CE 494 : BTP I

Optimization of Battery Electric Vehicle Charging Infrastructure Along A Highway Corridor

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Abstract

- Despite the availability of reasonably priced electric vehicles, the sluggish growth of EV adoption in the country can be attributed primarily to inadequate infrastructure.
- Objective: 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 initial phase of the study concentrates on a simplified model of a single corridor, incorporating the calculation of optimal battery range and charger power
- Refinement to The objective function are suggested to enable more precise optimization and analysis

Literature Review

- Optimization methods for designing EV infrastructure focus on chargers or swapping stations. Few DC fast chargers can support extensive intercity routes (Jochem et al., 2016).
- Density cluster-based approaches for charger location can be used for optimization (Raphaela Pagany et al.).. But these were rejected over corridor based approach
- Corridor-centric approaches, like the Michigan State EV Charger System, are relevant to this study (Ghamami et al.)
- Valuable insights from industry experts:

  Fast chargers at equal distances along the highway can cater to EV charging needs (Tata Motors).
  Low EV penetration and trip frequency on highways in India (Tata Motors).
  Range anxiety and reliability of chargers impact EV commuting (Exponent Energy).
  Placement of chargers is more predictable in longer highway strips (Exponent Energy).

Model Formation - Simple Corridor Model

1. **Model Design(Nie and Ghamami) :**

- Variables = EV battery Capacity E, Charger Power P and Level of Service δ
- 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).
- Assuming,
  - All trips start and end at the two ends of corridor. All station in between are equally spaced
  - Each station must have enough charging ports to accommodate all trips
  - There is a upper bound T as the maximum time delay

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

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

Minimizes Cost

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

Controls a Level of Service

Model Formation - Simple Corridor Model

2. Optimization and Analysis :

Let the constant values in the objective function be:

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

Solution:

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

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

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

The Lagrangian of the problem is:

$$L = C_1C_3\frac{P}{E} + Cp\left(\frac{C3}{E} - 1\right) - C_1P + C_2E - \mu(TP + \varepsilon\theta E - C_3\varepsilon\theta)$$

And the Krush-Kuhn-Tucker conditions are

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

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

$$\mu(TP + \varepsilon\theta E - C_3\varepsilon\theta) = 0$$

Case Study

Applying 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 Code

Applying the simple corridor model to Mumbai Ahmedabad

Program:

A. Libraries used

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

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')
```

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

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

Results And Discussion

1. In India, the BIS standard plan out broadly three level of EV charging (Ministry of Power, GOI):
- Level 1 (AC and DC charging) @ < 7kW
- Level 2 (DC Charging) @ <22 kW
- Level 3 (DC Fast Charging) @ 50kW to 250kW
1. The Battery Capacity of some popular Indian Electric Vehicles are (Johnson):
- Tata Nexon EV - 30.2 kWh
- MS ZV EV - 44.5 kWh
- Tata Tigor EV - 26 kWh

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

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.

Results And Discussion

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

- From Figure 1(b) , 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
- In Fig2(b), as the penetration of EV increases, the charging power increases and converges around 61kW. This shows the current level 1 and 2 chargers either mandate the use of expensive high-capacity batteries or force the EV users to tolerate a lower level of service.

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

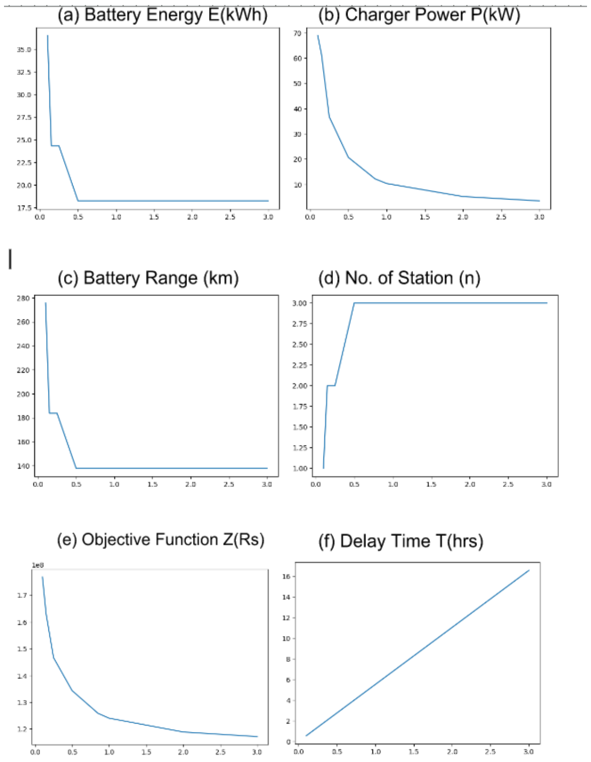

Fig. 1 Sensitivity of Infrastructure Variables against Delay Factor (Level of Service)

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

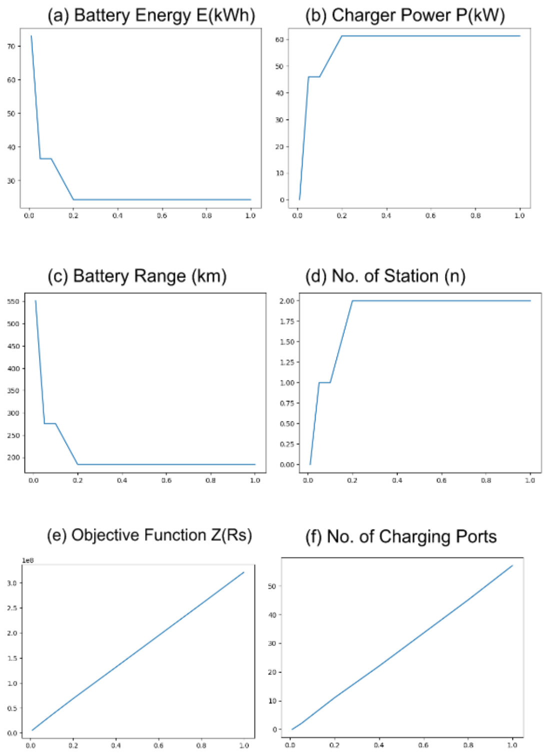

Fig. 2 Sensitivity of Infrastructure Variables against EV Penetration (veh/km)

Results And Discussion

3. Current battery sizes available can provide a good level of service for highway transportation of medium length

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

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

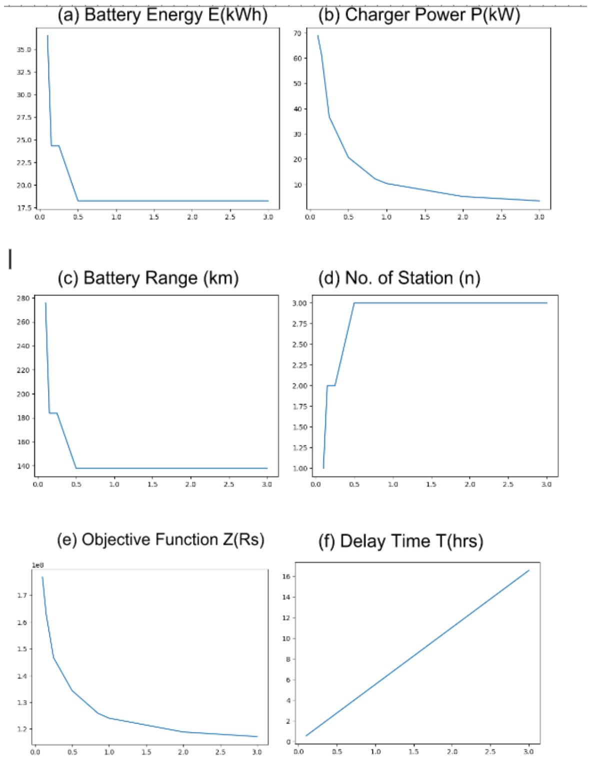

Fig. 1 Sensitivity of Infrastructure Variables against Delay Factor (Level of Service)

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

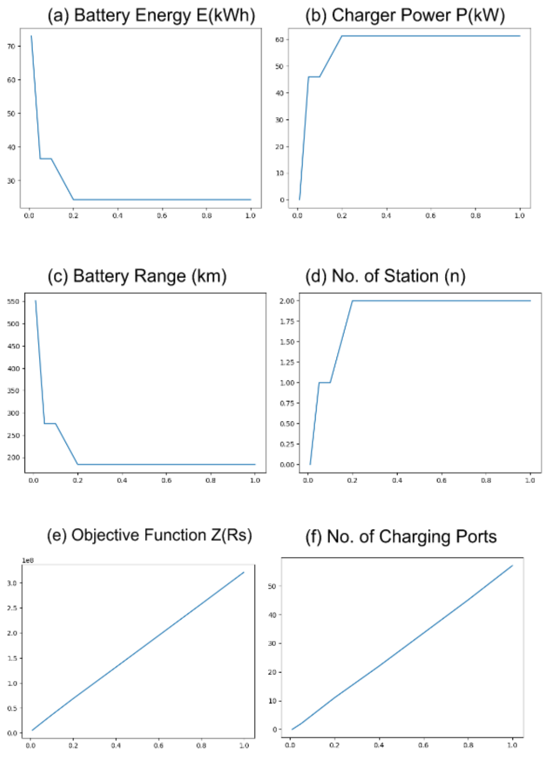

Fig. 2 Sensitivity of Infrastructure Variables against EV Penetration (veh/km)

Drawbacks

No Choice of Station

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 (charging ports at a station as high as 50), making them large and prone to act as a bottleneck in case of failure

Oversimplified Corridor

A single exit and single entry are considered here for simplicity. Corridors must have multiple exits and entries

Time as Cost

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.

Prospective Improvement

- 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)/ . 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 tL = charge lost/P. Given a cost associated with time of user (CT) , cost to user = CT * tL .
- 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.

This will be a mixed integer optimization problem with nonlinear constraints can only be solved with a Simulated Annealing Optimization algorithm or advanced MINLP solvers. (Ghamami et al.)

Conclusion

Applying the simple corridor model to Mumbai Ahmedabad a

1. Optimized EV charging infrastructure models have the potential to provide design EV infrastructure for Indian Highways.
2. The models demonstrated that Level 3 DC fast charging is the most cost-effective approach for building the EV charging infrastructure
3. Level 1 and Level 2 charging stations are suboptimal in terms of cost and EV growth, emphasizing the need to transition to Level 3 charging as EV adoption increases.
4. Current battery capacities are sufficient for medium-length highway trips, and further increasing capacity has minimal impact on service level
5. Future improvements should address limitations, including multiple nodes within the corridor, time lost during charging/waiting, and optimal charging grid distribution

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