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Next-Generation Smart Electric Vehicles Cyber Physical System for Charging Slots Booking in Charging Stations

SURESH CHAVHAN[1,2], (Member, IEEE), NIKHIL DUBEY[3], ABHINAV LAL[3], DEV KHETAN[3], DEEPAK GUPTA[2,3], ASHISH KHANNA[2,3], JOEL J. P. C. RODRIGUES[2,4], (Fellow, IEEE), AND PLÁCIDO ROGERIO PINHEIRO[5,6], (Member, IEEE)

[1]Automotive Research Center, Vellore Institute of Technology, Vellore 632014, India
[2]Post-Graduation Program in Electrical Engineering (PPGEE), Federal University of Piauí, Teresina 64049-550, Brazil
[3]Department of Electrical and Electronics Engineering, Maharaja Agrasen Institute of Technology, New Delhi 110086, India
[4]Instituto de Telecomunicações, 1049-001 Lisbon, Portugal
[5]Graduate Program in Applied Informatics, University of Fortaleza, Fortaleza 60000-000, Brazil
[6]Graduate Program in Applied Informatics, State University of Ceará, Fortaleza 72467, Brazil

Corresponding author: Deepak Gupta (deepakgupta@mait.ac.in)

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ABSTRACT Owing to the increased worldwide awareness regarding pollution caused by the consumption of fossil fuels, Battery-powered vehicles are bound to take over the conventional Internal Combustion Engine. Keeping the difficulties faced by the economy of the city and the populace of adapting to an entirely grid-run charging infrastructure in mind, a framework incorporating electric vehicles to everything (EV2X) communication and Charge Slot booking based on data got from a survey conducted has been developed in this literature. The conclusions drawn from the survey develop key insights into developing statisticorating the use of LTE to support the conventional OCPP and promote user controlal models that are further explored in this context. Algorithms and strategies to implement next-generation efficient EV2X communications have been implemented and developed for the city. Further, we have established a priority order for slot booking and incorp over charge-cycles. Introducing IPMUs using an LTE connection to act as a supplement to the conventional OCPP is explored in this context. Besides that, we have built the M/M/m queuing model of EVs in the charging station and its optimisation. We have done the exhaustive evaluation of the robustness of the proposed system in a fairly large-scale network in a discrete-time event simulator. The proposed system's results (simulation, analytical, and comparison) show the reduction of waiting time, good accuracy, and saving of charging time and costs. These performances measures improve shows the real-time applicability of the proposed system.

INDEX TERMS Electric vehicles, charging stations, charging slots booking, EV2X, queuing model.

I. INTRODUCTION

As we move towards a smarter world, with a better understanding of our surroundings and resources, the conservation thereof is a widespread thought prevailing in the minds of the masses. The shift towards an all-Electric powered vehicle is no longer a possibility, but an eventuality. When measured against their predecessors, EV's are limited by the range they can traverse in one charge cycle and the output power that they can generate, limiting their use in heavy-duty automotive in the immediate future. For most second and third world countries, the concept of EVs comprising most of the on-road traffic is still synonymous with a pipe dream. By definition, a city-wide infrastructure alteration to meet the demands of an entirely grid-run electric-powered traffic will cause a major shock to not only the economic state of the city but will also adversely affect the portion of the population still operating on conventional source-powered vehicles.

According to the 2019 survey report by the National Automotive Board, India has around 278691 EVs (2-wheelers,

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e-rickshaws, buses, and 4-wheelers) on the road. By 2030, India takes overall fossil fuel vehicles into EVs and AVs for transportation, to realize the environment-friendly transportation system. Successful adoption of EVs might help India save up to 300 Bn (INR 20 Lakh Cr.) in oil imports and nearly 1 gigaton of Carbon Dioxide emissions, as per a recent report by FICCI and Rocky Mountain Institute. Besides, EVs can become a stepping stone towards designing an intelligent, futuristic transport infrastructure in India that can cater to the mobility needs of the country's vast population. The main idea of adoption of EVs is to replace the existing fossil fuel-powered vehicles, which reduces GHG emission into the air. In the urban cities, most of the time (i.e., 90-95%) vehicles be parked in the house, malls, office, public places, etc.

Owing to the adoptation of EVs in urban territories, there will be a rise in need of charging stations. Also, the mass adoption of EVs mandates a robust charging infrastructure, communication infrastructure between EVs [3]–[5] and charging stations [3]–[5], and highlights the necessity to build a communication infrastructure between a dedicated aggregator and grid [6], [7]. Managing power transaction processes of EVs because of the varying demands and highly intermittent renewable energy sources penetration at different periods will be a major challenge [22], [25].

Managing the charging profiles of EVs, power profiles of charge stations, handling different renewable sources [13], [16], [24] because of its randomness and timely management of demands and responses of power and EVs are few more issues involved in the dynamic nature of metropolitan cities [18]. Hence, there is a need for efficient techniques to analyse the urban city demands, identify the potential charging station and charging points, and provide seamless communication connectivity between EVs and charging station for power transaction along with the intelligent transport system in smart cities.

GA(Global Aggregator), as discussed in [1], controls and manages the slot booking in a localized group of chargers. Whenever an EV reaches in an area which generates a request to book a slot, the request will be transmitted via the RoadSide Unit (RSU) to the GA. Therefore, GA addresses the request based on the present conditions of charging stations. The IPMU is registered with the vehicle for checking the battery statistics with the help of OBD and can access the charge broadcasts made by the GA. The IPMU periodically provides to the user with more rigorous control over the vehicle statistics and consecutively allow them to schedule a charge based on their preferred time. Where the RSU malfunctions or cannot communicate to the vehicle, the connection between the vehicle and IPMU can be utilized by the vehicle to access charge broadcasts and subsequently make reserve charging slots if needed, immediate utilizing the mobile connection as an alternative route to communicate with the GA.

The main contribution of this paper can be outlined as follows:

1) Conducted the real time survey to collect the necessary data relevant to the study and drawn the conclusions from the collected data.
2) Developed the Framework and Architecture of the Next-Generation Communication based Online EVs Charging Slot Booking at Charging Station
3) We demonstrated the Communication Model of the EVs, RSUs, IMPU, GA and CSs with the algorithm
4) We built the stochastic queuing model for EVs in the charging station and derived the necessary equations.
5) We formulated the objective function of EV's charging at charging points in charging stations to determine the optimal charging time, minimal charging cost, least distance, minimal queuing delay and optimal duration for particular charging slots.
6) The proposed system has been tested in a fairly large scale network in the developed discrete-time event simulator.

The rest of the paper is organized as follows: Section II comprehensively discusses the few related works; Section III presents the real time survey of current perception of EVs in the eyes of general public; Using the inferences drawn from the survey, Section IV focuses on the proposed next generation communication based online EVs charging slot booking architecture; Section V addresses the issue of traffic management at a charging station by introducing a stochastic queueing model to address charging time; Section VI focuses on the formulation of the optimisation problem and analysis of the results is presented in Section VII. Section VIII concludes the paper along with future work opportunities.

II. RELATED WORKS

A. CHARGE SCHEDULING AND V2V COMMUNICATION

Authors in [1] proposed a scheme to manage EV charging that minimizes the charging waiting period (with pre-empted charging service) for heterogeneous EVs. Based on the knowledge of those EVs parked locally at CS's as well as those who make reservations for charging remotely. This detail helps plan charging schedules for EVs that will take place early with waiting time.V2V coordination flexibility (with DTN (Delay Tolerant Network) nature) to transmit the charging reservation of the EVs. Our research tackles this issue for a broader period and utilizes low-charge V2V contact to meet traffic conditions of heavy networks that impede the scope and service capabilities of RSUs.

B. VEHICLE TO INFRASTRUCTURE

Authors in [2] proposed a model to evaluate the throughput performance of multiple vehicles sharing the wireless resources of 802.11-based AP in a given mobility scenario to capture the impact of road capacity, vehicle density, and vehicle relative speed differences on the V2I communications throughput performance. The model incorporates this design method to allow vehicle density network as the scenario is one of transformation to a completely grid-run EV network.

Authors in [3] further elaborate the usage of V2I contact to collaboratively assess optimal speeds for EVs and other necessary measures to be performed with minimum delays while preventing threats to power grid components caused due to variation in Spatio-temporal EV demand patterns.

C. DETERMINATION OF OPTIMAL CHARGING STATION AND PRICING MODEL SETUP

Authors in [4] proposed a set of criteria to be exchanged over the contact network for the EV and the charging stations. This approach analyzed the effect of standardized and competitive pricing models on EV users' preferred range of charging sites, which further depended on distance of charging from the CS. A study was performed in this literature to quantify the gap between charging stations that can be scaled up based on population density, as well as economic conditions that fit various accessibility scenarios. Such frameworks can then be capitalised to exploit peak time payment prices by the state government to improve finances.

D. COMMUNICATION TECHNOLOGIES USED IN V2X AND EFFECTS ON POWER GRID

Authors in [5] discuss the significance of the possibility that the introduction of EVs would present risks to the current power system in the absence of two-way communications and provide a detailed collection of tools and methods to be included for the same. They makes use of a survey to generate a forecast market for EVs. Instabilities of the power grid and patterns of load demand profile can be estimated by the inferences drawn in the survey and subsequent action plan can be developed on the same.

E. WAITING TIME OPTIMISATION

Authors in [6] develop a theoretical model to reduce waiting period of charging by intelligently arranging spatially and momentarily charging tasks. It focuses on a theoretical analysis to formulate the question of decreased waiting time in charging scheduling and extract an upper bound efficiency. Our research emphasizes the scheduling of slot bookings which, by reducing charge time and collision scheduling, facilitates this operation.

III. SURVEY REPORT

The survey included questions about the present and upcoming scenarios for Electric Vehicles in the world from the eyes of final consumers. The survey was conducted in a typical form filling fashion with the sample audience being selected at random, thereby minimizing sample selection bias. The questions were designed by keeping in mind the facts that the individual remembers to the utmost clarity and thus aims at minimizing assumptions made by the subject.

Keeping in mind the wide distribution of the types of subjects and their driving habits, including but not limited to the number of days driven in a week and the distance travelled each day, an algorithm was developed to weigh the responses based on the time spent by the subject on the road. The following algorithm yields the statistics produced by an "average" individual. This model matches the average distance commuted in a day by 4 wheeler in Delhi [7] within the error range of 1.16 percent. The raw data input fields chosen here were selected by keeping in mind which facts the subject was most likely to remember with the most accuracy.

A corresponding data field containing the estimated monthly expenditure on fuel was used to cross-reference the distance travelled with an average of fuel prices for the past month. The entries with more than 40 percent of deviation were scraped from the final calculations. As a result, a total of 150 data entries were evaluated.

Variable definition

- Number of entries in a field is n
- D_{avg} indicates average distance travelled in a week
- UD_{avg} denotes mean deviation from average distance travelled
- Mu indicates average distance travelled
- $i = 1$ to n
- $MAX(X)$ is the maximum value in field X

Algorithm 1 Calculation of Modified Weighted Deviation

1: Extract the *"Number of Days Travelled in a Week"* and the *"Average Distance Travelled in a Day"* into A and B respectively to serve as the raw input data.
2: Calculate the *"Total Distance Travelled in a Week"* by multiplying the fields $AandB$ and storing the result in field C.
3: Calculate D_{avg} and UD_{avg} from field C.
4: Compute Mu for entries within range $(D_{avg} - UD_{avg}) \leq Xi \leq (D_{avg} + UD_{avg})$ from C.
5: Compute absolute deviation for each entry from Mu and store the result in field D.
6: Convert the entries of D by $Ei = 100 - (Di/MAX(D)X100)$ and store the result in field E.
7: Return E

A. INFERENCES

The following conclusions were drawn from the data collected:

- The majority of subjects own 2 vehicles, very few subjects own 1 vehicle and a minority possess more than 3 vehicles. The general trend follows that the number of subjects decreases with an increase in vehicles owned.
- Most subjects possess petrol-powered vehicles over diesel, CNG, and electric.
- More than 65 out of 150 subjects are likely to buy an EV as their next vehicle. The following plot demonstrates the probability distribution as shown in Figure 1. This, when coupled with the fact that over 63 percent of the subjects intend to purchase new vehicle within 5 years, highlights the urgency of the need to develop an architecture capable of sustaining the change.

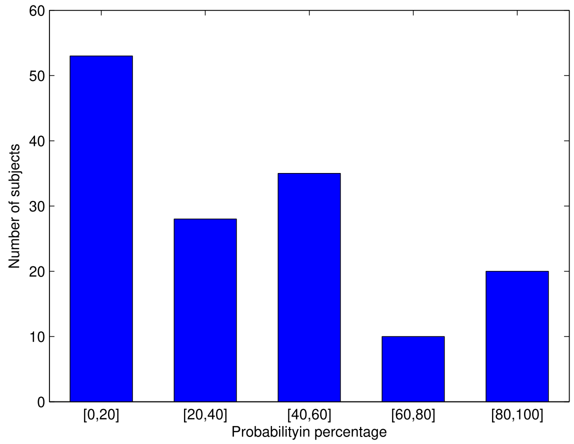

FIGURE 1. Probability distribution of subjects likely to purchase EV as their next vehicle.

- It was observed that almost 23 percent of subjects drive all 7 days in a week, on the other hand, more than 17 percent of subjects drive only 1 day in a week
- Subjects are more biased towards a normal distance on an EV i.e. they are not likely to go for very long journeys. They account for more than 38.7 percent.
- 49.3 percent of the subjects have a refuelling station situated within 1 Km radius from their residence and 8 percent of subjects have it within a 3-5 Km radius. The remaining subjects are situated within 1 to 3 Km of radius of a refuelling station.
- A majority of subjects wish for very little distance between refueling stations with almost 41 percent of subjects wishing for at most a 1 km distance. 43.3 percent of the subjects are comfortable with 1-3 Km radius and others are satisfied with a 3-5 Km deviation, they account for roughly 14 percent as shown in Figure 2. This is a potential indicator to the number of charging stations to be installed in a city.

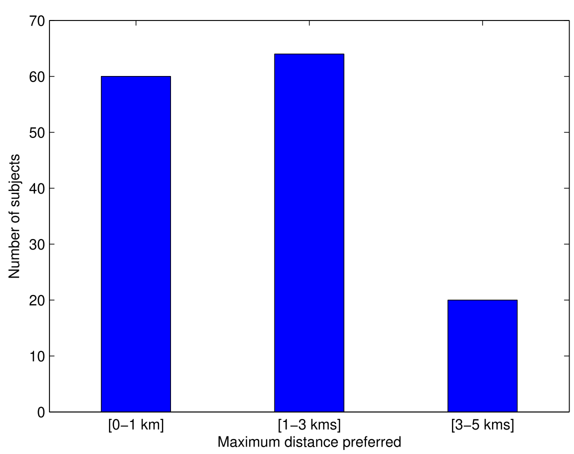

FIGURE 2. Maximum distance a subject is willing to traverse for the sole purpose of refueling.

- When it comes to charging preferences then 46.7 percent of subjects want a balance in charging cost and waiting time at charging stations. More than 58 percent of subjects are comfortable with charging their EV at night i.e. 8 PM – 12 AM, as shown in Figure 3. This serves to indicate the traffic density as well as the load on grid at different times of the day.

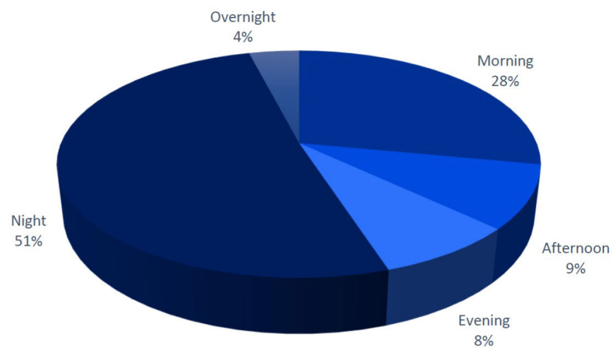

FIGURE 3. Preferred time interval for charging an EV.

The broad conclusions from the above-discussed points suggest that subjects wish to own an EV, they seem to be interested in buying or replacing their conventional vehicle with the EV. As evident from the outcome that 64.7 percent of subjects wish to opt for EV as an advantage over conventional vehicles. 32.7 percent of subjects consider that EVs will comprise of the majority of vehicles within the next 10-15 years. Moreover, over 56 percent think that EVs can save money for car buyers.

IV. PROPOSED ARCHITECTURE

Utilising the observations made in Section III, we developed next generation communication based online EVs charging slot booking architecture as shown in Figure 4. The model proposed utilizes a basic version of a GA, as presented in [1], [8], [9], to manage the charge request/reply in real-time. Road Side Units serve as a communication point between the EV and the GA. Immediate Proximity Mobile Units or IPMUs are introduced as smart devices registered with the EV, typically in the form of a smartphone or smart tablet which can work parallel to or substitute for RSUs in the case when RSUs are unavailable.

A. PARAMETERS IN COMMUNICATION MODEL USED BETWEEN EV, RSU, GA AND CS's

Before the drive begins, a connection is established to IPMU via the 802.11ah protocol which allows the connection to be established from a distance. This has the added benefit of functionality and safety checks. ECU is prompted for static parameters. Static Parameters include Battery SOC/percentage, Temperature, Average distance travelled per day, amongst others. Using these, estimations on average daily travel time and distance could be made which can be used to prompt the user for a suggested time of charging.

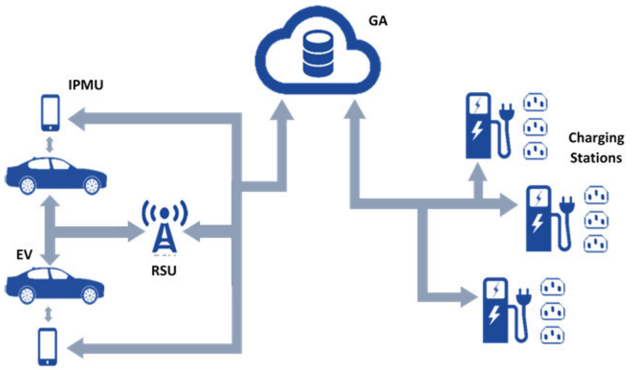

FIGURE 4. Proposed next-generation communication based online EVs charging slot booking architecture.

Once the destination coordinates are received from the driver, the charging station suggestions(if required) can be made which best suite the route with maximum time efficiency using the dynamic parameters. During traversal, after a set number of observations are made from the ECU, the earlier prompts can be updated dynamically.

Dynamic Parameters include Traffic conditions, Average speed, Current output, Temperature, Charging Rates, Peak Time, Time taken to charge, Availability of Ports, Type of charging available and charging stations present in route.

The Control Area Network (CAN) bus is an ISO industry norm for on-board vehicle communications [10]. Built to provide reliable connectivity with large rates of electrical noise in the very rugged automotive operating environment. A two-wire serial bus built to network smart sensors and actuators; can run at two rates: high speed (e.g. 1 M Baud) — used for essential operations such as engine monitoring, car stabilization, motion control; and low speed (e.g. 100 kBaud) — used for basic switching and illumination control, mirrors, mirror modifications, and instrument screens, etc. The protocol defines the method of addressing the devices connected to the Data format bus, speed of transmission, priority settings, error detection sequence, and control signals handling. The data frames are sequentially distributed through the bus.

RSUs always broadcast data and always receive data from GA. The 24×7 broadcast is useful as it will provide immediate information to EV users and hence drivers can select the CS best suited. RSU data packet contains CS available and their ID, location along with which mode of charging available. Since RSUs support 2-way communication/data flow, whenever an EV transmits a charging request it will be sent to nearby RSU via 802.11ah and the 802.11X protocols [2]. In case, when RSU is not present in that area where EV is present then request can be sent via IPMU to GA or data to EV can be sent via IPMU. RSUs send/receive data from and to the GA via LTE. This would enable extremely long-range data communications. The placement of RSU will be dependent on traffic statistics of the region and will, therefore, vary locally. In areas experiencing consistently high traffic, deployment of RSU's with exceptional high-speed data transfer and sustaining capabilities will be necessary. To overcome this, three methods are suggested: 1. The communication process can be supplemented by mobile networks and the gateway between the EV and the associated IPMUs be utilized to serve as a supplement on-demand accessible data set. This method makes use of the associated cellular bandwidth and therefore reduces RSU network traffic. 2. An array of high capability and broad-spectrum enabled RSUs to be equipped in areas sustaining high traffic conditions consistent periods. This will increase the overall system cost and will not prove to be beneficial in the long run unless the RSUs are designed to be mobile or can change the deployed location without extensive assets being utilized to change according to the changing trends in traffic experienced. 3. Use of V2V communication utilizing 802.15 (ZigBee protocol) [11] to serve as temporary servers in an arrangement similar to peer-peer data transmission can be utilized in conjunction with modern-day collision avoidance and speed limiting to maintain traffic conditions[12].

GA monitors each charging station in a particular limited area and also serves the local RSUs falling within the limits of its reach. At regular intervals, the GA prompts the charging stations for a charge broadcast. The Charge Broadcast is a data package comprising of available charging types, and possible slots and sends this information to RSUs. A GA also receives charge requests from RSUs and handles them on FIFO(First In First Out) basis [8], [9]. When a request is received, the GA checks the Charge broadcasts corresponds to that timestamp and the estimated charge time, then sends a recommendation as a reply to the request which consists of a list of CS's available: their IDs, location and recommendation ID. The recommendation can be sent via RSUs or IPMU (if the request is sent from an IPMU).

The charge request contains EV ID which is unique for each EV, type, and mode of charge for that EV, Request ID which will be generated new each time as of a One-Time Password (OTP). IDs are necessary for traversal of data to and forth, whenever recommendation received it will be sent to the ID only for which it is generated. Hence flow can be secured and reliable. Figure 5 demonstrates a pictorial summary of the Data Flow, representing the data format and transfer.

B. CHARGE REQUEST GENERATION

An EV, with sufficient energy above the SOC threshold, travelling on the road can access available time of charge information from aggregated Charging Stations via opportunistically encountered roadside units. If the driver opts for charging or if the EV reaches its SOC threshold, the EV generates a request to the GA.

Algorithm 2 has been developed focusing on driver inputs and the type of charging to be selected at the destination charging station, namely Battery Swapping and Wired Charging. These requests are then filtered to obtain optimum charging time and location most convenient to the driver.

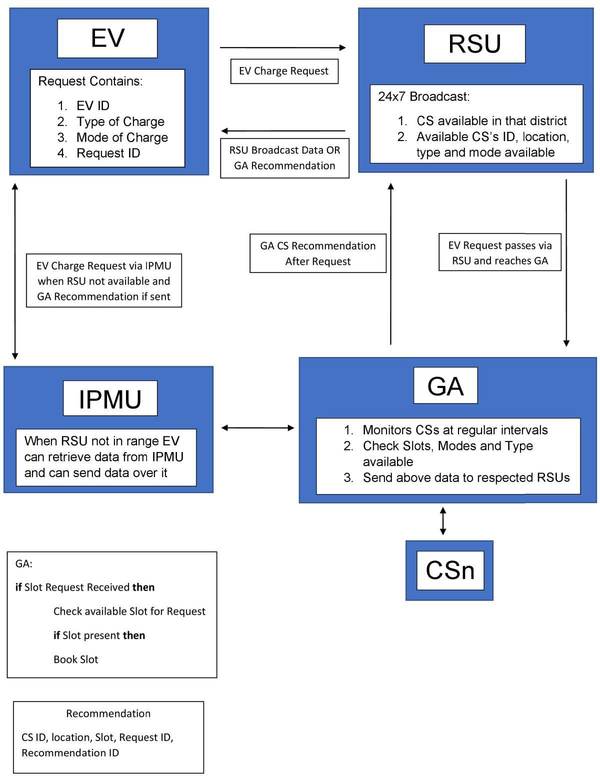

FIGURE 5. **Interactions, data flow and protocols to be used between EVs, RSUs, IPMU, GA and charing stations.**

Variable Definition
DD : *Destination Distance*
ED : *Estimated Distance*
RSU : *Road Side Unit*
RR : *Recommendation Received*
IPMU : *Immediate Proximity Mobile Unit*

C. CHARGE BROADCAST GENERATION AND SLOT BOOK REQUEST HANDLING

For managing charge broadcasts and the process of slot booking, an entry-level algorithm (Algorithm 3) was developed. The GA periodically prompts all the charging stations under its jurisdiction at a set frequency and prompts for charging requests, if made. The proposed algorithm assumes the following:

- The Charging Station's time distributed port availability is a two-dimensional matrix of the order *MXN*, where *M* depends on the broadcast frequency and *N* is the total number of ports in the charging station. The matrix follows column-wise traversal, which changes the starting point with every update in system time. Table 1 shows a sample port matrix.
- A certain number of Swap Batteries are kept aside for Emergency services, therefore the total number of Swap Batteries is calculated by computing the subtotal and the battery count is updated after each swap.
- The algorithm takes an input matrix of the order 1×3 with default value $[0, 0, 0]$. The first element is the charging preferred, the second element is the estimated amount of time required for charging, and the third element is the preferred time slot for charging.
- The algorithm returns two values, The Station Port Matrix, and the Acceptance status for each prompt.

Algorithm 2 Request Generation and Processing

Input: DD
Output: Return ED on the basis of current SoC
if DD > ED **then**
    Suggest Shorter path to conserve charge
    if User deny the suggested shorter path **then**
        Prompt user to book slot for charging
    else if Shortest path cannot be suggested **then**
        Prompt user to book slot for charging
    else if User Interacts **then**
        Go to book slot
    end if
else
    Go to check SoC
end if
Check SoC
if Current SoC $\leq$ Limit SoC **then**
    Switch to 'Power Saving' mode
    while User Interact with Book Slot $\neq 1$ **do**
        Prompt user at continuous interval to book a slot
    end while
end if
Book Slot
if Book Slot $== 1$ **then**
    Prompt for type of charging
    if Wired Charging $== -1$ **then**
        Generate Wired Charging Request
    else if Battery Swapping **then**
        Generate Battery Swapping Request
        if RSU Nearby $== 1$ **then**
            Send above generated request
        else if IPMU Nearby $== 1$ **then**
            Send above generated request
        end if
    end if
end if
while RR $== 1$ **do**
    Sort the list of charging station on the basis of location and waiting time
    Suggest shortest path to user for sorted charging station
end while
End

TABLE 1. Charge port matrix of a charging station with 5 ports for 5 time intervals.

Ports/ Time Intervals	P1	P2	P3	P4	P5
T1	0	0	0	0	0
T1	0	1	0	0	0
T1	0	1	0	0	0
T4	0	1	0	0	0
T5	0	0	0	0	0

Table 1 shows the sample charge port matrix of a charging station with 5 ports for 5-time intervals. Initial states of all the ports are 0 showing availability. Time slot T2 to T4 for P2 hold the value 1 indicating their reserved status.

Algorithm 3 Real-Time Charge Broadcast and Slot Booking

Input: In[3]
Station Port Matrix,, Acv
Data: $C, pol_1, \xi_{1,2,\ldots,j}(pol_1)$.
if $In[i] == 0$ **then**
    Update system time
    Return *Station Port Matrix,, Acv*
else if $In[i]$ ==Battery Swap **then**
    Update system time
    Check if battery is available for swapping
    if available **then**
        $Avc =$ *Swap Request Accepted*
        Update Available Battery count
    else if $Avc =$ *Request Denied* **then**
        Return *Station Port Matrix,, Acv*
    end if
else if In[i] == Battery Charge **then**
    Update system time
    $i++$
    $est.time = In[i]$
    $i++$
    time.slot $= In[i]$
    if Slot is available **then**
        $Avc =$ *Charge Request Accepted*
        Update Station Port Matrix
    else if $Avc =$*Request Denied* **then**
        Return *Station Port Matrix,, Acv*
    end if
end if
End

V. STOCHASTIC QUEUING MODEL FOR ELECTRIC VEHICLES IN THE CHARGING STATION

In the above section, we discussed the real time charge broadcasting and slot booking. Once the charging slot is booked and the vehicles arrive at the charging station, in this section, we discuss the EVs queuing delay, service rates, arrival rates, and average number of EVs (getting service and waiting in the queue). In addition, we will present the optimisation of waiting time and charging model.

As the market share of EVs increases results in on-road numbers of them grows which creates problems like how to manage and schedule them at charging stations. Figure 6 shows the conceptual framework of EVs queuing model at a charging station. Figure 7 shows the state transition diagram of EVs at the charging station. The stochastic model is based on "$M/M/m$" queuing model, where first M denotes the Poisson arrival with memory-less property, second M shows the Exponential service rate with memory-less property and m denotes the number of charging slots at a charging station. "$M/M/m$" queuing model is suitable for modelling the charging stations since the number of charging points (m) in a charging station can be changed based on that charging station's arrival and service rate. Therefore, the developed model describes that there are arrivals in the system which follow the Poisson process and the service rates are exponentially distributed. In the queuing model, the arrival is the EVs entry to the charging station, the service time is the time taken by a charging slot to full charge EV. In this model, we have assumed that the length of the queue is infinity and queue access or service is based on first come first out.

The steady-state probabilities of EVs at charging stations are denoted as p_n and are given as follows:

$$p_n = \begin{cases} p_0 \dfrac{(m\rho)^n}{n!}, & n \le m \\ p_0 \dfrac{m^m \rho^n}{m!}, & n > m \end{cases} \tag{1}$$

where ρ is utilization factor of charging points and is given as

$$\rho = \frac{\lambda}{n\mu} < 1 \tag{2}$$

p_0 is calculated by using above expression and the condition $\sum_{n=0}^{\infty} p_n = 1$.

We obtain,

$$p_0 = \left[1 + \sum_{m=1}^{n-1} \frac{(n\rho)^m}{m!} + \sum_{m=n}^{\infty} \frac{(n\rho)^m}{m!} . \frac{1}{n^m - m}\right]^{-1} \tag{3}$$

Probability of EVs queuing delay in charging station is given as

$$P(queuing) = P^Q = \sum_{m=n}^{\infty} p_m \tag{4}$$

$$P^Q = \sum_{m=n}^{\infty} \frac{p_0 n^n \rho^m}{n!} = \frac{p_0 (n\rho)^n}{n!} \sum_{m=n}^{\infty} \rho^{m-n} \tag{5}$$

The expected number of EVs waiting in queue at charging stations is given as

$$N^Q = \sum_{m=0}^{\infty} m p_{n+m} \tag{6}$$

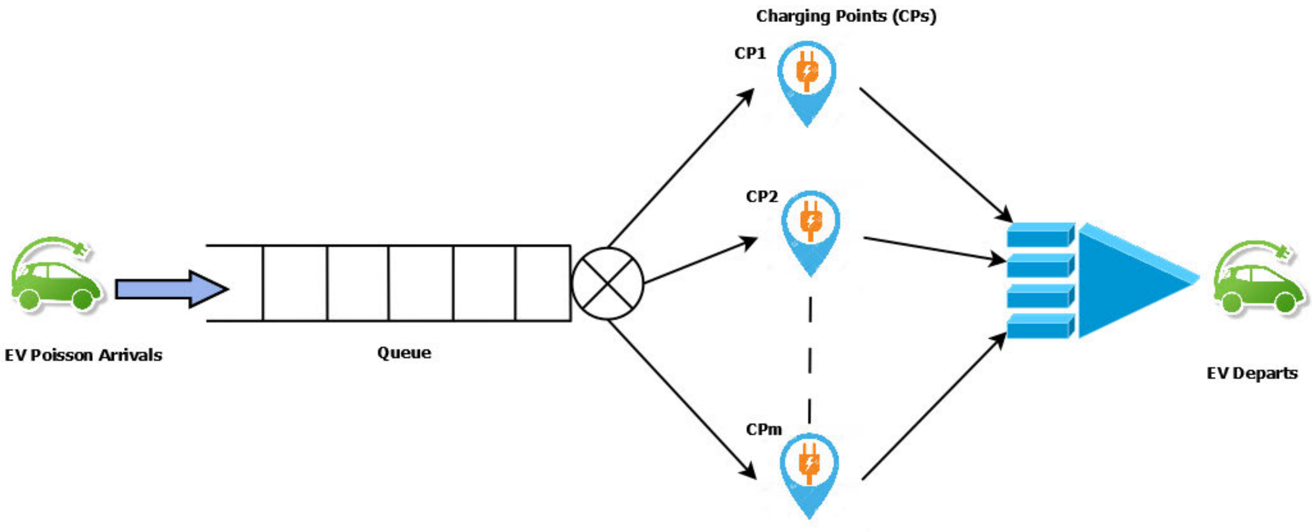

FIGURE 6. Conceptual framework of EVs queuing model at charging station.

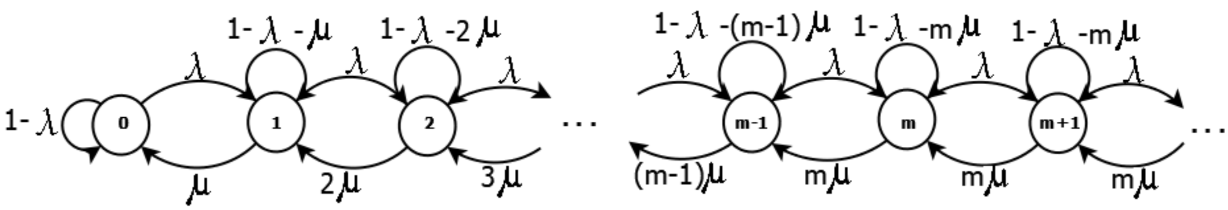

FIGURE 7. Stochastic EVs queuing model at charging station: discrete time Markov chain M/M/m model.

Above equation can be re-written as

$$N^Q = \sum_{m=0}^{\infty} np_0 \frac{n^n \rho^{m+n}}{n!} = \frac{p_0(n\rho)^n)}{n!} \sum_{m=0}^{\infty} m\rho^m \tag{7}$$

$$N^Q = P^Q \frac{\rho}{1-\rho} \tag{8}$$

From Little's Theorem, the average waiting time W of EVs in a queue is given as

$$W = \frac{N^Q}{\lambda} = \frac{\rho P^Q}{\lambda(1-\rho)} \tag{9}$$

Average delay per EV at queue is given as

$$T = \frac{1}{\mu} + W = \frac{1}{\mu} + \frac{P_Q}{m\mu - \lambda} \tag{10}$$

By using Little's Theorem, the average number of EVs in the charging station is given as

$$N = m\rho + \frac{\rho P_Q}{1-\rho} \tag{11}$$

VI. OPTIMISATION PROBLEM FORMULATION

In the above sections, we have presented the real-time charging station identification, booking charging slots and analytical queuing model of EVs in charging station. In this section, we will discuss after the slot booking once the EV comes for the charging at charging station, how to use the charge, reduce the waiting time and cost of the charge at peak and non-peak hour. Consider an utility function which comprises of EV travel time EV^{τ}, distance from EV i to charging station j ($D^{i,j}(t)$), EV's SoC of battery $SoC^i(t)$, queuing (average delay) time in a queue at charging station i ($T^i(t)$), EV charging time at charging slot in a charging station i ($QT^i(t)$), charging cost at charging station i ($C^i_Q(t)$). Energy of the EV_i is denoted by E_i and is given as

$$E_i = \sum_{t\in\tau_i} P_i(t).\Delta t_i \tag{12}$$

where τ_i is allowable charge time duration, $P_i(t)$ is charging power of the EV_i and Δt_s is the time slot s duration for EV charging. An EV_i may charge only on the booked slot and upto an allowable charge time duration τ_i, therefore,

$$P_i(t) = 0, \quad \forall t \notin \tau_i \tag{13}$$

Charging power of the EV should be within some permissible limits that is

$$P_{min}(t) \le P_i(t) \le P_{max}(t) \tag{14}$$

Load power of charging station ($L^P = m\ kW$), Maximum power capacity of the battery ($B^P = n\ kW$), Time taken to charge the EV at time t is denoted as $QT^i(t)$ and is given as follows

$$QT^i(t) = \frac{L^P}{B^P} \tag{15}$$

Percentage of final charge level of battery is the amount of charge extracted from the EV's battery which is denoted as SoC_{final}. The charge extracted from the EV's battery is a sum of simple integration of the current flowing into or out of the main branch of battery circuit and the initial charge level of EV's battery. The SOC_{final} is given as

$$SoC_{final} = SoC_{init} + \frac{1}{B^P}\int I(t)dt \tag{16}$$

where SoC_{init} is the initial charge level of battery, B^P is the maximum power capacity of the battery and $I(t)$ is the battery current in Amps. Every EVs charges at the charging station is estimated using B^P and $I(t)$ and is given as

$$\frac{1}{B^P}\int I(t)dt = SoC_{final} - SoC_{init} \tag{17}$$

EV_i charge acceptance rate is V_R^i and CP_R is charging points charging rate, optimal transaction of power between EV and charge points should satisfy the following condition

$$V_R^i \leq CP_R \tag{18}$$

Consider $v = [\alpha, \beta, \gamma, \delta]$ be the vector comprising of waiting factors with values belonging to [0,1] and their sum being equal to 1. These waiting factors provides the priority and importance to the $QT^i(t)$, $C_Q^i(t)$, $D^{i,j}(t)$, and $T^i(t)$. Let I be the set of available charging stations when EV asks for charging at time t for $w\ kWh$.

The objective function of electric vehicle's charging at charging points in charging stations determines the optimal charging time, minimal charging cost, least distance, minimal queuing delay at the queue and optimal duration for charging slot s. The function will be constrained with the above mentioned parameters. Hence, the objective function of EV_i is formulated as follows:

$$F = minimize\ \alpha QT^i(t) + \beta C_Q^i(t) + \gamma D^{i,j}(t) + \delta T^i(t) + \Delta t_s$$

$$\text{subject to: } i \in I(Charging\ Stations) \tag{19}$$

$$N(Avg.\ \#\ EVs\ in\ i) \leq m(CPs\ in\ i) \tag{20}$$

$$\frac{1}{B^P}\int I(t)dt \leq SoC_{final} - SoC_{init} \tag{21}$$

$$V_R^i \leq CP_R \tag{22}$$

$$E_i = \sum_{t \in \tau_i} P_i(t).\Delta t_i \tag{23}$$

$$P_{min}(t) \leq P_i(t) \leq P_{max}(t) \tag{24}$$

$$QT^i(t) \leq QT^{T,i}(t) \tag{25}$$

VII. SIMULATION AND RESULTS ANALYSIS

To test the robustness of the proposed system in a fairly large-scale network, we developed a discrete-time event simulator, using which tests have been conducted. The simulation parameters and assumptions are given in the subsequent subsection.

A. PARAMETERS AND ASSUMPTIONS

1) City dimensions: 200 km × 200 km.
2) Number of charging stations deployed: 50
3) Number of chargers at each station: 10, randomly deployed within the city boundaries.
4) Vehicles are generated following a Poisson's distribution at each grid point.
5) SoC level of each vehicle varies randomly in a range of 20% to 100%.
6) The battery specifications are kept constant.
7) Each generated vehicle randomly selects a destination point within the city limits and traverses the shortest distance between them.
8) The maximum number of vehicles allowed in a charging station at any point of time is 25 to keep the traffic at the charging station in check
9) The traffic pattern of each route randomly falls into one of four categories: low-traffic, moderate-traffic, and high-traffic, where the average vehicle arrival rates are 90%, 95% and 100% of λ, respectively.
10) Vehicles that do not need an additional charge to get to their destinations can decide to visit the nearest charging station based on a reverse probabilistic scale which increases the probability to go for a charge as the vehicle's SoC decreases to roughly emulate human behavior.

B. RESULTS ANALYSIS

The observations were recorded for each charging station and the results were obtained for a charging station at different number of vehicles present at the station.

Figure 8 shows the average delay per customer waiting in a queue at the charging station. The total time a vehicle has to spend at the charging station includes the time spent in the queue and the time taken to charge the vehicle. This time remains nearly constant until the number of vehicles at the station is equal to or less than the number of chargers at the station. In the event of a charger being booked, the waiting

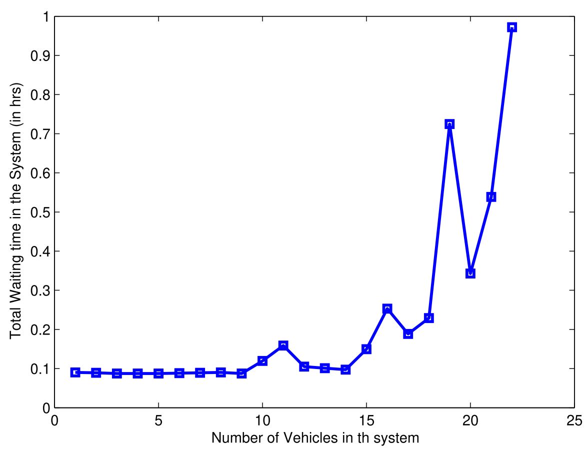

FIGURE 8. Distribution of average delay per customer waiting in queue.

time spikes due to the reduction in the number of chargers. The total waiting time increases when the number of vehicles crosses the number of chargers available at the station. The observed time further varies from 0.1 Hr to 0.2 Hr depending on the battery SoC at the time of entering the charging station. An increase up to 0.4 Hr is observed after the number of vehicles crosses the number of stations. This time is further compounded up to 0.9 Hr when the number of vehicles is increased to 21 and beyond.

Figure 9 shows the total time an EV has to spend at the charging station. The queue forms when the number of vehicles in the station is greater than the number of chargers available. The waiting time in queue increases when the number of vehicles cross 20 at the charging station and is capped at 25. In the event of a charger being booked, the waiting time spikes.

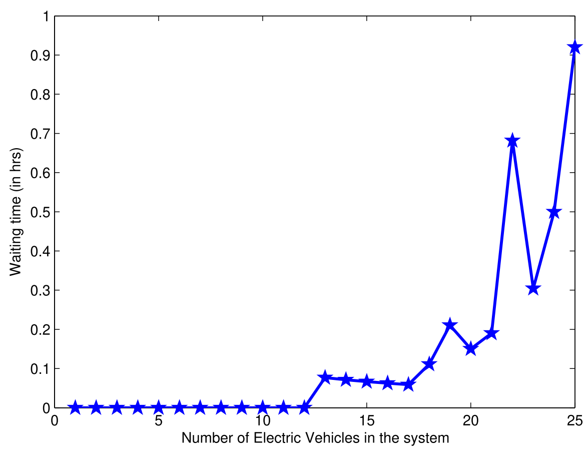

FIGURE 9. Distribution of total time an EV has to spend at the charging station.

Figure 10 shows the queue size depending on the number of EVs in the station. The queue forms when the number of vehicles crosses the number of chargers available at the station. The flats in the curve are observed whenever a charger has been booked at the station which reduces the number of chargers, increasing the number of vehicles waiting in the queue.

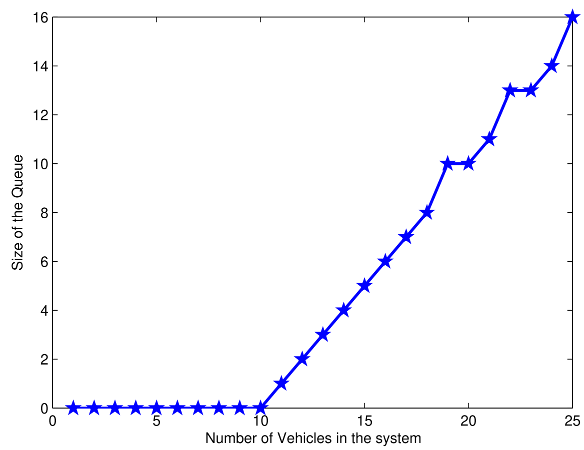

FIGURE 10. Distribution of the queue size depending on the number of EV in the station.

Figure 11 shows system capacity utilisation. The operational capacity depicts the capacity of the charging station under operation. The sharp dips in the curve represent a charger being booked, which reduces the overall dynamic capacity of the charging station.

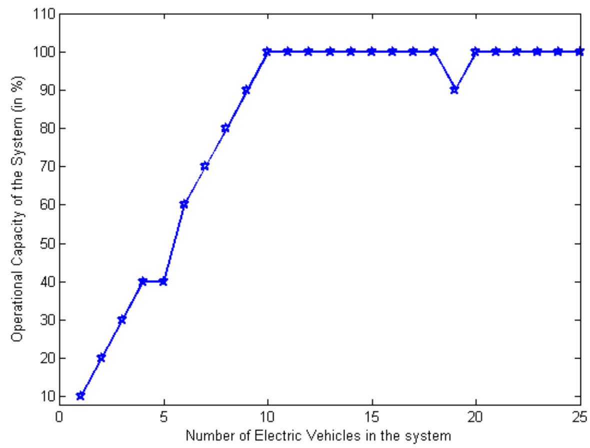

FIGURE 11. Probability that all the chargers are in use.

According to the EVs, platoon charging rates requirements they are classified into 4 different types that are Type I (low charging rate), Type II (medium charging rate), Type III (fast charging rate) and Type IV (fast charging rate). Figure 12 shows the different electric vehicles' (Type I to IV) average charging time with varying power load levels at the charging station. Figure 12 shows that the low charging rates EV platoon (Type I and II) requires more charging time at various load levels (from 30% to 90%). The fast charging rates EV platoon (Type III and IV) requires less charging time when the load level is above 50% then the charging time exponentially reduces and after 60% load level the charging time will be zero.

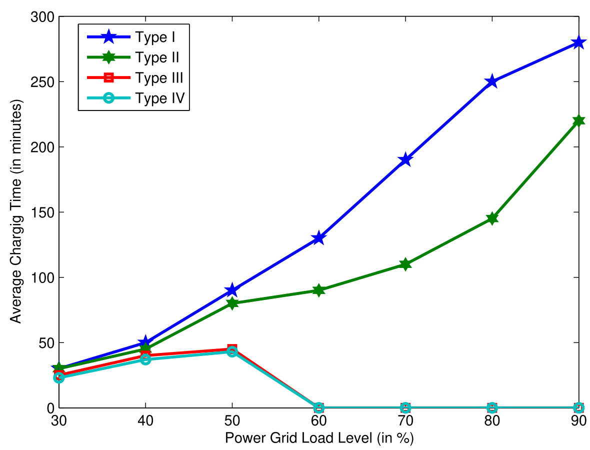

FIGURE 12. Average charging time with different power grid load levels.

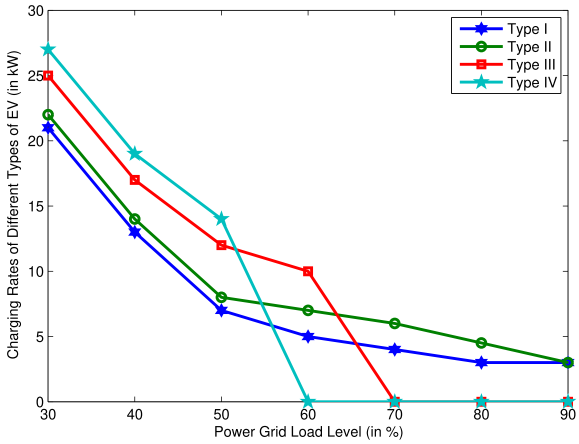

FIGURE 13. Charging rates of different types of EVs with different power grid load levels.

Figure 13 shows the different EV platoons charging rates by varying the load levels from (30% to 90%). To make the stable and smooth operation of the power grid and reduce the consumption of charging power, the charging rates of EV platoons are reduced. In Figure 13 we can see that when the Type IV and III power grid load level crosses 60% and 70%, respectively then their charging rates are zero. As the reduction EV platoons charging rates, definitely there will be an increase of charging times. In order to guarantee the quality of service of the EV platoons charging requirements, the EVs which are having least tolerance and waiting for the charging may not charge in the charging station and their services need to suspend.

Comparative analysis of the dynamic and static cost and rate to utilize charging stations as shown in Figure 14. In the simulation, 14.4 kW charging rate and fixed cost under different grid load level were considered. Fixed-Rate and costs are compared with the variable rate and costs, the cost of EVs charge is directly proportional to the charging rates and the scaling factor depends upon the grid load. The proposed system makes a platoon of electric vehicles determine optimal charging rates.

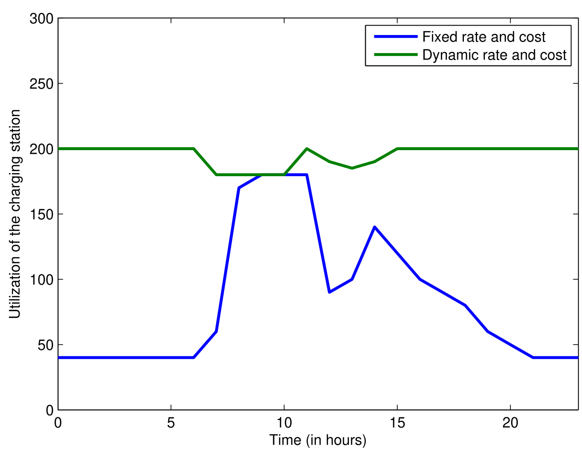

FIGURE 14. Utilization of charging stations.

Table 2 and 3 shows the savings of costs and charging time before and after the optimisation of the proposed model. It clearly shows that the proposed model saves both money and as well as time at charging station.

TABLE 2. Cost savings after optimisation of EVs charging at charging stations.

EVs	Charging Demand (kWh)	Cost before optimisation (Rs/kWh)	Cost after optimisation (Rs./kWh)	Cost Savings
EV 1	5.04	0.83	0.77	7.23%
EV 2	6.13	1.53	0.93	93.3%
EV 3	8.48	1.61	1.32	18%

TABLE 3. Time conservation after optimisation of EVs charing time at charging stations.

Charging Stations	Charging Time before optimisation (in minutes)	Charging Time after optimisation (in minutwa)	Time Savings
CS 1	30	25	5
CS 2	80	65	15
CS 3	120	80	40

VIII. CONCLUSION

In this paper, we discussed the next generation of smart electric vehicles cyber-physical system framework for cities transitioning to an entirely grid-run EV network. The conducted survey figured out the preferences of the masses regarding their current driving pattern and their expectation of an EV based traffic, which is an advancement to the current conventional engine-run traffic. An algorithm was developed to optimise the survey response by assigning a weight to increase the accuracy of the data from a relatively smaller data-sets. The proposed communication framework for EVs and charging station to generate and handle the online charging requests and booking the charging slots. The stochastic queuing model developed for EV platoons in the charging station and derived the average waiting time, utilisation factor, delay and number of EVs in the charging stations. In addition, we have developed an optimisation model where we have minimised the charging times, cost, the distance between EVs and stations, queuing and booked time slot duration. We have tested the robustness of the proposed system in a fairly large scale network in the developed discrete-time event simulator. The proposed system's performance analysis justified the improvement in the performance measures: cost savings (93.3%), time-saving (40%), etc.

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SURESH CHAVHAN (Member, IEEE) received the B.E. degree from the SDM College of Engineering, Dharward, India, in 2011, the M.Tech. degree from NITK Surathkal, in 2013, with MHRD Scholarship from Govt. of India, and the Ph.D. degree from IISc Bengaluru, in 2019, with MHRD Scholarship from Govt. of India. He was a Postdoctoral Research Associate for 1.5 years with the Department of ECE, IISc Bengaluru. He is currently a Distant Postdoctoral Fellow with the Federal University of Piauí, Brazil, and also working as a Senior Assistant Professor with the Automotive Research Center, Vellore Institute of Technology, Vellore, India. He is an Eminent Academician; plays versatile roles and responsibilities juggling between lectures, research, publications, consultancy, community service, Ph.D. supervision, and so on. With seven years of rich experience in research and two years of teaching experience, he focuses on rational and practical learning. His research interests include multi-agent systems, intelligent transportation systems, the Internet of Things, smart grid communication, blockchain, electric and autonomous vehicles, heterogeneous networks, resource allocation in LTE-A communication networks, and computational intelligence. His one of the ideas got shortlisted as one of the top 34 ideas for the prototype building phase of Mercedes-Benz Digital Challenge, India. He has published around 20 National/International Scopus/SCI index Journals/Conferences (in IEEE Transactions, Elsevier, and Springer). His professional activities include conducted many workshops/seminars/conferences at IISc Bengaluru as the Secretary of IEEE-IISc Student branch and worked as a Reviewer of the IEEE Transactions on Intelligent Transportation Systems, IEEE Access, the IEEE Transactions on Vehicular Technology, the IEEE Transactions on Emerging Topics in Computational Intelligence, the IEEE Internet of Things Journal, IET on ITS, ANTs (Elsevier), ICCST, ITSC, NCC, and KNOSYS.

NIKHIL DUBEY is currently pursuing the B.Tech. degree in electrical and electronics engineering with the Maharaja Agrasen Institute of Technology, New Delhi. His main research interests include data acquisition, sensory analysis, embedded systems, and EVs.

ABHINAV LAL is pursuing the B.Tech. degree in electrical and electronics engineering with the Maharaja Agrasen Institute of Technology, New Delhi. His main research interests include EV, the IoT, and embedded systems.

DEV KHETAN is currently pursuing the B.Tech. degree in electrical and electronics engineering with the Maharaja Agrasen Institute of Technology, New Delhi. His main research interests include cyber security, data acquisition, embedded systems, and EVs.

DEEPAK GUPTA received the Ph.D. degree from the Dr. A. P. J. Abdul Kalam Technical University. He is an Eminent Academician, plays versatile roles and responsibilities juggling between lectures, research, publications, consultancy, and community services. With 12 years of rich expertise in teaching and two years in the industry, he focuses on rational and practical learning. He has actively been an organizing end of various reputed International conferences. He has completed his Postdoctoral Research with Inatel, Brazil. He has authored/edited 37 books with national/international level publishers. He has published 92 research publications in reputed international journals and conferences, including 45 SCI-indexed journals. He was invited as a Faculty Resource Person/Session Chair/Reviewer/TPC member of different FDP, conferences, and journals. He has served as the editor-in-chief, the guest editor, and an associate editor of SCI and various other reputed journals.

ASHISH KHANNA received the B.Tech. and M.Tech. degrees from the GGSIPU, New Delhi, and the Ph.D. degree from the National Institute of Technology, Kurukshetra, in March 2017. He has expertise in teaching, entrepreneurship, and Research and Development. He has completed his PDF with the Internet of Things Laboratory, Inatel, Brazil. He has around 90 accepted and published research works in reputed SCI, Scopus journals, conferences, and reputed book series, including around 40 articles in SCI-indexed journals with a cumulative impact factor of above 100. In addition, he has authored, edited, and is editing 20 books. His research interests include image processing, distributed systems and its variants, such as MANET, FANET, VANET, and the IoT, machine learning, evolutionary computing, and many more. He is a Series Editor of "Intelligent Biomedical Data Analysis" series (De Gruyter, Germany).

JOEL J. P. C. RODRIGUES (Fellow, IEEE) is a Professor with the Federal University of Piauí, Brazil, a Senior Researcher with the Instituto de Telecomunicações, Portugal, and a Collaborator of the Post-Graduation Program on Teleinformatics Engineering with the Federal University of Ceará (UFC), Brazil. He is the Leader of the Next Generation Networks and Applications (NetGNA) Research Group (CNPq), an IEEE Distinguished Lecturer, a Member Representative of the IEEE Communications Society, IEEE Biometrics Council, and the President of the Scientific Council at ParkUrbis–Covilhã Science and Technology Park. He has authored or coauthored over 850 papers in refereed international journals and conferences and three books, holds two patents, and one ITU-T Recommendation. He had been awarded several Outstanding Leadership and Outstanding Service Awards by the IEEE Communications Society and several best papers awards. He is a member of the Internet Society and a Senior Member of the ACM. He was the Director of conference development with the IEEE ComSoc Board of Governors, the Technical Activities Committee Chair of the IEEE ComSoc Latin America Region Board, the Past-Chair of the IEEE ComSoc Technical Committee on eHealth and the IEEE ComSoc Technical Committee on Communications Software, a Steering Committee Member of the IEEE Life Sciences Technical Community, and the publications co-chair. He has been the General Chair and TPC Chair of many international conferences, including the IEEE ICC, IEEE GLOBECOM, IEEE HEALTHCOM, and IEEE LatinCom. He is the Editor-in-Chief of the *International Journal on E-Health and Medical Communications* and an editorial board member of several high-reputed journals.

PLÁCIDO ROGERIO PINHEIRO (Member, IEEE) received the B.Sc. and Licentiate degrees in mathematics from the Federal University of Ceará, in 1979 and 1984, respectively, the Licentiate degree in electrical engineering from the University of Fortaleza in 1983, the M.Sc. degree in mathematics from the Federal University of Ceará in 1990, and the Ph.D. degree in systems engineering and computing from the Federal University of Rio de Janeiro in 1998.

He held a postdoctoral internship at the Pontifical Catholic University of Rio de Janeiro (PUC/RJ) from 2012 and 2013. He is a member of the Cearense Academy of Mathematics. He is currently a Titular Professor of University of Fortaleza and an Associate Professor of the State University of Ceará. He has experience in industrial processes modeling applying mathematical programming and multicriteria. His academic formation allows publishing in applied mathematics area, with an emphasis on discrete and combinatorics mathematics, working mainly in mathematical programming and multicriteria.