Technical project - ReSkaLa

Project Documentation

# Mobility profiles and creation of a "journey generator"

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# 1. Introduction

As part of the research project ReSkaLa@FRA, Hochschule Darmstadt investigates the economic and technical potential of bidirectional charging of electric vehicles (EVs) within distribution grids. A central component of this research is the development of a digital twin of a distribution network integrated with charging infrastructure. This digital twin aims to realistically simulate the interaction between mobility patterns, charging behavior, and grid load.

To model mobility demands and charging requirements, a MATLAB-based simulation program is being developed that stochastically generates driving profiles for different vehicle types (passenger cars, trucks, vans, buses). The simulation is based on relevant technical vehicle parameters (e.g., nominal battery capacity, energy consumption) and statistical data on mobility behavior in Germany (e.g., average trip distance, driving time, speed). Additionally, the program takes external factors such as ambient temperature and charging speed into account to create realistic charging and consumption profiles.

This accompanying documentation explains the program's functionality, details the data sources, parameters, and calculation methods used, and provides an overview of the structure and potential applications of the developed simulation environment.

# 2. Research

Im Rechercheteil werden die im Programm verwendeten Parameter und Ausgangsdaten systematisch aufgeführt. Die zugrunde liegenden Werte stammen aus verschiedenen Quellen, darunter wissenschaftliche Publikationen, empirische Erhebungen, amtliche Statistiken sowie weitere verlässliche Online-Ressourcen. Sämtliche nachfolgend dargestellten Daten stammen aus unserer zentralen Datenbank, deren Inhalte zur Einsicht bereitstehen.

## 2.1. Basic information about electric vehicles

Section 2.1 provides the fundamental parameters of electric vehicles by category (PKW, Van, LKW, Bus). To enable more precise data synthesis, passenger cars are further broken down into sub-categories such as Mini, Kleinwagen, and Mittelklasse.

Table 1 summarizes the key vehicle specifications—nominal power, maximum range, energy consumption, and top speed—based on results from standardized test cycles (notably the WLTP

– Worldwide Harmonized Light Vehicle Test Procedure) and manufacturers' data. The underlying information was obtained primarily from official manufacturer websites and reputable German vehicle trading platforms (EV-Database) [1].

For full transparency, an accompanying Excel spreadsheet is included. It contains every recorded parameter, neatly organized by vehicle type, and serves as the data foundation for all subsequent analyses.

**Table 1: Basic information about electric vehicles**

| **Segment** | **Nominal Capacity** (kWh) [min – max] | **Range** (km) [min – max] | **Consumption** (Wh/km) [min – max] | Top Speed (km/h) [min – max] |
|---|---|---|---|---|
| Minis | 16 – 84 | 85 – 450 | 130 – 178 | 125 – 185 |
| Kleinwagen | 42 – 86 | 135 – 600 | 103 – 190 | 115 – 200 |
| Kompaktklasse | 23 – 97 | 105 – 700 | 115 – 238 | 135 – 260 |
| Mittelklasse | 47,8 – 113 | 260 – 700 | 122 – 238 | 150 – 261 |
| Obere Mittelklasse | 70 – 115,5 | 336 – 700 | 123 – 257 | 180 – 250 |
| Oberklasse | 60 – 118 | 335 – 690 | 96 – 245 | 160 – 322 |
| SUVs | 86 - 118 | 360 - 540 | 194 - 322 | 180 – 262 |
| Van | 33 – 100 | 120 – 370 | 194 – 295 | 120 – 180 |
| LKW under 7,5t | 35,8 – 170 | 116 – 460 | 210 – 420 | --- |
| LKW over 7,5t | 105 – 800 | 200 – 932 | 700 – 1420 | --- |
| Bus (Linienbus) | 150 – 800 | 125 – 700 | 800 – 2000 | --- |

Table 2 presents the total number of vehicles alongside their percentage share by vehicle category. The underlying figures are drawn from the Federal Motor Transport Authority's vehicle registration statistics as of January 2025 [2] and have been systematically processed and analyzed for this report.

**Table 2: Vehicle types by quantity and share (2025)**

| **Segment** | **Quantity** | **Percentage** |
|---|---|---|
| PKW | 1.602.772 | 92,19% |
| Van | 40.103 | 2,31% |
| LKW | 92.412 | 5,32% |
| Bus | 3.332 | 0,19% |

### 2.2. Driving behavior

In order to reflect actual traffic volumes in Germany, vehicle movement patterns were captured and analyzed by vehicle category.

Table 3 presents the speeds applicable in road traffic as specified by the German Road Traffic Regulations (StVO) [3]. On German autobahns there is no universal speed limit for passenger cars; nevertheless, § 3 of the StVO recommends a reference speed of 130 km/h. In contrast, vehicles with a permissible total weight of 3.5 t or more are subject to a mandatory maximum speed of 80 km/h.

For the purposes of this simulation system, only the scenario "autobahn with speed limit" is considered. Table 3 also includes the average operating speeds for each vehicle category.

**Table 3: Limit and Average Speeds by Vehicle Category**

| Segment | Speed limit according to StVO km/h | | | Average speed km/h | | |
|---|---|---|---|---|---|---|
| | urban | rural | highway | urban | rural | highway |
| PKW | 50 | 100 | 130 | 24 | 80 | 118 |
| Vans | 50 | 100 | 130 | 24 | 80 | 118 |
| LKW under 7,5t | 50 | 80 | 80 | 30 | 80 | 80 |
| LKW over 7,5t | 50 | 60 | 60 | 30 | 60 | 60 |
| Bus (Linienbus) | 50 | 60 | 60 | 13 | 30 | 45 |

Although no dedicated statistics on the average speeds of vans or light commercial vehicles (up to 3.5 t) exist, a study by the Federal Environment Agency [4] indicates that their speed profiles closely mirror those of passenger cars. Consequently, the simulation adopts a uniform average speed for both cars and vans of 24 km/h in urban areas [5], 80 km/h on rural roads [4], and 118 km/h on the autobahn [6].

An Internet survey "Internet survey among truck drivers" [7] reports that trucks typically travel at around 30 km/h in urban traffic. On rural roads and autobahns, they adhere to the legal speed limits—80 km/h for vehicles under 7.5 t and 60 km/h for those over 7.5 t—to maintain traffic flow.

Data from a statistical overview of route lengths and average speeds for scheduled buses on Betrugstest.com [8] show average speeds between 14 km/h and 30 km/h over routes of 5 to 25 km. Since city buses seldom use autobahns, the model assumes for buses an average speed of

13 km/h in urban traffic, 30 km/h on rural roads, and 45 km/h on the autobahn—values grounded in the cited data and realistic expectations for long-distance coach services.

Table 4, taken from Table 7 of the study by the Federal Environment Agency [9], shows the percentage distribution of mileage in road traffic across the three driving environments: urban, rural and motorway for different vehicle classes.

**Table 4: Distribution of mileage in road traffic (urban, rural, highway) by vehicle types**

| Segment | urban | rural | highway |
|---|---|---|---|
| PKW | 26% | 41% | 33% |
| Vans | 44% | 27% | 29% |
| LKW | 14% | 25% | 61% |
| Bus (Linienbus) | 57% | 37% | 6% |

Table 4 outlines the distribution of vehicle kilometers traveled across different road types—urban areas, rural roads, and highways—by various vehicle categories. This breakdown provides insights into typical usage patterns of each vehicle type and their operational environment.

- **Passenger Cars (PKW)**: Passenger cars have a balanced distribution, showing significant usage across all road types. Their substantial presence on rural roads (41%) and highways (33%) reflects typical commuting, regional traveling, and long-distance journeys. Urban travel (26%) remains significant, representing routine daily trips within cities.
- **Vans**: Vans exhibit a notable preference for urban roads (44%), driven primarily by their usage in logistics, delivery services, and trades, where frequent stops and short-range operations dominate. Their presence on rural roads (27%) and highways (29%) is also essential for regional deliveries and logistical connections between cities.
- **Trucks (LKW)**: Trucks predominantly utilize highways (61%) due to their role in long-distance freight transportation and logistics, which require efficient, rapid connectivity between distant commercial hubs. Their presence on rural roads (25%) is primarily due to distribution activities, whereas urban roads (14%) are least frequented by trucks due to logistical constraints and regulatory restrictions.
- **Buses (Public Transit Buses)**: Urban buses dominate inner-city roads (57%) reflecting their primary role in public transport, commuting, and short-range mobility. Their

limited usage of highways (6%) demonstrates their primary urban orientation, with a significant portion also covering regional routes on rural roads (37%).

This data will be utilized as input for mobility profiling programs, enabling accurate calculation of traveled distances for each vehicle type and ensuring the profiles closely reflect real-world usage patterns.

According to the study Autoverkehr und Elektromobilität – ein Einstieg in Mobilität in Deutschland [10], passenger cars in Germany are used primarily as private vehicles and as company cars, the latter accounting for 9 % of the total fleet. While private cars can be classified by trip purpose (commuting, errands, leisure, shopping), this model simplifies them into three main categories: Job & Education, Company Car and Private.

Drawing on the trip-purpose shares reported in Mobilität in Deutschland [11], the resulting vehicle-type distribution for the simulation is as follows:

- Job and Education: 30 %
- Company Car: 9 %
- Private: 61 %

According to the Passenger Mobility Statistics published by Eurostat in November 2021 [12], urban trips—defined as journeys of less than 100 kilometers within the same urban area—constitute a significant proportion of daily short-distance travel (up to 300 kilometers). In Germany specifically, urban trips account for approximately two-thirds of all daily passenger car mobility. This statistical insight forms the foundational basis for the distance randomization implemented in the simulation program.

In this program, the distribution of daily trip distances for passenger cars reflects the general mobility patterns identified by Eurostat, with 60% classified as short trips (less than 100 km), 30% as medium trips (ranging from 100 to 300 km), and 10% categorized as long trips (300 km or more). This general distribution serves as a baseline, but it is further refined based on the intended purpose or usage category of the vehicle, as travel behavior can significantly differ depending on the car's role or user requirements.

For instance, vehicles classified as "Company Cars" exhibit different travel behaviors compared to general-purpose private vehicles. To reflect realistic mobility patterns for these vehicles, the trip distance proportions have been adjusted accordingly. Specifically, Company Cars show a higher likelihood of undertaking medium-length journeys, with only 20% of daily trips being short (less than 100 km), 60% falling within the medium range (100 to 300 km), and 20% categorized as long-distance trips (300 km or more).

By adjusting the trip distance distributions according to vehicle purpose, the simulation more accurately mirrors real-world usage patterns, enhancing the reliability and applicability of generated mobility profiles.

Based on the key figures presented in the report "Eckwerte im Zeitvergleich – Unterwegssein, Wege, Zeit und Kilometer: durchweg Stabilität oder leichtes Minus" (Key figures in time comparison – Travel, routes, time and kilometers: consistently stable or slightly negative) from the Mobilität in Deutschland (MiD2023) [13], several critical mobility characteristics are derived to ensure realistic stochastic mobility profiles. According to the MiD2023 data, the average number of trips per person per day in Germany was approximately three trips in 2023. This empirical finding serves as a fundamental basis for the stochastic model, guiding the randomization of daily trips within the range of two to four trips to accurately reflect natural variability in travel behavior.

Furthermore, the MiD2023 report indicates an average daily travel distance per person of 35 kilometers, combined with an average total daily travel time of approximately one hour and 24 minutes. These specific parameters significantly influence the stochastic distribution of both travel distances and trip durations within the simulation model. By incorporating these figures into the stochastic algorithm, the generated mobility profiles authentically mirror real-world travel patterns, effectively capturing typical variations and maintaining adherence to observed mobility behaviors across the population.

### 2.3. Charging station and charging loss

This section explores the common types of charging stations for electric vehicles and the energy losses that occur during charging. Accurately accounting for these losses is crucial for precise estimation of charging times and the actual power delivered to the battery. Since different charging methods—such as plug-in (socket), AC, and DC—vary in efficiency and compatibility with various vehicle types, these factors are integrated into the simulation model to improve its realism and accuracy.

**Table 5: Charging station and charging loss**

| Charging station | Charging loss | SOC | Private / Public | Voltage Level | Share of Public Charging Stations |
|---|---|---|---|---|---|
| Sockets, AC 2,3 kW | 10 – 30% | Up to 100% | Private | Low voltage | |
| AC 3,7 kW | 5 - 10% | Up to 100% | Private / Public | Low voltage | 1,1% |
| AC 7,4 - 11 kW | 5 - 10% | Up to 100% | Private / Public | Low voltage | 17,9% |
| AC 22 kW | 5 - 10% | Up to 100% | Private / Public | Low voltage | 57,8% |
| AC 43 kW | 5 - 10% | Up to 100% | Public | Low voltage | 1% |
| DC 50kW | 6 - 8% | Up to 80% | Public | Low voltage | 4,2% |
| DC 75 kW | 6 - 8% | Up to 80% | Public | Low voltage | 1,6% |
| DC 150 kW | 6 - 8% | Up to 80% | Public | Low voltage | 9,6% |
| DC 300 - 350 kW | 6 - 8% | Up to 80% | Public | Medium voltage (10-30kV) | 8,6% |

Table 5 provides a detailed overview of various electric vehicle (EV) charging infrastructures currently utilized in Germany, focusing on their technical characteristics and practical implications for mobility profiling.

- **Charging station**: The infrastructure is categorized into two main types: Alternating Current (AC) and Direct Current (DC). AC charging stations typically range from 2.3 kW (standard household socket) to 43 kW, primarily intended for home charging or public parking areas. In contrast, DC chargers are designed for rapid charging, offering power levels from 50 kW up to 350 kW, significantly reducing charging times.
- **Charging Loss**: Energy losses during charging differ based on infrastructure type and power level. Standard AC charging exhibits higher losses (ranging up to 10-30% for lower power home sockets and 5-10% for AC chargers [14]) due to inefficiencies in converting AC to DC within the vehicle. In contrast, DC chargers have relatively lower losses (6-8%) [15] as the conversion from AC to DC occurs externally in the charging infrastructure, enhancing efficiency and energy savings.
- **State of Charge (SOC)**: The SOC indicates the recommended maximum battery charge level achievable through each charging type. AC chargers typically allow charging up to 100% due to their slower charge rates, which pose minimal risk to battery longevity.

DC chargers, however, commonly recommend charging only up to 80%, as higher power and rapid charging at higher SOCs can degrade battery lifespan significantly [16].

- **Private/Public**: Charging points vary in their accessibility. AC chargers are versatile, suitable for both private (home) and public locations. In contrast, high-powered DC chargers are predominantly installed in public areas due to their cost, complexity, and infrastructure requirements [17].
- **Voltage Level**: Charging stations typically operate within either low-voltage or medium-voltage networks. AC chargers uniformly operate within low-voltage grids, which simplifies installation but limits available power. DC chargers are also primarily connected to low-voltage grids, with ultra-fast charging stations (300-350 kW) frequently integrated into medium-voltage grids (10-30 kV) due to their higher energy demands. The parameters presented here have been compiled using actual German grid data alongside the mandatory specifications for charging stations in Germany.
- **Share of Public Charging Stations**: based on research by Deutsche Energie Agentur [18]. The distribution of charging infrastructures highlights their availability in public networks. Lower-powered AC stations (7.4-11 kW and 22 kW) are most prevalent due to lower installation and operational costs. Higher-powered DC stations are less common but increasingly critical for fast, long-distance travel.

This comprehensive dataset provides essential insights for developing accurate simulation models for EV mobility and charging profile.

**Table 6: Compatible Chargers by Vehicle Type**

| **Segment** | **Sockets_ 2,3kW** | **3,7 - 22 kW, AC** | **43 kW, AC** | **50 - 150 kW, DC** | **300 – 350 kW, DC** |
|---|---|---|---|---|---|
| PKW | • | • | • | • | |
| Vans | • | • | • | • | |
| LKW under 7,5t | | | (rarely) | • | • |
| LKW over 7,5t | | | (rarely) | • | • |
| Bus | | | | • | (Pantograph) |

Table 6 provides an overview of suitable charging stations for different vehicle categories, specifically distinguishing between passenger cars, vans, trucks (under and over 7.5 tonnes), and buses. This categorization is essential for accurately assigning charging infrastructure to vehicle types within mobility profiling programs. The parameters presented here were compiled using the vehicle model characteristics and specifications together with the specifications of charging stations in Germany.

- **Standard Household Socket**: Primarily suitable for passenger cars and vans due to their relatively smaller battery sizes and the lower power requirement. Heavy vehicles like trucks and buses typically require higher power and quicker charging solutions, making standard sockets impractical for them.
- **AC Chargers (3.7 – 22 kW)**: Widely compatible with passenger cars and vans. Their moderate charging rate matches the battery size and typical usage patterns of these vehicles, balancing convenience and charging speed effectively. Trucks and buses do not commonly use these stations due to their substantially larger battery capacities and operational demands.
- **AC Chargers (43 kW)**: This charging type is rarely used (marked as 'selten') primarily because it represents only about 1% of all charging infrastructure in Germany, limiting its availability. Typically, it caters mainly to passenger cars for faster charging compared to the lower-power AC options, but its limited presence significantly restricts widespread adoption.
- **DC Chargers (50 – 150 kW)**: These chargers are suitable for passenger cars, vans, and trucks below 7.5 tonnes. The higher power enables rapid charging, essential for vehicles requiring quicker turnaround times, especially commercial vehicles like vans and small trucks frequently used for logistics and delivery operations.
- **DC Chargers (300 – 350 kW)**: Primarily used by larger vehicles like trucks over 7.5 tonnes, due to their large battery capacities and the critical requirement for fast charging to minimize downtime. Such high-power stations are not typically used by smaller vehicles due to the unnecessary energy delivery, infrastructure complexity, and potential battery degradation from high charging speeds.
- **Pantograph Charging (Bus-specific)**: This system is exclusively employed by buses and involves overhead connections, making it fundamentally different from fixed-location stations. As pantographs move along specific bus routes and are not stationary charging points, they are excluded from fixed-location infrastructure considered in mobility profiling software and coding [19].

This comprehensive classification assists in selecting appropriate charging infrastructure when generating mobility profiles, ensuring accurate representation of real-world scenarios.

### 2.4. Influence of temperature

Table 7 illustrates how ambient temperature affects an electric vehicle's actual usable range and battery capacity. Since over 40 % of today's EVs use LFP (Lithium Iron Phosphate) batteries and more than 50 % use NMC (Lithium-Nickel-Manganese-Cobalt Oxide) batteries [20], our capacity-impact calculations draw on the thermal characteristics of these two chemistries [21]. The link between temperature and real-world driving range is based on statistical analyses from the Emobilio [22] and Geotab [23] platforms, ensuring that the simulation program produces realistic use-case scenarios.

**Table 7: Influence of temperature on capacity and range**

| Temperature | Capacity | Range |
|---|---|---|
| -20° to -10° | 45 – 55% | 40 – 50% |
| -10° to 0° | 55 – 70% | 50 – 75 % |
| 0° to 15° | 70 – 90 % | 75 – 90% |
| 15° to 35° | 95 – 100% | 95 – 100% |
| 35° to 40° | 90 – 95% | 75 – 95 % |

Between –20 °C and –10 °C, battery capacity drops to 45–55 % and the driving range decreases to about 50 %. Both capacity and range increase up to 15 °C. The ideal temperature range is between 15 °C and 35 °C. Why do we consider 35 °C instead of 25 °C as in theory? Because modern vehicles are equipped with thermal management systems for the battery. Within this range, the battery operates stably and achieves its maximum range. Above 35 °C, capacity decreases by about 10 % and range reduces by approximately 25 %, as the air conditioning system requires more power.

## 3. Calculation

In this section, the calculation formulas used in the program will be listed.

**Formula 1:** Calculation of vehicle energy consumption (Wh/km):

$$C_{vehicle}\ (\frac{Wk}{km}) = \frac{Cap_{full}\ (kWh)}{Range_{full}\ (km)} * 1000$$

**Formula 2:** Calculation of battery operating capacity affected by temperature (kWh):

POCT = Percentage of operating capacity at given temperature

$$Cap_{operating}(kWh) = Cap_{full}\ (kWh) * \frac{POCT\ (\%)}{100}$$

**Formula 3:** Calculation of vehicle driving range affected by temperature (km):

PORT = Percentage of operating range at given temperature

$$Range_{driving}\ (km) = Range_{full}\ (km) * \frac{PORT\ (\%)}{100}$$

**Formula 4:** Calculation of average speed over the whole distance (km/h):

$Dist_{total}$ = total distance traveled by vehicle during trips (km)

$$average\ speed\ \left(\frac{km}{h}\right) = \frac{Dist_{total}\ (km)}{total\ run\ time\ (h)}$$

**Formula 5:** Calculation of total capacity consumed during the trips (kWh):

$$Cap\ _{total,consumd}(kWh) = Dist_{total}(km) * C_{vehicle}\ (\frac{Wh}{km})$$

If the distance traveled by the vehicle is less than the vehicle's driving range under temperature effects, the vehicle will not recharge during the trip. The following formulas apply when the vehicle does not recharge during the trip:

**Formula 6:** Calculation of capacity loss due to temperature (kWh):

PCLT = Percentage of capacity loss at given temperature

$$Cap_{loss}\ (\text{kWh}) = Cap_{full}\ (kWh) * \frac{PCLT\ (\%)}{100}$$

**Formula 7:** Calculation of battery percentage remaining after trip ends (%):

$$battery\ percentage\ (\%) = \frac{Cap_{full} - Cap\ _{total,consumd} - Cap_{loss}}{Cap_{full}}$$

**Formula 8:** Calculation of remaining capacity in battery (kWh):

$$Cap_{remaiming}\ (kWh) = Cap_{full}\ (kWh) * battery\ percentage\ (\%)$$

**Formula 9:** Calculation of the battery's chargeable capacity based on the type of charging station (kWh)

The State of Charge (SoC):

- With AC charging stations, the vehicle can charge up to 100% of the battery capacity
- With DC charging stations, charging is limited to 80% of the battery capacity

$$Cap_{chargeable}\ (kWh) = Cap_{full}\ (kWh) * \frac{SoC}{100}$$

**Formula 10:** Calculation of the required charging capacity (kWh):

$$Cap_{reuired}\ (kWh) = \ Cap_{chargeable} - Cap_{remaiming}$$

**Formula 11:** Calculation of charging time (h):

The actual charging time is longer than the theoretical time due to energy losses during charging. These charging losses vary by charging method:

- Socket charging experiences losses of 10–30%
- AC charging stations have losses between 5–10%
- DC charging stations incur losses of 6–8%

$$t_{charge}\ (h) = \frac{Cap_{reuired}\ (kWh) * \left(1 - \frac{charging\ loss\ (\%)}{100}\right)}{chargingstation\ (kW)}$$

If the vehicle's traveled distance exceeds its driving range affected by temperature, it must be charged during the trip. The following formulas apply when mid-trip charging is required to complete the journey:

**Formula 12:** Calculation of distance exceeding driving range affected by temperature (km):

$$Dist_{excess}\ (km) = Dist_{total}\ (km)\ -\ Range_{driving}\ (km)$$

**Formula 13:** Calculation of minimum capacity required for additional charging (kWh):

$$\mathrm{Cap}_{\mathrm{required,additional}}\ (\mathrm{kWh}) = Dist_{excess}\ (km) * \frac{C_{vehicle}(Wh)}{1000}$$

**Formula 14:** Calculation of charging time on the road (h):

$$t_{charge,\ road}\ (h) = \frac{\mathrm{Cap}_{\mathrm{required,additional}}\ (kWh) * \left(1 - \frac{charging\ loss\ (\%)}{100}\right)}{chargingstation\ (kW)}$$

**Formula 15:** Calculation of the battery capacity to be charged after completing the trip based on the type of charging station (kWh):

$$Cap_{charge,end}(kWh) = Cap\ _{total,consumd} - \mathrm{Cap}_{\mathrm{required,additional}} - \ \mathrm{Cap}_{\mathrm{full}}\ * \left(1 - \frac{SoC}{100}\right)$$

**Formular 16:** Calculation of total charging time (h):

$$t_{charge}\ (h) = \ t_{charge,road}(h) + \frac{Cap_{charge,end}\ (kWh) * \left(1 - \frac{charging\ loss\ (\%)}{100}\right)}{chargingstation\ (kW)}$$

# 4. Programming

## 4.1. Requirement Specification (Lastenheft)

### 4.1.1. Definition of Mobility Profiles and Characteristics

The objective of this project is to create realistic mobility profiles for different vehicle types, including passenger cars (PKW), vans, trucks (LKW), and buses. The profiles are based on comprehensive data sources including EV segment data (from provided CSV files), charging infrastructure information, compatibility data for vehicle charging, and temperature influence on battery performance.

**Primary Data Sources:**

- EV segment data (ev_segments.csv)
- Charging infrastructure and compatibility (chargingStation.csv, chargingCompatible.csv)
- Temperature impacts (Temperatur.CSV)

**Key Mobility Profile Characteristics:**

- **Trip frequency and daily distribution:** Number of trips per vehicle per day.
- **Time-of-day distribution:** Departure and arrival times, travel durations, and stops.
- **Distance and speed profiles:** Urban, rural, and highway driving segments with realistic variations.

- **Vehicle usage types:** Commuters, private/leisure drivers, delivery services, service vehicles, education-related travel, and buses.
- **Vehicle-specific parameters:** Nominal battery capacity, energy consumption (Wh/km), driving range (km), state of charge (SoC), and charging requirements.
- **Charging details:** Charging locations (public/private), types (AC/DC), charging losses, and estimated time to full charge.

#### 4.1.2. Stochastic and Realistic Trip Generation

The mobility profiles generated by this project employ stochastic algorithms to ensure realistic variability. Trip characteristics, such as departure times, trip durations, stop durations, and travel distances, are modeled using suitable probability distributions. Specifically:

- Departure and arrival times, trip durations, and distances are generated randomly within predefined ranges, reflecting real-world distributions.
- Uniform distributions are employed to represent realistic variations, such as battery capacity, temperature effects, and travel speed.

### 4.2. Technical Specification (Pflichtenheft)

#### 4.2.1. Data Model

The data model is structured to reflect stochastic variations in vehicle mobility behavior, ensuring profiles realistically simulate daily vehicle usage patterns.

**Stochastic Model Components:**

- **Randomized trip parameters:** Gaussian and uniform distributions to vary departure times, trip lengths, stops, and battery performance.
- **Vehicle clustering:** Clearly defined categories including passenger cars (PKW with sub-categories: private, service, job & education), vans, trucks (LKW: over 7.5t, under 7.5t), and buses.
- **Temperature dependency:** Battery capacity and range variations are based on temperature data, influencing the realistic operational range and energy consumption.

### 4.2.2. Tools and Programming Languages

The project utilizes MATLAB as the core programming environment due to its robust statistical analysis capabilities and ease of data manipulation.

- **Programming language:** MATLAB
- **Simulation method:** Stochastic and time-based profile generation
- **Data formats:** CSV file input and output, containing vehicle segment data, temperature impact data, charging infrastructure compatibility, and generated mobility profiles.

### 4.2.3. Structure of the Trip Generator

The MATLAB-based trip generator is designed to systematically produce detailed mobility profiles with a clear structure:

- **Input Parameters:**
  - Vehicle type and quantity (PKW, LKW, VAN, BUS)
  - Desired distribution of vehicle use purposes (private, service, etc.)
  - EV segment characteristics (battery capacities, range, speed)
  - Charging compatibility data
  - Temperature data affecting battery performance
- **Information Processing Workflow:**
  - **Allocation of vehicle profiles:** Based on fleet share statistics
  - **Trip generation:**
    - Departure and arrival times randomly assigned within realistic daily windows
    - Trip durations and stops generated from defined stochastic distributions
    - Distance calculations segmented into urban, rural, and highway driving, proportioned realistically
  - **Battery and charging calculations:**
    - Consumption and range calculation adjusted for temperature conditions
    - Determination of charging needs based on total daily distance traveled
    - Charging type assignment (AC/DC) and associated location (public/private)
- **Output Data:**
  - Comprehensive mobility profiles with detailed parameters including:
    - Purpose, vehicle type, day type (workday/weekend)
    - Trip schedules (start/end times, durations, stops)

- Distances and average speeds
- Energy consumption and battery performance metrics
- Charging details including locations, types, state of charge, charging losses, and estimated charge times

This detailed but concise specification ensures the stochastic generation of realistic vehicle mobility profiles suitable for integration into larger digital twin simulations or traffic modeling projects.

### 4.3. Functionalities and User Benefits

This program generates realistic stochastic mobility and charging profiles for various types of electric vehicles (EVs), including passenger cars (PKW), trucks (LKW), vans, and buses. By leveraging comprehensive statistical datasets and detailed mobility studies, the program ensures that the generated profiles closely reflect actual vehicle usage and charging patterns. Key sources include authoritative publications such as ADAC Mobility Reports, Mobilität in Deutschland (MiD), detailed mobility surveys by Fraunhofer Institute, and statistical reports published by the European Union (Eurostat). These resources provide the necessary empirical foundation to achieve a realistic and representative stochastic modeling approach.

The primary functionality of the program lies in the generation of highly detailed individual vehicle mobility profiles. It accommodates user-specific requirements by allowing users to select the type of vehicles they wish to model—be it passenger cars, commercial vehicles (such as vans and trucks), or public transport buses—and specify the number of profiles to generate. Each generated profile includes comprehensive information such as daily distances, trip frequency, start and end times for trips, durations of travel and stop times, detailed energy consumption calculations, battery state of charge (SoC), and necessary charging sessions. Moreover, it includes temperature-dependent battery performance data, accurately reflecting realistic battery efficiency changes under varying environmental conditions.

The program's core algorithms rely on stochastic methods that utilize probability distributions, to realistically simulate variability inherent in daily travel behavior. The user receives outputs formatted as structured data files (typically CSV files), clearly presenting mobility information per vehicle and per day (e.g., distinguishing workdays and weekends). These profiles are particularly valuable for conducting detailed simulation studies, infrastructure planning, and evaluating the adequacy and placement of EV charging stations.

The detailed outputs enable users to directly integrate mobility data into digital twins—virtual representations of urban or infrastructure systems—facilitating informed decision-making for city planners, infrastructure providers, and fleet operators. Additionally, by providing realistic mobility patterns and charging behaviors, the profiles can support sophisticated forecasting models, infrastructure investment decisions, energy consumption predictions, and operational optimization in fleet management systems.

Furthermore, the program distinguishes between vehicle types in its logic, as each vehicle category exhibits different travel behaviors, usage patterns, and operational constraints. Passenger vehicles, for instance, follow a diverse range of patterns with varying trip purposes such as commuting, leisure, or services. Commercial vehicles (trucks and vans) have clearly defined usage parameters, influenced by logistics operations, scheduled deliveries, and fixed service routes, leading to structured constraints on their mobility profiles. Buses, as public transport vehicles, exhibit highly predictable routes and schedules with fixed operational parameters such as the number of trips per day, consistent routes, and defined stop durations.

By incorporating these vehicle-specific distinctions, the program precisely aligns generated profiles with actual statistical mobility data, enabling users to perform accurate and reliable analyses and assessments for various real-world applications.

### 4.4. Calculations and Logic

To turn high-level mobility statistics into detailed, per-vehicle driving and charging profiles, the program executes a multi-stage computational pipeline. Each profile—whether for a passenger car, van, truck, or bus—passes through the following steps:

#### 4.4.1. Daily Trip Count

Empirical data from MiD2023 show an average of 3 trips per person per day. To introduce realistic variability, the program draws an integer from a uniform distribution on {2, 3, 4} trips. This preserves a mean close to three while allowing occasional shorter or longer daily routines.

#### 4.4.2. Trip Timing and Sequence

- First-trip window: On workdays the first departure is randomly chosen between 04:00 and 15:00; on weekends between 06:00 and 12:00.
- Trip durations and stops: The first trip’s duration and subsequent inter-trip stops are sampled uniformly from empirically motivated ranges (e.g. 6–150 min for the first trip

duration, 6–90 min for the first stop on a workday). Later trips follow similar but slightly adjusted ranges.

- Chaining and constraints: Trip start and end times are chained so that each trip begins after the previous one plus its stop. The algorithm enforces:
  1. The final trip must end before midnight.
  2. Total stop time across all trips lies between 1 h and 3 h.
  3. The span from first departure to last arrival is between 4 h and 10 h. If any constraint fails, all timing parameters are redrawn until a valid daily schedule is attained.

### 4.4.3. Distance-Bin Assignment

To mirror observed distance distributions, each profile is assigned a “distance bin” with purpose-dependent probabilities:

- Private cars: 60 % short (< 100 km), 30 % medium (100–300 km), 10 % long (≥ 300 km)
- Company vehicles: 20 % short, 60 % medium, 20 % long
- Service vehicles: 20 % short, 60 % medium, 20 % long the chosen bin dictates acceptance criteria for the total daily distance computed in the next step.

### 4.4.4. Road-Type Splitting and Total Distance

The program splits the day’s total driving time among three roads categories—urban, rural, and highway—by sampling fractions around known averages (e.g. highway 61 % ± 5 %, rural 27 % ± 5 %, urban = remainder). It then multiplies each fraction by the corresponding average speed (from the vehicle segment table) and the total driving time to obtain distances on each segment. Summing these yields the total daily distance, which must fall within the earlier-selected bin; otherwise the split and total are redrawn.

### 4.4.5. Battery Capacity, Range & Temperature Derating

- Nominal capacity & range: For the vehicle’s segment (e.g. “Kompaktklasse” for cars, “Van” or “LKW” for vans/trucks), a full battery capacity and maximal range are sampled uniformly between the segment’s minimum and maximum values.
- Ambient temperature: A random temperature is drawn from the full range in the “Temperatur.CSV” lookup. The program locates the matching row of capacity and range reduction percentages for that temperature.

- Derated capacity & range: The full values are multiplied by the sampled reduction percentages to yield the active battery capacity and usable driving range for that day.

#### 4.4.6. Energy Consumption

Per-kilometer consumption (Wh/km) is computed as "consumption = (full_capacity_kWh × 1000) / full_range_km" Total energy required is then "consumption × total_distance_km", converted to kWh.

#### 4.4.7. Charging Logic & State-of-Charge (SoC)

- Charger selection: The vehicle's compatibility table determines whether it can use AC and/or DC chargers. A compatible charger type (e.g. "AC_11kW", "DC_150kW") is chosen at random.
- SoC targets: Fast DC chargers target an 80 % state of charge; AC chargers and depot charging target 100 %.
- Depot vs. on-road charging:
  - If total_distance < usable_range − 20 km, no on-road charging is needed. The remaining SoC after driving is computed; if it falls below the target, the time to recharge to that target is calculated by dividing the required kWh by the charger power, adjusted for a random charging loss (6–8 % for DC, 5–10 % for AC).
  - If total_distance ≥ usable_range − 20 km, the profile requires on-road charging. The "over-distance" beyond the safe range is converted to extra energy needed, and the time to charge that energy on the road is computed. Any further depot charging to reach the target SoC is then added, again accounting for charging losses.

#### 4.4.8. Charging Losses

To reflect real-world inefficiencies, each charging session applies a randomly drawn loss penalty: 6–8 % for DC sessions, 5–10 % for AC. This overhead extends the required charging time.

### 4.5. Vehicle Type Specific Differences and Reasoning

To ensure the realism and practical relevance of the generated mobility profiles, the program employs vehicle-type-specific logic and tailored parameter sets for each major vehicle group: passenger cars (PKW), trucks (LKW), vans, and buses. This differentiation reflects not only statistical realities but also the operational roles, constraints, and charging behaviors unique to each vehicle class. Below, the core differences and the reasoning behind these choices are summarized:

### 4.5.1. Passenger Cars (PKW)

**Purpose Differentiation:** Passenger car profiles are split among three core purposes: "Private", "Job & Education", and "Service." This allows the program to represent the breadth of personal mobility, commuting, and job-related travel seen in real-world statistics.

**Temporal Patterns:**

- Private cars benefit from the most flexible trip timing, reflecting the reality of personal trips for shopping, recreation, or visiting friends, which may occur at any time of day and vary widely in length and duration.
- Job & Education cars adhere to more regular morning departures and afternoon/evening returns, simulating typical workday commutes and school runs, with shorter stopovers during the day.
- Service vehicles (e.g., company pool cars, taxis, tradesperson vehicles) are programmed for regular, repeated use with higher daily activity and more constrained daily windows, simulating commercial needs.

**Trip and Distance Structure:** Each car purpose employs a different probability distribution for trip distances and frequency. For example, "Service" vehicles are more likely to have medium to long daily distances due to work-related errands or site visits.

**Charging Patterns:**

- Private cars primarily charge at home (private AC), but public AC charging is also included to reflect scenarios such as long trips or lack of home infrastructure.
- Job/Service cars are more likely to require public AC or even DC charging, due to higher daily utilization or when operating in fleet/service contexts.

### 4.5.2. Trucks (LKW)

**Category Split:** Truck profiles are automatically distributed between heavy-duty (>7.5t, 60%) and light-duty (<7.5t, 40%) trucks, matching real fleet distributions.

**Operation Logic:**

- Trip Patterns: LKWs are simulated with fewer trips per day, but each trip tends to be long, with minimal stops. This mimics real-life logistics and distribution operations, where trucks often travel long distances between warehouses, depots, or distribution centers.
- Time Windows: The program ensures truck schedules respect legal and operational constraints (e.g., rest periods and maximum driving windows) by enforcing minimum and maximum total operation times and realistic stop durations.

**Distance and Speed:** The majority of travel for LKWs is allocated to highway and rural segments, reflecting the predominance of intercity and regional freight movement.

**Charging:** Due to their long-distance roles and large battery capacities, trucks almost always require access to public DC fast chargers, and the program models this with high-priority assignment of such infrastructure. The charging time calculations also account for the higher energy needs and longer session durations typical of LKWs.

#### 4.5.3. Vans

**Operational Focus:** Vans in the program are designed to reflect their real-world role as urban and suburban workhorses for service, delivery, and logistics sectors. This includes frequent stops, higher numbers of short trips, and varied trip timing.

**Distance Profile:** Vans typically cover significant daily mileage, though split into a large number of relatively short trips (e.g., parcel delivery rounds or technician visits). The program enforces a spread of daily distances, ensuring some days with intensive use and others with less.

**Charging Strategy:** Vans can utilize both public and private charging infrastructure, with an increased likelihood of partial charging (e.g., topping up at the depot during breaks or using public chargers between deliveries). This approach reflects fleet operators' flexibility in charging and real-world strategies to maintain operational readiness.

#### 4.5.4. Buses

**Fixed-Route, High Frequency:** Bus profiles are built to simulate multiple fixed-route journeys per day, reflecting real-world scheduled public transport operation. Unlike other vehicles, buses have the strictest scheduling: they start early, run throughout the day, and make many short, predictable trips.

**Distance and Timing:** Total daily distance for buses is achieved through a high number of repeated, short-length trips, typically within a fixed time window. The number of trips, their start/end times, and intervals are all generated to mirror the fixed, repetitive schedules of urban transit.

**Charging Patterns:** Buses in the simulation overwhelmingly rely on depot-based overnight charging, which matches the dominant real-world strategy for e-buses. However, the logic also allows for on-route charging (e.g., via high-power DC chargers at bus terminals) on days with unusually high usage or insufficient depot charge.

### 4.6. Accuracy and Realism

A central strength of this mobility generation program lies in its foundation upon robust empirical data and proven statistical methodologies. All key simulation parameters—including the number of trips per day, distance categories, trip timing, energy use, and charging behaviors—are directly informed by recent large-scale studies and official statistical releases. By integrating findings from Eurostat's passenger mobility statistics, ADAC Mobility Reports, the "Mobilität in Deutschland" (MiD) study, and research from the Fraunhofer Institute, the program ensures that generated profiles fall within realistic boundaries for German and European mobility.

The program's randomization mechanisms are designed not for arbitrary variability, but for the accurate reproduction of observed real-world variability. For example, when distributing daily trip numbers or distance bands, the program uses proportions and limits derived from national travel surveys. This results in a synthetic dataset where the frequency of short, medium, and long trips, as well as the typical spread of vehicle usage, closely matches those found in population-scale studies. Charging events, battery range limitations, and temperature dependencies are all simulated according to real-life technical constraints and user behaviors, which further increases the credibility of the model outputs.

Additionally, the logic for each vehicle type incorporates operational details specific to that segment—such as the repetitive, high-frequency operation of buses or the long-haul nature of truck transport—mirroring both statistical findings and operational insights from industry partners. The outcome is that each mobility profile is not just a plausible scenario, but statistically representative of actual usage within its category.

By continually referencing up-to-date mobility research and updating its logic accordingly, the program maintains a high level of alignment with contemporary trends and evolving patterns in electric mobility. This makes it a valuable and realistic basis for scenario analysis, infrastructure planning, and future-proof simulation work.

### 4.7. Conclusion

In summary, the developed mobility profile generation program offers a sophisticated yet user-friendly solution for simulating electric vehicle usage across diverse real-world contexts. By harnessing a combination of authoritative data sources and flexible, type-specific simulation logic, the program produces mobility and charging profiles that are both detailed and relevant for today’s rapidly changing mobility landscape.

Users benefit from the ability to tailor outputs to a wide range of scenarios, whether evaluating the impact of different vehicle types on charging infrastructure, exploring daily patterns of EV use for policy assessment, or integrating realistic behavior profiles into digital twins and urban simulation platforms. The modular program structure allows for seamless expansion or adjustment as new data becomes available or as new research questions arise.

Ultimately, this program equips planners, engineers, and researchers with a high-quality tool for evidence-based decision-making. Its outputs support a better understanding of EV integration challenges and opportunities, contribute to the efficient deployment of charging infrastructure, and enable the detailed modeling necessary for sustainable urban and transport planning in the era of electrification.

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