Parking support model for open parking lots

VIJAY PAIDI

Microdata Analysis
School of Information and Engineering
Dalarna University, Borlänge, Sweden
2022
Abstract

Parking is a common process performed by vehicle drivers when they arrive at their destination. It is considered to be the last mile transportation problem of personal vehicles. Some of the common problems observed by drivers are additional cruising, congestion, pollution, and driver frustration. This thesis is focused on open parking lots that provide free parking spaces. Since parking spaces are provided free, open parking lots are in high demand leading to additional cruising and pollution. One of the primary reasons for these problems is the lack of information on parking availability. Such information can be provided using a parking support model, or a smart parking system. As open parking lots do not provide any direct return on investments, no parking support models were available on the market. Therefore, this thesis aims to develop a parking support model suitable for open parking lots which can facilitate in providing real-time and short-term forecast of parking availability. This thesis also examines the magnitude of additional cruising and CO2 emissions observed in an open parking lot. A thermal camera was utilized for collecting data on open parking lots as it is not susceptible to varying illumination and environmental conditions. Since there were no pre-trained algorithms for enabling object detection using thermal camera images, a dataset was created with varying environmental and illumination conditions. This dataset was utilized by deep learning algorithms to facilitate multi-object, real-time detection. The developed parking support model facilitates in providing a real-time and short-term forecast of parking availability. Despite the use of low volume of data, the methods utilized in this thesis facilitated providing better detection and forecasting results. Algorithms, such as ResNet18 and Yolo, facilitated in providing real-time, multi-object detection with high accuracy. Similarly, a short-term forecast of parking availability was provided for the open parking lot using methods such as the Ensemble-based method, LSTM and SARIMAX. Ensemble-based method and LSTM provided better test prediction results with lower errors compared to SARIMAX. A new CO2 emissions model was proposed to estimate the magnitude of emissions observed at an open parking lot. The mean CO2 emissions of additional cruising is 2.7 times more than optimal cruising. Despite the individual CO2 emissions of vehicles being lower, aggregating CO2 emissions from multiple vehicles leads to higher pollution. This problem can be reduced by utilizing the parking support model.

Keywords: parking, deep learning, pollution, cruising, detection, tracking, forecasting

Vijay Paidi, School of Information and Engineering, Microdata Analysis

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urn:nbn:se:du-41094 (http://urn.kb.se/resolve?urn=urn:nbn:se:du-41094)
To my family, friends, and well-wishers.
Acknowledgment

My interest in research started in Sweden while pursuing my Master degree. I deeply appreciate guidance and encouragement from my teacher, Anders Avdic in pursuing PhD. I feel grateful to have a wonderful team of supervisors to pursue PhD project in the domain of smart parking. Johan Håkansson, my primary supervisor has always been there guiding and developing me in becoming a better researcher. My co-supervisors, Hasan Fleyeh and Roger G. Nyberg helped me to improve my skills in communication, collaboration, and teaching. I would like to mention Kenneth Carling who gave valuable feedback and helped me to think of out-of-box solutions. There are several other colleagues at Dalarna University who supported in improving and developing my thesis. I thank all these persons from the bottom of my heart who helped me grow personally and professionally by challenging my skills from time to time.

I would like to give special thanks to my wife, Haritha and kids, who were helping, supporting, and encouraging me throughout the course of my PhD. I also would like to thank my whole family who supported me throughout my life. I extend special thanks to my sister and brother-in-law, Maya Paidi and Ravi Vatrapu for guiding me towards post-graduation in Sweden.
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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1. Background

Parking is a common process performed by vehicle drivers on reaching a destination. Parking in public places is usually performed at parking lots, which are found in several places in both major and minor cities around the globe. The vehicles referred in this thesis are cars. Even though there may be an abundant number of parking spaces in a city, these might still be insufficient during peak hours and popular destinations. Problems with parking, such as congestion, additional cruising, pollution and frustration of drivers, occur due to scarcity of available parking spaces (Polycarpou et al., 2013). According to (Shoup, 2006), the time taken to find an empty parking space is between 3.5 to 14 minutes. Congestion can occur in and around the parking lot which leads to higher pollution and driver frustration. If available parking spaces can also impact business opportunities. As illustrated in Figure 1(a), during non-peak hours, there are several empty spaces available, and the driver can easily find and occupy an empty parking space. As shown in Figure 1(b), during peak hours, when there are limited empty parking spaces, the driver can miss empty parking spaces in one row and can carry out additional cruising to find and occupy another empty parking space. Similarly in 1(c), again during peak hours, the driver cannot find an empty parking space and will be forced to park at an alternate location.

The capacity of parking at locations, such as, a retail store, shopping centre, etc., varies from a few to thousands of parking spaces. For instance, a group of parking spaces can house thousands of parking spaces, while a small local store can house parking spaces of less than 50. There exist different kinds of parking lots, such as multi-storey, underground, or open space. Normally, open-space parking lots around shopping centres or retail stores occupy large geographical areas, and this has become a problem in urban areas. Therefore, parking lots are housed underground or in a multi-storey building with dedicated floors of parking spaces occupying smaller geographical areas. Parking lots are expensive despite their location, i.e., open spaces or within buildings. The acquisition or renting of a large geographical area for open-space parking lots is expensive. Similarly, the construction and maintenance of parking lots at a multi-storey building is also expensive. Parking lots are everywhere around us and they facilitate surrounding businesses. Normally within a city, the number of these parking lots would depend on the number
of business places and population. Therefore, it is important to use this resource efficiently.

Figure 1. Illustration of parking at multiple periods: (a) Parking during non-peak hours with several parking spaces available; (b) parking during peak hours with few parking spaces available; (c) parking during peak hours when there are no parking spaces available

Lack of a sufficient number of empty parking spaces is majorly dependent on space, location, size of a parking lot and surrounding population (Tsai & Chu, 2011). During peak hours in traffic-dense environments, 30-50% of drivers are looking to occupy an empty parking space (Boltze & Puzicha, 1995; Gallivan, 2011; Polak & Vythoulkas, 1993; White, 2007). Destinations can be
several types of locations, such as shopping centres, airports, residential places, etc. Vehicle traffic to these locations varies spatially and temporally (Tsai & Chu, 2011). In this thesis, parking lots are classified into two general categories, open and closed parking lots. Open parking lots provide free parking spaces for a limited duration of time, while closed parking lots provide parking spaces for a fee. Closed parking lots are commonly gated or within buildings, while open parking lots are located in open areas. Open parking lots are commonly housed in open spaces to facilitate the free flow of customers to adjoining business places. Open parking lots at popular destinations, such as shopping malls or retail stores, are often in higher demand which leads to higher vehicle traffic (Paidi et al., 2018).

1.1 Problems with open parking lots

The presence of open parking lots facilitates in improving business opportunities in the surrounding locations. However, their presence also increases traffic and additional cruising, leading to excess CO\textsubscript{2} emissions and congestion. Even though additional cruising and excess CO\textsubscript{2} emissions are not high for individual drivers, they are considered high when we aggregate cruising and emissions of multiple drivers searching for empty parking spaces (Paidi et al., 2022). According to (Shoup, 2006), open parking lots or low priced parking lots need to be replaced with closed parking lots, and the parking charge should be controlled dynamically, according to the location of the parking lot. For instance, the price of parking spaces should be higher during peak hours, and lower during non-peak hours. This business model is not suitable for all locations and businesses. Therefore, alternative ways of addressing the problems with open parking lots must be explored. Hence, this thesis facilitates the driver in making informed decisions and reducing associated problems, such as additional cruising, pollution, and congestion.

1.2 Parking information systems

Information on available empty parking spaces can be provided using smart parking systems. Smart parking systems utilize underground or overhead sensors to obtain information on available parking spaces (Hassoune et al., 2016; Mimbela & Klein, 2000; Revathi & Dhulipala, 2012). Such information could be utilized by the driver in making informed decisions when occupying empty parking spaces. These smart parking systems are referred to as a parking support model in this thesis, which serves as a decision support model. A decision support model is a computer application that helps the user to make
decisions (Power, 2008). The parking support model (PSM) referred to in this thesis facilitates in providing real-time and short-term forecasts of parking occupancy information. Real-time occupancy information is beneficial when the driver is already in the parking lot. Similarly, short-term forecast information of available parking spaces is beneficial for drivers in planning their arrival at the parking lot. Unlike closed parking lots, parking spaces are provided free of charge in open parking lots and do not generate any direct revenue. Hence, parking support models were not available for open parking lots which can facilitate in reducing search times and additional cruising to find empty parking spaces. Therefore, as a first step, an affordable and suitable tool must be selected which can be utilized in any open parking lot.

1.3 Tools suitable for open parking lots

Open parking lots are exposed to harsh weather conditions and varying illumination conditions as they are commonly placed in open spaces. Tools, such as GPS, cameras, underground sensors, like magnetometers, microwave radars, can be utilized at open parking lots. GPS devices are one of the tools which can be used for data collection at open parking lots as they perform better in open spaces. However, their accuracy depends on the position of the satellite (Dogan et al., 2014), and the frequency of pings should be for every second, due to the size of open parking lots. The use of GPS also restricts the collection of data to volunteers. GPS data are well suited for collecting mobility information of vehicles travelling larger distances (Paidi et al., 2021). According to (Paidi, Nyberg, et al., 2020), tracking of drivers during last-mile transportation was enabled using GPS. The driver travels large distances to make deliveries at multiple locations. Hence, the use of GPS devices was well suited for covering large areas, and it is ruled out for this thesis as drivers cruise for shorter distances in the parking lot. Underground sensors, such as magnetometers and microwave radars, facilitate in capturing accurate parking occupancy and duration information. However, underground sensors are not suitable for the open parking lot investigated in this thesis as they require high expenditure in installation and maintenance activities. Data collection can also be performed using remote sensing. Radars, such as synthetic aperture radar (SAR), can be utilized to detect objects. This radar can be used to capture data and detect objects, even with heavy cloud cover (Wu et al., 2021). However, it is not ideal for real-time detection of vehicles for an open parking lot as it would be expensive to have a dedicated satellite for this purpose. Overhead sensors, such as ultrasonic, are not suitable for open parking lots as they are sensitive to the harsh environment. Optical cameras are one of the overhead sensors which can be utilized in collecting data from open parking lots, as they provide an overview of multiple moving and stationary vehicles in the parking
lot. However, an optical camera needs a good amount of illumination to detect vehicles in varying illumination conditions. The use of an optical camera can lead to privacy issues, as pedestrians or drivers can be recognized (Asghar et al., 2019). Therefore, in this thesis, I utilized a thermal camera to collect data from open parking lots. There are other IR-based sensors, such as Time of Flight (ToF), for detecting and measuring objects (Foix et al., 2011), which are primarily utilized in logistics operations for measuring the volume of boxes. However, since distance of multiple objects to the camera is not necessary, ToF is not utilized in this thesis. Pedestrians, drivers, or vehicles cannot be recognized using the thermal camera, as objects are represented using pseudo colours based on emitted heat intensity. In previous papers, the use of thermal cameras was scarcely utilized in parking lots for data collection purposes. It was predominantly utilized for surveillance and security purposes. A thermal camera is a viable tool that can be utilized in varying illumination and environmental conditions, such as an open parking lot (Paidi & Fleyeh, 2019; Paidi, Fleyeh, et al., 2020). Therefore, it is utilized as a data collection tool in this thesis.

1.4 Overview of parking support model

The PSM is developed for open parking lots in this thesis. As illustrated in Figure 2, the owners of the PSM can be the municipality, if the open parking lot is in a public place, or it can be a business owner, if the open parking lot is near a shopping centre, retail store, etc. An open parking lot beside a shopping centre was selected for this thesis. Therefore, the business owner can own the developed PSM. The problem at open parking lots is lack of parking availability information, resulting in the driver carrying out additional cruising, leading to excess CO₂ emissions. The PSM provides real-time and short-term forecast information on parking availability to the driver, who is also the user. The end-users of the PSM are drivers, while it facilitates in improving business opportunities and reducing excess CO₂ emissions, due to parking. Therefore, the stakeholders of the PSM are drivers, municipalities, and business places.
There are currently no information services available which provide either real-time or forecast of parking occupancy information for open parking lots. Open parking lots also receive higher traffic which varies spatially and temporally. Due to higher traffic at open parking lots, a greater number of vehicles search for empty parking spaces, leading to high additional cruising and CO₂ emissions (Paidi et al., 2022). Despite these problems, there is a scarcity of research performed on open parking lots to obtain parking occupancy information and comprehend the amount of cruising and CO₂ emissions. Hence, this thesis aims to develop a parking support model for open parking lots, derived from best practices, which facilitate in providing a real-time and short-term forecast of parking availability. It also examines the amount of excess cruising and CO₂ emissions observed in an open parking lot.

The below research questions were formulated to achieve the aim of the thesis, which were addressed in the papers attached with the thesis.

1. How can parked vehicles be detected using a thermal camera?
2. How can a short-term prediction be provided of empty parking spaces in an open parking lot?
3. How can cruising vehicles be tracked in an open parking lot using a thermal camera?
4. What is the estimated amount of cruising and CO₂ emissions observed in an open parking lot?

These research questions facilitate in developing the components necessary for a parking support model. An overview of the components is illustrated in Figure 3. Use of a thermal camera facilitated the collection of data from the open parking lot. The first research question evaluates and identifies a suitable method that facilitates real-time detection of multiple vehicles. This enables the provision of real-time parking occupancy information. The second research question facilitates the provision of short-term predictions of parking availability at an open parking lot. This enables the driver to plan their arrival.
at the location. The first two research questions facilitate in providing information on parking occupancy. The rest of the research questions facilitate in comprehending the magnitude of excess cruising and CO$_2$ emissions observed in an open parking lot. The third research question identifies the method suitable for detecting and tracking cruising vehicles. The fourth research question identifies and analyses excess cruising and CO$_2$ emissions data observed at an open parking lot. In this way, this thesis facilitates in developing a parking support model to generate parking occupancy information. A similar method can be utilized in other open-space parking lots. This thesis demonstrates the data collection and processing part of a parking support model. However, the last phase, which is to communicate the information to the user, is not demonstrated in this thesis.

This thesis makes a contribution to research in multiple areas. A thermal camera was utilized to collect data at an open parking lot to withstand harsh weather and varying illumination conditions. The performance of multiple deep learning algorithms was evaluated in detecting parking occupancy. This can be utilized to capture real-time parking occupancy in an open parking lot where there can be varying weather and illumination conditions. Vehicle movement in an open parking lot was captured to identify cruising behaviour. This facilitates the understanding of the amount of cruising and pollution observed in an open parking lot during peak and non-peak hours. Even though a parking lot consists of vehicle short trips, these trips are made by hundreds of vehicles each day. The amount of cruising and emissions also varies temporally and spatially. Along with real-time parking occupancy information, this thesis also demonstrates the forecasting of parking occupancy information. Multiple forecast algorithms were evaluated and compared. The forecast model developed in this thesis can also be utilized for a similar demographically placed open parking lot. A single thermal camera can be installed for two weeks to one month at an open parking lot to collect data, which can be utilized to provide forecast information for up to 60 minutes with reasonable accuracy. Finally, the thesis demonstrates the data collection and processing of a decision support system in providing real-time and forecast of parking occupancy information.

The remaining parts of the thesis are organized in the following way. The second section focuses on methodology, discussing the framework and methods used in answering the aim and research questions. The third section consists of the papers included in this thesis, while the final section presents a concluding discussion.
2. Methodology

This section discusses the research design implemented in this thesis in addressing the aim and research questions. Generally, thesis and research work are categorised by research domains or frameworks. There are several established frameworks, such as computer science, statistics, applied economics, etc. Such frameworks help the reader in finding relevant research, with less filtering or conditional search. Thus, this thesis is also categorized into a transdisciplinary research domain, that of Microdata Analysis (Dalarna, 2019). Transdisciplinary research requires collaboration with stakeholders (Wickson et al., 2006). The research on an open parking lot was carried out in collaboration with the business owner of the shopping centre, where findings and knowledge generated were shared and discussed enabling this research transdisciplinary.

Microdata analysis (MDA) involves several research areas, such as decision support systems, forecasting, artificial intelligence, and resource management. The phases involved in MDA are data collection, data assessment and transformation, data storage, reports and analysis, and decisions. The parking support model developed in the thesis facilitates the driver in making informed decisions on occupying empty parking spaces, thereby reducing excess cruising and CO₂ emissions. However, the driver must be motivated to use this model to reduce parking associated problems. If the driver is not interested in using PSM or other similar systems, then we might not see a reduction in parking associated problems. Despite using a PSM, the driver can still perform additional cruising to find an empty parking space, if forced to visit the open parking lot during peak hours, due to an appointment or other similar task. Therefore, if there are no empty parking spaces available, use of PSM cannot help the driver in finding an empty parking space. Thus, use of PSM does not solve additional cruising and CO₂ emissions completely. However, it facilitates in reducing these problems, if the driver is willing to use this data and make a conscious decision.
2.1 Relation of papers to MDA

The phases involved in the MDA and its relevance to the papers attached with this thesis are discussed in the following section.

**Data collection:**

All the papers included in the thesis perform some kind of data collection. The first paper performs a literature review to find suitable tools for open parking lots, based on expenditure, varying illumination, and weather conditions. I setup a thermal camera on top of a university building to collect data of an open parking lot. This data was utilized in the second paper. The videos of the parking lot were converted to frames and annotated to generate a dataset that was utilized by multiple deep learning algorithms, to detect vehicles in varying illumination and environmental conditions. Publicly available parking lot datasets were not available for thermal images. Therefore, the required dataset was generated by performing manual annotation and labelling. Annotation is the process of drawing a bounding box over the vehicle, while the label is the name given to a particular bounding box. The thermal camera was installed over a shopping centre for the third paper. The movement of vehicles was captured in this paper. Therefore, a new dataset was created to detect and track moving vehicles. In the second paper, the dataset was created to detect stationary vehicles, while the dataset in the third paper is created to detect moving vehicles. The fourth paper collects data on cruising of vehicles, while the fifth paper collects data on parking occupancy.

**Data assessment and transformation:**

Data is mainly collected by video. In the second and third papers, multiple videos were utilized to create datasets for training and testing purposes. Videos were converted to images that were annotated and labelled to create the dataset. The annotations and labels from each image were utilized to train the algorithms. The fourth paper utilizes the trip segments of each vehicle searching for an empty parking space. The trips were utilized to calculate cruising and CO₂ emissions. Trips made by multiple vehicles are distinguished using colours, and the data association of each track was maintained by the Kalman filter. Similarly, in the fifth paper, historical data was utilized to predict parking occupancy. Parking occupancy data was collected for the 5-minute interval.
Data storage:

The videos collected from the parking lot were collected over a period of hundreds of days, consuming hundreds of gigabytes. In this thesis, data from two parking lots were collected. The first parking lot utilized was beside a university, while the second parking lot was situated beside a shopping centre. Even though the thermal camera collects videos in a public space, it does not violate privacy regulations as people or vehicles are not recognized or identified. Therefore, ethical approval was not necessary for the storage of parking lot videos.

Reports, analysis and decisions:

All papers in this thesis generate reports which were analysed in making decisions. The first paper presents and analyses several available technologies and tools suitable for open parking lots. The second paper compares and analyses the detection results of multiple deep learning algorithms. The third paper compares, and analyses vehicle trips generated by deep learning algorithms. A modified You look only once (Yolo) algorithm detected and tracked the movement of vehicles better than other algorithms. Therefore, a decision was made to collect vehicle movement trips using a modified Yolo algorithm. The fourth paper utilizes the modified Yolo algorithm proposed in the third paper, and collects multiple vehicle movement trips. This trip data is further analysed to identify optimal, non-optimal cruising behaviour and CO$_2$ emissions observed in an open parking lot. Based on observed high non-optimal behaviour during peak hours, a few suggestions, such as providing real-time or forecast information of parking occupancy and reducing the duration of parking time, were proposed. The fifth paper uses multiple forecasting algorithms to predict parking occupancy information. The performance is analysed, based on evaluation metrics, such as root means square error. Finally, a decision is made to select an algorithm that produced forecasting information with lower errors.

2.2 Components of parking support model

This thesis facilitated the development of skills to evaluate multiple algorithms in detection of parked and cruising vehicles, using thermal camera data. Insights were gained on open parking lots by estimating cruising distance and CO$_2$ emissions of vehicles in an open parking lot. Multiple forecasting methods were evaluated to provide short-term forecast of parking availability, which facilitates decision making. Figure 3 illustrates the components which facilitate the decision-making process. A thermal camera is utilized to collect
videos, and frames are captured from these videos. These frames are used to annotate objects, and these annotated images are used to create datasets utilized by deep learning algorithms. The trained, deep learning algorithms facilitate the detection of multiple vehicles. This data is utilized to provide real-time vehicle occupancy information. Similarly, detection of cruising vehicles facilitated the capture of cruising distance and estimated CO₂ emissions in an open parking lot. The vehicle occupancy information can be stored and utilized to train forecasting algorithms. Forecasting algorithms can be improved by using historical data and real-time. The forecast of parking occupancy information helps the users to plan their time of arrival.

Figure 3: The components facilitating parking support model

The paper aims to develop a parking support model which provides real-time and short-term forecasts of parking availability. It also examines the magnitude of excess cruising and CO₂ emissions observed in an open parking lot. The papers attached with this thesis facilitate in achieving this aim, as illustrated in Figure 3. A literature review was conducted in Paper 1, which explores suitable data collection tools for open parking lots. It also establishes that there are no available smart parking applications for open parking lots. Underground sensors and optical sensors were suggested as suitable sensors for open parking lots, which can withstand varying illumination and environmental conditions. This thesis work was conducted in Sweden where illumination conditions vary seasonally. During winter, the daylight is minimal with snowy conditions, while daylight lasts until night during summer conditions. Hence, in Paper 2, a thermal camera was utilized to collect
data from the parking lot which is unsusceptible to these varying conditions. Due to seasonal variations, the dataset was created in these multiple weather conditions. The parking lot observed in the second paper is beside a workplace where vehicles are parked for longer durations. The heat intensity of vehicles changes based on time, and the created dataset also includes varying heat intensity of vehicles. Multiple deep learning algorithms were trained and evaluated using this dataset. In the third paper, the observed open parking lot was beside a shopping centre. Cruising of vehicles was detected and calculated in Paper 3. In this paper, the dataset was created from vehicles moving in the parking lot instead of stationary or parked vehicles. Unlike the parking lot in the second paper, the heat intensity variations observed in vehicles were minimal as vehicles were parked for short durations. Detection of moving vehicles was performed with deep learning algorithms. The trajectory of detected vehicles was maintained using Kalman Filter. The method developed in the third paper was used to calculate trajectories of moving vehicles in the parking lot. The estimated cruising distance of vehicles looking for empty parking spaces was generated from the trajectories in Paper 4. Cruised distance, time and average speed were applied to estimate the amount of CO\textsubscript{2} emissions in the observed parking lot. Parking occupancy data was collected using a thermal camera, which was utilized by forecasting methods in Paper 5. The volume of data utilized to train the forecasting algorithms was low. However, Ensemble-based method and long short-term memory (LSTM) performed considerably well which produced lower errors. The papers are attached in Section 3 where a more detailed discussion can be found.
3. Papers

Papers are not included in the electronic fulltext version.
4. Concluding discussion

Open parking lots provide free parking spaces and are in high demand. The number of drivers cruising for empty parking spaces increases during peak hours compared to non-peak hours, which also leads to higher additional cruising and CO₂ emissions. Aggregating additional CO₂ emissions of multiple drivers searching for empty parking spaces leads to high emissions, even for a small geographical region as an open parking lot. Additional cruising occurs due to lack of information on available empty parking spaces. Therefore, I conclude that the parking support model developed in this thesis would facilitate in providing a real-time and short-term forecast of parking availability. Deep learning-based algorithms were able to learn and detect features of vehicles with varying heat intensities. The computational capacity of the deep learning algorithms facilitates real-time detection. The short-term forecast accuracy was also reasonably good, despite the use of low volume data. Hence, this model can also be deployed for other similar open parking lots.

The rest of this section discusses and concludes the research questions and future work. Deep learning algorithms, such as Residual Neural Network (ResNet) and Yolo, detected vehicles with high accuracy. Data utilized in this paper are captured using a thermal camera and the objects of interest are vehicles. Objects or vehicles are displayed in a thermal camera using pseudo colours. The intensity of pseudo colours depends on the amount of heat emitted by the vehicle. In places such as shopping centres, vehicles are illustrated by bright pixels which are easier to distinguish. However, vehicles tend to appear dark, or they are hard to distinguish when they are parked for long durations. This kind of behaviour is commonly observed at workplaces. Despite this problem, deep learning algorithms performed considerably well. Detected vehicles are utilized to establish occupied and empty parking spaces in a parking lot. This enables the provision of real-time vehicle occupancy information.

Drivers can be provided with real-time parking occupancy information, or a forecast of the number of empty parking spaces. The real time occupancy information can be utilized by drivers who are already in the parking lot. Due to lack of visibility of empty parking spaces, vehicles tend to cruise for empty
parking spaces. Hence, with information on the availability of empty parking spaces, the number of vehicles cruising for empty parking spaces would be reduced, leading to reduced CO\textsubscript{2} emissions. Short-term forecast of empty parking spaces helps the driver to make decisions on reaching the open parking lot. The driver can avoid the parking lot when there is a lower number of empty parking spaces, thereby reducing potential CO\textsubscript{2} emission. This reduces the number of vehicles cruising non-optimally for empty parking spaces during peak hours.

Forecasting parking occupancy was performed using deep learning and machine learning methods. Ensemble-based learning approach produced prediction results with lower errors, despite the small amount of training data. Patterns of parking occupancy were better grasped by LSTM and Ensemble-based approach using decision trees and random forest. Decision trees are considered weak classifiers, however, aggregating results from several decision trees and random forests lead to lower errors in providing predictions. When there is a sudden change in parking availability, none of the utilized forecasting methods was able to predict it. This might be mainly due to the usage of low volume data. With a higher volume of training data, forecasting methods, such as LSTM, might provide better predictions with lower errors.

Parking lots are small geographical areas where often hundreds of vehicles traverse each day. These moving vehicles were detected using modified Yolo based deep learning, and detected vehicles were tracked using Kalman filter. Yolo based algorithms were chosen for detecting moving vehicles as they are computationally efficient. Cruised distance and time were calculated using the generated trajectories. Driving behaviour was categorized into optimal and non-optimal, based on drivers cruising in one or more parking rows. It was found that 30\% of non-optimal drivers’ cruised equivalent distances to 70\% of optimal drivers. The number of non-optimal drivers was also higher during peak hours when there were limited, or no, available parking spaces. Due to lack of information, drivers tend to cruise non-optimally, leading to higher CO\textsubscript{2} pollution. Despite the average CO\textsubscript{2} emissions emitted by each vehicle being lower, accumulating emissions of hundreds of vehicles cruising in the parking lot was higher. The CO\textsubscript{2} emissions were also concentrated in a smaller region and prolonged exposure can lead to respiratory health problems. Hence, it is vital to reduce non-optimal cruising by providing real-time and forecast of empty parking spaces.

In this thesis a thermal camera was the primary source of data collection. A thermal camera is well suited for collecting data in varying weather and light conditions. This overcomes the limitations associated with an optical camera, which is dependent on light and visibility conditions. The existing deep learning algorithms are designed mainly for optical camera images. However,
they also performed well with images from the thermal camera. The object features of a vehicle in a thermal camera are distinguishable even in pseudo colours. Hence, detection of multiple vehicles was performed with existing deep learning architectures. However, when the thermal camera is not in the rear, front or top views of the vehicles, the features of objects are not distinguishable. All the vehicles appear to be connected when viewing from a thermal camera, as discussed in Paper 3.

Multi-object detection was performed using deep learning algorithms. Very deep network architectures are not suitable for real-time detection of vehicles as it is computationally expensive. Therefore, in this thesis, deep learning algorithms based on ResNet18 and Yolov3 were utilized for object detection, which facilitated real-time object detection. ResNet18 consists of 18 layers, which are not too deep and are capable of real-time multi-object detection. Similarly, Yolov3 is a logistics regressions based, deep learning algorithm, capable of real-time multi-object detection. Tracking of multiple vehicles by video was also achieved due to the lower computational costs of these deep learning algorithms.

4.1 Limitations and future work

In this thesis, a parking support model is developed to facilitate in providing a real-time and short-term forecast of parking availability. However, this model is not deployed and utilized by drivers. Hence, in the future, this model can be deployed and evaluated. It would be interesting to know if drivers are willing to use it, and, if they use it, does it help to reduce any associated parking problems. Only deep learning algorithms were evaluated in this thesis for the detection of multiple vehicles. Hence, in future, different algorithms based on reinforcement and genetic learning can be evaluated. Since the number of occupied parking spaces is utilized in training prediction algorithms, sensors can be deployed at all entrance and exit positions in the future to cover the whole area of the parking lot. The amount of time a vehicle is parked in the parking lot can also be a useful predictor which can be evaluated in the future.
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