Designing an optimized schedule of transit electric bus charging:

A municipal level case study

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Abstract:

In regards to increasing reliance on oil importations, anti-environmental contemplations, and a necessity for ecological automotive reforms, today Indian economy is descending towards serious financial and societal challenges. To respond, automotive technology has been transcending towards safe, efficient, connected, and comfortable electric mobility. However, public transport e-mobility being an emerging sector, the study of techno-commercial and administrative facets is essential to optimize several constraints like driving range, charging time & cost, electricity grid, scheduling, and so on. Hence, with an intention to minimize charging time during the service period of the bus, appropriate scheduling of vehicles is advocated in this study. A municipal level investigation has been conducted for Pune at PMPML route no. 139 from Nigdi to Shewalwadi, to evaluate the influence of scheduling by optimizing the charging time for Electric Urban transit Buses. This paper deals with the optimal scheduling of public transport e-buses by considering charging rate, discharging rate of batteries, rest time between consecutive trips, and distance between charging stations & estimation of the minimum required charging time between consecutive trips considering given constraints of the journey, also explains how does it help in the optimized scheduling of electric buses.

Keywords: Public transport, e-mobility, driving range, transit network, electric bus.

1. Introduction:

The conventional Internal Combustion Engine (ICE) driven vehicles emit high CO₂ in the air leading to various environmental problems and hence resulting in the degradation of the environment. The companies are also paying high penalties for high CO₂ emissions. Electric vehicles can be a solution to these problems as it can help to make the country pollution free ([Ingrid Malmgren, 2016](#)) and least dependent on oil-rich countries. The replacement of urban buses with electric buses could be a great start for the implementation of this greener technology. Although, electric transit buses have many advantages including High energy efficiency, cost-effectiveness, Low CO₂ emissions ([Lajunen and Lipman, 2016](#)), a major issue for them is their limited driving range. The survey reveals that diesel buses in metropolitan zones can run for 300 km but on the other hand contemporary, the electric buses can run 25 to 65% lesser than diesel buses i.e. between 70 - 200 km. So, this makes electric buses challenging to function uninterruptedly devoid of re-charging ([Mahmoud et al., 2016](#)), hence proper scheduling is of importance. Also, the Electric buses require approximately 2-3 hours to get completely charged from 0% SOC to 100% SOC, while diesel vehicles require much less time. This makes it important to have an optimized schedule for electric buses to provide proper service without compromising the operation and frequency of buses.

To overcome these drawbacks and ensure easy operation of Electric Buses, one of the following methods is proposed. First is, Battery Swapping Method (BSM), in which a new battery replaces the old one after being used up. This method acts costlier and substantial research is available ([Choi and Kim, 2014](#); [Dai et al., 2014](#)). The second method is Method of charging bus at charging station, here the electric buses which are to be charged need to be scheduled first, then to define the charging station locations and a respective number of charging

ports available. Mathematical model of Electric vehicle Routing with energy minimizing objective is already formulated ([Shuai Zhang, 2018](#)), also the Electric vehicle routing problem with the intent to minimize total traveled distance is also being already done ([Tomislav Erdelic, 2019](#)). This paper helps in finding minimum charging time required at a charging station, which is used to generate the optimum schedule to increase the availability of charging stations to upcoming new buses. More recently machine learning techniques have been employed for automated classification applications and which also can be applied for current domain ([Patange Abhishek D, 2019](#)).

One more major factor which is discussed in this paper is the gradual replacement of current urban buses with electric buses. Whatever research is done for scheduling of urban buses till now uses the current transit network as the basis for scheduling electric buses ([Yusheng Wang 2016](#)); so while implementing such schedules, replace all the existing buses with electric ones at the same time which is economically not feasible. The current framework keeps the flexibility for the gradual replacement of urban buses to incorporate electric buses more pragmatic and easier.

2. General Terminology

- Node: It is the main stop where the bus stops for a time longer than required for boarding and leaving of passengers. It is not necessarily a charging station.
- Waiting time: The waiting time is the time for which an electric bus waits at a charging station for it to start charging, as charging station is not available at that moment (i.e. Charging of some other bus is going on at that moment)

- Charging time: Charging time is the actual time for which the bus charges on a charging station.
- Rest time: Rest time is the time interval between the forward trip and the return trip for which the bus is not carrying the passengers.
- State of Charge (SOC): The charging percentage of battery at a time 't' is the SOC of battery at a time 't'.
- Threshold of charging Percentage: The lowest value of SOC below which discharging of batteries is avoided.
- Vehicle frequency: It is the number of electric buses making a round trip between two nodes.
- Range of Bus: It is the maximum distance traveled by bus when charged to 100% SOC.
- Service Hours: Service hours of an electric bus are the hours for which bus is actively handled by the driver to pick up the passengers.
- Trip: Trip is the cyclic journey which includes journey from, start point to end point and end point to start point.
- Trip number: Trip number at given instant of time is number of trips performed by the bus until that period of time.

3. Parameters considered:

The following parameters are used for the study.

- *Schedule parameters:* Distance between two consecutive nodes, Time required to go from one node to other (including the time for boarding and leaving of passengers),

Vehicle frequency, Rest time, Range of the bus. The schedule parameters are obtained from the data collected from the case study explained later.

- *Battery parameters:* Rate of fast charging, Maximum charge possible with charger, Minimum battery Threshold Charge, Charging, and discharging rate. The battery parameters are obtained from the specification sheets of the batteries being used for electric buses. These are kept pliant and can be varied with the batteries.

4. The methodology of Charging at respective Charging station:

In this method, we use charging ports to charge the buses, also avoid the deep discharging of batteries and the full charging of batteries at each time. Deep discharging is avoided for better battery performance, life and battery capacity ([Evelina Wikner & Torbjörn Thiringer](#)), and complete charging till 100% SOC is avoided as it requires more time for batteries to charge at higher percentages ([Evelina Wikner & Torbjörn Thiringer](#)). Thus the Electric bus preferably works between lower threshold of charging and maximum SOC in-service hours.

For the case study performed in this paper, the Threshold of charging is 20% SOC ([T. Guena, P. Leblanc](#)). These parameters are kept variable in the algorithm considered so that these can be changed according to battery specifications and user requirements. It is to be noted that, even if we avoid charging the battery to 100% each time after each trip, but we charge the battery to 100% overnight as we have sufficient time for charging at night without affecting the schedule of Bus. It is of prime importance to situate the charging station at proper position ([Weiwei Kong,2019](#)), also it's necessary to charge the buses for the optimal period of time at each charging station as explained: The charging Stations of electric buses have a limited time for charging of a specific bus and the newly arriving vehicles may have to wait before getting

Recharged because of the queue, Which increases the total cost by 1% to 26 % ([Merve Keskin, 2019](#)), also while the bus is waiting to get charged or charging at a station, this time is idle time ([David L.,2019](#)) i.e. the bus is not available to pick up the passenger, hence it is necessary to reduce charging as well as waiting time of the bus, which is possible by charging the bus to the only extent, required for completing the day with the threshold charging percentage remaining at the end of the day.

In the method described in this paper, we are able to generate this minimum value of charging time required on one end (In case of charging station available at one end only) or on both ends (In case of charging station available at both the ends), so that charging percentage left at the end of the last trip of the day is equal to the Threshold value of charging. The minimum charging time suggests the minimum time for which the bus should be charged between the two consecutive trips, so that at the end of the day charging percentage is equal to the Threshold charging percentage.

4.1 Necessity for finding the minimum charging time between two consecutive trips:

- We can get an optimum schedule with a minimum number of buses and chargers.
- We can reduce the waiting time as each bus will only charge the battery to the required minimum extent, hence it will actually reduce its time of overall engagement with the charging station.
- We can maximize the number of trips as we decrease the idle time of the bus by minimizing charging time and waiting time.

4.2 Factors required for the calculation of the minimum charging times are as follows:

- Range of bus with full charging(Range is the maximum distance a bus can travel with 100% SOC at the start)
- Distance of journey
- The time required for complete charging of Battery
- Average time required for completing the journey
- Rest time at the start point and endpoint

These factors are obtained from the case study at PMPML Route 139, Pune, Maharashtra, India.

5. Assumptions made:

The assumptions considered in the optimization are stated here.

1. *Charging and discharging rate is constant over the range of charging available:* It means that time required to charge a battery by a specific amount of charging percentage is always equal irrespective of charging percentage at the start of charging.
2. *All electric buses are homogenous and have the same driving range:* It means that all the Electric buses coming under the schedule have same battery specifications and same Bus requirements.
3. *One electric bus serves only one route and there may be multiple electric buses on one route:* One particular electric bus only serves one route and it follows the same route again and again in each cycle while there might be multiple buses on the single route. Hence we consider that the distance traveled on each trip for a particular bus is constant and hence the decrease in the charging percentage is the same in each trip for a particular bus.

4. *Energy stored is directly proportional to the duration of charging:* As we consider the charging rate is constant, the increase in the percentage of charge will also be constant, which will be directly proportional to the time available for charging the vehicle. The relation between the time of charging and the energy stored is assumed to be linear.
5. *Energy discharged is directly proportional to the distance travelled:* The relation between the percentage of SOC discharged and distance travelled is assumed to be linear.
6. *Recharging process is continuous:* We have also assume that recharging is a continuous process without any lag or time delay, causing the particular increase in stored energy of a battery in a particular time and any time lag or fluctuations aren't considered while charging . Once the vehicle starts the charging there is no lag further or voltage fluctuation which will cause the non-uniformity in the charging process and process is to be completely continuous from start of the process to the end of the process. When the bus comes on the charging station it might have to wait for some time due to non-availability of chargers but once it starts charging, the charging process continues for given charging time.
7. *Electric buses are fully charged overnight:* All electric buses are charged to 100% of SOC overnight, so that full charging is available at the start of the journey.

6. Designing the Algorithm:

The algorithm is designed to calculate % of charging left at particular time and station for given travelling distance. The input parameters to be provided for the algorithm are: waiting time, charging time and rest time at both the stations. The different abbreviations used in the algorithm are:

- T_{AB} : Time required for the bus to go from A to B
- T_{BA} : Time required for the bus to go from B to A
- T : Time of the day at particular instant
- T_E : Time of the day at which day ends
- R : Range of electric bus(Maximum distance the bus can travel with 100 % charging at start)
- T_f : Time required for complete charging of the bus from 0% SOC to 100% SOC
- d_{AB} : Distance covered by the bus to go from A to B
- d_{BA} : Distance covered by the bus to go from B to A
- %C: Charging percentage of a battery of electric vehicle at given instant of time
- T_{CB} : Charging time at B
- T_{CA} : Charging time at A

Figure 1 shows the flowchart. If the time left after performing a round trip is smaller than the time required for the journey from A to B, then the next trip is performed otherwise the bus stops at that node. It is assumed that if the bus travels a distance of 200 km then the charging percentage drops from 100% to 0%. According to our assumption charging falls linearly with distance, so if in 200 km charging drop is 100%, then in “x” km it will drop by a particular amount which can be found, as there is a positive linear relation between “charging % drop” and “Distance”. It is also assumed that the bus charging percentage increases linearly with charging time. That is as charging time increase, charging percentage increase linearly, so if the bus charges from 0% to 100% in 3 hours, then in time of “t” hours it will charge by $(100*t)/3$.

Figure 1: Flowchart of an algorithm

7. A Municipal level case study:

A municipal level investigation has been conducted for Pune India, at PMPML (Pune Mahanagar Parivahan Mahamandal Limited) route no. 139 from Nigdi to Shewalwadi. This investigation is based on factors like the optimal scheduling of public transport e-buses by considering charging rate, discharging rate of batteries, rest time between consecutive trips, and distance between charging stations.

- PMPML Circuit Route: 139

The starting point(A): Nigdi JakatNaka

Endpoint(B): Shewalwadi Bus Depot

Distance to be covered from A to B: 28km

Distance to be covered from B to A: 28 km

Time for traveling from A to B: 1 hour45minutes

Time for traveling from B to A: 1 hour 45 minutes

- Charging/discharging of the bus:

Range of bus: 200 km/Full charge

Rate of fast charging: (0-100) % State of Charge (SOC) in 3hours =0.55% per minute

Rate of Discharging: 0.5% per km

Minimum SOC threshold: 20%

- Working hours:

Cycle commences at 7.50 am (bus fully charged)

Cycle ends: Approximate 12 AM.

The manufacturer of the bus is Olectra and the model is K7. For the first half, the cycle starts at Nigdi Jakat Naka (A)and ends at Shewalwadi Bus Depot (B), and later starts at Shewalwadi Bus Depot (B)and again comes back to Nigdi JakatNaka (A). The distance between A and B through a particular root, is 28 km. The range of the buses used in the PMPML is 200 km per hundred percent charging. For a hundred percent charging it requires 3 hours charging time. The minimum SOC is 20% as that of the maximum charge possible. To ensure an optimum time schedule without hindering the battery life and performance first trip starts at 7.50 am, and the last trip ends before 1 is, hence the working hours are from 7.50 am to 1 am. The average time required for a bus to go from A to Band B to A is 1 hour 45 minutes.

7.1 Possibilities:

Two possibilities are considered here:

7.1.1 Possibility I: Charging station available at both ends of a trip: An example of a journey with the following parameters as in the case study.

- Range of bus with full charging: 200 km
- Distance between the start point (A) and endpoint (B) of the journey: 28 km
- The time required for complete charging of Battery: 3 hours
- Average time required for completing the journey: 1h:45m:00s
- Rest time at start point (A): 20 minutes
- Rest time at the endpoint(B):15 minutes
- Start of the day: 7:50 AM
- Maximum time allowed at the end of the last trip: 12 AM

Some constraints to solve for minimum charging time:

- Charging time at A < Rest time at A
- Charging time at B < Rest time at B
- Charging percentage left at the end of the day = 20 (Threshold charging percentage)
- Start of the day = X AM, End time of last trip < Y (AM/PM)

Result for Possibility I: Minimum charging time was calculated with the help of the Microsoft Excel solver tool, under the above constraints. The observations are:

- Minimum charging time of the bus at charging station A (Start Point): 00:08:31 (hh: mm: ss)
- Minimum charging time of the bus at charging station B (Endpoint): 00:08:01 (hh: mm: ss)

Table 1: Result for the possibility I

Time	Location	Total distance travelled (km)	Remaining charging (%)	Trip No.
7:50 AM	A	0	100	1
9:35 AM	B	28	86	
9:50 AM	B	28	90.45 (Charged for 8m:1s)	
11:35 AM	A	56	76.45	
11:55 AM	A	56	81.18 (Charged for 8m:31s)	2
1:40 PM	B	84	67.18	
1:55 PM	B	84	71.63 (Charged for 8m:1s)	
3:40 PM	A	112	57.63	
4:00 PM	A	112	62.36 (Charged for 8m:31s)	3
5:45 PM	B	140	48.36	
6:00 PM	B	140	52.81 (Charged for 8m:1s)	
7:45 PM	A	168	38.81	
8:05 PM	A	168	43.54 (Charged for 8m:31s)	4
9:50 PM	B	196	29.54	
10:05 PM	B	196	33.99 (Charged for 8m:1s)	
11:50 PM	A	224	19.99

Figure 2: Trend of % charging vs. the time scale for the possibility I

Figure 3: Distance covered vs. time for the possibility I

7.1.2 Possibility II: Charging station available at one end only: An example of a journey with the following parameters as in the case study.

- Range of bus with full charging: 200 km
- Distance between the start point and endpoint of the journey: 28 km
- The time required for complete charging of Battery: 3 hours
- Average time required for completing the journey: 1h:45m:00s
- Rest time at start point: 20 minutes
- Rest time at the endpoint :15 minutes
- Start of the day: 7:50 AM
- Maximum time allowed at the end of the last trip: 12 AM

Some constraints to solve for minimum charging time:

- Charging time at A < Rest time at A
- Charging time at B = 0
- Charging percentage left at the end of the day =20(Threshold charging percentage)
- Start of the day = X AM, End time of last trip < Y (AM/PM)

Result for Possibility II: Minimum charging time was calculated with the help of the Microsoft Excel solver tool, under the above constraints. The observations are:

Minimum charging time of the bus at charging station A (Start Point): 00:19:12 (hh:mm: ss)

Table 2: Result for possibility II

Time	Location	Total distance travelled (km)	Remaining charging (%)	Trip No.
7:50 AM	A	0	100	1
9:35 AM	B	28	86	
9:50 AM	B	28	86 (No charging at B)	
11:35 AM	A	56	72	
11:55 AM	A	56	82.66 (Charged for 19m:22s)	2
1:40 PM	B	84	68.66	
1:55 PM	B	84	68.66 (No charging at B)	
3:40 PM	A	112	54.66	
4:00 PM	A	112	65.33 (Charged for 19m:22s)	3
5:45 PM	B	140	51.33	
6:00 PM	B	140	51.33 (No charging at B)	
7:45 PM	A	168	37.33	
8:05 PM	A	168	48.00 (Charged for 19m:22s)	4
9:50 PM	B	196	34.00	
10:05 PM	B	196	34.00 (No charging at B)	
11:50 PM	A	224	20.00

Figure 4: Trend of % charging vs. the time scale for possibility II

Figure 5: Distance covered vs. time for possibility II

8. Results:

After comparing the results for both the cases, the following inferences can be made.

- For charging stations at both the nodes Nigdi and Shewalwadi, the charging time at each station is approximately 8 min.
- For charging station only at Nigdi (or only at Shewalwadi), the charging time is approximately 19 min.

Now, considering these results along with the availability of chargers for the obtained time and other buses of the same route, it is possible to predict if the charging station is required at a particular node. In our scenario, if the chargers are available for more than 19min 12 sec at Nigdi, then it is not needed to build a charging station at Shewalwadi. The availability of chargers for a given time can be predicted using the schedule of other buses coming at the same charging station for charging and the number of chargers available at a particular charging station. Sometimes, it is enough to just increase the number of chargers at a particular station than creating the entire charging station at some other node. This method is used for the given route parameters, but the flexibility of input parameters ensures the application of the method to any similar route.

It is understood that at the end of the last trip(i.e. end of the day), charging remaining should be equal to the threshold value for perfect optimization of schedule. If this value is greater than the threshold, it indicates that extra time was spent for charging which was not needed. If the value is lesser than threshold, it connotes that charging time was not sufficient with respect to predefined threshold value. From this, we can conclude that, there exists a particular 'Charging time' on charging station A as well as B, which can be found by giving constraints as specified,

which gives the exact threshold charging percentage at the end of the last trip of the day, thus giving the optimized schedule.

9. Conclusion:

The study provides the most optimized charging time at a particular charging station for both the cases: when charging stations are available at starting, ending point and when charging station is available only at the starting point. This provides us with the charging percentage remaining and the total distance covered at every moment of the day. Nevertheless, this information can help us predict the necessity of charging station at a particular transit point by comparing the two cases, one with charging station and other without charging station. The incorporation of the study in the actual transit network is gradual and hence it will not affect other engine buses while designing the route for an electric bus.

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