Chapter 2

Stochastic Modelling of PHEVs

2.1 Introduction

A stochastic model of PHEVs is needed to analyze its positive and negative impacts on the distribution system. The stochastic model provides the data relevant to charging and discharging of PHEVs and the amount of energy exchange between the distribution system and PHEVs.

The stochastic modelling of PHEVs can be classified in two categories. The first category deals with vehicle design perspective such as, battery capacity, All Electric Range (AER), State of Charge (SOC), Total Energy Required (TER) for charging and V2G connection analysis. Whereas, the second category deals with dynamic nature of driving pattern such as, *daily distance travelled*, *start-trip-time* and *last-trip-arrival-time*. These two categories are correlated to each other, and tries to model realistic nature of EV loads on distribution system.

In this chapter, firstly, the PHEV characteristics based on design perspective is discussed, and then the stochastic simulation of PHEV load considering the uncertainties related to driving pattern is developed. The data obtained in this chapter is used in later chapters for generation of stochastic PHEV load profile on distribution system, aiming several perspective of distribution system planning and operation.

2.2 PHEV Characterisitics

PHEVs connected to the distribution network will be charging/discharging on the network, so its characteristics are presented to analyze its effect on the network. In this section, various characteristics of the vehicles are discussed.

2.2.1 PHEV battery

The battery considered for charging/discharging in the vehicle is of Lithium-ion type [149]. Its capacity is mainly defined in terms of miles it can drive the vehicle in electric mode. The range of battery used in the vehicle is from 7.8 kWh to 27.6 kWh. Table 2.1 shows battery capacity for the different types of vehicle with different AER. Table 2.1 depicts that a compact sedan having a 7.8 kWh capacity, when fully charged, can drive up to 30 miles AER (PHEV30).

Table 2.1: Size of battery for PHEVs (kWh)

Type	Vehicle	PHEV30	PHEV40	PHEV60
1	Compact sedan	7.8	10.4	15.6
2	Mid-size sedan	9	12	18
3	Mid-size SUV	11.4	15.2	22.8
4	Full size SUV	13.8	18.4	27.6

2.2.2 State of Charge (SOC)

State of charge (SOC) is the battery's level of charge, similar to a fuel gauge in internal combustion cars, usually expressed as a percentage of full capacity. It is not an absolute measure in Coulombs, kWh or Ah of the energy left in the battery. The preferred basis for SOC measurement is the rated capacity of a new cell rather than the current capacity of the cell. The SOC is not directly measurable during vehicle operation because the battery SOC is directly related to battery parameter that is the open circuit voltage (OCV) [150], which is the steady terminal voltage of a battery in open circuit. The relationship between OCV and SOC can be acquired through experiments. Accurate knowledge of SOC is required for calculating the energy required from the grid to charge battery and amount of energy that can be injected into the grid. A higher value of SOC is charged in shorter time. There are many methods for determining the SOC but *columb counting* method is most commonly used [151].

Mathematically SOC for PHEVs can be expressed as follows.

$$SOC = \begin{cases} (1 - \frac{\gamma d}{AER}) \times 100 & \gamma d \leq AER \\ 0 & \gamma d \geq AER, \end{cases} \tag{2.1}$$

where AER is the All-Electric Range of the PHEV, d is the total distance travelled by the PHEV in a day and γ is the percentage of a distance travelled by PHEV in electric mode.

2.2.3 Total Energy Required (TER)

The amount of energy drawn from the grid to charge battery of the vehicle depends upon SOC, battery capacity, and the charging efficiency. Assuming the charger efficiency as 88% [9], the energy drawn from the grid is given by,

$$E_g = \left(\frac{1 - \frac{SOC}{100}}{0.88} \right) \times C, \tag{2.2}$$

where C is the battery capacity.

2.2.4 Energy schedule for battery charging

Charging duration directly depends on the energy required to charge, and level of charging used, i.e using fast charging method decreases the time duration to charge the battery. Charging level of 240 $VAC/30A$ ORNL (Oak Ridge National Laboratory) standard is used in this study. This charging level charge at a peak rate of 6 kW/hr [152]. Based on this charging level time scaled charging schedule for all four types of PHEV60 (battery capacity shown in Table 2.1) are presented in Table 2.2.

Table 2.2: Power requirement (kW) schedule for PHEV60

Type	1^{st}hour	2^{nd}hour	3^{rd}hour	4^{th}hour	5^{th}hour	Total kWh
Compact sedan	6.0	6.0	3.6	0	0	15.6
Mid-size sedan	6.0	6.0	6.0	0	0	18
Mid-size SUV	6.0	6.0	6.0	4.8	0	22.8
Full-size SUV	6.0	6.0	6.0	6.0	3.6	27.6

2.2.5 Vehicle-to-Grid (V2G)

V2G is a concept in which the remaining amount of energy stored in the battery can be injected into the grid after the *last-trip-arrival-time*. A properly designed electric drive vehicle, which supports the bidirectional flow of power, (i.e. G2V and V2G) can facilitate the withdrawal of up to 10 kW amount of power from vehicle to grid, which can be utilized to meet the average load demand of the 10 houses in a day [153]. The charging station must have on-board power electronics and proper communicating system to facilitate the bidirectional flow of power. Now a days, telematics communication system is used for control and management of power flow between vehicle and grid. In addition to this, precise metering system is also used to measure the power which is provided by vehicle. V2G technology can provide backup for emergencies as well as spinning reserve which improves reliability of distribution system.

2.3 Stochastic Model of PHEVs Load

Stochastic model of PHEVs load can be generated in two possible ways, one is based on Demand Response (DR) with variation in penetration levels and, another is based on scheduling problem perspective. First approach is based on demand response which responds to charging and discharging energy tariff in real-time distribution system. Whereas, in second approach, PHEVs load profile is generated with perspective that PHEVs can be charged and discharged many times in between of *last-trip-arrival-time* and *start-trip-time* to maintain distribution system performance.

2.3.1 Charging/discharging profiles based on penetration and demand response

The data of the driving patterns of vehicles including *daily-distance-travelled*, and *last-trip-arrival-time* are taken from the National Household Travel Survey (NHTS) 2009 transportation report of U.S. [154]. The NHTS 2009 database consists of 1048575 single trips and each trip has 150 attributes. The sum of all the trips during a day is the *daily-distance-travelled.* The charging and discharging patterns for the PHEVs considering

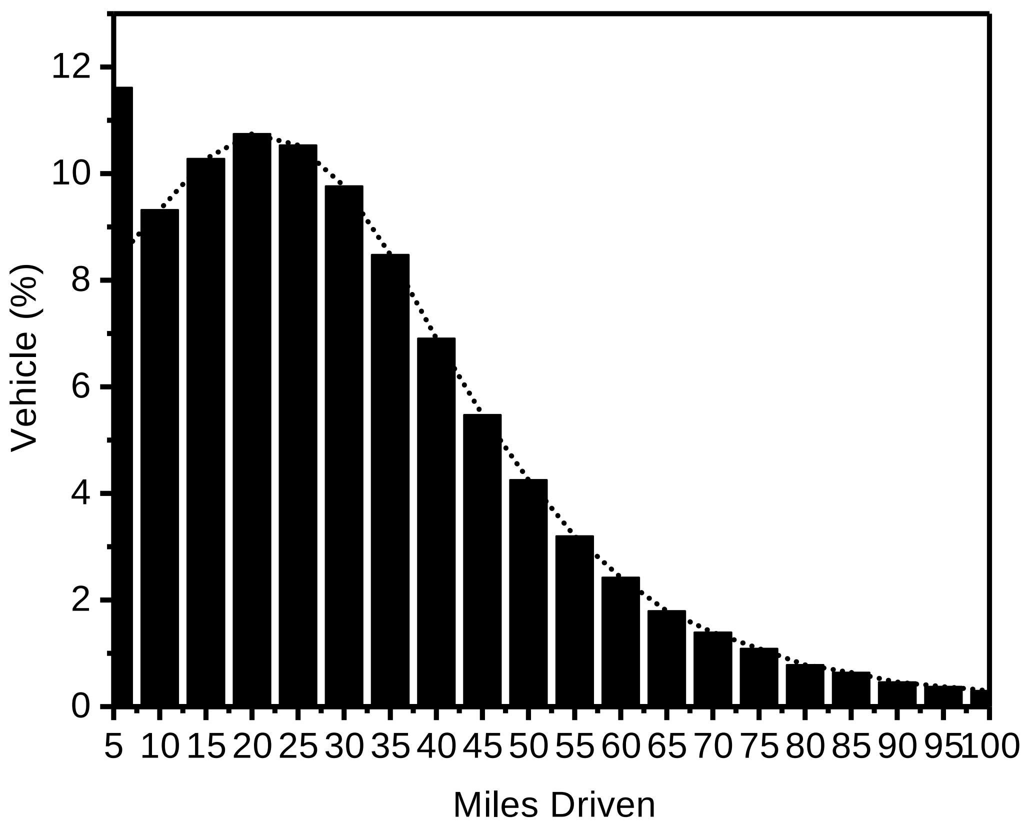

Figure 2.1: Daily miles driven by PHEV

different levels of DR was generated using Monte-Carlo simulation considering following points.

1. The percentage of *daily-distance-travelled* in electric mode by a PHEVs, distribution factor γ, was taken to be random value between 0.5-1. Accordingly, the SOC for PHEVs was calculated.

2. While generating the charging data for 90% DR, it was considered that 90% of

vehicles will respond to the tariff and charge during 01 : 00 - 06 : 00 hours. The rest 10% would be distributed uniformly over the whole day. In a similar way the charging data was generated for 70% and 50% DR.

3. The distribution of *daily-distance-travelled* by PHEVs was generated as per NHTS 2009 data and is shown in Fig. 2.1.

4. During discharging hours i.e between 18 : 00 - 24 : 00 hours the vehicle is assumed to discharge the remaining energy in battery after *last-trip-arrival-time*. Similar to the case of charging time, for DR of 90%, it was assumed that 90% of vehicles will respond to tariff and discharge the batteries during 18 : 00-24 : 00 hours. The rest 10% of discharging would be distributed over 24 hour period. The discharging data was generated in the similar way for 70% and 50% DR.

5. The rate of charging the battery is taken as 6 kW/hr whereas the discharging rate is taken as 2.8 kW/hr.

The loading patterns are generated using Algorithm 1 and relevant data from NHTS 2009 survey [9], [154]. The travel data such as PHEVs types, *daily-distance-travelled*,*last-trip-arrival-time* and *start-trip-time* for 100 vehicles are considered. For example a sample data point generated using Algorithm 1 can be demonstrated as follows.

Let the vehicle type chosen be 4 (Full-size SUV) and let the AER be PHEV60 and the distance travelled be randomly taken as 40 miles and $\gamma = 85\%$. Then the SOC for the vehicle is calculated as

$$SOC = \big(1 - \frac{0.85 \times 40}{60}\big) \times 100$$

$$SOC = 43.33\%$$

and referring to Table 2.1, battery capacity = 27.6 kWh

$$E_g = \frac{1 - \frac{43.33}{100}}{0.88} \times 27.6$$

$$= 17.774kWh$$

Thus, energy required from grid is 17.774 kWh to charge the battery. The hourly charging/discharging pattern of vehicle is provided in Table 2.3. Let the assumed time of charging be 01 : 00 hour and discharging time be 18 : 00 hour. Then the vehicle would be fully

Algorithm 1: Generation of charging and discharging profile for a PHEV

Select vehicle type (1, 2, 3 and 4)

Select AER (PHEV30, PHEV40 and PHEV60)

Select distance travelled randomly ($\mu = 3.253$ and $\sigma = 0.968$) and γ fixed in range 0.5-1.0

Calculate battery SOC,

$$SOC = \begin{cases} (1 - \frac{\gamma d}{AER}) \times 100 & \gamma d \leq AER \\ 0 & \gamma d \geq AER \end{cases}$$

Calculate TER to charge vehicle,

$$E_g = \left(\frac{1 - \frac{SOC}{100}}{0.88} \right) \times C$$

Randomly allocate time of charging between $01:00$-$06:00$ hours ($\mu = 3.603$ and $\sigma = 1.728$)

Calculate charging duration

Generate charging load profile

Calculate battery energy after *last-trip-arrival-time*

Randomly allocate time of discharging between $18:00$-$24:00$ hours ($\mu = 20.778$ and $\sigma = 2.012$)

Calculate discharging duration

Generate discharging load profile

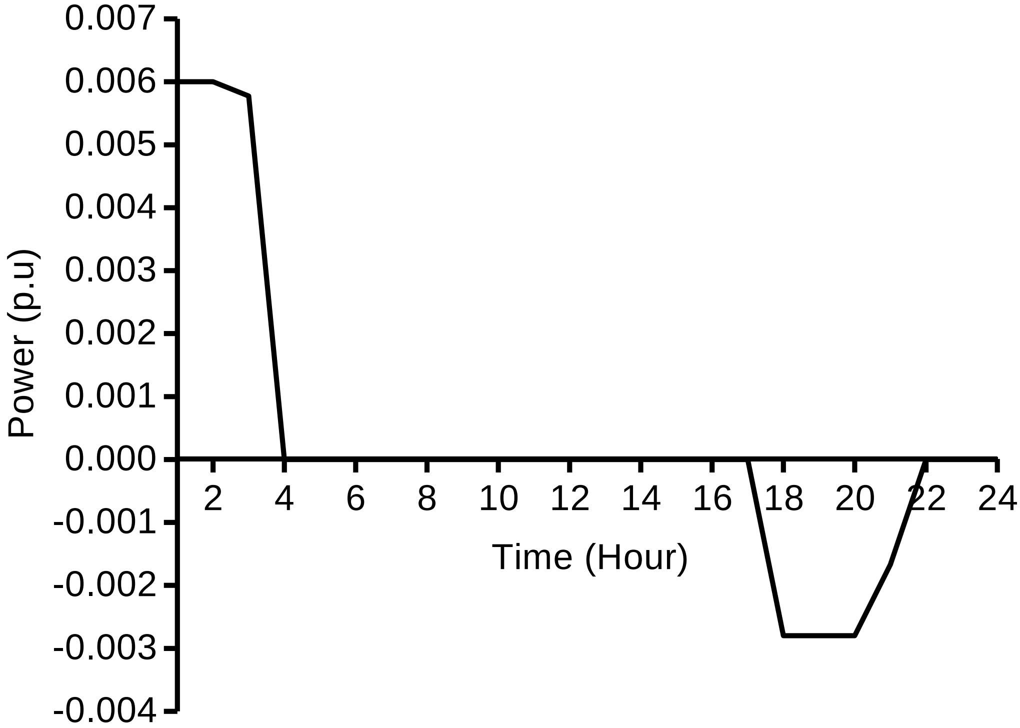

Figure 2.2: Charging/discharging of single PHEV

charged by 03 : 00 hour and fully discharged by 21 : 00 hour as per charging/discharging pattern shown in Fig. 2.2 for a single PHEV.

Table 2.3: Charging/discharging time for full size SUV vehicle with AER 60 miles

	Charging				Discharging			
Time (hour)	1^{st}	2^{nd}	3^{rd}	4^{th}	18^{th}	19^{th}	20^{th}	21^{th}
Power (kWh)	6	6	5.774	0	2.8	2.8	2.8	1.67

In every iteration of Monte-Carlo simulation, a sample of load profile is generated randomly considering the type of Vehicle, ($i = 1,\ 2,\ 3$ and 4) battery capacity (7.8 kWh - 27.6 kWh), *daily-distance-travelled* by vehicle ($\mu = 3.253$ and $\sigma = 0.968$), starting time of charging in range 01 : 00 - 06 : 00 hours distributed randomly ($\mu = 3.603$ and $\sigma = 1.728$) and starting time of discharging in range of 18 : 00 - 24 : 00 hours distributed randomly ($\mu = 20.778$ and $\sigma = 2.012$). The simulation is iterated for all PHEVs several times. Then, the samples are averaged to generate final load profile. A typical hourly loading profile for the system due to PHEVs is shown in Figs. 2.3 & 2.4.

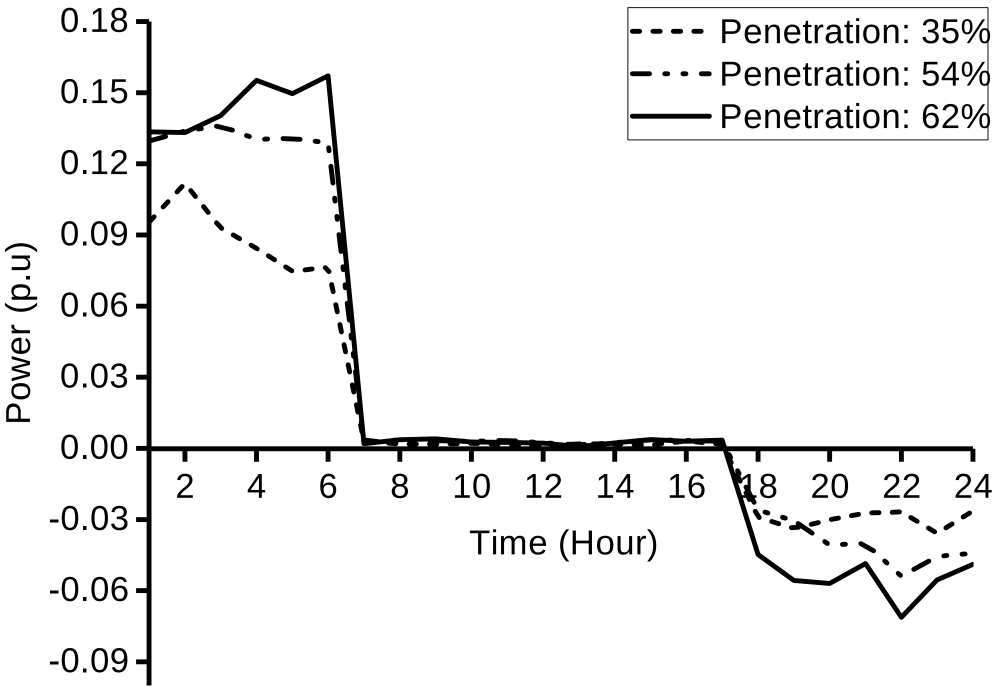

Figure 2.3: Simulated 24-Hour loading profile at 90% DR for different penetration levels of PHEVs

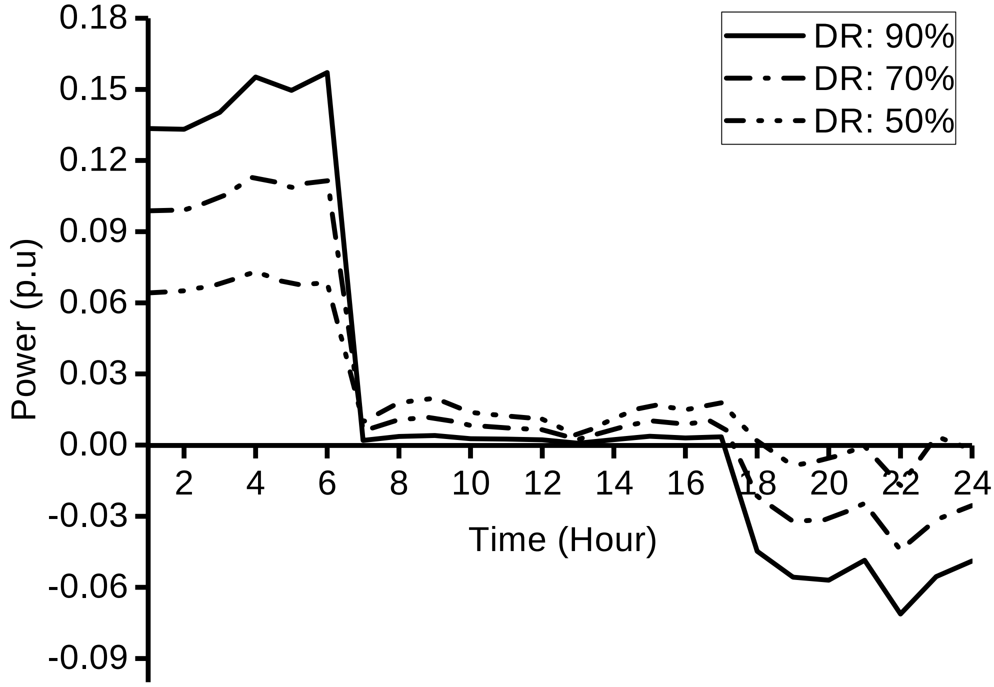

Figure 2.4: Simulated 24-Hour loading profiles at 62% penetration of PHEVs for different DR levels

Fig. 2.3 shows hourly loading profile of PHEVs for three penetration levels as per forecast for 2020, 2030 and 2050 [5] which are 35%, 54% and 62% respectively at 90% of demand responsiveness of vehicles. The level of demand responsiveness (50%, 70% and 90%) decides the percentage of vehicle to charge or discharge on the grid in response to tariff. Fig. 2.3 shows that the 90% of vehicles at each penetration level will charge in response to low tariff period (01:00-06:00 hours) and rest 10% of vehicles will charge any time during the whole day. In a similar way, 90% of vehicles at each penetration level will discharge in response to high tariff period (18:00-24:00 hours) and rest 10% of vehicles will discharge any time during the whole day. DR plays crucial role to decide the Peak-to-Average Ratio (PAR) of the grid. Whereas, Fig. 2.4 shows hourly loading profile for three different DR levels (i.e 50%, 70% and 90%) at 62% of penetration level of vehicles.

2.3.2 Stochastic simulation model of PHEVs based on conventional approach

Stochastic modelling for generation of SOC profiles of PHEVs are discussed and developed in this section.

The data of the driving patterns of vehicles including *daily-distance-travelled*, and *last-trip-arrival-time* are taken from the National Household Travel Survey (NHTS) 2017 transportation report of U.S. [155]. The NHTS 2017 database consists surveys of total 129,112 households. The sum of all the trips during a day is the *daily-distance-travelled.* The departure time (t_{dep}) is considered as *start-trip-time* and its arrival time (t_{arr}) is considered as the *last-trip-arrival-time.* It is assumed that the driving patterns of vehicles owner will not change in the near future. The travel survey is used to predict the driving pattern. The probability distribution functions (pdfs) of the *daily-distance-travelled*, *start-trip-time* and *last-trip-arrival-time* can be fitted from NHTS 2017 data. The quality of pdfs is evaluated by Sum of Square Error (SSE).

$$SSE = \sum_{i=1}^{n} \omega_i (y_i - \hat{y}_i)^2, \tag{2.3}$$

where y_i is observed data and $\hat{y}_i$ is the predicted value from the pdfs, ω_i is the weighting coefficient and set $\omega_i = 1$.

The distribution of *daily-distance-travelled* can be described by a log-normal distribution [156] for NHTS 2017 data. The pdf of the *daily-distance-travelled* is shown in Fig.

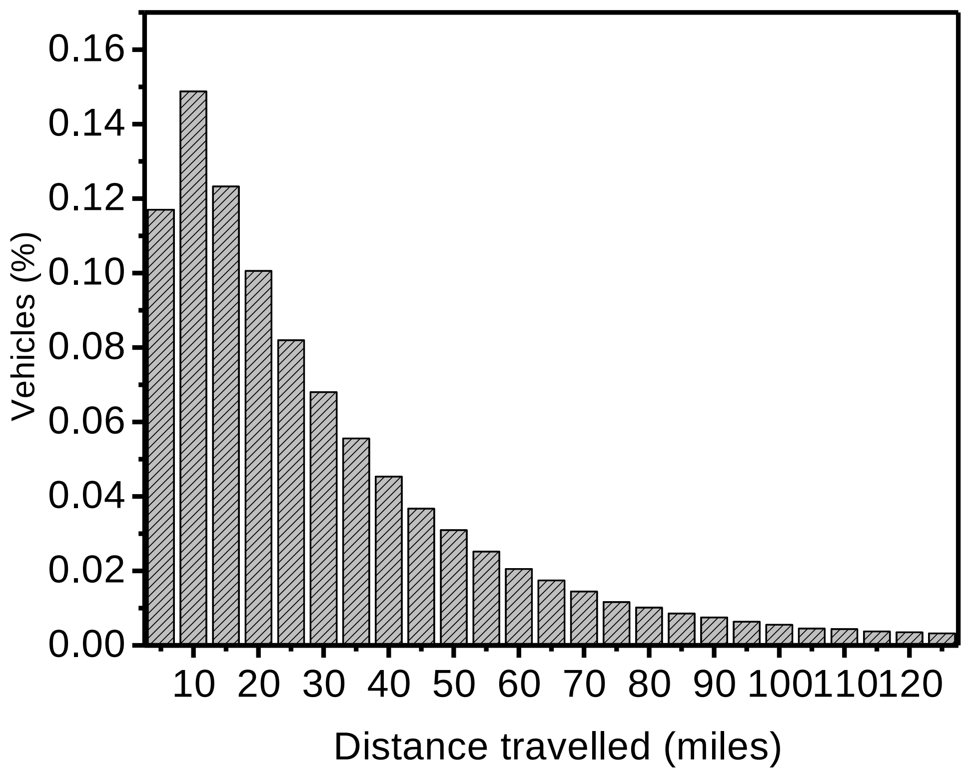

Figure 2.5: Percentage of vehicles versus *daily-distance-travelled*

2.5. The pdf of the *daily-distance-travelled* can be expressed as follows.

$$F_d(t) = \frac{1}{d\sigma\sqrt{2\pi}} e^{(\ln(d)-\mu)/2\sigma^2}, \tag{2.4}$$

where d is the distance travelled ($d > 0$), μ is the mean of $ln(d)$, and σ is the standard deviation of the log-normal distribution.

The pdfs of *start-trip-time* and *last-trip-arrival-time* of vehicle can be expressed by normal distribution as shown in Figs. 2.6 & 2.7. The pdfs can be expressed as follows.

$$F_{arr}(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{(d-\mu)/2\sigma^2}, \tag{2.5}$$

$$F_{dep}(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{(d-\mu)/2\sigma^2}. \tag{2.6}$$

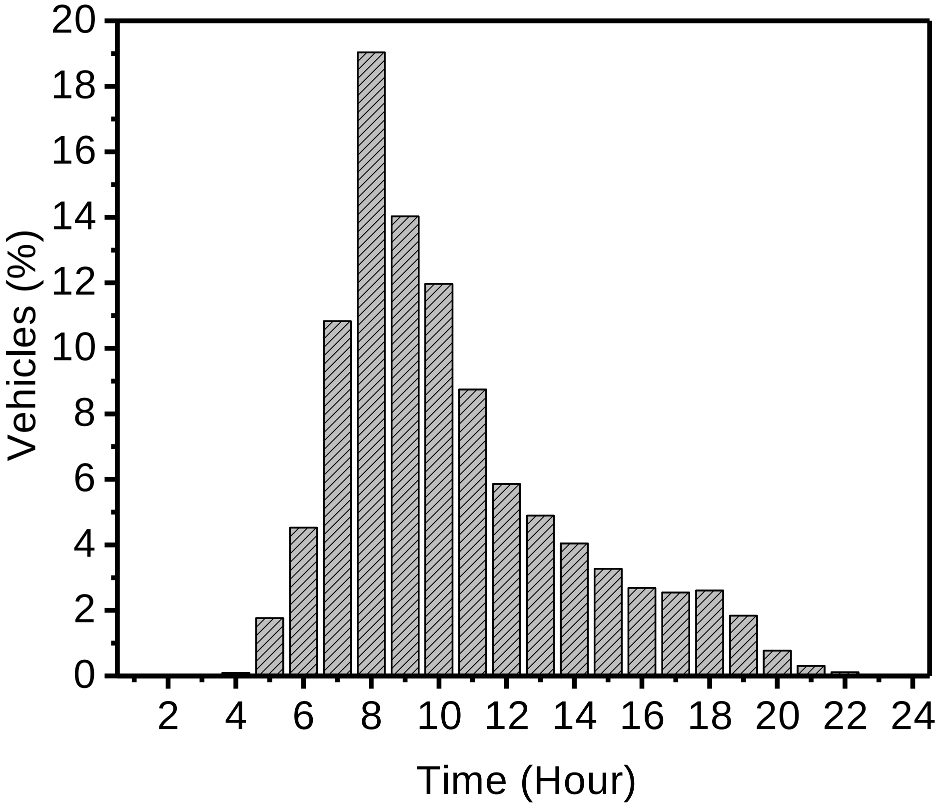

Figure 2.6: Percentage of vehicles versus *start-trip-time*

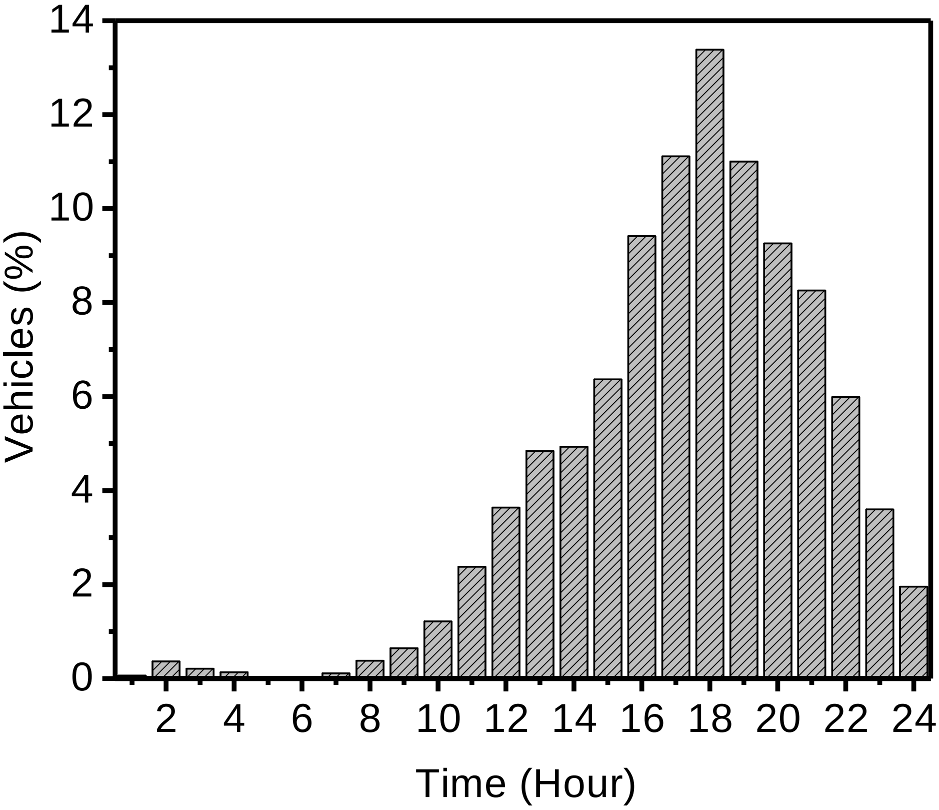

Figure 2.7: Percentage of vehicles versus *last-trip-arrival-time*

The statistical parameters of driving pattern such as *daily-distance-travelled*, *start-trip-time* and *last-trip-arrival-time* are depicted in Table. 2.4 for NHTS 2009 and NHTS 2017.

Table 2.4: Statistical parameter of driving pattern

Parameter	NHTS 2017			NHTS 2009		
	μ	σ	SSE	μ	σ	SSE
Daily-distance-travelled	2.933	1.102	0.0025	3.253	0.968	0.0018
Start-trip-time	13.65	4.288	0.0635	17.015	3.186	0.0568
Last-trip-arrival-time	13.672	4.313	0.0099	9.975	2.432	0.0156

μ : Mean σ : Std. deviation

SSE : Sum of square error $0 \geq t \leq 24$

The SOC profile of PHEVs after *last-trip-arrival-time* are generated by Monte-Carlo Simulation (MCS). According to the pdfs of PHEVs driving pattern, a set of a random number which includes the PHEVs *daily-distance-travelled*, *start-trip-time* and *last-trip-arrival-time* were sampled using MCS technique. The generation of distance travelled by the vehicle, *start-trip-time* and *last-trip-arrival-time* for a e^{th} PHEV is taken according to its corresponding pdfs. In every iteration, a representative SOC profile with higher probability is picked up. The flow chart of stochastic SOC profile simulation is shown in Fig. 2.8.

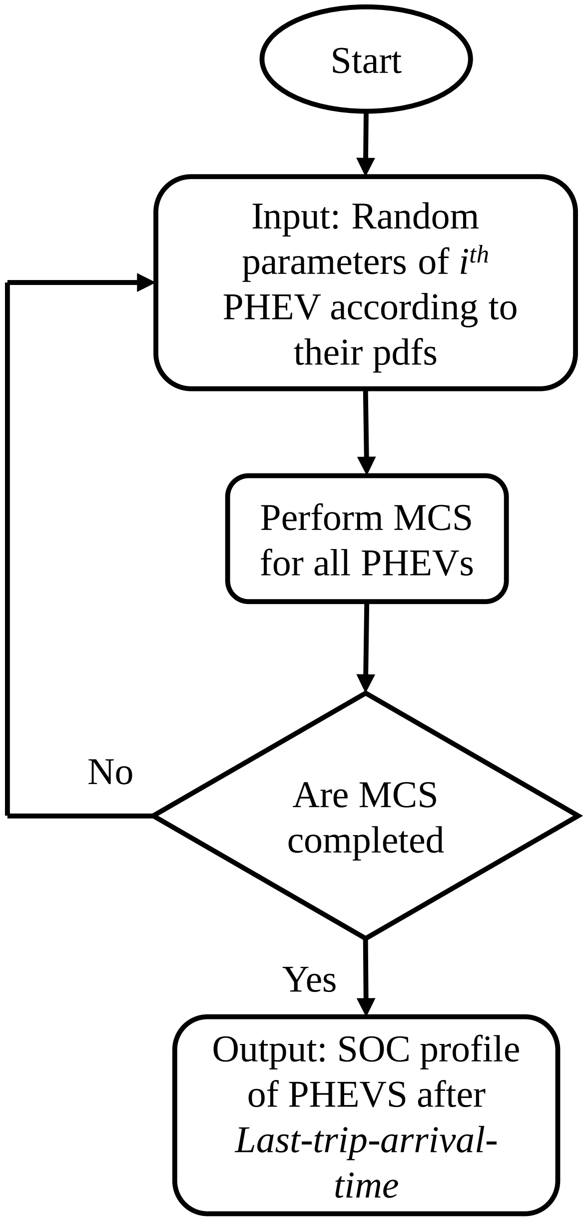

Figure 2.8: Flow chart of stochastic simulation of PHEVs

2.4 Summary

This chapter focuses on stochastic modelling of PHEVs load profile on distribution system. The charging/discharging load profile of PHEVs is generated with consideration of three different DR levels and three different penetration levels as forecasted by EPRI in future. Different load profiles on distribution system are obtained under consideration of demand responsiveness and increased penetration of PHEVs. In order to use PHEV load in scheduling problem perspective, PHEV load profile is generated just after *last-trip-arrival-time* and statistical parameter related to uncertain nature of vehicle's driving habit is also obtained.

As expected electric vehicle penetration will go up in future, this chapter will help distribution system planner/operator to generated EV load profile for analyses of its impact on modern distribution system.