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Algorithmic Planning, Simulation and Validation of Smart, Shared Parking Services using Edge Hardware

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***Abstract*—A major problem with vehicles used in densely populated areas is parking. Part of the problem is the scarcity of the resource in busy areas and the non optimal utilization of private spots. We propose the 'Smart Shared Private Parking' model that aims at including in the parking pool also private parking spots. In an urban area with both commercial and residential buildings, frequently household owners do not utilize their own parking lots during office hours, long duration of shopping and vacations. At the same time, such owners want to be able to park in their lots when needed. Therefore, to engage the residents and allow them to provide their parking spaces when unused one needs a real-time, distributed infrastructure that supports dynamic allocation of spaces. We propose a conceptual deployment of edge hardware and communication mechanisms to enable shared private parking sharing. We illustrate an infrastructure setup required to analyse various aspects of the model and show its effectiveness in parking allocation in terms of vehicular emission, utilisation rate, and revenue as metrics considering all the stakeholders. A simulation based on a district of Dublin provides quantitative instances for these metrics.**

***Index Terms*—V2X, VANET, Vehicular Communication, Smart Shared Private Parking, Smart Gate, Edge Computing**

I. Introduction

Urbanization and Industrialization are the major factors contributing to the increased dependence on vehicles [3]. The increased dependence on vehicles leads to problems like traffic congestion and pollution. Due to the recent COVID pandemic, the use of public transport has decreased while the use of private transport has increased [2]. The increase in usage of private transport leads to higher turnover and demand for parking. Hence, there is a need for new model that can increases the supply of parking lots. The present work proposes a parking model that aims to increase the supply of parking lots. The contributions include:

- A novel model for the sharing of private parking lots that considers user preferences while offering the possibility to optimize utilization rate.
- A design and implementation of the model.
- A simulation based on the city of Dublin to evaluate the model effectiveness.

The rest of the paper is organized as follows. Section II overviews related work that addresses the problem of parking optimization and mobility models. Our proposed design is illustrated in Section III and its implementation in Section IV. The evaluation of the proposal by means of simulations is presented in Section V. A discussion and final remarks are offered in Section VI.

II. State of the Art

Innovative parking and mobility models have been investigated before, e.g., Some of the works that are used to derive the points of common knowledge are [4, 17, 9, 18, 3, 12, 7, 6]. One of the motivations for designing parking solutions is to solve the problem of commute time in searching for a parking spot [18]. Not only time, but also vehicular (CO_2) emissions increase with the difficulty of finding a spot. The effect of increased vehicular (CO_2) emissions contributes to poor air quality of the considered urban area. Vehicular (CO_2) emission is an important parameter to quantify the efficiency of parking and mobility solutions [12]. Apart from vehicular (CO_2) emissions, traffic congestion is another important factor to be considered to quantify the quality of a parking model [17]. The goal of a typical innovative parking model is to improve the air quality by reduced emissions and reduced traffic congestion [9]. These points form the current common knowledge and are predominantly used in the related work.

A. Parking models

Modelling the parking demand and supply management has been the goal of several works. The importance of different parking modelling strategies is highlighted in [5]. Also, the authors of [5] propose to bring up a balance of the new additions through geospatial analysis [5]. A parking allocation model using a centroid based approach for finding an optimal parking spot is used.

1) Shared parking model I - Focus on overtime parking information: The boons of shared parking and managing the overtime stay through different correlation analyses are illustrated in [17]. In particular, the correlation between various parameters such as vehicle arrival numbers, parking duration and overtime occupancy are considered and the authors define a model where residential areas can be used to contribute to

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the parking demand in an urban area. The model maximizes the revenue by considering the optimal combination of the given parameters.

2) Shared parking model II- Focus on walking distance and other preferences: Driver and owner preferences are the focus of [9].The basic parameters for the shared parking model are the location of the parking lot with respect to the most visited destination points in the area, the distance between the parking lot and the destination being within an acceptable walking range, and parking lots being open to the public. The model maximizes the utilisation rate of the parking lots and minimises the walking distance between the parking lots and destination points. The model supports the use of parking lots in residential areas to serve the users having nearby commercial buildings as destination points.

B. Large scale mobility models and simulation scenarios

Large scale mobility models and simulation scenarios are necessary in assessing the routine traffic and formulating steps required to manage varying traffic scenarios. These models also serve as a base to assess different concepts of mobility such as parking and intermodal mobility.

1) MoST and PyPML: Simulation scenarios based on the city-state Monaco are proposed in [6]. The MoST scenarios are based on a synthetic traffic demand rather than on actual data [6]. The demand presents a peak hour in the morning which could possibly comprise intermodal traffic. The scenario can help to optimise individual planning of mobility and related mobility demands like parking. Such planning in turn helps to study the impact on traffic congestion based on the used optimization model. The use cases are implemented using Eclipse Simulation of Urban MObility (SUMO) [20].

PyPML is a Parking Monitoring Library designed using SUMO and using the Monaco SUMO Traffic (MoST) scenario [7]. The library assumes that optimal placement is already defined. The core functionalities of the library are related to monitoring, optimization, and control of the parking conditions.

2) Smart parking using Vehicular Ad Hoc Network (VANET) in the Dublin scenario: The authors of [12] analyse vehicular communication aspects such as the model for placement of Road Side Units (RSUs) and illustrate a process for the gathering a data from the websites of the Administration department of Inner city of Dublin. In their work, only commercial parking lots have been considered for the analysis. Details on the choices of software components and methods to generate the datasets required for the work are given. Vehicle to Vehicle (V2V) communication frameworks like VEhicles In Network Simulation (VEINS) [25], Objective Modular Network Testbed in C++ (OMNET++) [24] are used along with Eclipse SUMO [20] to realize the idea of *"Smart parking using VANET*." Simulation results comparing CO_2 emissions per vehicle between a model without using vehicular communication and a model using vehicular communication conclude the work.

C. Existing commercial providers

In addition to research work, a number of companies are already providing services in the field of smart parking. Zenpark is a shared parking solution available in France and Belgium [26]. The idea is to allow individuals and other commercial landowners to rent out their unused parking spots. Mobypark also offers a similar solution for the capitals of France, Belgium and the Netherlands [22]. Bosch community-based parking is a solution based on cars informing of the availability of vacant spaces via a dedicated cloud [4]. Noticeable is the fact that the information about the sender is anonymous ensuring privacy to members of the community.

III. System Design

The work proposed employs smart gate hardware (with the same capabilities as an RSU) in place of a common RSU. The objective is to reduce the costs incurred due to the provisioning of separate hardware units that generally add up the expenses of a smart city. Conceptually, the hardware is said to be in place of an electrical garage device to sense the spots, communicate and actuate the mechanical parts of the parking lot when required. In the work, each RSU or smart gate hardware represent a parking lot in the simulation. In the requirement analysis phase, we distributed a survey to 34 employees from various German locations of the company Itemis AG. The survey was conducted in December 2020. The goal was to assess the mindset of car drivers and residential parking lot owners. The results of the survey are in line with the the conclusions of the works [9, 17] and help us derive the mathematical model at the heart of our proposal, illustrated next.

A. Mathematical model

The mathematical model of the work is designed considering the concept of overtime parking and drivers' preference to walk for a certain distance. Utilisation rate U_m in Equation 1 is the result of matching time preferences and additional preferences of a vehicle with a parking lot. In a parking lot m, the variable x_{mn} (satisfying time preferences and additional preferences) equal to 1 multiplied by duration of parking gives the utilisation rate of parking lot m by a vehicle n. The sum of utilisation by vehicles $n_1....n_N$ at a particular hour gives the overall utilisation of a parking lot m at a particular hour. Equation 1 is an extended version of the mathematical model in [9]. The extension comes by combining the model with the utilisation rate, as defined in Equation 3. The revenue generated by a parking lot is also part of this extended model. Finally, the model considers a distribution of the traffic to lots by considering for how long a parking was not utilized for a threshold duration (say last 5 minutes). The distribution is ensured by the introduction of $t_{lr,m}$ variable.

$$U_m = \frac{\sum_{n=1}^{N} t_{dur}^n \cdot x_{mn}}{T_m(H)} \tag{1}$$

$$x_{mn} = \begin{cases} 1 \text{ if, } (D_m \leq D_{max,n}) \text{ \& } (P_m = P_n) \text{ \& } \\ \quad (t_{start,m} < t + t_{dur}^{n} < t_{end,m}) \text{ \& } \\ \quad (F_m > 0) \text{ \& } (t - t_{lr,m} > t_{th}) \\ 0 \text{ Otherwise} \end{cases} \tag{2}$$

where U_m is the utilisation rate of the parking lot 'm', t_{dur}^n represents the duration for which the vehicle 'n' needs parking. $T_m(H) = t_{end,m}$-$t_{start,m}$ represents the total duration of availability of a parking lot. $t_{start,m}$ is the time at which parking lot 'm' starts to being offered. $t_{end,m}$ is the time at which parking lot 'm' is no longer available. But in the work, the value of $T_m(H)$ is equal to 1 as we consider the simulation scenarios on a per hour basis. $_{lr,m}$ is the time at which a parking lot is last reserved. t_{th} is the threshold time before which a parking lot can be utilized. D_m is the actual walking distance between the parking lot 'm' and the destination. $D_{max,n}$ is the preferred walking distance by the driver of vehicle 'n' to the destination. P_m is the set of service offering parameters from the residential parking lot 'm' and P_n is the set of services demanded by the driver of vehicle 'n'. F_m is the number of free spots available in the parking lot 'm'. m = m_1,.......m_M, Each of the values of m represent the response i.e. by a parking owner offering a parking. n = n_1,.......n_N, Each of the values of n represent the demand i.e. a driver of vehicle 'n' looking for a parking.

In Equation 3, Revenue R_m is the collective sum of parking charges and overtime parking charges incurred by vehicles n_1,.......n_N using the parking lot m. The decisions x_{mn} and $x_{od.mn}$ (given by Equations 2 and 4) coordinate the decisions of considering the parking usage of vehicles whose timings and preferences have been matched with the parking lot.

$$R_m = \sum_{n=1}^{N} [(t_{dur}^{n} \cdot x_{mn} \cdot c_m) + (t_{od}^{n} \cdot x_{od.mn} \cdot c_{od.m})] \tag{3}$$

$$x_{od.mn} = \begin{cases} 1 \text{ if, } (t > t_{dur}^{n}) \text{ \& } (x_{mn} = 1) \\ 0 \text{ Otherwise} \end{cases} \tag{4}$$

where R_m is the revenue generated by a shared residential parking lot 'm'. t_{dur}^n is the duration for which the vehicle 'n' occupies a parking lot. x_{mn} is the decision variable that denotes whether a vehicle 'n' occupies a parking lot 'm' or not. c_m is the fixed cost to occupy a spot in parking lot 'm' for an hour. t_{od}^n is the duration for which the vehicle 'n' is parked overtime. $x_{od.mn}$ is the decision variable that denotes whether a vehicle 'n' occupies a parking lot 'm' overtime or not. $c_{od.m}$ is the cost to occupy a spot in parking lot m overtime for an hour.

IV. Implementation

The base framework used to implement the proposed model is Eclipse MOSAIC [11]. MOSAIC is a combination of several simulators coupled together to demonstrate connected mobility and to assess their effects on large scale city-based traffic scenarios. We chose this framework as it supports aspects of connected mobility in the form of simulators. Also, support for applications development using a high level language (JAVA) made this framework a good choice for the work proposed.

A. Simulators

Simulation of Urban Mobility (SUMO) is a free, open-source simulation software for modelling inter-modal traffic systems [20]. Simple Network Simulator (SNS) is the network simulator which is a part of Eclipse MOSAIC framework. The simulator has all the basic communication attributes required for vehicular communication. The role of the environment simulator is to simulate events such as obstacles and weather conditions. Apart from the mapping simulator, the Application Simulator emulates the necessary application that needs to be deployed in the components such as RSU or vehicles.

B. Setup

The Scenario-Convert tool is a part of Eclipse MOSAIC [11]. The tool is used to generate cleaned SUMO network from an Open Street Map (OSM) file. It also generates the configurations required for other simulators. In the work proposed, shared parking lots are to be provisioned at different geographic coordinates using Google maps [14]. The cleaned network obtained through this step is given by Figure 1. The basic building blocks of such a SUMO network are edges, lanes and junctions which can be seen in Figure 1.

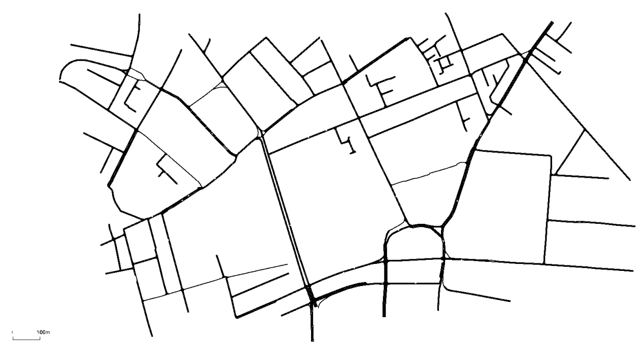

Fig. 1. SUMO road network extracted using Scenario-Convert tool

We generate parking lot data preserving essential details such as geographic coordinates, the number of free spots, the presence of charging spots. Using the coordinates where the parking lots are provisioned, we create a database of parking lot entries and schema for reservations and overtime estimates (given in Figure 2).

C. Demand data and integration into the scenario

The real demand is used in the simulation. We do so by resorting to the demand data from the official website of Dublin administration [10]. The data is collected by means of a survey taken at 33 locations around the city centre. The survey locations are strategically planned so that the number of inbound and outbound vehicles are tracked accurately. The survey locations are marked in Figure 3. We consider the number of vehicles moving in and out of the city at entry

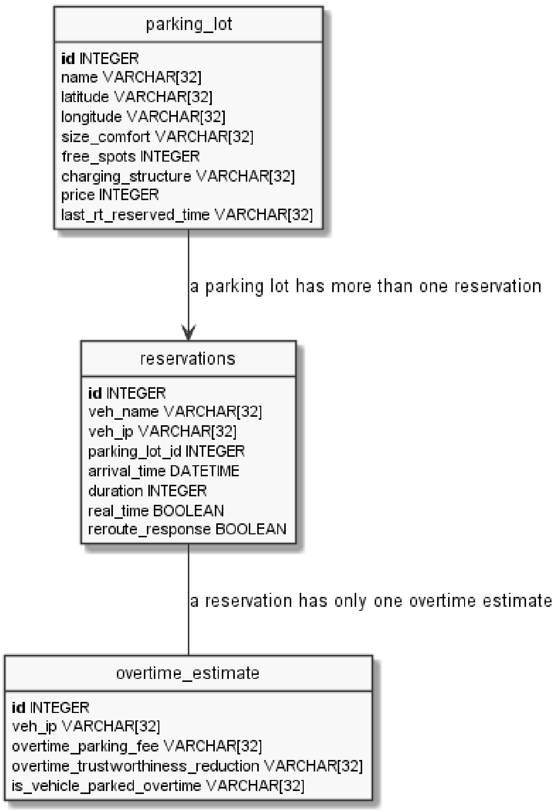

Fig. 2. Class diagram to explain the schema of the generated dataset

point 31. Routes denote the paths taken by the vehicles in SUMO network. Although the scenario-convert tool of Eclipse MOSAIC is capable of converting a set of geographic coordinates into SUMO routes, the newly generated routes cannot be directly merged into the route navigation database which is a small shortcoming of the tool (observed until December 2020). To overcome this, a custom script is developed to use the existing route generation functionalities of Eclipse MOSAIC.

D. Applications

The components involved in the simulation are vehicles and RSU. We developed applications that need to be deployed in each component. The application represents the behaviour of the component (say parking functionality in a vehicle). The modules that a vehicle in simulation possesses are a navigation module, an in-built operating system that coordinates with internal components and a communication module capable of Vehicle to Everything (V2X) communication. The vehicle's application in the work proposed involves the usage of these three modules. RSU forwards the request from the vehicle to cloud-based web services. In the shared parking model, RSU represents the smart gate hardware which can be equipped with a vehicular communication stack, enabling the sensing of the arrival of vehicles and also the actuation of the gate, when required. The smart gate hardware is thus the edge component that ultimately enables the smart sharing of the parking lots. Similar to a vehicle, RSU is also equipped with a navigation module, a communication module and an Operating System (OS).

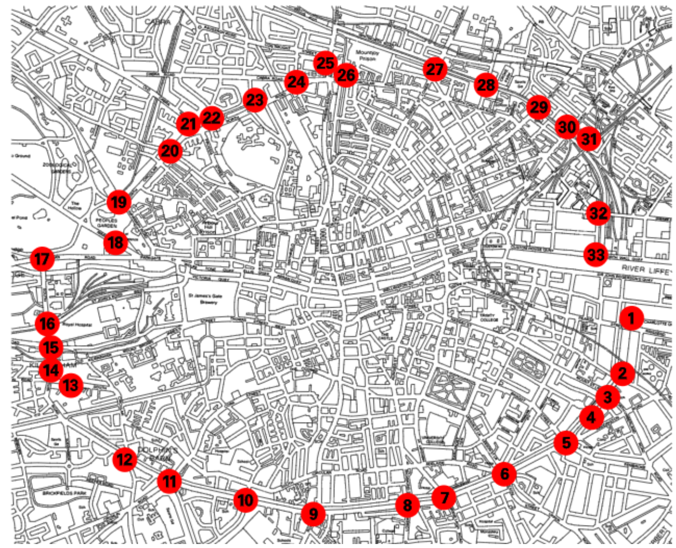

Fig. 3. Survey locations where inbound and outbound vehicles of Dublin City Centre are tracked [10]

E. Data flows

To help understanding the operation of the system, let us consider the two most relevant data flows, that is, the parking request and the resume signal.

1) Parking request: The parking request from a vehicle flows through RSU to the web service. The vehicle or car driver initiates the demand for a parking request by sending a geocast message consisting of a request for parking. Geocast message communication is a form of message communication where the message is sent to all the potential receivers in a geographical location [23]. A RSU receives the message and passes it to the web service. The web service makes use of the shared private parking model to allocate a suitable parking lot to the vehicle/car driver. The smart gate hardware units serve both the vehicle parked in the parking lot and the vehicles that request . At the same time, they represent the shared residential parking lots in the system. The hardware unit receives the response from cloud-based web service regarding the parking lot allocated in the destination of the vehicle. Figure 4 illustrates how a parking request is initiated by a vehicle, served by the web service and how the communication from and to the vehicle through the Smart gate hardware units (or RSU) occurs. Finally, the hardware (or RSU) communicates the parking lot availability through a unicast message. A unicast message is a message intended for a particular receiver in a geographical location. In the simulation, the IP address of the vehicle uniquely identifies the receiver [19].

2) Resume signal: The resume signal originates from a vehicle when the parking is completed. The parking duration varies randomly. In order to resume the journey, the resume signal is sent to a RSU nearby, which forwards the signal with all necessary details to the cloud. The aim of this signal

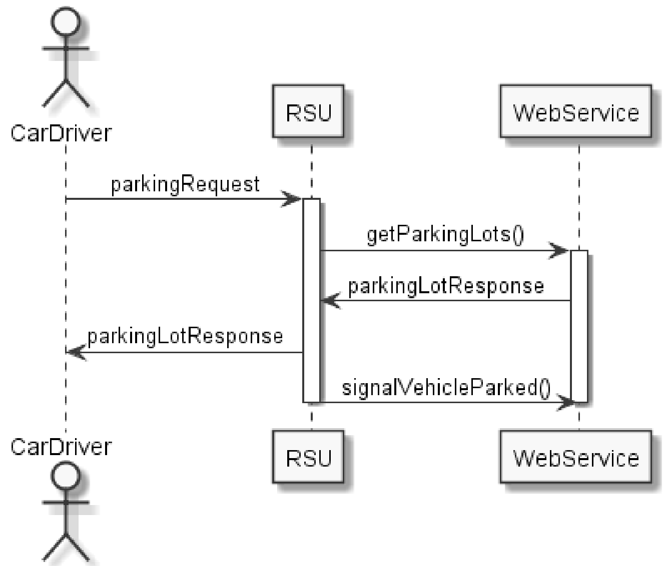

Fig. 4. Sequence of the simulation for parking request

transfer is to assess the overtime parking revenue of each parking lot and to make parking lots available for vehicles looking for parking. The RSU communicates the overtime estimation calculated in the web service to the vehicle for future acceptance of vehicles by the parking lots. In short, as shown in Figure 5, the resume signal flow resembles the parking request but differs by the input signal's content and the overtime response content.

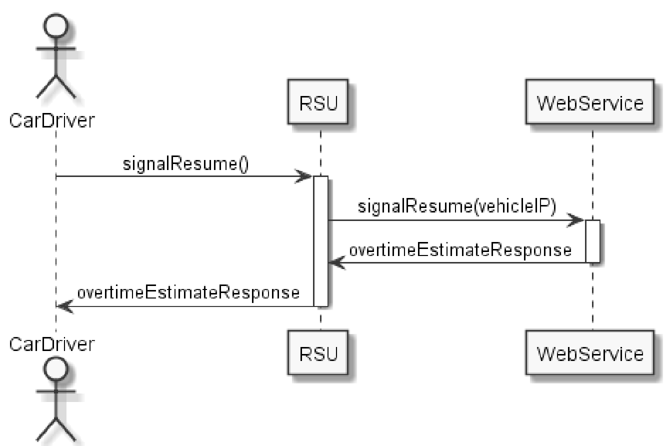

Fig. 5. Sequence of the simulation for resume signal

F. Web Service and Shared Parking model

The cloud-based web service incorporates both the base and shared parking model. Application interfaces act as the access to the web service, since it differentiates and redirects the request from RSU. The evaluation module receives the request from the application interface and proceeds to gather and elaborate the data and then finally responds to the requester with the appropriate response. A database is also a part of the web service. The database consists of details about commercial and shared residential parking lots. An important objective is to match the vehicle's preferred walking distance and the distance between the parking lot and the destination of the vehicle. Open Source Routing Machine (OSRM) provides routing and navigation facilities offline and is based on OSM data [21]. We deploy the service as a docker container [8]. Then comes the matching strategies in which one of them matches the current time and duration of parking with the availability of parking lots. Another strategy is to match the preferences of vehicle with the services offered by a parking lot. Finally, an allocation module is present to distribute the demand. In a demand-supply management application, the important focus is to distribute the demand evenly. This is applicable to satisfying the different parking demands of the car drivers by the parking lots. Hence, there is a need for a decision based allocation module that takes care of even distribution. In the work proposed, we use a Cellular Automaton model for this purpose.

A Cellular Automaton (CA) (*Plural: Cellular Automata*) is a decision making module that work on a group of cells [1]. Using a CA, each cell's next state is decided by it's current state and the nearby cells' current state [1]. A rule takes care of the transformation of cell's states into new state [1]. In the work proposed, a one-dimensional CA is used for the purpose of distributing the traffic in the microscopic area chosen. The proposed work uses rule 51. In the work proposed, *mapping* is done in such a way that occupancy of parking lots in circular area with destination of the car driver as centre and with preferred walking distance of the driver as radius are mapped to lattice of parking lots as current state and then transformed into new state. This realisation is the implementation of a one-dimensional or linear CA as we only take occupancy (0 or 1) of parking lots in an area into account but not other parameters like area. The reason is that distance manipulation module takes care of sensing parking lots in the neighbourhood area considered. The efficiency of using rule 51 in the work proposed is proven by utilisation analysis of the shared private parking lots which mainly requires the parking lots to be distributed with the demand evenly.

In this work, by *lattice* we refer to an ordered group of individual cells [1]. Each cell represents a parking lot. Figure 6 illustrates the working of Rule 51 in graphical form. Three contiguous cells on the top indicate the current state of cells where the middle one is the considered cell and cells on either side indicate its neighbours [1]. Cells are binary: a black cell represents an occupied lot, while a white one an empty lot [1]. The cell on the bottom indicates the transformed state. Figure 7 illustrates the process of how the mapping illustrated before is realised in the work proposed. The allocation module ensures that for a reservation, the closest parking lot that was not reserved in the threshold time (t_{th}) duration is used. The calculation of the previous state of the parking lots starts by getting the state of the parking lots nearest to the destination. Obtaining parking lots nearby is taken care of by *distance manipulation* module. Then the field *last reserved time* helps to calculate the previous state. The next step is to filter the parking lots on the basis of the threshold time. The step *calculation of previous state* ensures this. Rule 51 transforms the cells of the lattice into the next state in the *transformation* step. The vehicle demanding parking is allocated the parking lot enabled by the allocation module. In the case of multiple enabled parking lots in the lattice, the first and foremost entry in the lattice satisfies the demand generated by a vehicle. Wolfram's Rule 51 helps to distribute traffic evenly. A single CA represents a lattice of parking lots.

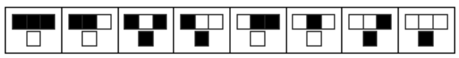

Fig. 6. Definition of Rule 51 [1]

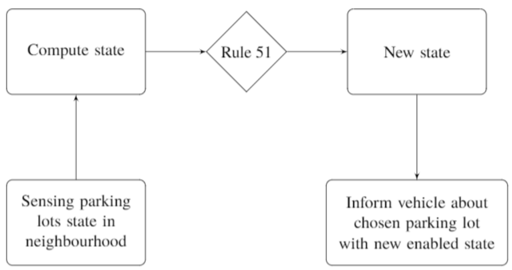

Fig. 7. Transformation of cell states

V. Results and Evaluation

We evaluate the model and its implementation on the data of the city of Dublin. The evaluation is run along five dimensions: (A) Realisablity of a simulation-testbed, (B) Utility of Vehicle to Infrastructure communication in terms of emissions, (C) Correlation between emissions and parking ease, (D) Economic benefits for the parkign owners, and (E) Effects of the number of available parking lots.

A. Realisation of a simulation-based testbed to assess the shared private parking model

To arrive at a stable infrastructure required for the proposed work, the performance and the applicability of various V2X frameworks have been analysed. According to the *College of Computing, Georgia Institute of Technology and School of Civil and Environmental Engineering, Georgia Institute of Technology*, a *simulation-based testbed* can be defined as a testbed being capable of simulating different components required for the experiment, operating the components simultaneously as in real-world, and observing the proposed system design changes through logs [13]. Here, we intend to set up a simulation-based testbed for a microscopic area. The testbed must be scalable in terms of number of vehicles and parking lots. Figure 8 illustrates the setup we realized. After each simulation run, the scripts facilitate getting logs for each of the research questions (denoted by the processing and consolidation step in the figure). The logs are common to both the base model and the shared model. The logs extracted are then used as inputs for comparison and correlation analyses. The logs that are useful for the analyses are listed next.

1) *Emission logs* help to assess vehicular emission output of all the vehicles.
2) *Database records (Reservation and Overtime Estimate)* help to extract the following data:
   - Reservation data (to estimate utilisation)
   - Revenue and Overtime Estimates (to estimate overall revenue of each parking lot).

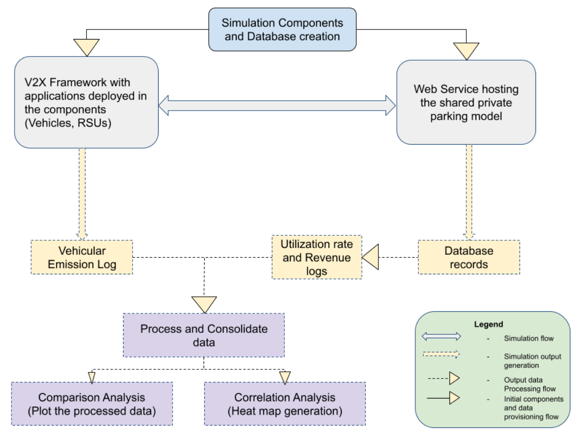

Fig. 8. Simulation-based testbed setup

B. Benefits of employing a communication strategy between vehicles and parking lots

We consider a scenario consisting of 4 parking lots each with 2 spots as capacity and 76 vehicles, 20 of which are actively look for parking. The metrics that are used to illustrate the benefits of the proposed model are "Mean Vehicular CO_2 Emission" and "Reroutes." The base scenario is realized in SUMO. The scenario reflects the realistic behaviour of a driver. When the free spots are not available in a parking lot, a driver looks for another parking lot in the vicinity. This information comes to the knowledge of the driver when the vehicle is near the parking lot. Searching for another parking lot is interpreted as a reroute and this, in turn, leads to more CO_2 emissions by each of the vehicles. In scenario with a communication strategy i.e. proposed model, vehicles receive information about services offered through V2X messages. The vehicle's On-Board Unit (OBU) processes the received V2X message and instructs the navigation module of the vehicle to go to the parking lot with free spots. In both the scenarios, vehicular emissions and reroutes are extracted using the inbuilt logging features of SUMO and MOSAIC. These values are obtained after running the simulation.

The results show that a communication system makes the drivers aware of the services offered and redirects the vehicle to a corresponding parking lot with **lesser vehicular CO_2 emissions** i.e. substantially reduced reroutes.

The results are presented in Table I and Figure 9 and they highlight that the rate of decrease in mean vehicular emission when equipping the scenario with a communication strategy is **46.75%**. The number of reroutes in the proposed model scenario is **0** as the services offered are communicated to the vehicle before it reaches the destination whereas, in the case of the base model scenario, it is **16**.The value 16 is obtained as a result of running the base simulation using SUMO. Reroute is a standard metric related to parking. The value increases with the number of times vehicles are getting redirected in search of a parking spot., which is part of SUMO simulations.

TABLE I
RESULTS OF EVALUATING THE BENEFITS OF EMPLOYING A COMMUNICATION STRATEGY - I

Metric	**Unit**	**Base Scenario**	**Proposed model scenario**
Mean Vehicular CO_2 Emission	milligrams (mg)	1.909×10^6	1.016×10^6
Reroutes	(No unit)	16	0

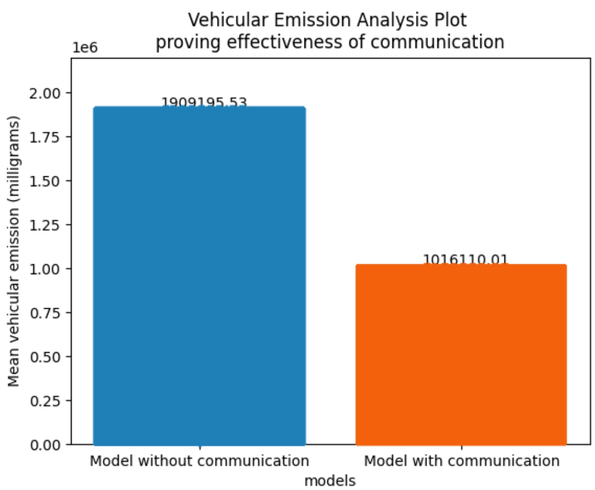

Fig. 9. Results of evaluating the benefits of employing a communication strategy - II

C. Benefits for car drivers

The vehicles moving in the simulation might have abnormal routes which eventually change the emission values. Hence, in order to remove this abnormality, we run the simulations several times to consolidate the result. The hours during which the simulation is run is between 7:00 to 18:00. The reason behind this decision is that the demand data obtained from [10] gives the vehicle volume within this time period. The simulation scenario is run for each hour and the logs are deserialized. The process is repeated for the base model and shared model scenarios for each hour of the day separately and the results are consolidated for further analyses. The infrastructure for the simulation of the base model scenario has a V2X framework simulation scenario and Python-Bottle based Web Service [16]. In particular, we consider two cases: a base model and a shared model scenarios. The first one consists of 4 commercial parking lots ranging from 500 to 1100 spots. The second one has varying number of parking lots and demand. The demand data varies each hour. For each hour, the entire simulation is run for 3 varying number of shared parking lots i.e. 24, 28 and 32 in addition to the commercial parking lots (with capacity ranging between 500 and 1100).

To estimate emissions, we resort to the model proposed in [15] which gives the guidelines to estimate emission output by the vehicles in the simulation. We quantify the benefits achieved by the proposed model through vehicular emissions in terms of CO_2. Emission logs are recorded for every time step of the simulation for all vehicles involved, i.e., both those looking for parking and the other ones.

1) Relationship between CO_2 emission and distance travelled: to establish the relationship between CO_2 emission value and distance, we perform a correlation analysis. The results, presented in Figure 10), show that there is a strong linear correlation between CO_2 emission values and distance i.e. with the increase in emission values, distance increases.

2) Linear regression model: The data coming from this setup is amenable to fit a linear regression model. This is useful to estimate distances for the emission data coming from the simulations.

3) Comparison between base and shared models : the two setups, one not including private parking and one including them, are compared on the basis of CO_2 emissions (milligrams) and distance travelled (metres) by vehicles in the simulation. At each time of the day, the parking demand changes. The results of the comparison are presented by Figure 11 and Table II. Figure 11 represents the comparison analysis between base model (without shared private parking lots) and shared model (with shared private parking lots) in terms of vehicular emissions and distance travelled by vehicles in the simulation. Three sets of plots are present in Figure 11. From top to bottom, each set is plotted for base model and shared model at different hours of a day. For each hour of a day, mean vehicular emission and mean distance travelled by vehicles in the simulation are plotted. Each blue bar and blue stem represents vehicular emission and distance travelled by vehicles respectively for the base model. Each orange bar and orange stem represents vehicular emission and distance travelled by vehicles respectively for the shared model.

Table II is constructed by considering vehicular emissions in all hours of a day. In Table II, the mean value of vehicular emissions of all the vehicles in base model and shared model are compared. Base model and shared model are compared and evaluated by considering the rate of decrease in emissions in Table II. The base parking model remains the same as part of the comparison for all the ratios. But based on the demand at a particular hour of a day, the output emissions and distance values change for the shared parking model due to the varying number of shared parking lots. The results show that as the number of shared private parking lots increases, the emission value decreases. The rate of decrease in vehicular emissions (when compared to the base parking model) is 2% linearly with an increase in shared parking lots of 4. Since distance travelled is linearly dependent on emission values, there is a decrease in distance travelled by the vehicles in the shared

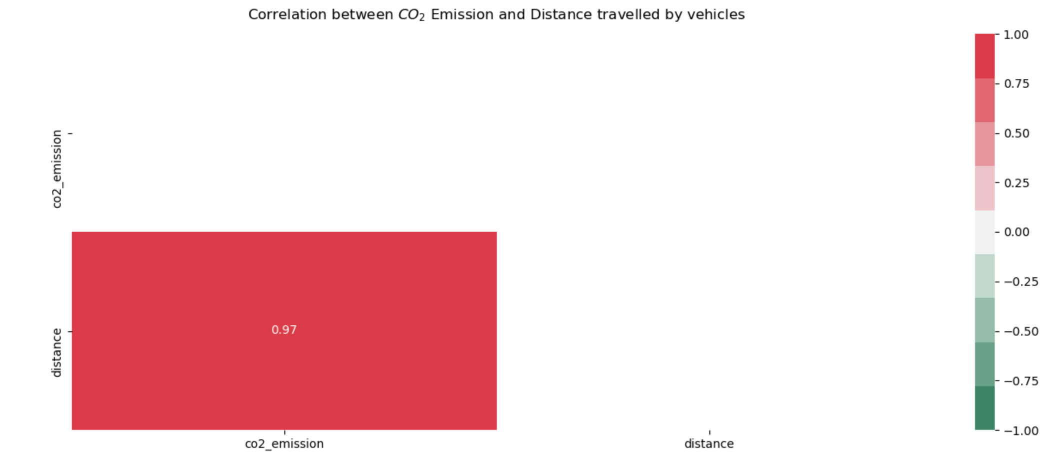

Fig. 10. Correlation analysis between CO_2 emission and distance travelled by vehicle

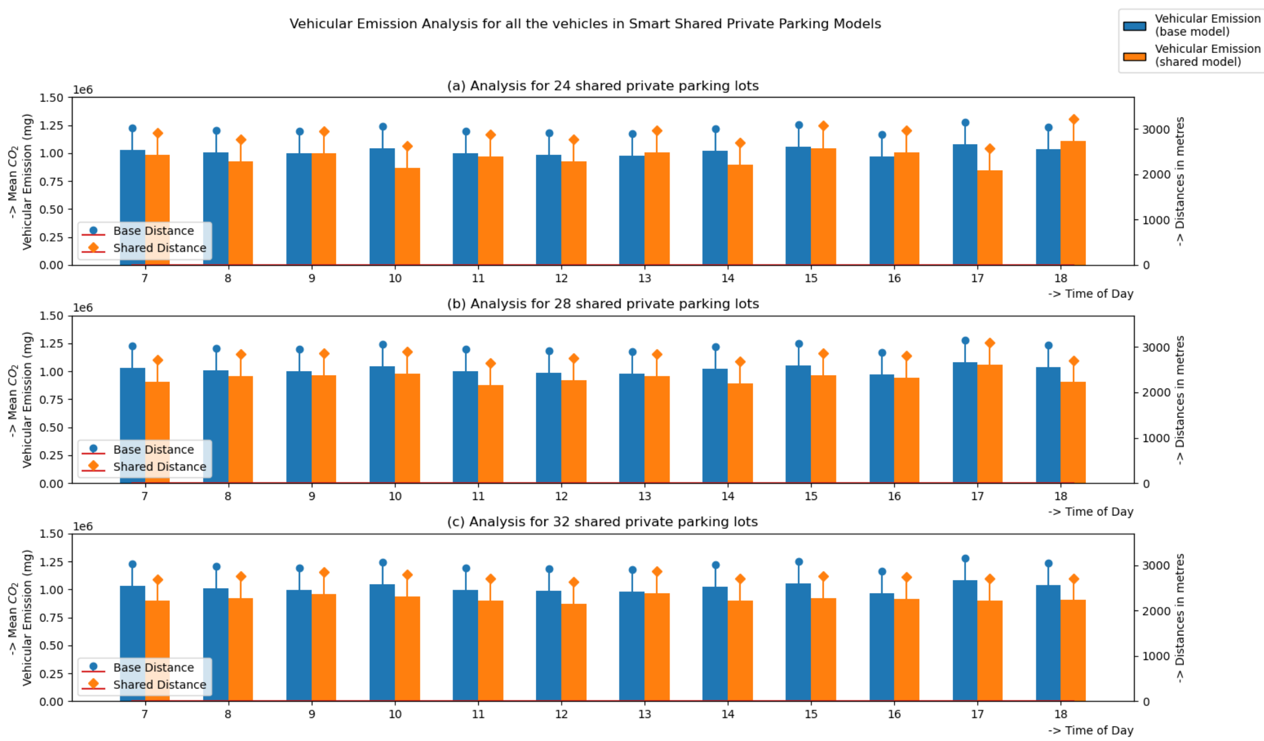

Fig. 11. Results of analysing the CO_2 emission and distance travelled by vehicles in the base model and the shared model

private parking model with respect to that in the base parking model.

D. Benefits for parking owners

The utilisation rate of a parking lot is the sum of all the reservation time of a parking lot over the unit of time. The expression for utilisation rate is given by Equation 1. The records from the database are interpreted for estimating the utilisation rate of each parking lot. The reservation entry is also associated with over time estimates. If the vehicle is parked over time, then there is an entry as over time estimate associated with the reservation. As per the mathematical model, reservation of a spot is done only when all the conditions are satisfied, the most important of which is the preferred distance to travel by foot for a car driver. The distance by foot from the parking lot must be lower than the maximum distance preferred by the car driver to walk. Apart from the walking distance condition, we also consider free spots availability and plan to consider additional preferences such as disability preferences and presence of charging spots.

TABLE II
COMPARISON BETWEEN BASE PARKING MODEL AND SHARED PARKING MODEL IN TERMS OF VEHICULAR CO_2 EMISSION

Number of shared parking lots	**Mean CO_2 emission in base parking model (mg)**	**Mean CO_2 emission in shared parking model (mg)**	**Rate of decrease in vehicular emission (%)**
24	1.016×10^6	9.65×10^5	5.01
28	1.016×10^6	9.44×10^5	7.08
32	1.016×10^6	9.16×10^5	9.80

1) Description of comparison analysis plots: In Figure 12 and Figure 13, utilisation and revenue generated are compared between the scenarios with base model (without shared parking lots) and shared model (with shared parking lots) in Figure 12 and Figure 13. Due to varying number of shared private parking lots, there are three sets of comparisons between same base model scenario but different shared model scenarios (i.e. from top to bottom in each comparison set, shared model with 24, 28 and 32 shared private parking lots).

2) Comparison analysis between commercial and shared parking lots in terms of utilisation rate and revenue: Figure 12 compares the the base model and the shared model in terms of utilisation rate. In Figure 12, each block has a set of line plots with utilisation rate in y-axis and time of day in x-axis. The set of plots include utilisation of different commercial parking lots along with combined utilisation of many shared private parking lots. *ILAC* parking lot is a commercial parking lot in North-Western part of Dublin. From Figure 12, *ILAC* parking lot (plotted in green in each block of Figure 12) is utilized more than that of the other commercial and shared parking lots in the proximity. This is due to its location being in a strategic point that makes it more preferred than any other.

The allocation module (equipped with CA) is intended to make sure that the demand is evenly distributed among the parking lots in the shared parking model (including the commercial parking lots). But in the process, due to the strategic location of some parking lots and the vehicle driver's end destination, the strategically located parking lots are preferred more than others. This is evident from the maximised utilisation of *ILAC* parking lot. We analyse how shared parking lots are utilized when compared to commercial parking lots. With the increase in the number of shared private parking lots, the demand satisfied by the shared parking lots increases. This in turn decreases the utilisation of the commercial parking lots. The presence of shared parking lots contributes to a considerable drop in the utilisation of commercial parking lots, especially *ILAC*. This is evident from Figure 12.

In Figure 13, each block has a set of line plots with revenue in y-axis and time of day in x-axis. The set of plots include revenue generated by different commercial parking lots along with combined revenue generated by many shared private parking lots both in base model and shared model. When considering collectively, the overall revenue generated by the parking lots is proportional to the utilisation rate. As the utilisation rate increases, revenue also increases. But the randomized overtime parking behaviour of the vehicles helps the parking lots to earn more.

It is also important to note that the utilisation rate and revenue of shared parking lots are constant for all graphs of Figure 12. This is because we denote the changes in the utilisation rate of shared parking lots collectively and not individually. The constant number of shared parking lots each with 2 spots satisfy the maximum demand possible. But when there are no vacant spots within the range of the driver's preference, the rerouting occurs. This rerouting also contributes to maintaining the constant utilisation of parking lots.

3) Change in utilisation of shared parking lots: Let us now take the perspective of the single parking lot. For this purpose, 3 shared parking lots are considered. The pattern by which these parking lots are utilised varies for each simulation run, thus generating many possible configurations. In Figure 14 we show few patterns of the utilization of the three parking lots.

From the plots in Figure 14, the important inference is that each of the parking lots is guaranteed to get utilized at least twice (Parking Lot 3 in (a) and Parking Lot 1 in (c)). This is guaranteed by the allocation module using Rule 51. In the case of other parking lots, at some time of the day, the utilisation exceeds 2 and ranges between 2 to 3. This is due to their location and also to the destination of the vehicles at that time. This contributes evidence to the fact that shared private parking lots are utilized evenly. Also, the presence of such shared parking lots decreases the dependency on commercial parking lots as visible in Figures 12 and 14).

E. Effects of the number of available parking lots

Lastly, we evaluate the effects of the ratio between shared parking lots and commercial parking lots available. The results are from the driver's and the parking lot owner's perspective. This collection helps us to correlate how the variation of the ratio could benefit the shared private parking model. From the simulation one can identify the optimal number of parking lots needed for the benefit of the stakeholders. Also, it further helps to understand how to extend the model from a part of a city to a full city-based scenario such as for the MoST. The parameter *Vehicular Emission* denotes the effects on the vehicles to changes in the number of shared parking lots from a driver's perspective. The parameters *Redirects* and *Supply to demand* denote how the model with a certain number of shared private parking lots react to the *demand* (number of vehicles) at a particular hour. Figure 15 shows the results of correlation analysis in the form of a heatmap.The gradient of correlation of different parameters with each other is represented by heatmap. The gradient is represented by numerical variation between -1 and 1 and also, in the form of coloring scheme from dark green to dark red in Figure 15.

1) Relationship between ratio and vehicular emission: Figure 15 shows that the ratio and the mean vehicular emission of all the vehicles in the simulation are moderately correlated

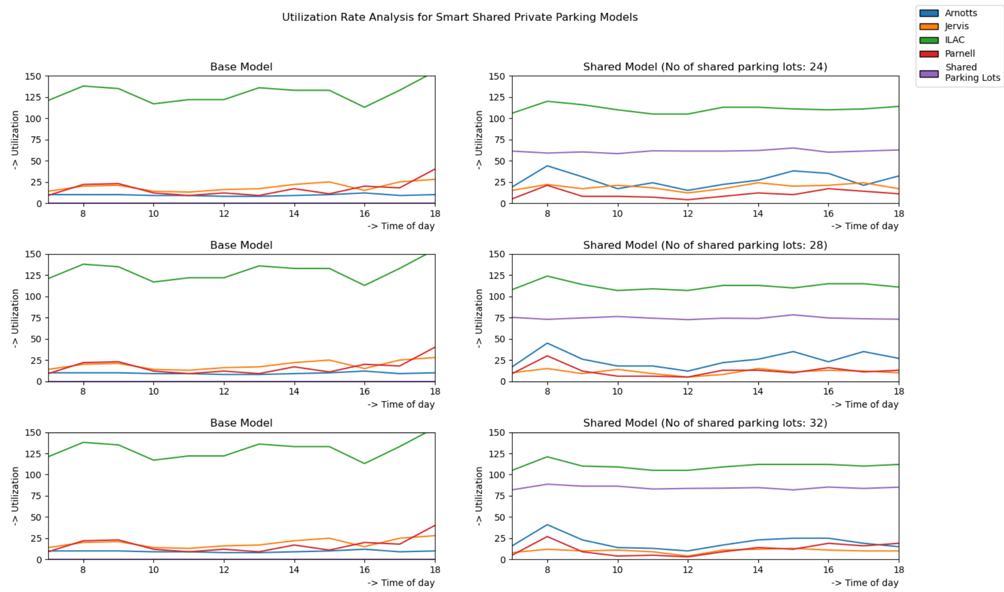

Fig. 12. Results of analysing the utilisation of different commercial parking lots and shared parking lots, collectively

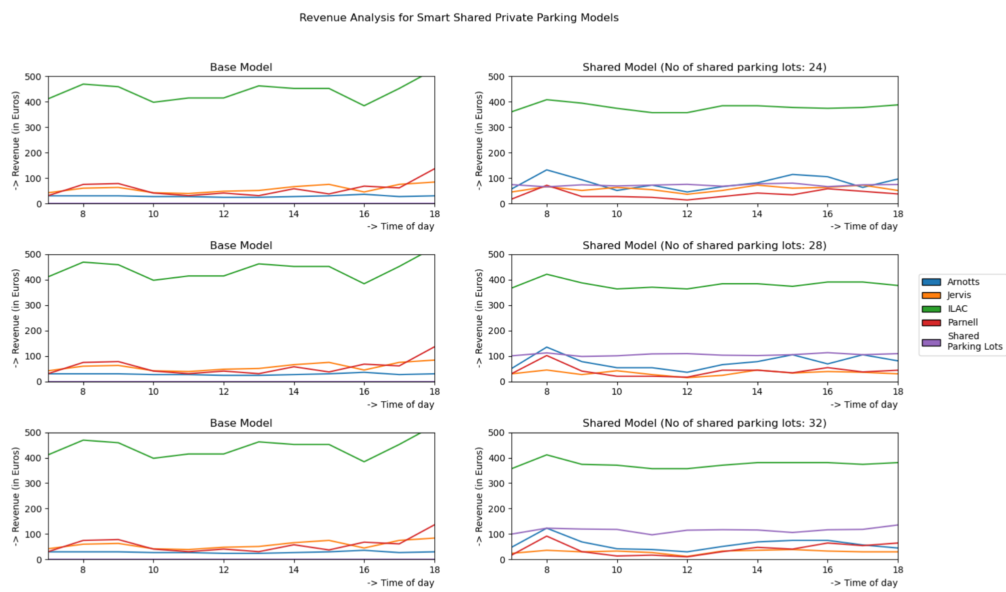

Fig. 13. Results of analysing the revenue of different commercial parking lots and shared parking lots, collectively

with a correlation of **-0.32**. This correlation can be best described as with the increase in the number of shared parking lots, there is a moderate decrease in vehicular CO_2 emissions. From the driver's perspective, this means that the vehicular emission due to additional cruise time to search for parking spot reduces considerably.

2) Relationship between ratio and supply to demand: the term *supply to demand* denotes the number of reservations made by the vehicles in the shared parking lots instead of the commercial parking lots. There is a strong positive correlation of **0.82** that shows that with the increase in the number of shared parking lots, more vehicles utilize the shared parking lots rather than resorting to the commercial parking lots.

3) Relationship between ratio and redirects: The term *redirects* indicates the number of vehicles that are not served by the shared parking model. The correlation heat map shows that the correlation coefficient is **-0.5**. The conclusion is that as the number of shared parking lots increases, the number of vehicles not served decreases. In the present simulation, varying the number of shared parking lots, the best-suited value is 32.

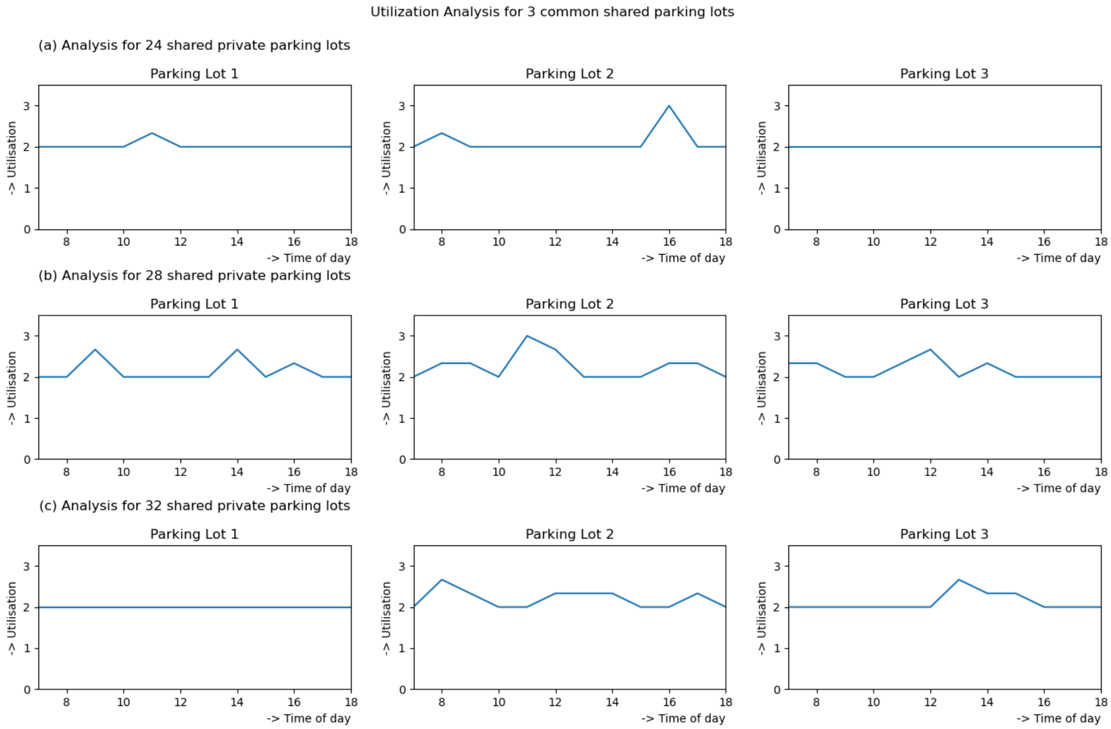

Fig. 14. Utilisation of individual parking lots

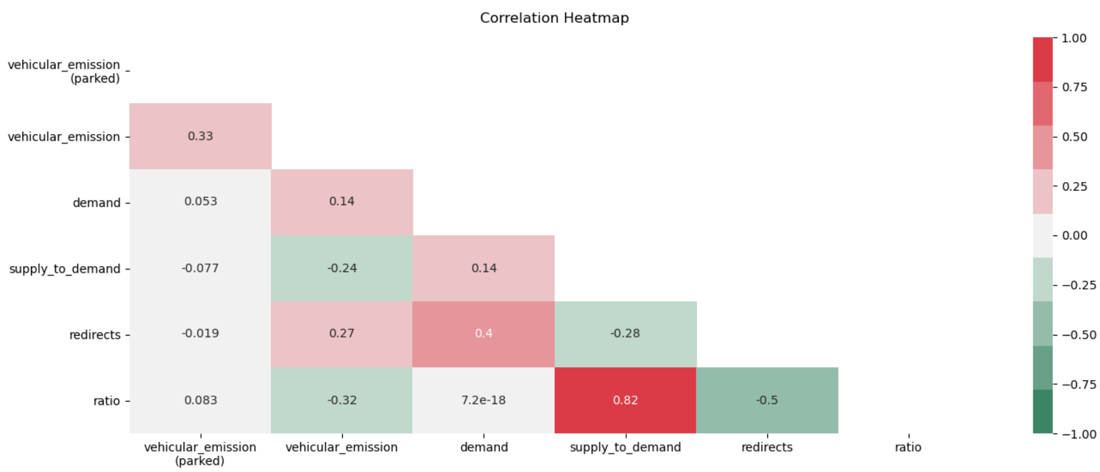

Fig. 15. Results of analysing the effects of change in number of shared parking lots

VI. Conclusions

Smart cities try to optimize the way in which the shared infrastructure is used by its citizens, opening to the possibility of people actively participating resource utilization. The work proposed here provides a fully worked solution on how to address the problem of parking scarcity. Additional benefits of sharing private parking spots in terms of environmental and economic benefits are also identified. We proposed a setup of a simulation-based testbed to realize and analyze the shared private parking model, required number of framework researches and trial runs. The design, implementation and evaluation via simulations show the high potential benefits of the smart shared parking model in terms of CO_2 emission reductions, decrease of driven distance, and economic compensation for private parking owners. Finally, an important outcome of the work is that the results demonstrate how the change in the number of shared parking lots affects the model itself and the participants of the shared parking model.

A. Limitations

Limitations of the present study include the following ones. The scalability of the setup ensures that the applicability to different demand data varying by each hour. But the simulation has to be re-initiated for each hour. This is due to the fact that the retention of the number of free spots (of each parking lot) after respective vehicles resumed is not certain. This uncertainty is due to possible communication failures of the resume signal of the vehicles.

The parking and overtime parking behaviour of each vehicle is modelled in the simulation as random entry. The random entry is chosen by each vehicle from the set of defined entries (taken care of by the application deployed in each vehicle involved in the simulation). For example, for vehicle A, the parking duration and the resuming duration are chosen randomly from the defined set as 30 minutes and 35 minutes, respectively. Though the duration pair is a fixed one from the defined set, the method of choosing a pair from the set is random. There is a need to model the driver's behaviour to park overtime and incur additional charges due to overtime parking which has not been addressed in the work proposed.

Apart from modelling the parking behaviour externally, the vehicle resume activity needs to be triggered externally to reflect the externally modelled behaviour. There are few standard metrics to analyse a shared parking model. In the work proposed, the beneficial perspectives of the model of a vehicle and a parking lot are quantified by vehicular emission, utilisation rate and revenue. But, from a smart city's perspective, some additional standard metrics could be added. This will pave the way for more standard ways of evaluating a shared parking model (for example quantifying traffic congestion created due to parking searches).

Finally, the messages sent between various components in the simulation needs a standard. There are accepted standards of messages based on priority. In the work proposed, the prioritisation of the parking request and response messages is not addressed. Hence, an evaluation of how other messages related to co-operative mobility get along with the messages related to service requests and responses is in order.

B. Future work

The work proposed has a microscopic area as the simulation-based testbed. One can extend it to a large city as the testbed for assessing the benefits of the smart shared private parking model. The work proposed can be extended to Hardware In Loop (HIL) simulation or to a digital testbed. This helps to address the realistic uncertainties that go unaddressed due to the software simulation (e.g., hardware or firmware issues of components involved in V2X communication). The shared parking model is present as a single, centralized web service. This setup could be made as a distributed architecture with proper synchronisation of the distributed data pushing the logic to the periphery of the network in an Edge Computing fashion. Apart from considering the preferred walking distance of the car driver, one could also consider adding other forms of travel options, such as a bike, an electric scooter, or public transportation. This could further reduce the congestion in the considered area. Accordingly, there will be some liabilities for the car drivers as they use the property of the owner. The mathematical models used in the work proposed could be extended in order to evaluate the effects of the change in terms of metrics discussed in the work or by adding additional metrics.

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