage of annual emission reduction in transportation per pollutant
- Percentage of city CO_2 emissions reduced by electrification (kg/year)

2.2.6 Benefits

The benefits calculations put the emissions reductions in context by quantifying the social costs avoided by switching to EVs. In this section, the user cannot input information directly and will be using the default input data to assess benefit impacts. This is done to simplify calculations and align data sources.

The factors determining the "value of social cost" are complex and vary by emission type and source. The sources and estimations for social cost used in this tool is available in Annex 2. These values are subjective in nature and are only intended to provide a general estimate for initial planning purposes.

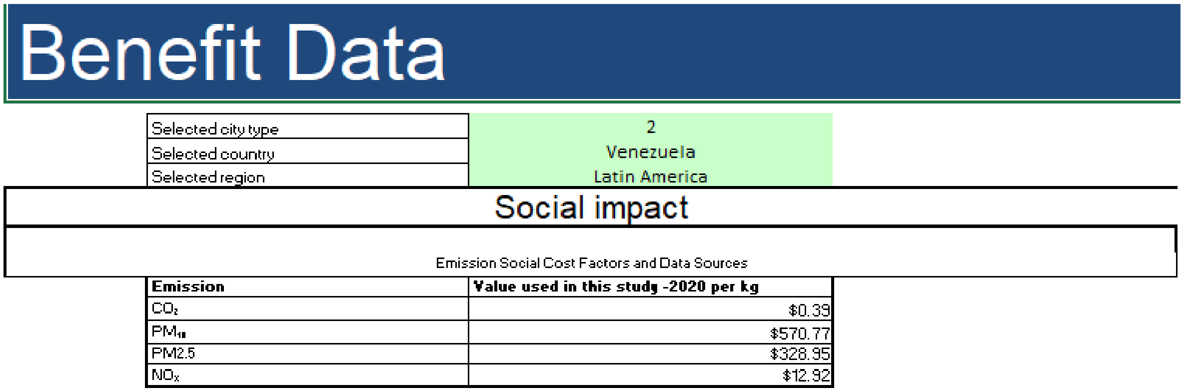
Benefit Input (Default information – 'Benefits Default')

- **Emissions social cost factors (SCFs)** (USD 2020/kg): the social cost of key pollutants (CO_2, PM10, PM2.5. NO_x) per kilogram emitted based on the Social Cost Factor (SCF).
- **ICE emissions factors** (kg/km): the amount of key pollutants emitted per km of different ICE vehicle classes.
- **EV emissions factors** (kg/km): the amount of key pollutants emitted per km of different EV classes.
- **Total emission reduction per pollutant** (kg/year): the total reduction of pollutants caused by electrifying vehicles as calculated by Emissions section.
- **Total ICE vehicles**: the total number of ICE vehicles existing in a city sourced from Mobility Calculations.
- **Total EVs**: the total number existing in a city as calculated by Mobility Calculations.
- **Vehicle Kilometers travelled**: (km/day): the number of kilometers each vehicle mode travels each day in a city calculated by Mobility Calculations.

Benefits Default Input Assumptions

- Emissions social cost factors (SCFs) (USD 2020/kg):
    - All SCFs come from (Victoria Transport Policy Institute 2018) and the Transport Emissions & Social Cost Assessment Tool (Su 2017). (details are available in Annex 2)

Figure 13: Benefit Data sheet, showing the emission social cost factors used in the tool.



Benefit Data

Selected city type	2
Selected country	Venezuela
Selected region	Latin America

Social impact

Emission Social Cost Factors and Data Sources

Emission	Value used in this study -2020 per kg
CO_2	$0.39
PM_{10}	$570.77
PM2.5	$328.95
NO_x	$12.92

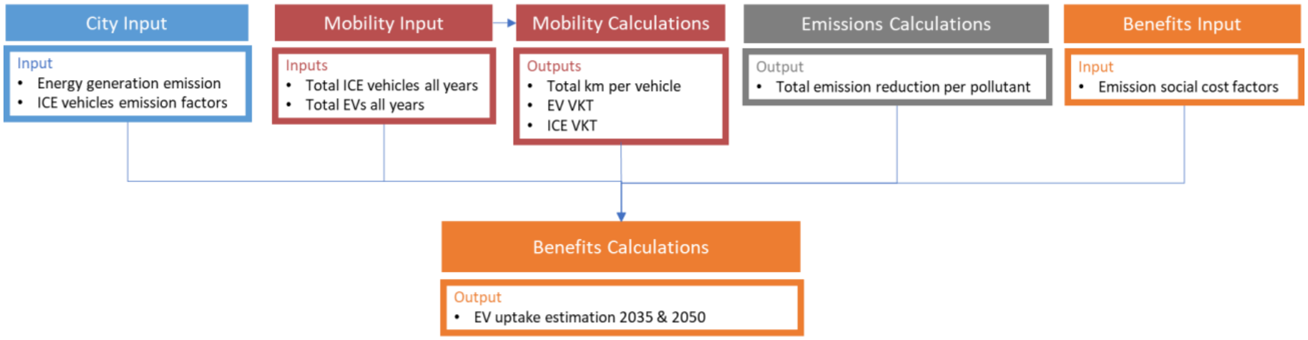
Source: WRI

Benefits Calculations (Calculation sheet – indicated below)

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- p = pollutant (CO_2, PM10, PM2.5, NO_x)
- n = selected years
- All ICE VKT= Vehicle kilometers travelled assuming all vehicle growth is with ICE vehicle mode, calculated in Mobility section
- Sc EV VKT = Vehicle kilometers travelled by EVs, calculated in Mobility section
- Sc ICE VKT= Remaining number of ICE vehicles after EV uptake, calculated in Mobility section
- ICE_e = ICE Vehicle emissions factor
- EV_e = EV emissions factor
- SCF = Emission Social Cost Factor (details available in Annex 2)

Figure 14. Benefits Calculations use input data from City Input, Mobility Input and Benefits Input sheets.

Outputs produced in the Mobility Calculations and Emissions Calculation sheets are also used.



1. **Social cost avoided (selected years)** (Calculation sheet - 'Benefits Calc 1 – Emissions')

The social cost avoided is calculated for each pollutant from each vehicle in 2020, 2035, and 2050. Social costs are calculated for CO_2, PM2.5, PM10, NOx.

   a. Annual emissions reductions by vehicle mode (m) and pollutant (p)

$$Emissions\ reductions_{n,m,p} = \left(Baseline\ ICE\ VKT * ICE_p\right) - \left[\left(Sc\ EV\ VKT * EV_p\right) + \left(Sc\ ICE\ VKT * ICE_p\right)\right]$$

$$Annual\ Emissions\ reductions_{n,m,p} = Emissions\ reductions_{n,m,p} * 365$$

   b. Social cost avoided (selected years)

$$Total\ social\ cost\ avoided_{p,n,m} = Annual\ Emissions\ reductions_{p,m,n} * SCF_p$$

Variables:

- m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
- n = selected years
- p = pollutant (CO_2, PM10, PM2.5, NOx)
- SCF_p = Emission Social Cost Factor (USD/ton of pollutant)
- All ICE VKT= Vehicle kilometers travelled assuming all vehicle growth is with ICE vehicle mode, calculated based on Mobility section
- Sc EV VKT = Vehicle kilometers travelled by EVs, calculated based on Mobility section
- Sc ICE VKT= Remaining number of ICE vehicles after EV uptake, calculated based on Mobility section

2. **Social cost avoided (cumulative)** (Calculation sheet - 'Benefits Calc 1 – Emissions')

$$Total\ social\ cost\ avoided_{p,n,m} = \sum_{p} Annual\ Emissions\ reductions_{p,m,n} * SCF_p$$

Variables:

    - m = vehicle mode (private car, private two-wheeler, shared fleet, public bus)
    - n = selected years
    - p = pollutant (CO_2, PM10, PM2.5, NOx)
    - SCF_p = Emission Social Cost Factor (USD/ton of pollutant)

Benefits Output

- Social cost avoided (USD 2020) from CO2, PM10, PM2.5, and NOx selected.
- Social cost avoided (USD 2020) from CO2, PM10, PM2.5, and NOx accumulated.

2.2 Results

The results from the tool are all displayed on one results tab. Below is a list of every result produced by the tool.

Costs Results:

The cost estimation is based on the total vehicles needed to fulfill population demand in the given years. In terms of vehicles, it adds both internal combustion engine and EVs' cost.

- **Total investment in EVs** (million USD 2020) per vehicle mode per year (See Cost Calculation 2)
- **Total public investment in EVs** (million USD 2020) per vehicle mode per year (See Cost Calculation 2)
- **Total maintenance cost for EVs** (million USD 2020) per vehicle mode per year (See Cost Calculation 3)
- **Total chargers' investment cost** (million USD 2020) per charger type per year (See Cost Calculation 5)
- **Total public investment in chargers** (million USD 2020) per charger type per year (See Cost Calculation 5)
- **Total electricity transmission cost** (million USD 2020) (See Cost Calculation 6)
- Total public investment in electricity transmission cost (million USD 2020) (See Cost Calculation 6)
- **Total electricity consumption cost** (million USD 2020) per vehicle mode per year (See Cost Calculation 6)
- **Total public investment electricity consumption cost** (million USD 2020) per vehicle mode per year (See Cost Calculation 6)

Infrastructure Results:

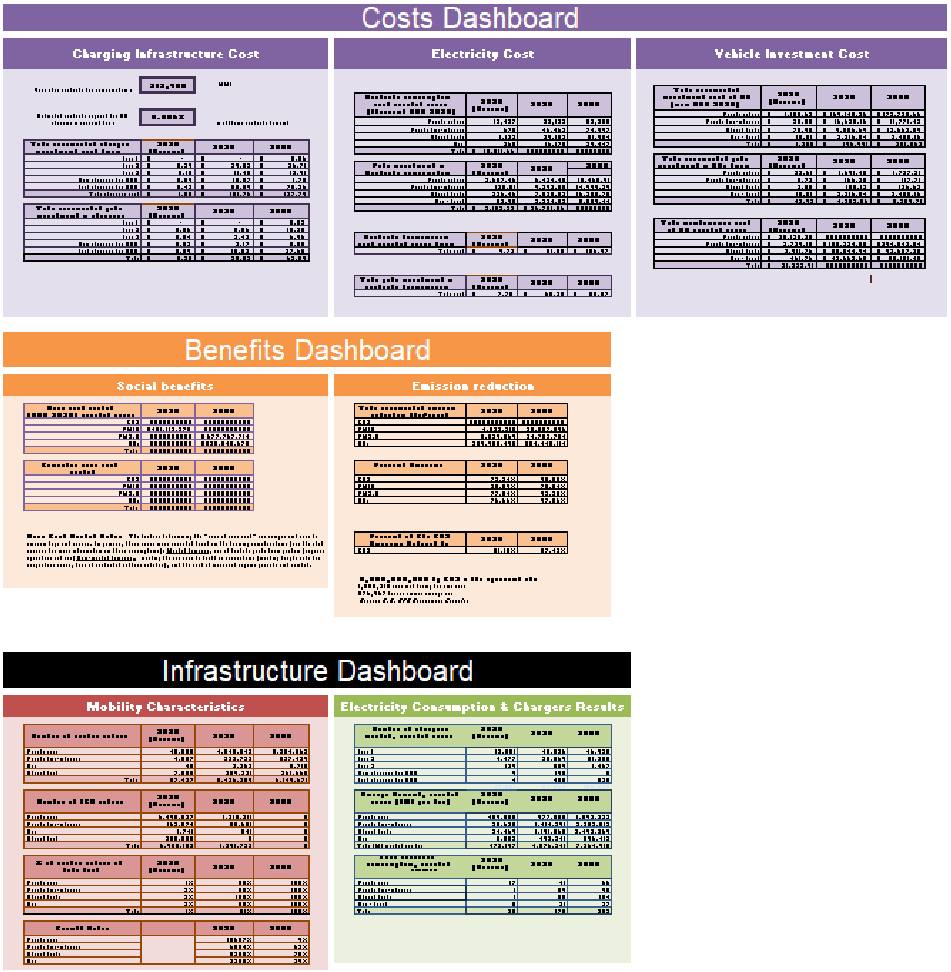
- Total number of EVs per vehicle mode and year (see Mobility Calculation 3)
- Total number of internal combustion vehicles per vehicle mode and year (see Mobility Calculation 3)
- Percentage of EV over the total fleet per vehicle mode and year (see Mobility Calculation 3)
- Growth rate of EVs over the fifteen-year period (see Cost Calculation
- Total number of new chargers needed per charger type and year (see Charging Infrastructure Calculation 2)
- Electricity Demand in kWh per day per vehicle mode and in selected year (see Charging Infrastructure Calculation 1)
- Total electricity consumption in MWh per vehicle mode and year (See Cost Calculation 3)

Benefits Results:

- **Social cost avoided selected** (USD 2020) from CO2, PM10, PM2.5, and NO_x (See Benefit Calculation 1)
- **Social cost avoided accumulated** (USD 2020) from CO2, PM10, PM2.5, and NO_x accumulated (See Benefit Calculation 2)

- Total accumulated emission reduction kg/year per pollutant (See Emissions Calculation 5)
- Percentage of annual emission reduction in transportation per pollutant and year (see Emissions Calculation 6)
- Percentage of City CO2 emissions reduced by electrification, selected years (See Emissions Calculation 7)

Figure 15. Screenshot of the Infrastructure & Emissions Results tab, showing demonstration results. Source: WRI



2.3.4 Yearly Selected Costs and Benefits (Results sheet—Yearly Selected Costs & Benefits)

In addition to the results page, some costs and benefits are annualized on the Yearly Selected Costs and Benefits sheet.

- Social cost avoided (million USD 2020) calculated by *Benefit Calculation.*
- **Vehicle cost (million USD 2020)** calculated by *Cost Calculation.*
- Vehicle maintenance cost (million USD 2020) calculated by *Cost Calculation.*
- Charging infrastructure cost (million USD 2020) calculated by *Cost Calculation.*
- Electricity consumption cost (million USD 2020) calculated by *Cost Calculation.*
- Electricity transmission cost (million USD 2020) calculated by *Cost Calculation.*

- Public investment in vehicles (million USD 2020) calculated by *Cost Calculation.*
- Public investment in charging infrastructure (million USD 2020) calculated by *Cost Calculation.*
- Public investment in electricity consumption (million USD 2020) calculated by *Cost Calculation.*
- Public investment in electricity transmission (million USD 2020) calculated by *Cost Calculation.*

3 Conclusion

The FMC is designed to help cities analyze the impact of their future electrification plans. Cities around the world have set ambitious goals for electrifying their vehicle fleets, but few cities have prudently analyzed the impacts (both positive and negative) and requirements that these EVs will bring. These electrification objectives depend on evidence-based planning. Planning, in turn, requires solid estimates of the expected costs and benefits, such as those provided through the FMC. Through the FMC, cities around the world will have a new tool to help them intelligently navigate their own planning processes.

The FMC is a tool that, for a given range of city-specific inputs, estimates the costs, requirements, and benefits of different electrification scenarios. While these data points are critical for planning and gaining political support for electrification, the tool does have some limitations. For example, the FMC is not intended for (nor does it provide) a comparative cost-benefit analysis against other propulsion technologies such as diesel or CNG. The tool is also not designed to provide guidance on what percentage of vehicle fleets should be electrified in future plans; rather the tool provides analysis on the costs and benefits of scenarios which are predefined by the user. Furthermore, like any model, the FMC is only as good as its underlying inputs. If users are unable to provide robust city-specific inputs, the results may not be directly applicable to their city. If users understand intended use of FMC, they can leverage this tool to quantitatively enhance EV planning in their city.

Early iterations of this tool were tested with scenarios from Beijing, Bogota, and Delhi, and the authors found results to be reasonable.

Future iterations of this tool may consider adding spatial analysis to identify appropriate locations for chargers, impacts of electrifying urban freight vehicles and inclusion of non-exhaust emissions to capture the overall emissions impact if the share of energy mix (renewable energy source v/s fossil-fuel based source) in the city changes.

While the FMC is not a panacea for EV planning and analysis, it does allow cities to understand the real-world implications of enacting EV policies. EV adoption is critical to help combat climate change and clear urban air of local pollution; however, it represents a new and daunting challenge. The FMC can help cities navigate these obstacles as they sail off into the uncharted waters of vehicle electrification.

Annex

Annex 1

Integrated into the FMC are four city typologies. Each city type is linked to a set of default inputs. These default inputs are broad generic estimations intended to fill informational gaps in a user's city-specific input data. Two primary variables were used to develop the four typologies:

- Population density
- GDP per capita

Each city typology is defined by a range of values associated with these variables. The city types developed from this are

(1) emerging economy – high density
(2) developed economy – low density,
(3) developed economy – high density, and
(4) emerging economy – low density.

City density is informed by population densities. GDP per capita informs whether the city is an emerging or developed economy. The attributes of each City Type are defined in Table A1.

Table A1.-Intervals of the main city type variables. Source: Elaborated by WRI with data from UN Habitat and World bank Data.

Criteria	Emerging economy, high density	Emerging economy, low density	Developed economy, high density	Developed economy, low density
GDP per capita (USD 2020)[1]	693.3 - 13,221.2		13,221.2 - 24,462.3	
Population density	Above 13,500	Below 13,500	Above 13,500	Below 13,500

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[1] National GDP per capita, PPP (current international $). GDP per capita based on purchasing power parity (PPP). PPP GDP is gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as the U.S. dollar has in the United States. GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in current international dollars based on the 2011 ICP round. Source: World Bank Data. Based on 50% percentile values. High income OECD Countries: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

(population/km^2)[2]				

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[2] Urban agglomeration population density (population/km^2). Source: UN HABITAT http://data.unhabitat.org. Based on S percentile values.

Table A2.- Urban population density and GDP per capita of selected cities Source: World Bank national accounts data, and OECD National Accounts data files.

Country name	City name	Urban agglomeration population density (population/km^2)	GDP per capita, PPP (current international $)
USA	Phoenix	1,200	$ 59,531.66
USA	York	1,800	$ 59,531.66
USA	Georgetown	1,900	$ 8,162.60
Finland	Helsinki	2,400	$ 44,865.84
New Zealand	Auckland	2,400	$ 41,109.01
USA	Los Angeles	2,400	$ 59,531.66
Netherlands	Amsterdam	2,500	$ 52,503.27
Belgium	Brussels	2,600	$ 47,840.20
Denmark	Copenhagen	2,700	$ 51,364.14
Malaysia	Kuala Lumpur	3,400	$ 29,431.47
Brazil	Brasilia	3,600	$ 15,483.54
Russia	Moscow	3,600	$ 25,533.00
France	Paris	3,800	$ 42,850.39
Armenia	Yerevan	4,000	$ 9,647.49
Russia	St. Petersburg	4,100	$ 25,533.00
Ghana	Accra	4,200	$ 4,641.32
Spain	Barcelona	4,300	$ 37,997.85
Japan	Yokohama	4,400	$ 43,278.99
China	Beijing	5,200	$ 16,806.74
India	Chandigarh	5,300	$ 7,055.55
UK	London	5,900	$ 43,268.78
Greece	Athens	6,000	$ 27,601.90
Thailand	Bangkok	6,200	$ 17,870.52
Burkina Faso	Ouagadougou	6,300	$ 1,869.76
Brazil	Sao Paulo	6,500	$ 15,483.54
Mexico	Guadalajara	6,500	$ 18,258.10
Tanzania	Dar es Salaam	6,500	$ 2,945.88
Central African Republic	Bangui	7,100	$ 725.95
Kenya	Nairobi	8,000	$ 3,285.91
Ethiopia	Addis Ababa	8,300	$ 1,899.21
Egypt	Cairo	9,100	$ 11,582.59
Rwanda	Kigali	9,300	$ 2,035.65
Indonesia	Jakarta	9,600	$ 12,283.62
Singapore	Singapore	10,200	$ 93,905.42
Nigeria	Abuja	10,500	$ 5,860.85
India	Kota	12,100	$ 7,055.55

Nigeria	Lagos	13,300	$ 5,860.85
Morocco	Casablanca	14,200	$ 8,217.46
Philippines	Manila	14,800	$ 8,342.80
Colombia	Medellin	19,700	$ 14,552.01
India	Mumbai	31,700	$ 7,055.55
Bangladesh	Dhaka	44,500	$ 3,868.82

Annex 2

Social cost assessment

The social cost of pollutants is the measure, in a certain currency, of the long-term damage done by a ton of each pollutant emissions each year. Each pollutant derived from motor vehicles produce different harm to the environment and human health. While some are local or regional impacts, in other cases the location is less important.

Table A3. Vehicle pollutant emission Source: Victoria Transport Policy Institute (2018)

Emission	Description	Sources	Harmful effects	Scale
Carbon dioxide (CO_2)	A product of combustion	Fuel production and tailpipe	Climate change	Global
Fine particulates (PM_{10})	Inhalable particles	Tailpipe, brake lining, road dust, etc.	Human health, aesthetics	Local or regional
Nitrogen oxides (NO_x)	Various compounds, some are toxics, all contribute to ozone	Tailpipes	Human health, ozone precursor, ecological damage	Local or regional

The monetary assessment of the selected pollutant does not account for the impact on health as this impact is separately evaluated in the previous section. We have selected values from Victoria Transport Policy Institute 2018 (VTPI). VTPI converted original values from different publications to 2007 USD, adjusted based on the CPI, and the authors inflated them further to 2020.

Emissions Social Cost Factors	CO_2	Per kg	The value of social cost for CO2eq is originally sourced by UK Department for Environment, Food and Rural Affairs - AEA Technology Environment (2005) and included in table 5.10.4-14 in Victoria Transport Policy Institute (2018). This number represents the upper bound estimate of the abovementioned sources, since this figure was on par with other estimates in other major sources (such as Downing et al. [2005] who indicate this figure is well within one standard deviation of the average estimates). This number was converted from dollars

			per ton to dollars per kilogram and then adjusted for inflation to 2020 USD.
	PM_{10}	Per kg	The value of social cost for PM10 is originally sourced by Rowan Williams Davies and Irwin Inc (RWDI) (2006) and included in table 5.10.4-1 in Victoria Transport Policy Institute (2018). Since it is difficult to find reliable and robust sources for information on the value of the social cost associated with PM10, this figure represents a number provided for PM2.5, which was converted to PM10 by dividing by a conversion factor of 0.6, based on WHO (2014). This number was converted from dollars per ton to dollars per kilogram and then adjusted for inflation to 2020 USD.
	PM2.5	Per kg	The value of social cost for PM2.5 is originally sourced by Rowan Williams Davies and Irwin Inc (RWDI) (2006) and included in table 5.10.4-1 in Victoria Transport Policy Institute (2018). This number was converted from dollars per ton to dollars per kilogram and then adjusted for inflation to 2020 USD.
	NO_X	Per kg	The value of social cost for NOx is originally sourced by AEA Technology Environment (2005) and included in table 5.10.4-1 in Victoria Transport Policy Institute (2018). This number was converted from dollars per ton to dollars per kilogram and then adjusted for inflation to 2020 USD.

Emission	Value used in this tool $(2020) per kg
CO_2	$ 0.39
PM_{10}	$ 575.98
PM2.5	$ 345.59
NO_X	$ 12.83

Calculations:

Emission	$ (2007) /ton (from sources)	kg/ton	$(2007) /kg	inflation	$ (2020) /kg
CO_2	310	0.001	$ 0.31	24.6%	$ 0.39
PM_{10}	462265	0.001	$ 462.27	24.6%	$ 575.98
PM2.5	277359	0.001	$ 277.36	24.6%	$ 345.59
NO_X	10293	0.001	$ 10.29	24.6%	$ 12.83

Assumption for Inflation 24.6% (13-year period)
https://www.usinflationcalculator.com/

Another good source for users of this tool to find the input to social costs of carbon specific to their country is Ricke et al. 2018. The supplementary information from their research, which includes data for all countries is available here: https://country-level-scc.github.io/ .

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