Optimal distribution of Electric Vehicle Types for Minimizing Total CO$_2$ Emissions

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Abstract—**With the rapid growth of electric vehicles, power systems would face serious difficulties to supply the excessive electricity demand in the near future. In this paper, a planning method is introduced to prevent the environmental and technical issues that the introduction of electric vehicles may cause for non-smart electricity grids. The idea of this method is to employ the differences between EV types in order to achieve the minimum total emission which is the sum of vehicles emission and power system emission. The proposed method considers the importance of decreasing urban area emission and determines the optimal number of every EV type. The IEEE RTS 24 system, and real world vehicle specifications is used to demonstrate the capability of the proposed method. Results suggest that for low daily trip distances, the best option depends on the priority of urban area emission reduction. On the other hand, for higher distances, the plug-in types would lead to lower total emissions.**

Index Terms—**CO$_2$ emissions, Hybrid Electric Vehicle, Plug-In Hybrid Electric Vehicle, Pure Electric Vehicle**

NOTATION

Indices

i	index of system buses running from 1 to nb
t	index of time slots running from 1 to T
u	index of generating units running from 1 to ng
s	index of blocks of generating units heat rate running from 1 to S_u

Constants and Input Data

d	Daily trip distance for all vehicles [mile]
R_{PEV}	Maximum driving range of PEVs [mile]
AER	All-electric range of PHEVs [mile]
bc_{PEV}	Battery capacity of PEVs [kWh]
bc_{PHEV}	Battery capacity of PHEVs [kWh]
C_{PEV}	PEV chargers rated power [kW]
C_{PHEV}	PHEV chargers rated power [kW]
T_{PEV}	Needed time to fully charge a PEV [number of time slots]
T_{PEV}	Needed time to fully charge a PHEV [number of time slots]
$L_{PEV,t}$	Load of charging a PEV in every time slot [kW]
$L_{PHEV,t}$	Load of charging a PHEV in every time slot [kW]
e_{PHEV}	Total CO$_2$ emitted in one day from a PHEV [kg]
e_{HEV}	Total CO$_2$ emitted in one day from an HEV [kg]
B	Matrix of transmission line Susceptances
$load_{i,t}$	Load at bus i and in time t [MW]
N	Specified total number of vehicles

$demand_{PEV}$	Amount of electricity used by a PEV in one-day trips [kWh]
$demand_{PHEV}$	Amount of electricity used by a PHEV in one-day trips [kWh]
CPK_{HEV}	CO$_2$ emission rate of HEVs [kg/mile]
CPK_{PHEV}	CO$_2$ emission rate of PHEVs while using fuel [kg/mile]
M	Matrix of mapping the generation units to system buses [0/1]
S_b	Base power of the system [MW]
$H_{u,s}$	Incremental heat rate value in every step [MBtu/MWh]
e_u	CO$_2$ emission rate of units [kg/MBtu]
α	Importance factor for urban area emission

Variables

E	Total CO$_2$ emissions (objective value) [kg]
VE	Total CO$_2$ emission from vehicles [kg]
GE	Total CO$_2$ emission from electricity generation [kg]
$x_{i,PHEV}$	Number of PHEVs in bus i
$x_{i,HEV}$	Number of HEVs in bus i
$x_{i,PEV}$	Number of PEVs in bus i
$Pg_{u,s,t}$	Amount of generation of unit u in step s and time t [MW]
$P_{u,t}$	Total amount of power generation for unit u in time t [MW]
$P_{i,t}$	Total amount of power generation in bus i in time t [MW]
$Pl_{i,j,t}$	Transmitted power between bus i and j [MW]
$\delta_{j,t}$	Voltage angle of bus i at time t [rad]
$EVload_{i,t}$	Load of EV charging at bus i and time t [MW]

I. INTRODUCTION

During 2010, global CO$_2$ emissions increased by 4.6%. In this year, transportation sector was responsible for 22% of total CO$_2$ emission and almost three-quarters of this share was due to road transport [1]. Therefore, reducing the carbon intensity of passenger vehicles could have a large effect on reducing global CO$_2$ emissions. Electrice vehicles (EVs) are the most suitable option for this purpose. During the years, EVs technology developed dramatically and governments conducted different plans to further grow EV usage. These efforts are paying off and global EV sales has doubled between 2011 and 2012 [2]. But this rapid growth rises another concern: What happens to electricity grids which are going to feed this new enormous load? Can they handle large amounts of EVs that are planned to hit the roads in the near future?

The impact of EVs on electricity grids has been the subject

of many researches recently. Some of the researches are focused on the economic impacts of EVs on electricity grid such as [3], [4]. Kiviluoma and Meibom [5] analysed the effect of EVs on Finland power system and concluded that "smart" charging can save 227€/vehicle/year compared to "dumb" charging. Lyon et al. [6] showed that despite saving billions of dollars, smart charging cannot compensate its essential infrastracturs cost. Fernandes et al. [7] estimated the impacts of EVs on a system with different levels of renewable energy penetration. They used three scenarios for EVs number in the system and concluded that co-optimizing the electricity and EVs can cover the intermittency of renewable energy sources and cause more savings for the grid.

Technical impacts of EVs has been studied in several papers. Clement-nyns et al. [8] investigated the impacts of EVs on IEEE 34 bus test feeder and concluded that uncoordinated charging can cause distribution transformers to overload if the penetration level of EVs is high; although coordinated charging can prevent any damage to system. Shafiee et al. [9] developed a model to investigate PHEV impacts on residential distribution systems. Results of this paper show that voltage profile will hardly suffer from PHEVs but losses and peak load will increase dramatically with PHEV penetration level. Authors of this paper concluded that it is necessary to control the charging time of PHEVs in order to protect the distribution system from being damaged by the increased load. Impacts of EVs charging load on typical British distribution feeders are analysed in [10]. It is showed that when the number of vehicles are high, distribution transformer and primary cables need to be strengthen to meet the increased load. Otherwise they would be badly overloaded. Effects of EVs on distribution transformers aging are evaluated in [11] and [12]. It has been concluded that large number of EVs with uncontrolled charging can severely damage transformers and reduce their lifetime.

EVs are mostly favored due to less fossil fuel usage, but the fuel they use, which is electricity, is also generated mostly by use of fossil fuels in power plants. Therefore, the anticipated environmental benefits from EVs, are not as much as expected; and highly depend on the circumstances of the grid supplying them. Many researches have been done to evaluate the effect of a large EV fleet on power grid emissions. McCarthy and Yang [13] used an hourly electricity dispatch model to simulate the California power system response and determine its "marginal electricity mix" with the presence of EVs. Simulation results show that although being supplied by inefficient gas-fired power plants, EVs can reduce the overall CO_2 emission compared to CVs. But the difference is not that much in short term. Environmental impacts of EVs in the state of Ohio are evaluated comparing controlled and uncontrolled charging in [14]. Results indicate that although smart charging can successfully shift the charging time to low-load periods and decrease the costs, the controlled charging yield to higher emissions compared to uncontrolled charging, since Ohio has large number of coal-fired inexpensive power plants. Wu et al. [15] studied the effects of vehicle electrification in three developed regions in china. Authors conclude that plug-in hybrid electric vehicles (PHEVs) and pure electric vehicles (PEVs) may rise emission levels in

highly carbonized power systems, and hybrid electric vehicles (HEVs) are suggested as the best option in these situations.

In case of reducing the impacts of EVs on power systems, solutions are not diverse. Majority of researches are focused on "smart charging" as the best solution for reducing the Impacts of EVs. Fan [16] borrowed the concept of congestion pricing in internet traffic control and used it to create a demand response framework to manage PHEVs. Smart charging is used to smooth out the load variance in a single household in [17]. Nguyen and Le [18] has co-optimized EV and home smart energy schedule to achieve minimum total energy cost of the household. In several researches, smart charging is used to cover the uncertain nature of renewable energy sources. It was shown in [19] and [20] that EVs smart charging can help grids to further employ wind farms. Birnie [21] investigated the possibility of charging EVs with solar panels during daytime by using smart charging. A few other approaches that are used in papers include reinforcement of distribution system [10] and allocating distributed generation sources [22].

Smart charging is a promising solution as it co-optimizes the electricity and transportation sectors. Consequently, it could reach the global optimum solution. However, it cannot be used without smart grid infrastructure. Thus for the situations where smart grid is not available, the problem remains unsolved.

In contrast to the previous researches, that try to cure the problem after its occurrence, this paper intend to prevent the expected environmental and technical porblems of EVs, by properly planning their growth. This planning is done through an optimization which objective is to minimize the total CO_2 production form both vehicles and generation units and is constrained to power system security through optimal power flow equations. Therefore the output plan is going to address the environmental and technical problems of EVs. Decision variables of this optimization are the number of every EV type and the amount of power generated by every unit. In other words, the main idea of this paper, which is going to be fully discussed in the following sections, is to determine the number of every EV type, in a way that not only minimizes the CO_2 emissions, but also maintains the power system security, even if it is not smart.

The rest of this paper is organized as follows: in Section 2, characteristics of different EV types and their effect on power system is described. Section 3 contains the formulation and description of the proposed method. The case study and simulation results are demonstrated in Section 4. Finally, section 5 represents the concluding remarks.

II. CHARACTERISTICS OF DIFFERENT EV TYPES

The proposed method in this paper utilizes the characteristics difference between EV types to minimize emissions. So, a brief description of EV types and their characteristics is essential for better understanding the equations in the next section. There are three main EV types are used in this paper:

A. Pure Electric Vehicles

Pure Electric vehicles or PEVs (some papers refer to them as BEV), rely only on electricity to run. They use electric motors

for traction and batteries as energy source. Lack of fossil fuel combustion gives them important advantages over CVs such as absence of emissions, independence from petroleum and smooth and quiet operation. However, limited driving range and relatively low performance are their most important weakness, which held them back during 20th century [23].

PEVs should have large battery packs in order to achieve a reasonable driving range. This causes the battery chargers to have high power consumption rating. Because the charging time should not take longer than the period in which, the car is parked at home.

Relevant specifications of EVs to this study, are their CO_2 emission and electricity consumption. As mentioned before, PEVs consume large amounts electricity but do not produce GHG directly. The amount of electricity that a PEV consumes from the batteries while running, is calculated using (1).

$$demand_{PEV} = \frac{d}{R_{PEV}} bc_{PEV} \qquad (1)$$

As can be seen in (1), it is assumed that the energy consumption of PEVs, is linearly proportional to trip distance; and the effects of driving conditions are neglected.

B. Hybrid Electric Vehicles

Hybrid Electric vehicles or HEVs are the combination of PEVs and CVs. They use both electric motor and internal combustion engine (ICE) for traction; and have batteries in addition to fuel tank. Thus, they have the advantages of both PEVs and CVs and overcome their disadvantages. HEVs characteristics are in contrast with PEVs; they do not consume electricity form the grid, but produce GHG. In fact, from the viewpoint of this paper, their characteristics are mostly identical to CVs. They just consume less fuel, and hence produce less GHG. The amount of CO_2 that an HEV produce in one day is calculated according to (2).

$$e_{HEV} = CPK_{HEV} \cdot d \qquad (2)$$

C. Plug-In Hybrid Electric Vehicles

As the name suggests, a Plug-In Hybrid Electric Vehicle or PHEV, is an HEV which can be plugged into the grid. Unlike HEVs, battery is not a temporary energy source in PHEVs. So, the batteries in a PHEV are larger than an HEV, but not as large as the ones in a PEV.

There are two main operation modes for PHEVs: charge-sustaining(CS) mode and charge-depleting(CD) mode. In CS modes, the vehicle uses electricity and gasoline alternatively in order to maintain the state-of-charge (SOC) of the batteries in a predefined region. But in CD mode, the vehicle uses the electricity until the batteries get depleted, and then switch to gasoline. The distance that a PHEV can run on CD mode is called "All-Electric Range" or AER. The AER of a PHEV is usually enough for one-day trip distances. Which means that if the vehicles are fully charged at the beginning of the day, which is the case in this paper, PHEVs and PEVs behave very similarly from the aspect of this study. But the ability to run on gasoline or any other fossil fuel adds great level of flexibility and

reliability compared to a PEV; and overcomes the low driving range disadvantage of PEVs.

In this paper, it is assumed that PHEVs always run in CD mode. So, CO_2 emission from a PHEV in one day can be calculated by:

$$e_{PHEV} = \begin{cases} 0 & \text{if} \quad d < AER \\ (d - AER)CPK_{PHEV} & \text{if} \quad d > AER \end{cases} \qquad (3)$$

As states, if is less than the AER of PHEV, then the vehicle doesnt consume any fuel, hence doesnt produce CO_2. But if exceeds the AER, the vehicle will consume fuel and emit CO_2 linearly proportional to the extra distance. The same happens for energy consumption of a PHEV in one-day trips:

$$demand_{PHEV} = \begin{cases} \frac{d}{AER} bc_{PHEV} & \text{if} \quad d < AER \\ bc_{PHEV} & \text{if} \quad d > AER \end{cases} \qquad (4)$$

Regarding (4), if trip distance is less than AER, the amount of energy consumed from batteries is proportional to . But if trip distance is more than AER, the vehicle consumes all its stored electricity and use fossil fuel to cover the remaining distance. So the total electrical energy that the batteries need to be fully charged again, is equal to their capacity.

III. PROPOSED METHOD

In this paper, both the environmental and technical impacts of EVs on power system is tackled by optimally determining the number of every vehicle type, and generators production. This optimization relies on the differences between EV types.

A. Assumptions

The problem which is addressed in this paper is consist of numerous complex parameters. In order to avoid the overwhelming complexity, and to emphasize on the idea of the method, some assumptions has been made:

- Vehicles can only be charged in the drivers house and after the last daily trip.
- For the sake of simplicity, it is assumed that vehicles will be fully charged at home and start the next day with full batteries.
- The purpose of this paper is to investigate the situation where there is no smart charging available, and vehicles start to draw power from the grid as soon as they are plugged in. Therefore, it is assumed that the charging session is continuous and takes place in peak hours of the system.
- The optimization period is one day and the vehicles are assumed to just travel inside the city.
- In order to observe the situations in which the charging session takes less than an entire hour, every hour is divided into 6 periods and the optimization is run for every 10 minute.
- All the vehicles are assumed to travel the same distance, which is extracted from the real-world data.
- The heat rate of the generating units is approximated by a piecewise linear function to avoid the complexity of the non-linear programming.

B. Method Formulation

In this method, both the vehicles emission and power system emissions are considered and minimized at the same time. Therefore, the objective function is formulated as:

$$\min \quad E = \alpha VE + GE \tag{5}$$

VE is calculated by:

$$VE = \sum_{i=1}^{nb} x_{i,PHEV} e_{i,PHEV} + x_{i,HEV} e_{i,HEV} \tag{6}$$

It is worth reminding the x_i is the main decision variables and therefore, the main outcome of the proposed planning method. Power system emission is a function of generators power output which is calculated by using OPF:

$$GE = \sum_{i=1}^{nb} \sum_{u=1}^{ng} e_u \cdot \sum_{s=1}^{S_u} Pg_{u,s,t} H_{u,s} \tag{7}$$

$$P_{u,t} = \sum_{s=1}^{S_u} Pg_{u,s,t} \tag{8}$$

$$P_{i,t} = \sum_{u=1}^{ng} P_{u,t} M_{u,i} \tag{9}$$

$$\underline{Pg_{u,s}} \le Pg_{u,s,t} \le \overline{Pg_{u,s}} \tag{10}$$

$$P_{i,t} = S_b \sum_{j=1}^{nb} B_{i,j} \delta_{j,t} + load_{i,t} + EVload_{i,t} \tag{11}$$

$$Pl_{i,j,t} = -B_{i,j}(\delta_{i,t} - \delta_{j,t}) S_b \tag{12}$$

$$\underline{Pl_{i,j}} \le Pl_{i,j,t} \le \overline{Pl_{i,j}} \quad \forall i, j \in \mathbf{Nl} \tag{13}$$

$$Pl_{i,j,t} = 0 \quad \forall i, j \notin \mathbf{Nl} \tag{14}$$

equations (7) to (14) represent common DC OPF formulations. $EVload_{i,t}$ in (11) is calculated according to:

$$EVload_{i,t} = x_{i,PHEV} L_{PHEV,t} + x_{i,PEV} L_{PEV,t} \tag{15}$$

In order to avoid complexity, it is assumed that vehicle chargers power is equal to their rated power and does not change during charging period. Therefore, the needed charging time for a PEV or PHEV is simply calculated by dividing the consumed energy from batteries by the chargers rated power according to (16) and (17), respectively:

$$T_{PEV} = \frac{demand_{PEV}}{C_{PEV}} \tag{16}$$

$$T_{PHEV} = \frac{demand_{PHEV}}{C_{PHEV}} \tag{17}$$

Therefore, the charging load for every time period for an individual PEV and PHEV is calculated using (18) and (19) respectively:

$$L_{PEV,t} = \begin{cases} C_{PEV} & \text{for} \quad t \le [T_{PEV}] \\ 0 & \text{for} \quad t > [T_{PEV}] \end{cases} \tag{18}$$

$$L_{PHEV,t} = \begin{cases} C_{PHEV} & \text{for} \quad t \le [T_{PHEV}] \\ 0 & \text{for} \quad t > [T_{PHEV}] \end{cases} \tag{19}$$

In (18) and (19), it is assumed that charging session of the vehicles is continues. Note that, if the number of vehicles is unbounded, the outcome becomes zero; because vehicles would definitely increase the total CO_2 emissions. But the fact is that the reason behind vehicle usage is transportation needs, not the power system requirements. Therefore, the total number of vehicles should be specified and fixed in this optimization.

$$\sum_{i=1}^{nb} (x_{i,HEV} + x_{i,PHEV} + x_{i,PEV}) = N \tag{20}$$

It can be seen in the above formulations that CVs are not included in the optimization, as their characteristics are similar to HEVs from the aspect of this research.

IV. CASE STUDY

A. Input data

In this paper, vehicle data is obtained from real world EVs which are the best sellers in their category [24]. summarizes the vehicle specifications using the data in [25],[26] and [27].

The power system used in this paper for case study is the IEEE RTS 24 bus system. This system have different generating unit types which is a suitable option for the propose of this paper. One of the most important input parameters of this optimization is the daily trip distance which is applied to all of the vehicles. The data obtained from [28] shows that the most probable daily trip distance in U.S. is between 6 to 10 miles.

B. Simulation results

In this section, four cases has been investigated to better understand the results.

- Case 1: in this case, the proposed method is used to optimally calculate the number of every EV type which minimizes total CO_2 emissions.
- Case 2: in this case, all the vehicles are from HEV type and by optimally dispatching the generation units, total emissions from electricity generation is minimized.
- Case 3: in this case, all the vehicles are PHEV, and vehicles location in the power system and units generation is calculated to minimize total emissions.
- Case 4: all vehicles are PEV, and total CO_2 emission from power system is minimized by allocating vehicles and generation.

Fig.1 shows total CO_2 emission for the four cases for trip distance ranging from 6 to 10 miles. These results are calculated

TABLE I
VEHICLE SPECIFICATIONS

Name	Type	CPK (kgCO$_2$/mile)	bc (kWh)	R (miles)	C (kW)
Toyota Prius	HEV	0.177	-	-	-
Nissan Leaf	PEV	-	24	84	6.6
Chevy Volt	PHEV	0.240	17.1	38	4

Fig. 1. Total emission in all cases for $\alpha = 2$

Fig. 2. Share of EV types in the optimal case for $\alpha = 2$
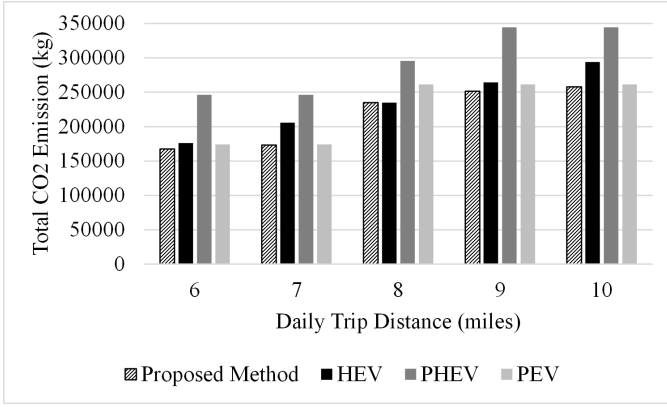
for $N = 83000$ and $\alpha = 2$ which means reducing one unit of CO_2 produced in cities is 2 times more important than reducing the same amount in power plants. This chart showes the dominance of the proposed method over the other four cases, in which the EV shares are not optimized. It is also notable that the total emission for HEVs is linearly proportional to daily trip distance as they do not interfere with power system operation. But for PHEVs and PEVs, the relationship is not linear in this little distance range. That is the reason behind the volatility of EV share which is demonstrated in Fig.2. Another important point is that although PEVs do not consume fossil fuel, using them as the only EV technology can cause higher total emissions compared to the optimal share which is calculated by the proposed method. Keep in mind that this results are for $\alpha = 2$, and for lower values which indicate lower willingness of the planner in reducing urban area emissions, HEVs share become much bigger. Fig.3 shows the shares for $\alpha = 1.6$. It is obvious in this chart that for this distance range, if reducing urban CO_2 emission does not have high priority, HEVs would be better choices. This is because of the high pollution level of the test system, and for systems with less carbone intensity in electricity production, PEVs would be more preferred.

In order to investigate the results for higher daily trip distances, the optimization is done for $d = 10$ to $d = 80$ which is the range limit of PEVs. Fig.4 and Fig.5 show the EV shares at this range for $\alpha = 1.6$ and $\alpha = 2$, respectively. The results show that for high trip distances, PEVs are the best option among three EV types even if urban CO_2 reduction is not in high priority. Another important result is the absence of PHEVs. Regarding the data in Table I, which is the real vehicle data, PHEVs have lower efficiency in all-electric mode compared to PEVs and in conventional mode compared to HEVs. So the optimization omits them in every combination of α and d.

V. Conclusion

In this paper, the potential impacts of EVs on power system were addressed through an optimization-based method which utilizes the differences between electric vehicles specifications. Three types of EVs were employed in this paper including PEVs, PHEVs and HEVs. The proposed method optimally determine
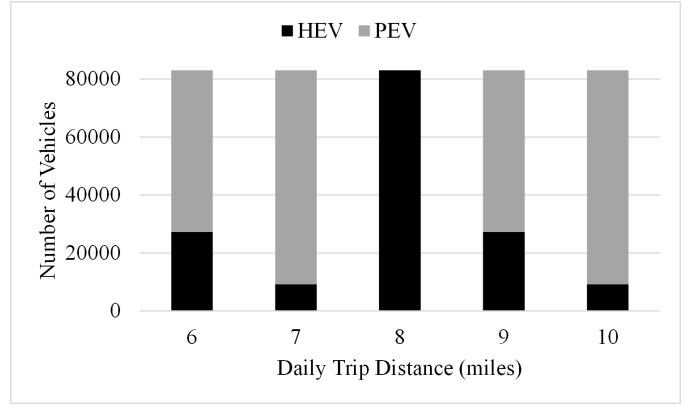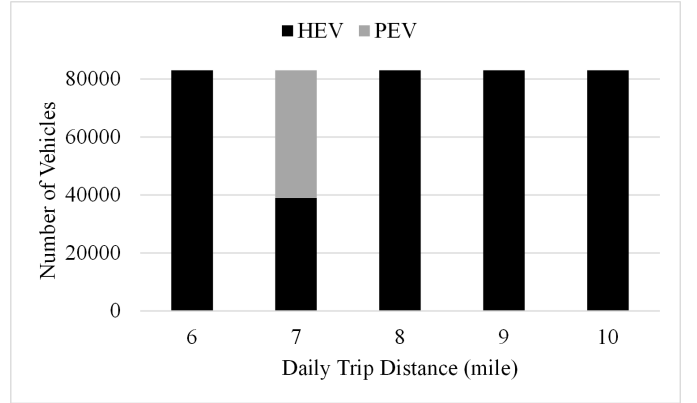

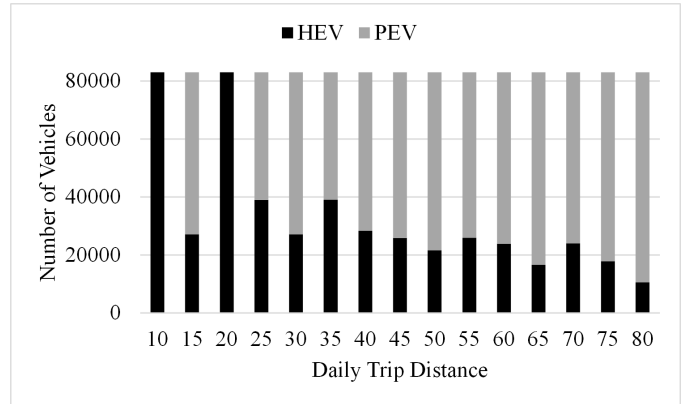Fig. 3. Share of EV types in the optimal case for $\alpha = 1.6$

Fig. 4. Share of EV types in the optimal case for $\alpha = 1.6$

the number of every vehicle type in every bus of the power system in a way that the total CO_2 emission from transportation and electricity generation sectors are minimized. The method also maintains the operation of the power system in its secure limits using OPF. In order to show the methods capability, a case study is executed on the IEEE 24 Bus Reliability Test System, and real-world vehicle data is used. Results showed that for low daily trip distances, the best option for electrifying the personal transportation sector depends on how much reducing urban area emission is important. Because of the high carbon intensity of
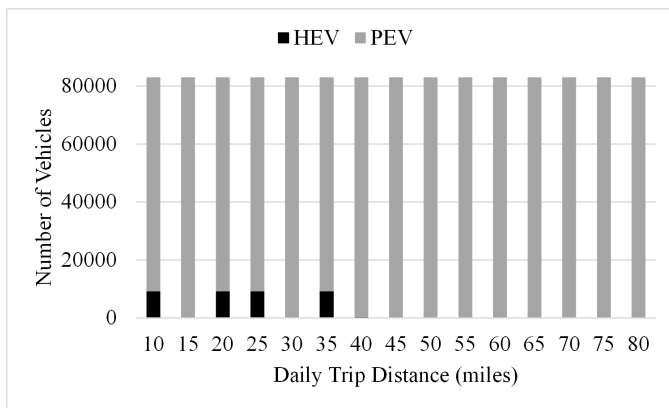
Fig. 5. Share of EV types in the optimal case for $\alpha = 2$

the IEEE RTS system, if CO_2 emission reduction in cities does not have high priority, the best option would be HEVs, which do not consume electricity from the grid. Otherwise, PEVs are a better option as they do not produce CO_2 directly although increasing the power system emissions. Results for high daily trip distances are different, where PEVs cause less total emissions whether the urban emissions are considered very dangerous or not. But the important result is that in order to minimize total CO_2 emissions, a mixture of all vehicle types is needed, and using just one type would not be the optimum choice. Simulation results also highlight the role of vehicles efficiency as PHEVs share was zero in all of the discussed situations. This is the result of the lower efficiency in all-electric mode compared to PEVs and lower fuel efficiency when using gasoline compared to HEVs.

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