HDV CHARGE MODEL

ICCT HDV CHARGE model v1.1 documentation

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

INTRODUCTION

The electrification of medium-duty and heavy-duty vehicles (MHDVs) is crucial for achieving climate goals and mitigating the health impacts of air pollution. Deployment of electric charging and hydrogen refueling infrastructure are key not only for accelerating market adoption of zero-emission MHDVs, but also for enabling vehicle-side policies supporting this market development. A precise understanding of energy and power requirements—how much, where, and when—is essential, alongside a clear grasp of the number of chargers and refueling stations needed to supply this demand. Detailed information is vital for informing stakeholders about the local deployment of chargers and refueling stations, and necessary upgrades to the electric transmission and distribution grids.

To inform this complex task, the ICCT developed the HDV CHARGE model. HDV CHARGE is a Python-based tool designed to assess charging and refueling infrastructure needs for zero-emission heavy-duty vehicles (including medium-duty trucks, heavy-duty trucks, and buses) at any scale: from local (e.g., zip-code level) to supra-national (e.g., the European Union), for any market, and at any time horizon, based on specific inputs.

HDV CHARGE was first developed in 2024 by Jakob Schmidt, Nicole Egerstrom, Gabe Hillman Alvarez, and Pierre-Louis Ragon. Its methodologies are based on the work outlined in Ragon et al. (2023)[1]. The initial development was generously funded by the CRUX Alliance and the Aspen Global Change Institute. Version 1.1 was developed in 2025 by Jakob Schmidt.

DEFINITIONS

1. Vehicle type: The broad category of vehicle - Bus, Medium Duty Truck, or Heavy Duty Truck.
2. Vehicle segment: A subcategory within a vehicle type (e.g. regional truck, long-haul truck, coach) that can be defined by the user.
3. Charger type: The category of charger based on its power output and intended use, such as overnight, fast, or ultrafast.
4. Charger location: The category indicating where a charger is installed, either at depot (private) or a public location.
5. Charger setting: A specific combination of charger type and charger location. For example, an overnight charger at a depot.
6. Charging priority sequence: The preferred order of charger types used by a vehicle segment to meet its daily energy needs. For example, overnight first, then fast charging, followed by ultrafast charging.

[1] Ragon, P.-L., Kelly, S., Egerstrom, N., Brito, J., Sharpe, B., Allcock, C., Minjares, R., & Rodríguez, F. (2023). Near-term infrastructure deployment to support zero-emission medium- and heavy-duty vehicles in the United States. International Council on Clean Transportation. https://theicct.org/publication/infrastructure-deployment-mhdv-may23/

7. Charging session: The duration that starts when a vehicle is plugged in and ends when it is unplugged. A session is characterized by its duration and the average effective power output during the session.
8. Charger utilization: The number of charging sessions per charger per day for a given charger setting, or the amount of time a charger is used to charge a vehicle during a day, expressed as a percentage.
9. Charger efficiency: The ratio between the power output transferred to the vehicle's battery and the energy drawn from the power grid by the charger. It accounts for power losses within the charging equipment, on-board charger (if applicable), and vehicle battery.

SCOPE OF THE MODEL

The HDV CHARGE model is designed to be versatile and comprehensive, offering a flexible selection of charging options and covering a wide range of needs for MHDVs:

- Comprehensive Coverage of MHDV segments: The model caters to all MHDV segments and can be flexibly specified to meet any region-specific vehicle segments, such as 2b and 3 in the US, or VECTO Group 0 in the EU, as long as the respective underlying data is provided. It models the charging needs of battery electric vehicles (BEV), and the hydrogen refueling needs for hydrogen-powered MHDVs – either fuel-cell electric vehicles (FCEV) or hydrogen combustion engine vehicles (H_2-ICE).
- Flexible charging and hydrogen refueling station categories: Conductive station charger types cover a wide range of power levels – from AC level 2 charging to fast DC charging to megawatt charging. The model distinguishes between the charger location types private and public. Additionally, it supports battery swapping stations and hydrogen refueling stations.
- Geographical Granularity: The model supports different levels of geographical granularity, allowing for analyses ranging from local (e.g., zip code) to supra-national (e.g., European Union) scales.
- Projections: The model provides projections over various time horizons, enabling stakeholders to plan for both near- and long-term infrastructure needs.

This flexibility and comprehensiveness make the HDV CHARGE model a helpful tool for assessing and planning the charging infrastructure necessary for the successful electrification of MHDVs.

Within the model framework, we use the following categories:

Charger settings are defined by the combination of **charger location** and **charger type**. The charger locations can either be public or depot. The charger types can be overnight, fast, or ultrafast. Additionally, battery-swapping stations and hydrogen refueling stations can be modeled.

Vehicles are specified by their **vehicle type**, which can be ‘Bus’, ‘Medium Duty Truck’, and ‘Heavy Duty Truck’. For each vehicle type, the user can define custom **vehicle segment**s, such as ‘Regional Truck’, ‘Long-Haul Truck’, ‘Coach’, etc. This allows the user to model the charging needs for region- and case-specific subcategories of vehicles.

METHODOLOGY

Overview

HDV CHARGE follows an activity-based approach to calculate the energy demand of the electrified MHDV fleet and the necessary number of chargers, power output, and energy distribution across charger settings to meet that demand. It is important to clarify that the number of chargers refers to the total number of connections a charging station can support simultaneously. Each charger can serve a maximum of one vehicle at a time. For instance, if a charging station has two connections available for simultaneous use, it is counted as two chargers. The following points apply to conductive chargers, while battery swapping stations and hydrogen refueling stations needs are calculated slightly differently. Please find detailed descriptions in the sections after this overview:

1. Calculate the projected MHDV fleet’s energy demand per vehicle segment.
    - This calculation is based on geospatial traffic data and high-level fleet information, including vehicle activity growth projections and the share of electric vehicles in future years.
    - Typical sources of traffic data include region-specific annual average daily traffic (AADT) data, which provides detailed information on vehicle traffic patterns. Additionally, telematics data can serve as a source for geographic activity data. However, aggregate data on electric vehicle kilometers traveled (VKT), stock, and energy intensity, which are used to calculate energy demand, need an additional data source to be disaggregated by vehicle segment. This data can be derived from the ICCT’s Roadmap model[2].
2. Calculate the distribution of each vehicle segment’s daily energy demand across different charger settings (i.e., specific combinations of charger type and location type).
    - This calculation is based on the typical distribution of each segment’s daily activity, obtained by a lognormal parametrization (see equation below) of each segment’s daily activity
    - Scenarios for the preferred charging priority sequence are used to allocate portions of the daily energy needs to different charger settings.
3. Calculate the required number of chargers and installed charging power.
    - HDV CHARGE distributes the daily energy demand of the vehicles (according to step 1) across different charger settings (according to 2.). This provides the energy demand per charger setting.

[2] https://theicct.github.io/roadmap-doc/

- Based on inputs about charger utilization and charger efficiency for each charger setting, the required number of chargers is calculated from the energy demand.

Fleet Energy Demand Modelling

The fleet modeling process uses information on vehicle traffic and fleet characteristics to estimate the energy use of electric trucks and buses. It starts with traffic data, which tells us how much different types of vehicles are driven and where. We then add fleet details (e.g., from ICCT's Roadmap model), which helps predict how the number of electric vehicles and their energy needs may change over time. By combining this data, the model can show both current and future energy demand across various regions and types of vehicles. The following steps outline how traffic data and complementary fleet data are integrated:

Traffic data forms the foundation of our analysis by providing detailed information on vehicle activity distributed across various locations. This data is typically measured in vehicle kilometers traveled (VKT) and can vary in granularity from road segment-level details to country-wide summaries. Common sources of traffic data include annual average daily traffic (AADT) counts reported by government agencies. The data encompasses various vehicle categories and powertrains, offering insights into the movement patterns of vehicles across different regions. This information is crucial for understanding the current state of vehicle activity, geospatial distribution, and serves as a baseline for calculating present-day energy consumption.

High-level fleet data, as provided by the ICCT's Roadmap model, supplements traffic data by providing high-level fleet characteristics and projections. This includes detailed information on vehicle fleet composition by segments, energy intensity, and scenarios for future electrification growth. The Roadmap model provides customizable electrification scenarios that project the growth of electric vehicle kilometers traveled (EVKT) within the fleet. This data is essential for forecasting future energy demand by modeling how the fleet's composition and energy use are expected to evolve over time.

The process of calculating energy demand involves the integration of both traffic data and high-level fleet data in a structured manner:

- Present-Day Energy Demand Calculation:
    - Traffic data provides the current VKT for various vehicle categories and powertrains, with a high level of spatial granularity that enables us to precisely determine where the VKT occurs. If the traffic data lacks details on the share of electric VKT (such as BEVs and FCEVs) or specific vehicle type ratios, the fleet data from the Roadmap model fills in these gaps. Care must be taken to ensure the completeness of the traffic data, or alternatively, scaling methods should be applied to account for activity not captured by AADT data or similar sources.
    - The energy intensity data from the Roadmap model is then applied to the electric VKTs extracted from the traffic data, allowing for an accurate calculation of the current energy consumption of the fleet.

- Future Energy Demand Calculation:
  - The Roadmap model's electrification scenarios project the future share of electric VKTs within the overall traffic data.
  - These projections are combined with the detailed activity data to estimate future energy consumption, considering the expected growth in electric vehicle adoption and changes in fleet composition.
  - By applying the projected energy intensity to the forecasted VKTs, the model provides a comprehensive analysis of future energy demand, maintaining accuracy in both spatial distribution and representation of energy requirements. It should be noted that the model maintains the spatial distribution of traffic data, reflecting 'where the energy is consumed' rather than 'where the energy is recharged'. Additional post-processing is required to map the consumption to the charging sites.

This hybrid approach ensures the model captures detailed spatial information while also providing robust forecasts of future energy demand by integrating real-world traffic data with high-level fleet information and projections.

Energy Distribution Across Charger Settings

To inform the share of energy that is provided by different charger settings (i.e., specific combinations of charger type and location type), we consider the technical characteristics of chargers as well as the daily activity and charging behavior of each vehicle segment.

The approach assumes that each vehicle segment has a preferred order for using different charger types to meet their daily energy needs. Vehicles start recharging with their preferred charger setting, and additional charging sessions are added if needed to meet the daily energy demand. For example, a regional delivery truck might primarily use an overnight charger at its depot and then use one or more fast-charging sessions at customer’s warehouses or at highway charging stations to meet any additional energy requirements. This sequential pattern of charging sessions ensures that vehicles recharge efficiently based on their specific needs and preferences, and the available charging infrastructure. This flexible ‘charging priority sequence’ is defined for each vehicle segment in the model. For each charging session, the model calculates the energy provided based on charge duration, power level, and charger efficiency, along with the vehicle battery's maximum rechargeable capacity. This allows for accurate modeling of how vehicles meet their energy needs using different charger types. Importantly, the model does not account for differences in charger setting preferences across different fleets within a single vehicle segment unless input data for each fleet is specified separately by the user.

Daily VKT and energy consumption (calculated as the product of VKT and energy intensity) are assumed to follow a lognormal distribution. The probability density function PDF of this distribution is described by following equation, where x stands for the daily VKT or energy, μ for its respective mean, and σ for its respective standard deviation:

$$PDF(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right)$$

Figure 1 illustrates the lognormal distributions of daily VKT and energy consumption for various vehicle segments.

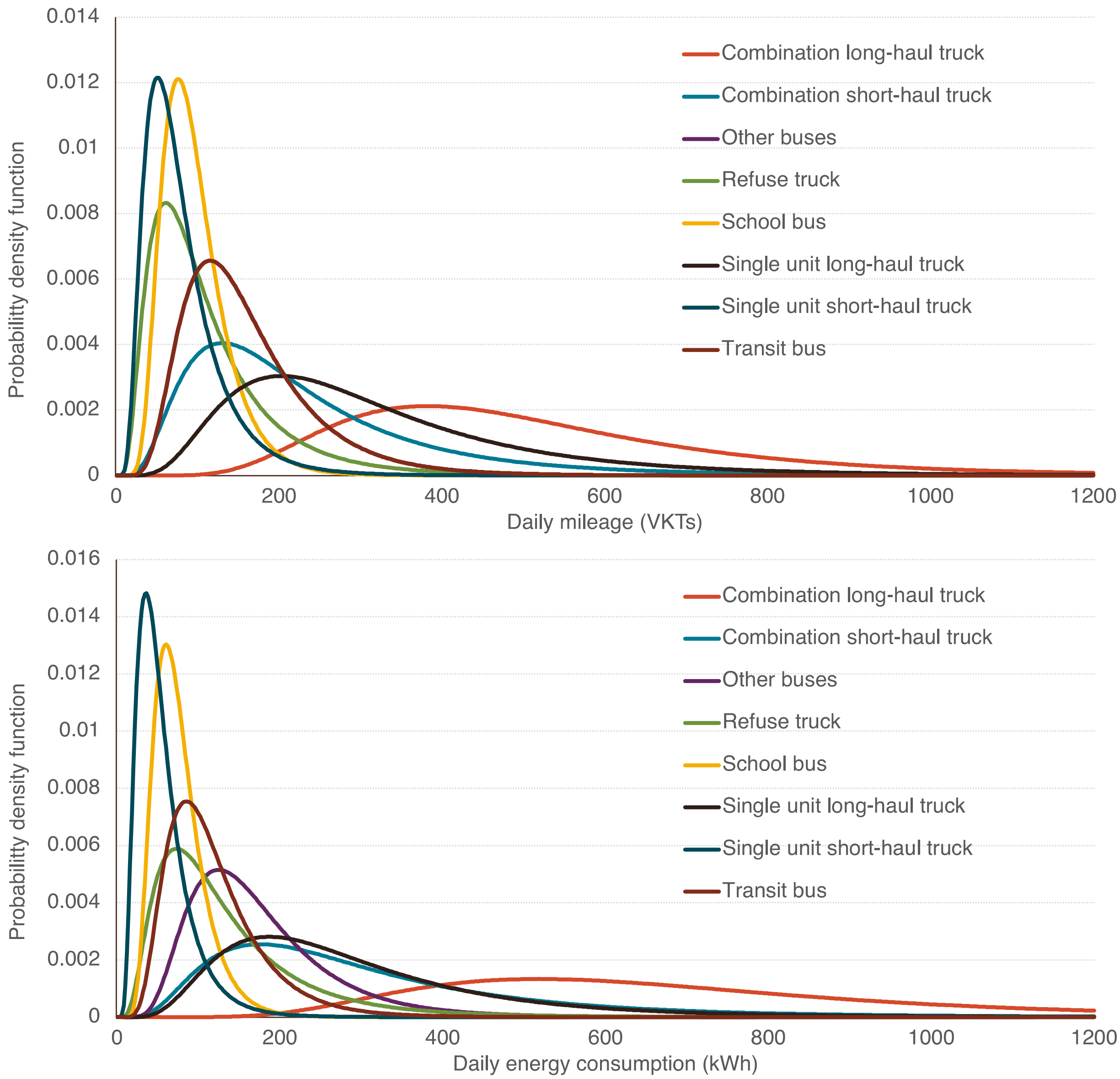

Figure 1: Lognormal daily VKT and energy distribution for several Vehicle Segments (https://theicct.org/publication/infrastructure-deployment-mhdv-may23/, Figure 4)

This distribution is combined with the preferences in charging settings to determine the share of each vehicle segments' daily energy demand that is met by each charger setting. Those shares are then applied to the total activity and energy consumption informed by the fleet and activity inputs to obtain the number of charging sessions per charger type and vehicle category. For example, if 50 percent of a segment's vehicles meet their energy needs with one overnight charging session, and the other 50 percent require an additional fast-charging session (i.e., one overnight and one fast-charging session), then the average vehicle in this segment would need one overnight and half of a fast-charging session. This is because all vehicles require one overnight session, while only half need the additional fast charge. Figure 2 illustrates a charging pattern and energy demand distribution.

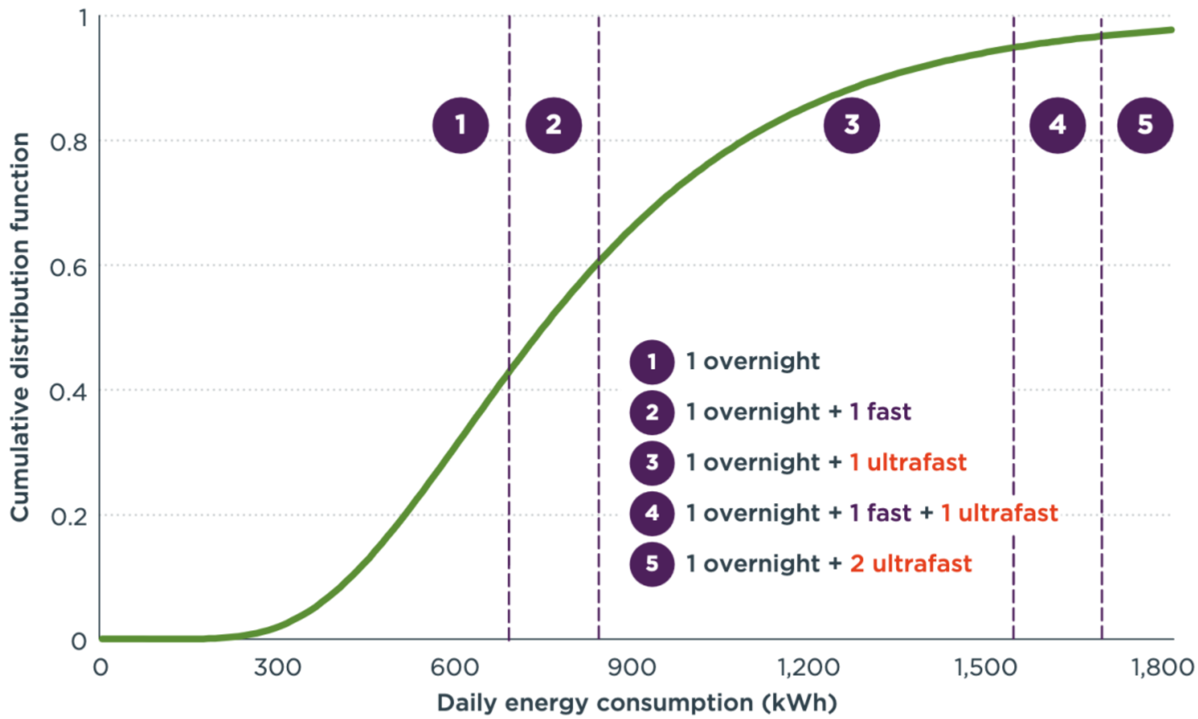

Figure 2: Illustration of charging pattern to meet the energy demand of vehicles (https://theicct.org/publication/infrastructure-deployment-mhdv-may23/, Figure 5)

Based on the average number of sessions and energy per session, the model calculates an average energy distribution across different charger settings for each vehicle category, and across the entire fleet.

Calculate Number of Required Chargers

From this distribution of energy demand across various charger settings and the energy that can be delivered per unique charging session, the model calculates the required number of chargers for each location using an average utilization rate – defined as the number of sessions per charger per day for each location (see equation below). Charger utilization is a key parameter considered by charge point operators (CPOs), transport operators, and other parties involved in deploying charging infrastructure. It determines the ability of the CPO to recoup the upfront cost in setting up a charging station (charger hardware and installation costs, grid connections, software, operating, and maintenance costs) and therefore defines the economic case for operating a given charging station. It should be noted that costs are not directly considered by the HDV CHARGE model and are also not an output of the model.

In HDV CHARGE, charger utilization is a central parameter that defines how many chargers are needed to provide the required number of charging sessions. Charger utilization can be specified by the user to reflect the specificities of each charger setting in the region of analysis. Alternatively, default utilization values are provided within HDV CHARGE.

The number of chargers N for a certain charger setting, for a specific vehicle segment is determined by the daily energy need E_{need} of the vehicle segment, the average energy delivered by a charging session E_{session} , and by the utilization U, which is defined as number of sessions per day per charger for that specific setting:

$$N = \frac{E_{\text{need}}}{E_{\text{session}} \cdot U}$$

Battery Swapping Stations

The model allows the evaluation of the demand for battery-swapping stations (BSS) in regions where battery-swapping is applicable to MHDVs. BSS can be added to the list of charger types and considered in vehicle segment-specific charging priority sequences. If the modelling of BSS is enabled, the user is asked to specify the number of batteries that are swapped per station in a day, the capacity of those batteries, and the minimum state of charge at which vehicles swap batteries.

As for wired chargers, the daily energy demand $E_{\text{need, BSS}}$ at BSS is calculated from daily energy distributions and preferences in charging settings. Based on the average daily number of swaps S that a BSS performs, the battery capacities C_{Battery} of each vehicle category, and the minimum state of charge SOC_{Min} at which vehicle drivers swap their batteries, the required number of BSS N_{BSS} can be determined:

$$N_{\text{BSS}} = \frac{E_{\text{need, BSS}}}{C_{\text{Battery}} \cdot (1 - \text{SOC}_{\text{Min}}) \cdot S}$$

Hydrogen Refueling Stations

Calculation of the required number of hydrogen refueling stations is based on the daily energy demand $E_{\text{need, H}}$ of hydrogen-powered MHDVs – either fuel-cell electric vehicles (FCEV) or hydrogen combustion engine vehicles (H_2-ICE). The model assumes that all the energy of these vehicles is covered by hydrogen refueling stations. The hydrogen vehicle fleet's energy need is converted into hydrogen capacity requirements based on the hydrogen fuel's lower heating value H_{HV} of 120 megajoule per kilogram – assuming supply of compressed gaseous hydrogen at 700 bar. The number of required stations N_H is then calculated based on the maximum daily hydrogen capacity per station Q_H, and the average utilization rate U_H – defined as the share of that maximum capacity that is used:

$$N_H = \frac{E_{\text{need, H}}}{H_{\text{HV}} \cdot Q_H \cdot U_H}$$

INPUTS AND OUTPUTS OF THE MODEL

Inputs

Table 1 lists the necessary inputs to HDV CHARGE. The model includes default assumptions for many of them. The default assumptions are listed in the default modeling assumptions section. Each input can be specified for individual years, vehicle categories, charger categories, and location, where applicable.

Table 1: Inputs fed to the HDV CHARGE model

Input	Description
HDV Fleet	Contains energy intensities (MJ per km) and distributions of different powertrains and vehicle categories, necessary for disaggregating traffic data and calculating ZEV stock share.
Traffic Data	Specifies the total VKT (km) travelled by vehicles at different locations. Necessary to determine detailed geographical information of energy consumption.
Battery Information	Specifies battery capacities (in kWh) and usable state of charge (in %SOC) for different vehicle types, limiting the maximum energy transferable per charging session.
Battery Swapping Station Capacity	Refers to the number of batteries swapped per station per day, essential for calculating necessary BSS based on vehicle charging patterns and daily VKT (km) distribution.
Charger Efficiency	The charger efficiency (in percentage) accounts for the power losses within the charger and represents the proportion of power that reaches the vehicle compared to the power that the charger draws from the power grid.
Charger Information	Details rated maximum power output (kW) and maximum charging session duration (h) of different charger types.
Charger Utilization	Provides utilization rates for different charger settings based on EV stock share, defined as the number of charging sessions per day per charger.

Power Delivery Ratio	Ratio between the maximum power output of a charger and the average power output during a session.
Order of charging settings	Specifies the order of charging settings (charging priority sequence) vehicles use to meet daily energy demand.
Depot Fraction	Indicates the fraction of vehicles charging at depot chargers versus public chargers, based on vehicle type and charger type.
H2 Station Parameters	Details the daily capacity of hydrogen stations (kg/day), hydrogen fuel lower hearing value (kWh/kg), and hydrogen station utilization (percentage).
VKT Distribution Parameters	Provides lognormal mean and standard deviation parameters to compute the daily VKT (km) distribution of different vehicle categories, necessary for modelling daily energy needs (MJ) distribution of vehicles.

Outputs

The HDV CHARGE model provides, as standard outputs, the number and installed nameplate capacity of charging stations (including wired chargers, battery swapping stations and hydrogen refueling stations), activity and energy demand of the fleet, broken down by vehicle category, charger category, year, and geographical location.

The model can round the number of chargers to integers at the finest sub-categorization level (defined by charger setting, vehicle type, and geographical location). In scenarios with many categories and a low overall charger count, this rounding can lead to significant overestimates of charging needs. Alternatively, the model can output unrounded results, requiring the user to interpret decimal values and assign integer charger counts accordingly.

The outputs of HDV CHARGE can be used in further post-processing, such as creating typical load curves and siting of charging demands at specific locations using latitude and longitude data of potential charger sites. Siting can be based on policy targets, current commercial sites, and existing highway stations.

DEFAULT MODELING ASSUMPTIONS

Default assumptions are provided for all the inputs required to run HDV CHARGE. Each of those assumption can be overwritten by user-defined inputs.

Battery Information

The battery capacity is provided in kWh.

ISO	Vehicle	Battery_Capacity	Battery_Usable_SOC
Global	MDT	150	0.8
Global	HDT	400	0.8
Global	Bus	300	0.8

Charger Efficiency

The charger efficiency accounts for the power losses within the charger and represents the proportion of power that reaches the vehicle compared to the power that the charger draws from the power grid.

ISO	Charger_Efficiency
Global	0.8

Charger Information

The power output is provided in kW.

ISO	Charger_Type	Charge_Duration	Rated maximum power output (kW)
Global	Overnight (CCS)	8	60
Global	Fast (CCS)	0.5	300
Global	Ultrafast (MCS)	0.5	850

Charger Utilization

The utilization is provided as number of sessions per day for plug-in chargers. For H2 station the utilization refers to the share of the maximum capacity that a station is utilized.

ISO	Charger_Location	Charger_Type	Utilization
Global	Depot	Fast	3
Global	Depot	Overnight	1
Global	Depot	Ultrafast	3

Global	Public	Fast	6
Global	Public	Overnight	1.5
Global	Public	Ultrafast	6
Global	Public	H2	0.75

Power Delivery Ratio

Ratio between the maximum power output of a charger and the average power output during a session.

ISO	Power Delivery Ratio
Global	0.85

Depot Fraction

Fraction of charging events of a vehicle type and charger type combination that happens at a depot charger.

ISO	Vehicle	Charger_Type	Depot_Fraction
Global	MDT	Overnight	1
Global	MDT	Fast	0.5
Global	MDT	Ultrafast	0.5
Global	HDT	Overnight	0.5
Global	HDT	Fast	0.25
Global	HDT	Ultrafast	0.25
Global	Bus	Overnight	1
Global	Bus	Fast	1
Global	Bus	Ultrafast	1

H2 Station Parameters

The lower heating value is provided in MJ/kg, while the H2 capacity is provided in kg.

ISO	H2_Heating_Value	H2_Capacity
Global	120	1,000

Daily VKT Distribution Parameters

ISO	Vehicle	Mean_Daily_VKT	SD_Daily_VKT

Global	MDT	150	50
Global	HDT	300	150
Global	Bus	150	20

Battery Swapping Station Capacity

This parameter determined how many batteries are swapped per station per day on average. This should not be confused with the maximum number of batteries swapped, or the number of batteries present at a battery swapping station.

ISO	Swaps_Per_Day
CHN	190

Charging Priority Sequence

Until 2027, vehicles are assumed to charge their batteries in the following order: one overnight session first. If this overnight session is not enough to fill the battery, they will use fast-charger sessions until their energy needs are met.

From 2027 onwards, the charging pattern changes with the introduction of ultrafast chargers. The new sequence is:

1. Start with one overnight session.
2. If not sufficient, use one overnight and one fast-charger session.
3. If more charging is needed, try one overnight session followed by one ultrafast session.
4. If that still isn't enough, use one overnight session, one fast session, and one ultrafast session.
5. If the battery is still not full, the vehicle will use one overnight session and two ultrafast sessions.

ISO	CY	Priority	Overnight	Fast	Ultrafast
Global	2020	1	1	0	0
Global	2020	2	1	1	0
Global	2020	3	1	2	0
Global	2027	1	1	0	0
Global	2027	2	1	1	0
Global	2027	3	1	0	1
Global	2027	4	1	1	1
Global	2027	5	1	0	2