Optimization of Battery Electric Vehicle Charging Infrastructure Along A Highway Corridor

Harsh Meel

Roll no: 190040041

Department of Civil Engineering

Indian Institute of Technology Bombay

CE 494 ; BTP I

Instructor: Prof. Tom V. Mathew

14th May 2023

Index:

Abstract

This report presents a comprehensive analysis of the optimization of battery electric vehicle (EV) charging infrastructure along a highway corridor, considering the growing significance of EVs as an alternative to combustion vehicles in India. Despite the availability of reasonably priced electric vehicles, the sluggish growth of EV adoption in the country can be attributed primarily to inadequate infrastructure. Therefore, this study aims to develop an optimum charging infrastructure that minimizes travel and charging delays while ensuring a high level of service and economic feasibility for both users and service providers.

The project commences with a comprehensive review of existing studies in the domain of infrastructure optimization for EV charging. In order to gather insights from industry experts, consultations were conducted with experts in the industry from Tata Motors and Exponent Energy, a leading electric charging startup. These discussions were instrumental in refining the problem statement to focus on the optimal placement of EV chargers along a highway corridor.

The initial phase of the study concentrates on a simplified model of a single corridor, incorporating the calculation of optimal battery range and charger power. The objective is to minimize the total cost while maximizing the level of service. Notably, the results demonstrate that investment in charging infrastructure yields greater rewards and is more crucial than solely extending the battery range..

Subsequently, the objective function is refined to enable more precise optimization and analysis. This enhancement serves as a basis for further improvement in infrastructure design and the inclusion of more variables involved in charging, like queuing at chargers, etc.

In conclusion, this report underscores the significance of designing an optimized EV charging infrastructure that minimizes travel and charging delays, offers a high service level, and proves economically viable for all stakeholders. By addressing these crucial factors, India can expedite the growth of EV adoption and usher in a sustainable future for transportation.

Literature Review

Lately, a lot of work has been done on finding methods to design electric vehicle infrastructure, and many of them fall into optimization of chargers or swapping stations. (Jochem et a. 2016) Shows that a small number of DC fast chargers can support a large and wide area of intercity routes. Many earlier studies have used density clusters of EV users to locate electric chargers (Raphaela Pagany et al.) . Such methodologies don't work with highway-based transport as a typical user leaves the city boundaries with almost complete charge before entering the highway. Therefore, the user location data has little use.

(Ghamami et al.) Takes a corridor-centric approach to charging infrastructure designing the Michigan State EV Charger System. Their method is best suited for this study. The simple corridor model used here is based on (Nie and Ghamami) paper, with data on Indian roads and cars.

During the project, valuable insights were obtained from discussions with industry experts in order to finalize the problem statement. A representative from Tata Motors highlighted that electric cars primarily charge during long-distance travels on highways and rarely in city travel. He suggested that fast chargers placed at equal distances along the highway should be sufficient to cater to the charging needs of electric vehicles. Additionally, the expert emphasized that the penetration of electric vehicles and trip frequency on highways in India are currently low. Another discussion with an expert from Exponent Energy, a Bangaluru-based EV charging startup, shed light on the significance of range anxiety in EV commuting, as the reliability of electric chargers remains relatively low. It was emphasized that longer corridor-like highway strips offer more predictability for the placement of chargers.

Simple Corridor Model

Some key variables of the electric vehicle infrastructure are EV battery capacity, Maximum power supplied by an EV charger, and level of service. A larger battery can ensure long trips without much need of charger outlets. However, it leads to huge user costs. A powerful charger can ensure a faster rate of charging and serviceability but leads to high costs on the vendor's side. Thus, first, we must find an optimum battery capacity and charger power, minimizing costs and maximizing the level of service.

Model Design (Battery Capacity vs Charger Power)

Based on the corridor-centric approach as given in (Nie and Ghamami)

Let us take a single highway corridor of length l , between two city centers. The density of EVs is uniformly distributed over the length as d (cars/km). The frequency of trips per vehicle is f *(trips per day).* So, the total number of EVs on the route is dl, and their trips total to dlf. The energy capacity of an EV is variable E. The power of a charger outlet is the variable P. The number of charging stations along the corridor to be made is n, where at each station, there are m charging ports.

Assuming,

1. All trips start and end at the two ends of corridor
2. Each station must have enough charging ports to accommodate all trips

Therefore,

$$m \geq min(dl, dlf) = dl\, min(1, f) \tag{1}$$

Regarding the battery, let the charging efficiency of charger be ε . β is the avg. distance traveled by an EV per kWh of energy consumed.

To map the range anxiety, let us consider $\theta[0, 1]$, as the range anxiety factor. A driver would only drive a car till the capacity of the battery drops to 100(1-θ)%. Therefore, higher θ leads to higher distances traveled.

Now, assuming all stations are equally distanced from each other and the terminals:

$$\text{Distance between two stations} = \frac{l}{n+1}$$

$$\text{Maximum distance traveled until range anxiety} = \beta\theta E$$

If the driver charges EV to full capacity at every charger, this gives:

$$\beta\theta E \geq \frac{l}{n+1} \Rightarrow n \geq \frac{l}{\beta\theta E} - 1 \tag{2}$$

Now to measure the level of service provided, we can use a factor δ , called delay factor, to measure time T it takes to travel the corridor against time without any delay due to charging.

$$\text{i.e., } T = \delta \frac{l}{v} \tag{3}$$

where, v = avg flow speed of traffic

Now, assuming T as the maximum delay allowed:

$$Time\ it\ takes\ to\ charge\ vehicle\ at\ n\ stations \leq T$$

$$m\frac{\varepsilon\theta E}{P} \leq T \tag{4}$$

Regarding the costs, assume Cp is the construction cost for building/remodeling a charging station, Cs is the installation cost per unit charging power, and Ce the unit manufacturing cost for the battery.

$$\textit{Cost of station} = (Cp + mPCs);\ \ \textit{Cost of battery} = CeE \tag{5}$$

$$Cp = (A + m\,a)\,Ca \tag{6}$$

where, A is the fixed construction area for each charging station, a is the variable construction area required for each charging slot, and Ca is the unit construction cost (Rs per square feet).

So the objective function of cost $z(P, E)$ is:

$$min \quad z(P, E) = (Cp + mPCs)\, n + dlCeE$$

from eqn (1) and (2) using the lower bound of m and n respectively,

$$\boldsymbol{min} \quad \boldsymbol{z(P, E)} = (Cp + dl\, min(1, f)Cs)\left(\frac{l}{\beta\theta E} - 1\right) + dlCeE \tag{7}$$

s.t

$$\left(\frac{l}{\beta\theta E} - 1\right)\frac{\varepsilon\theta E}{P} \le T \tag{8}$$

Optimization and Analysis:

Let the constant values in the objective function be:

$$C_1 = dl\, min(1, f)Cs\,; \quad C_2 = dlCe\,; \quad C_3 = \frac{l}{\beta\theta} \tag{9}$$

where, C_1 is the variable cost of charging facility, C_2 is the total cost to manufacture all batteries to meet the demand, and C_3 is the energy a battery has to hold in order to travel through corridor without being depleted below the range tolerance.

Using eqn (9) in eqn (7) and (8):

The Lagrangian of the problem is:

$$L = C_1C_3\frac{P}{E} + Cp\left(\frac{C3}{E} - 1\right) - C_1 P + C_2 E - \mu(TP + \varepsilon\theta E - C_3\,\varepsilon\theta) \tag{10}$$

And the Krush-Kuhn-Tucker conditions are

$$\frac{\delta L}{\delta P} = \frac{C1C3}{E} - C_1 - \mu T = 0 \tag{11}$$

$$\frac{\delta L}{\delta P} = -C_1C_3\frac{P}{E2} - Cp\frac{C3}{E2} + C_2 - \mu\,\varepsilon\theta = 0 \tag{12}$$

$$\mu(TP + \varepsilon\theta E - C_3\,\varepsilon\theta) = 0 \tag{13}$$

$$\mu \ge 0\,; \quad TP + \varepsilon\theta E - C_3\,\varepsilon\theta \ge 0 \tag{14}$$

Solving for E and P we get:

If $\mu = 0$

$$E_0 = C_3 \; ; \quad P_0 = \frac{C2C3 - Cp}{C1} \tag{15}$$

Thus, (E_0, P_0) is indeed a solution to the KKT conditions, which means it is at least a local solution for the design problem. Note that $C_3 = \frac{l}{\beta\theta}$ can be interpreted as the battery energy required to travel up to a distance l without range anxiety. Thus, the above solution essentially advises completely giving up charging stations and building a battery with enough capacity to traverse the corridor without having to stop.

If $\mu > 0$

$$E_1 = \frac{C3}{\eta} \; ; \quad P_1 = \frac{C3 \; \varepsilon\theta}{T}\left(1 - \frac{1}{\eta}\right)$$

$$\text{where} \quad \eta = \sqrt{\frac{C3(TC2 + \varepsilon\theta C1)}{\varepsilon\theta C1C3 + TCp}} \tag{16}$$

Also, for $C_2C_3 > Cp$ *ensures* $\eta > 1$

Integer solution: The analytical solution obtained in the previous section could lead to a non-integer number of charging facilities, which is obtained as

$$n1 = \frac{l}{\beta\theta E1} - 1$$

Now to determine optimal integer solution, we need to compute $[n_1]+$ and $[n_1]-$. Where [a]+ and [a]- are the first integers obtained by rounding the real number up and down, respectively. Using the constraints of the design problem, [E*]# and [P*]# (# = +,-) can be computed from:

$$[E^*]^{\#} = \frac{l}{\beta\theta([m^*]^{\#} + 1)}; \quad [P^*]^{\#} = \frac{\alpha\theta[E^*]^{\#}[m^*]^{\#}}{T_0}, \# = +, -;$$

Where $m^* = n_1$; $\alpha = \varepsilon$; $T_0 = T$

Then, the optimal integer solution would be the one that minimizes z([E*]#, [P*]#), # = +,-;

<u>Case Study:</u>

Let us apply the simple corridor model to Mumbai Ahmedabad using the following data:

Table 1

Parameter	**Description**	**Unit**	**Value**
l	Corridor length	km	441
f	Avg trip frequency	trip/day	0.13
d	EV fleet density	vehicle/km	0.5
ε	Charging efficiency	-	1.3
β	Battery performance	km/kWh	7.55 (Tata Nexon EV)
δ	Delay Tolerance	-	0.15
θ	Range Tolerance	-	0.8
A	Minimum Construction area	sqft	2000
a	Per spot construction area	sqf	300
Ca	Unit const. Cost for station	Rs/sqft	1414
Ce	Unit manufacturing cost of battery	Rs/kWh	17283 (Tata Nexon EV)
Cs	Per spot const cost of outlet	Rs/kWh	11607
v	Average speed	kph	80

Program:

A. Libraries used

```
import numpy as np
import math
import matplotlib.pyplot as plt
```

B. Function used

```
def chargerinfra(l, f, d, eps, beta, delta, theta, A, a, Ca, Ce, Cs, v):

  m = int(d*l*min(1,f))
  T = delta*l/v
  C1 = d*l*min(1,f)*Cs
  C2 = d*l*Ce
  C3 = l/(beta*theta)
  Cp = Ca*(A + m*a)

  E0 = C3
  P0 = (C2*C3-Cp)/C1
  eta = math.sqrt((C3*(T*C2 + eps*theta*C1))/(T*Cp + eps*theta*C1*C3))
  E1 = C3/eta
  P1 = C3*eps*theta*(1-1/eta)/T

  n1 = -1 + l/(beta*theta*E1)
  n1_plus = math.ceil(n1)
  n1_minus = math.floor(n1)

  E_plus = l/(beta*theta*(n1_plus + 1))
  E_minus = l/(beta*theta*(n1_minus + 1))

  P_plus = eps*theta*E_plus*n1_plus/T
  P_minus = eps*theta*E_minus*n1_minus/T

  l_plus = C1*C3*(P_plus/E_plus) + Cp*(-1 + C3/E_plus) - C1*P_plus + 
C2*E_plus - (C1*(eta-1)/T)*(T*P_plus + eps*theta*E_plus - C3*theta*eps)
  l_minus = C1*C3*(P_minus/E_minus) + Cp*(-1 + C3/E_minus) - C1*P_minus + 
C2*E_minus - (C1*(eta-1)/T)*(T*P_minus + eps*theta*E_minus - C3*theta*eps)
```

```
  if l_plus >= l_minus:
    sol = [E_minus, P_minus, E_minus*beta, n1_minus, l_minus, m, T]
  else:
    sol = [E_plus, P_plus, E_plus*beta, n1_plus, l_plus, m, T]

  return E0, P0, eta, E1, P1, n1, m, sol
```

C. Plotting data for Delay and density

```
def plot(x,y,mode='delay'):
  # x is list, y is number starting from 0, to last index of 'sol'
  sol_list = []
  if mode == 'delay':
    for i in range(len(x)):
      _,_,_,_,_,_,_,sol = chargerinfra(441,0.13,0.5,1.3,7.55, x[i]
,0.8,2000,300,1414,17283, 11607, 80 )
      sol_list.append(sol[y])
      print( x[i],sol[y])

  elif mode == 'den':
    for i in range(len(x)):
      _,_,_,_,_,_,_,sol = chargerinfra(441,0.13,
x[i],1.3,7.55,0.15,0.8,2000,300,1414,17283,11607,80)
      sol_list.append(sol[y])
      print( x[i],sol[y])
  plt.plot(x,sol_list)
  return
plot([0.1,0.15,0.25,0.5,0.85,1,2,3],2,mode='delay')

plot([0.01,0.05,0.1,0.2,0.4,0.8,1],2,mode='den')
```

Results

For data given in the case study.

Table 2

Energy E(kWh)	Charging Power P(kW)	Battery Range (km)	No. of Charging Stations n	Objective Function Z Rs (10^7)	No. of charging ports at a station (m)	Travel Time delay T(hrs)
24.33	61.22	183.74	2	16.28	28	0.82

Optimum Values with respect to different Level of service (Time delay δ):

Table 3

Delay Factor δ	Energy E(kWh)	Charging Power P(kW)	Battery Range (km)	No. of Charging Stations n	Objective Function Z Rs (10^7)	No. of charging ports at a station (m)	Travel Time delay T(hrs)
0.1	36.50	68.87	275.625	1	17.67	28	0.55
0.15	24.33	61.22	183.74	2	16.28	28	0.82
0.25	24.33	36.73	183.74	2	14.66	28	1.37
0.5	18.25	20.66	137.82	3	13.43	28	2.75
0.85	18.25	12.15	137.82	3	12.58	28	4.68
1	18.25	10.33	137.82	3	12.39	28	5.51
2	18.25	5.16	137.82	3	11.88	28	11.02
3	18.25	3.44	137.82	3	11.71	28	16.53

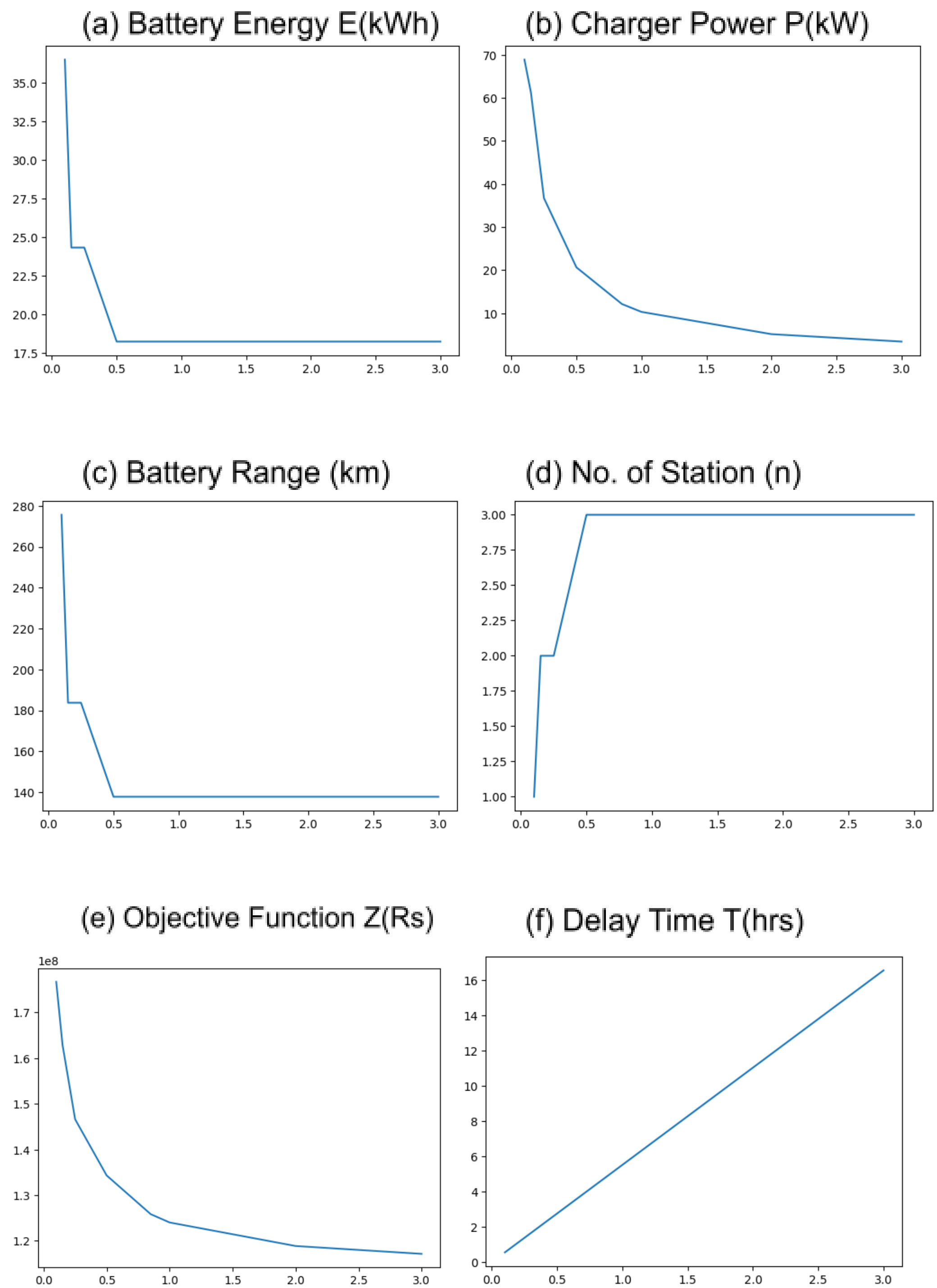

Fig. 1 Sensitivity of Infrastructure Variables against Delay Factor (Level of Service)

Optimum Values with respect to different penetration of EVs d(vehicle per km):

Assuming Delay Factor = 0.15

Table 3

Density d (veh/km)	**Energy E(kWh)**	**Charging Power P(kW)**	**Battery Range (km)**	**No. of Charging Stations n**	**Objective Function Z Rs (10^7)**	**No. of charging ports at a station (m)**	**Travel Time delay T(hrs)**
0.01	73.01	0.0	551.25	0	0.5	0	0.82
0.05	36.50	45.91	275.625	1	1.9	2	0.82
0.1	36.50	45.91	275.625	1	3.5	5	0.82
0.2	24.33	61.22	183.74	2	6.8	11	0.82
0.4	24.33	61.22	183.74	2	13.11	22	0.82
0.8	24.33	61.2	183.74	2	25.74	45	0.82
1	24.33	61.22	183.74	2	32.09	57	0.82

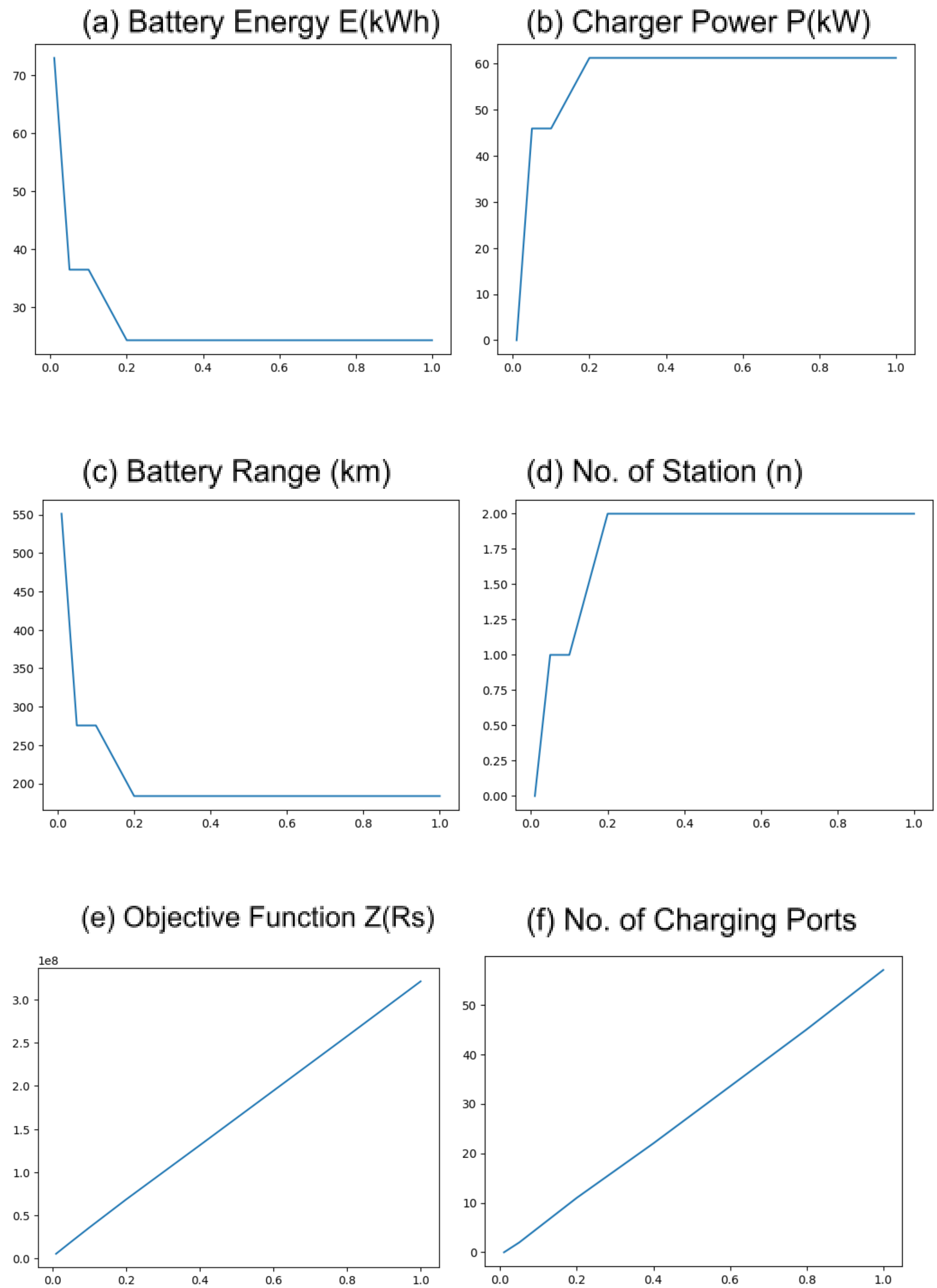

Fig. 2 Sensitivity of Infrastructure Variables against EV Penetration (veh/km)

Discussion

1. In India, the BIS standard plan out broadly three level of EV charging (Ministry of Power, GOI):
    a. Level 1 (AC and DC charging) @ < 7kW
    b. Level 2 (DC Charging) @ <22 kW
    c. Level 3 (DC Fast Charging) @ 50kW to 250kW

The Battery Capacity of some popular Indian Electric Vehicles are (Johnson):

a. Tata Nexon EV - 30.2 kWh
b. MS ZV EV - 44.5 kWh
c. Tata Tigor EV - 26 kWh

Thus, from Table 2,

- The electric vehicles presently available have sufficient capacity for the travel
- The infrastructure of DC Fast charging Level 3 needs to be developed for optimal level of service.

2. **The models show Level 3 DC fast charging as the most cost-effective way to build the infrastructure for electric vehicles.**

From Figure 1(b) , it can be seen as the Charger Power decreases, the delay factor increases, decreasing the level of service. From Fig. 1(e) , the increase in Objective function is relatively minimal as charger power increases.

An important observation is Fig2(b), whereas the penetration of EV increases, the charging power increases and converges towards 61 kW. This shows the current level 1 and 2 chargers are suboptimal for electric vehicle cost and growth, as they either mandate the use of expensive high-capacity batteries or force the EV users to tolerate a lower level of service.

This also explains why Level 1 and 2 Charging stations are the most common type of chargers currently deployed in the country. It isn't optimal to start with Level 3 chargers when the penetration of EV is very low (d ~ 0.01 to 0.2) from Fig1(b).

3. The model shows current battery sizes available can provide a good level of service for highway transportation of medium length. As shown in Fig1(a), a further increase of Battery capacity over 25-30kWh has a minimal increase in the level of service at the cost of a much more increase in the objective function, Fig1(e).

More so, Fig 2(a) shows that at a given level of service = 0.15, optimal battery capacity reduces as the penetration of electric vehicles increases.

Drawbacks and Prospective Improvement

Major Drawbacks of the simple corridor model are

1. It assumes every car trip will stop at every station, and every station must be able to accommodate them all at the same time. This burdens every single station (Fig2(f) no. of charging ports at a station as high as 50), making them large and prone to act as a bottleneck in case of failure.
2. A single exit and single entry are considered here for simplicity. Corridors must have multiple exits and entries.
3. There is no incorporation of the time value of money lost in the objective function. The charging time only acts as a constraint. The inclusion of time lost in charging and waiting in line in the objective function can provide more realistic results.

Some methods by which this can be addressed is:

- The corridor can be divided into N nodes where each node can be a point of exit, entry or charging station. Each node is at an equal distance l km.
- Let say the car enters from the pth node, to reach the qth node. Meanwhile it stops at ith node and jth node,to charge. where, $0 \leq p \leq i \leq j \leq q \leq N$.
- Now the charge lost from p to i is = ((i-p)*l)/ β . Note the constraint is the distance between (p, i, j, q) $\leq \beta\theta E$ ($anxiety\ distance$)
- We can calculate time it will take to charge at ith station t_L = charge lost/P
- Given a cost associated with time of user (C_T) , cost to user = C_T * t_L. Further, if there are m number of ports in the charger and the number of cars demanding power G > mP, there

will be an additional queuing time ∝ (G-mP). **Thus we can incorporate waiting time and queuing time as a user cost.**

- Minimising the queuing time along with data of trips between each (p,q) pair will help us decide which nodes should have chargers and the number of ports (m) at each charger. This will give a much more optimal and distributed charging grid.

However, the objective function in this case will be a mixed integer optimization problem with nonlinear constraints. It can only be solved with a Simulated Annealing Optimization algorithm or advanced MINLP solvers. (Ghamami et al.)

Conclusion

In conclusion, the optimization of electric vehicle (EV) chargers along a highway corridor in India presents significant opportunities for enhancing the infrastructure and services for EV users. Through the analysis and modeling conducted in this project, several key findings have emerged:

- Firstly, it was observed that the current battery capacities of popular Indian EVs are sufficient for the travel demands. However, the infrastructure for Level 3 DC fast charging needs to be developed to provide an optimal level of service. The models demonstrated that Level 3 DC fast charging is the most cost-effective approach for building the EV charging infrastructure.
- Furthermore, the research highlighted the suboptimal nature of Level 1 and Level 2 charging stations in terms of cost and EV growth. As the penetration of EVs increases, it becomes evident that these lower levels of charging power either require expensive high-capacity batteries or result in a lower level of service for EV users. Thus, there is a need to transition towards Level 3 charging stations as EV adoption grows.

- The analysis also revealed that current battery sizes can adequately support medium-length highway transportation, and further increasing battery capacity beyond 25-30 kWh has minimal impact on the level of service. Additionally, optimal battery capacity decreases as the penetration of EVs increases, indicating the need for continuous evaluation and adjustment of charging infrastructure based on evolving EV trends.

Despite the valuable insights obtained from the corridor model, some limitations were identified. The assumption that every car trip stops at every charging station and the lack of multiple exits and entries within the corridor oversimplify the real-world scenario. Additionally, the absence of the time value of money in the objective function limits the realism of the results. Future improvements could address these drawbacks by incorporating multiple nodes within the corridor, considering the time lost during charging and waiting, and optimizing charging grid distribution to minimize queuing time.

Addressing these limitations would require the application of more advanced optimization algorithms, such as Simulated Annealing or MINLP solvers, as the problem becomes a mixed integer optimization problem with nonlinear constraints.

In conclusion, the optimization of EV chargers along a highway corridor in India holds promise for enhancing the infrastructure and services for EV users. By considering the findings and potential improvements discussed in this project, policymakers and stakeholders can make informed decisions to support the growth and efficiency of the electric vehicle ecosystem in the country.

Works Cited

Ghamami, Mehrnaz, et al. "Electric Vehicle Charger Placement Optimization in Michigan: Phase I -Highways." *TRR*, vol. 2675(s), 2021.

Ghamami, Mehrnaz, et al. "A general corridor model for designing plug-in electric vehicle charging infrastructure to support intercity travel." *Transportation Research Part C : Emerging Technologies*, vol. 68, 2018, pp. 314-329.

Johnson, Mariya. "Comparison of Electric cars in India- Battery capacity and range." *YoCharge*, 20 March 2022, https://yocharge.com/comparison-of-electric-cars-in-india-battery-capacity-and-range/. Accessed 15 May 2023.

Ministry of Power, GOI. "Untitled." *Ministry of Power*, https://powermin.gov.in/sites/default/files/webform/notices/Final_Consolidated_EVCI_Guidelines_January_2022_with_ANNEXURES.pdf. Accessed 15 May 2023.

Nie, Yu (Macro), and Mehrnaz Ghamami. "A corridor-centric approach to planning electric vehicle charging infrastructure." *Transportation Research Part B*, vol. 57, 2019, pp. 172-190.

Raphaela Pagany,, et al. "A review of spatial localization methodologies for the electric vehicle charging infrastructure." *International Journal of Sustainable Transportation*, 2018, pp. 433-449.

Scott Hardman, et al. "A review of consumer preferences of and interactions with electric vehicle charging infrastructure." *Transportation Research Part D*, 2018, pp. 508-523.