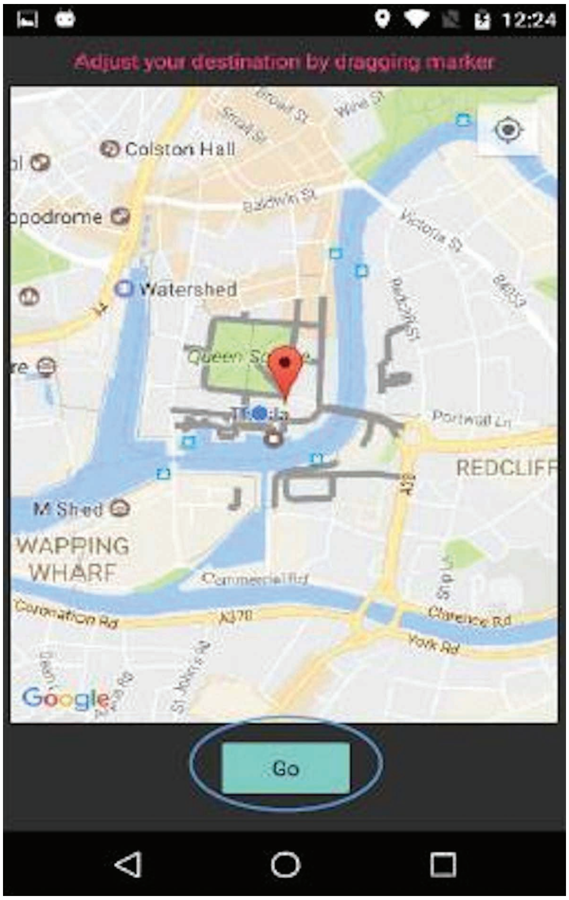

Reducing Parking Space Search Time and Environmental Impacts

A Technology Driven Smart Parking Case Study

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Over the last half century, the proportion of humans living in cities has dramatically risen from around a third to just over half. As cities continue to rise in popularity, demand for basic services such as transportation increases. The automobile has been the dominant method of inner city transportation for many cities across the globe, resulting in increased congestion and air pollution. As the demand for transportation rises, so does the number of vehicles, which leads to greater competition for publicly available parking spaces. Use of land for parking can be an inefficient use of space, and it is expensive, both in terms of real and opportunity costs. Addressing these issues requires cities to more effectively manage their public on-street parking spaces and road network infrastructure. The ParkUs solution discussed here provides one parking and infrastructure management approach, with potential benefits for citizens, businesses, and cities.

A key component of parking is finding a vacant space to park in. When this aspect was studied in Los Angeles in the U.S., the average time spent searching for a vacant parking space (also known as cruising) by a driver was just over 3 min. While seemingly insignificant, over a year this equated to an excess of roughly 932 000 km vehicle driven miles, generating approximately 730 metric tons of greenhouse gas emissions in just that one city [1].

Various studies conducted over the last century covering cities in North America such as New York, Detroit, Los Angeles, as well as European cities such as Freiburg and Barcelona conclude that at any given time, approximately 30% of inner-city traffic is looking for a vacant parking space. With the proportion of humans living in

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cities set to increase (the UN estimates by 2050 roughly two-thirds of humanity will live in cities), it is likely that competition for parking spaces will only increase. Cruising for parking will undoubtedly also impact levels of congestion, contributing directly to air quality problems in cities, with the worst effects felt by those in inner-city districts — often the least well-to-do inhabitants.

Other effects of inefficiencies around parking include increased driver frustration with increasing likelihood of accidents, wasted time, fuel, and money, and other effects such as missed appointments and loss of productivity. In a study in [2], 72 families were randomly surveyed to identify main reasons for missing hospital appointments, and it was found that almost 32% of missed appointments were due to inadequate car parking facilities. In this context, it is worth noting that missed appointments cost the U.K. National Health Services (NHS) £790 million (U.S.$993 million), annually.

One response explored by Shoup and other researchers [3] was to find the optimal price for parking to both reduce congestion and pollution in cities by minimizing the time spent by drivers circling blocks to search for parking. A parking price per hour that results in 60–80% level of occupancy (averaged over the day) is deemed to be ideal since there will always be some space for the next driver to park (thus cutting down on search times), while not being so expensive that the public resource is underused.

The city of San Francisco implemented an on-street parking scheme designed to achieve an optimal level of occupancy averaged across the day through the use of variable parking space pricing. The system, called SFpark, cost over U.S. $23 million to implement and covers 7000 on-street parking spaces and 14 publicly owned and managed parking garages. In its evaluation, the San Francisco Municipal Transportation Agency (SFMTA) found that in pilot areas the target parking occupancy of 60–80% was met 31% more often. This is in contrast to control areas (where there were no parking meter price changes based on user demand) where parking spaces were full 1.5 times more often than pilot areas. Furthermore, they estimate a 30% decrease in vehicle miles driven in SFpark pilot areas, equating to reduction of 2.1 metric tons of daily greenhouse gas emissions (from 7.0 tons before the introduction of SFpark pilot to 4.9 tons) [4].

Though relatively successful at reducing congestion and emissions, SFpark relies on a substantial initial investment and ongoing running costs to operate successfully. Furthermore, it only covers a small percentage of the total stock of on-street parking in San Francisco. As attractive as the SFpark solution may appear, financial constraints being experienced in most municipalities mean that such solutions could struggle to see acceptance. There is no doubt that solving congestion and air pollution problems are a high priority of most cities, and parking management could be a key tool in addressing these concerns. However, it also goes without saying that this should also be achievable in an economically sustainable manner without substantial upfront capital costs and subsequent ongoing running costs.

Many parking management systems rely on physical infrastructure being installed, such as smart parking meters and street mounted ultrasonic sensors (SFpark), Closed Circuit Television Cameras (CCTV) overlooking parking bays [6], or ultrasonic distance measuring transducers mounted on moving vehicles [7]. While successful in some cases, the hassle and initial cost of physical infrastructure can be prohibitive in nature. An extensive review of smart parking solutions that assist drivers in finding parking spaces (efficiently) through the use of information and communications technology can be found in [5].

Several studies have also been conducted in the literature analyzing various factors associated with parking information systems beyond technical KPIs. For example, the impact of pricing on parking in urban areas is highlighted in [23]. This study was conducted in Rome with 400 respondents particularly with the goal of understanding how user behaviors may impact the success of a parking policy strategy. In [24] user acceptance factors are analyzed in a study with 221 respondents for Android based parking systems. In particular, key factors are identified that are shown to have a significant impact on user behaviors that include performance and effort expectations.

Similarly, in [25], a smart parking solution designed specifically for a college campus is studied. The main aim in this solution is to allow students and faculty members to reserve a parking spot prior to their arrival on campus. A college-wide survey was circulated in order to acquire feedback from students for over two months that resulted in 38 responses, predominantly acknowledging the difficulty in parking on campus and supporting the need for a reservation-based parking system.

Encouraged by the high penetration rate of smartphones globally and wireless Internet access availability in cities, various smartphone based parking solutions have also been developed and researched. Most smartphones have a combination of sensors, likely to include a Global-Positioning-System (GPS) module, as well as accelerometers, gyroscopes, and magnetometers. Consequently, systems such as PhonePark [8] and Park Here [9] attempt to leverage smartphone users and crowdsource parking data to aid drivers with finding parking spaces efficiently. PhonePark and Park Here utilize GPS, accelerometers, magnetometers and Bluetooth connections to detect changes in user transit behavior, i.e. when they transition from driving to walking or vice versa. Instead, ParkSense [10] relies on constructing Wi-Fi

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access point ID maps in order to both infer velocity of a user (as they drive or walk) as well as parking location. Although all the above cited systems were able to achieve reasonably high detection accuracies (approximately 80% true positive rate) they often relied on some form of user tagging and large data collection campaigns to achieve such levels of reliability. However, early adopters of any of the above-mentioned systems are not likely to see much benefit given the granularity of the data, i.e., since each user effectively only provides a single data point: when and where they parked/un-parked. To obtain real-time data about parking occupancy across a neighborhood in this manner requires nearly universal adoption by users.

To address some of these issues, the ParkUs phone app, the subject of this paper, was developed with a high parking/un-parking detection accuracy while requiring less energy expenditure per detection. Overall, it achieved a higher true positive detection accuracy (over 98% for parking/un-parking events) than previous attempts, while utilizing less energy [11]. To aid real-time parking occupancy data, ParkUs was enhanced [12] to detect when drivers are searching for a vacant parking space. This was achieved with the understanding that every road or row (in a car park or garage) traversed by the user in their search for a vacant parking space indicates that all preceding spaces would, most likely, have been occupied. In practice, it is also likely that at least some of the drivers may cruise past vacant parking spaces for a variety of other reasons (including passing spaces not suitable for larger vehicles or a space dedicated to specific types of users such as disabled or family parking spaces). To counter this, road segments were labeled as occupied only if more than one user has cruised there. Even this adjustment would (in theory) allow for far richer data gathering with fewer users.

To evaluate ParkUs in a real-world setting, we developed a pilot trial with the University of the West of England (UWE) located in the city of Bristol, U.K. This trial allowed the functionality of the solution to be tested, as well as providing an opportunity to elicit feedback from participants on usability and effectiveness. All activities with participants took place in accordance with the UWE code of ethics under appropriate ethics permissions. It is worth noting that ParkUs does not require the user to have the smartphone mounted to the vehicle or placed in a particular fashion. Furthermore, the user is not required to interact with the smartphone while driving, thereby ensuring compliance with a vital motor regulation in most nations, that is, not using a phone while driving.

This article builds on earlier work of this author team, which described the cruise detection algorithm and some results from a preliminary evaluation [12]. We take this work forward along several dimensions: 1) We further develop and then trialed the ParkUs app incorporating the cruise detection algorithm in a real world trial, 2) We show a positive impact on cruising time when ParkUs shows parking availability information, 3) We evaluate and show the generalization capability of the cruising detection algorithm, 4) We perform a qualitative study of parking behaviors focusing on usability and performance aspects of the app, and present this alongside a statistical analysis of the trial data, 5) We lay out a future roadmap for the app.

ParkUs Overview

ParkUs is a parking-availability predictor which uses an Android app to both display current availability and obtain data to populate its model. The availability is displayed using a road network overlaid with colored segments to indicate which roads are likely to have spaces. The ParkUs architecture is illustrated in Figure 1. The main research questions that we set out to address are:

- How to detect if a user is cruising without having to manually label parts of the journey?
- Does ParkUs provide an effective proxy for cruising and does it work in practice?
- Having detected cruising, how can that information be fused with data from other users to label parking availability information on different road segments?
- Will ParkUs be used by drivers, and if so will it have a positive effect on parking behaviors?
- How might ParkUs functionality be best deployed to achieve beneficial outcomes?

As illustrated in Figure 1, by logging various sensors and location data and using these to train a cruising classification model (see "Cruising Direction" section for more detail), it is possible to detect cruising behavior, which can be used as a proxy for non-availability of parking on road segments where the vehicle cruises.

Parkus Operation

Prior to setting off on their trip, users are asked to enter their desired destination postal code or street name. The requested destination is displayed (red pin, as shown in Figure 2) on a map along with the parking availability within a 100 m (328 ft) radius. The radius is user configurable, to allow adjustments based on users' willingness to walk from where they have parked their vehicles. Gray colored road segments indicate no current data available. This is due to not many users using ParkUs in the requested area. As ParkUs users appear in the area, the gray segments change to shades of Green/Yellow/Red depending on the availability of parking.

Once a user has decided on their destination and which car parks or streets to target by tapping the "Go"

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button, the application commences data collection. Only when the user drives near to their set destination radius does the application start storing (local memory) time-stamped sensor and location data. Any data collected prior to the user driving within the set radius is discarded. Furthermore, the heatmap is updated during transit in real time to aid park searching when the user is near their destination.

Once the user has found a parking space (with or without cruising) and has pressed the "parking done" button, the app then prompts the user by asking if there are any available parking spaces in sight, which the user answers by clicking "Yes/No" as shown in the figure. It should be noted that this functionality was only enabled for the trial as it helps in validation of the ground truth and that the app can still function without such user input. Finally, the user needs to click on the "Send data" button to upload raw sensing data. GPS trace, on which the heatmap is currently built using the online cruising detection method (illustrated in Figure 1), is sent separately. For raw data, users have the option to either upload to the servers immediately or wait until they are within range of a Wi-Fi network (to avoid incurring any excess data charges). The collected raw sensing data is then used in conjunction with GPS-based cruising labels, to build a generalizable classification model that does not rely on the destination input. This information, along with the location where the user parks, can be used to update the heatmap of parking availability information at the central backend server. Updates from all the user data can be easily aggregated and displayed to other users also searching for parking in their area of interest. In the instance where no user reports are available in a particular area, parking availability is marked as "unknown" and displayed with a "grey legend" in the heatmap. In the absence of user updates, the probability of parking availability decays exponentially and is reflected in the heatmap through colors turning lighter with the passage of time. This ensures that information decay is accounted for in the solution. In summary, the more users that contribute information to the system, the more accurate is the

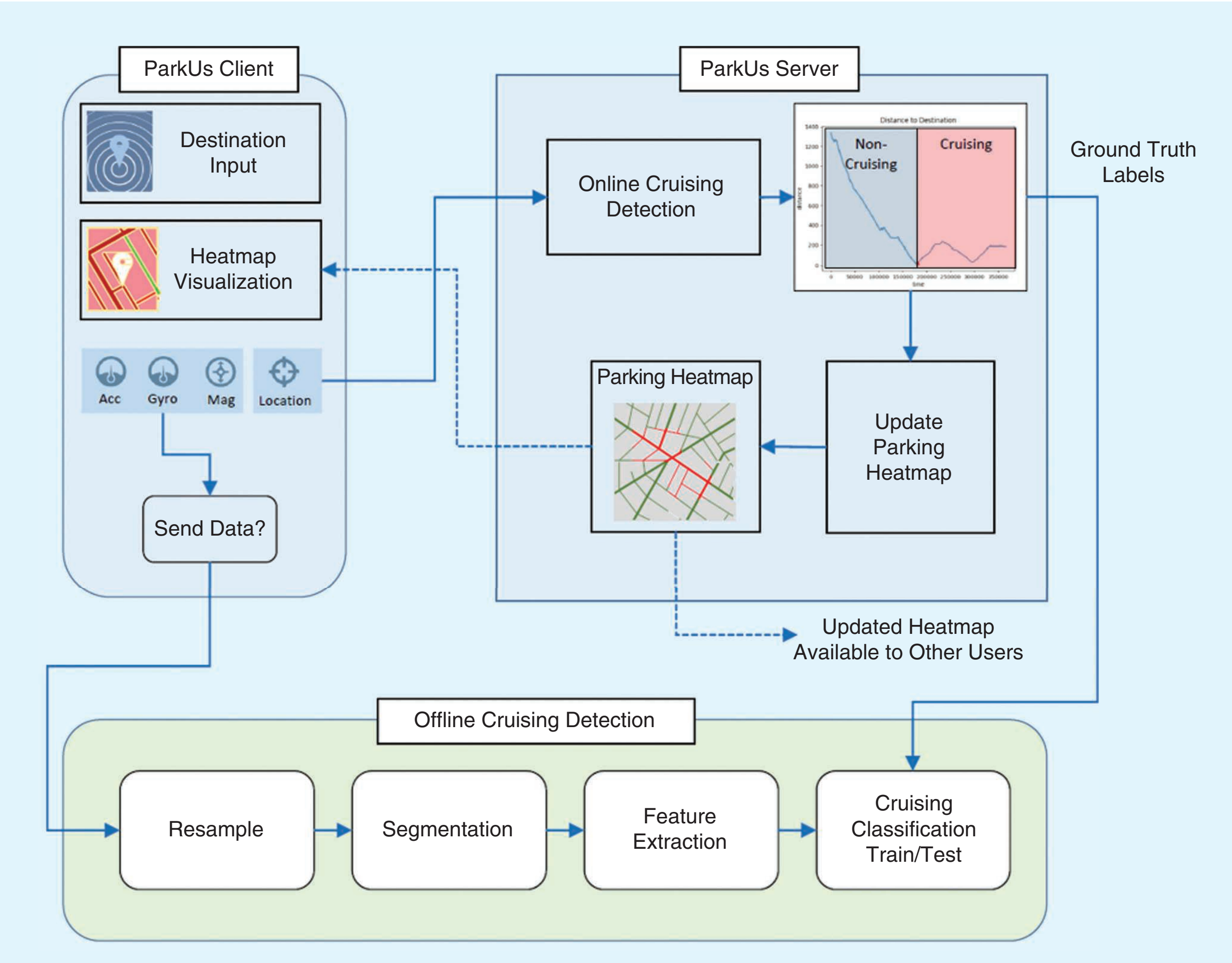

FIGURE 1. Overview of the ParkUs system used in the UWE trial in Bristol, U.K.

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information maintained by the backend system and available to users.

ParkUs has been designed keeping in mind the need to scale quickly and cost effectively. To this extent the application is optimized to only record data with a maximum sampling rate of 25 Hz when users are close to their destination address. In practice, smartphones are unlikely to be able to sample GPS faster than 1 Hz, and therefore effective parking and cruising detection can only be performed at reduced rates. It is estimated that 15 min of recorded driving activity generates around 2.5 MB of data for the backend system to receive and process. As it stands, the backend has been fairly well-provisioned and will easily cater to trials in a city. Since the app requires reporting data in real time, users would need access to cellular coverage. However, once cruise and parking/unparking detection have been thoroughly generalized, it is not inconceivable for the smartphone to have a pre-trained detection model installed and running. This could drastically reduce the amount of data sent to the back-end servers. Thus, scalability would not be an issue for a mass adoption scenario.

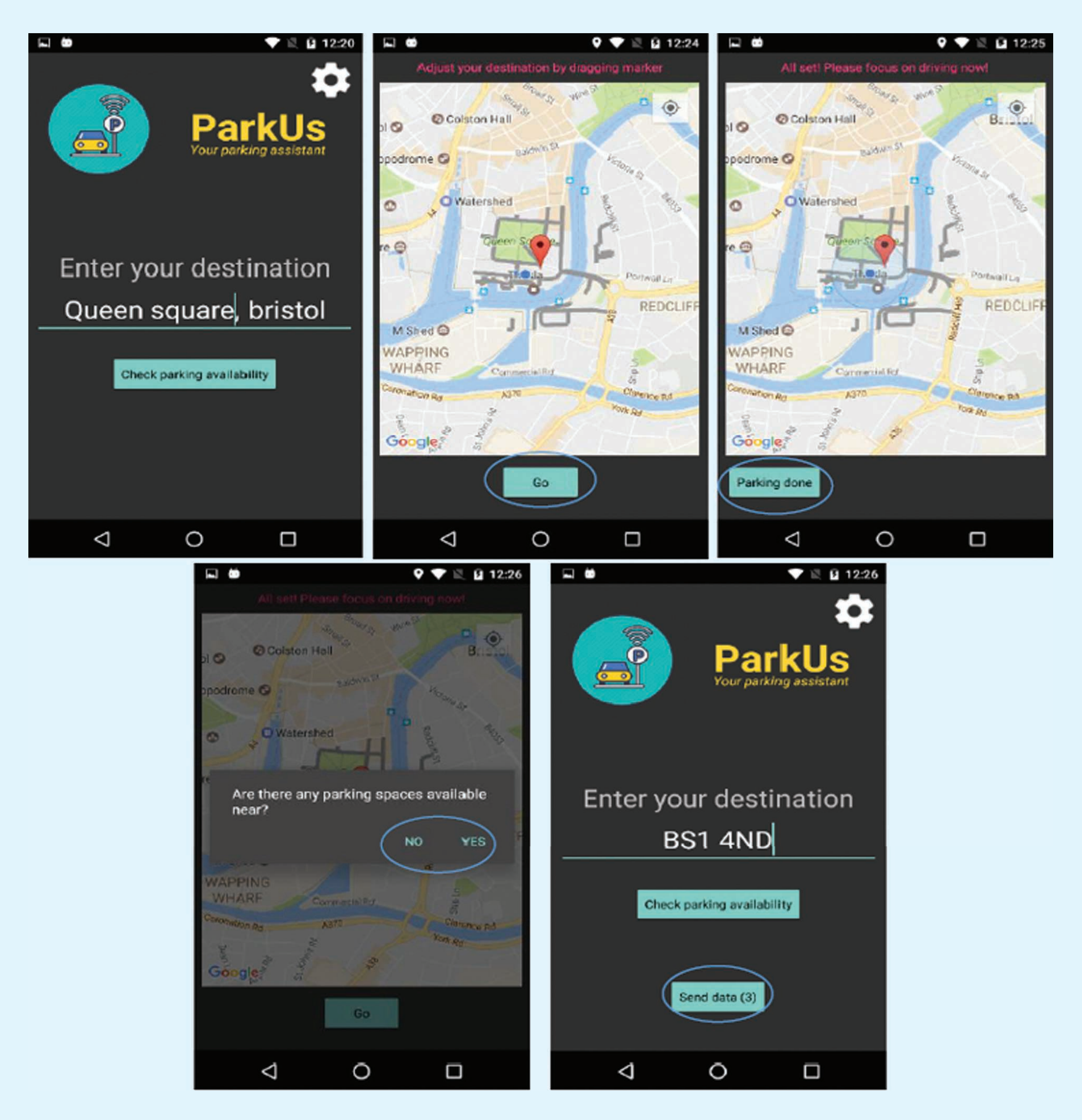

FIGURE 2. Screenshots of the ParkUs Android smartphone application at various stages of operation.

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Cruising Detection – The Parkus Approach

Cruising detection is a method that discerns between travel to a destination, and movement dedicated to actively searching for parking. Manually identifying and labeling the starting time of cruising for each journey would be a time-consuming, error-prone task and is also not practically scalable. To mitigate this problem, the method of determining these timestamps was automated by taking into account the distance to the destination as it decreases until it hits a local minimum. At that point the distance increases again as the driver starts moving further away from their destination in the search for parking. This minimum might be caused by the driver passing by their destination and observing that no parking is available, or it might be caused by a circular route or S-shaped curve as might be observed in a parking lot. This is based on the assumption that a driver ideally would like to park as close to their destination as possible.

This constitutes the cruising ground truth, which is used to train machine learning classifiers to automatically detect cruising using a combination of sensor data (accelerometer, magnetometer, etc.) collected from the users' smartphones. Overlapping time windows are used (segmentation) followed by extracting various features as shown in Figure 1. The importance of using machine learning to detect cruising stems from the removal of the requirement to input a destination in order for cruising to be detected. This allows the smartphone application to detect cruising dynamically as users go about their everyday driving and also enables updating of the heatmap without the need for users to provide a destination. In addition to this, it also allows the heatmap to benefit not only from more data, but also from more timely data as cruising can be detected as soon as it happens rather than at the end of a journey (since the distance to a destination curve can only be effectively generated at the journey end).

For evaluation purposes, three classifiers were trained using the data collected from the trial including, 1) decision trees, 2) k-nearest neighbors, and 3) support vector machines. The output of the classification step was then post-processed using the approach of [12], in order to reduce the effect of the classifier producing short "gaps" of non-cruising during true cruising, or vice-versa. The post-processing step is based on a mean filter applied to the series of 0s and 1s representing the classifier output. To alleviate potential bias introduced by cross validation schemes such as in a standard k-fold cross validation scheme, a leave-one-user-out cross validation technique was applied for evaluation of the classifiers [13]. We also used the dataset collected in [12] to perform several experiments testing generalization capabilities of the automated cruising detection system.

Field Trial

The main objective of the field trial was to answer the research questions posed earlier, but in a real-life scenario. The objective was to understand the performance of the cruise detection algorithm in a real world setting, and reflect on its generalization capability, to better understand the impact of parking availability information on cruising behavior and finally, to gain feedback on the usability aspects of ParkUs.

Practical Challenges and Evaluation Parameters

Signing people up to use a parking app requires that the app provides accurate parking information. At the same time, providing accurate parking information requires a critical mass of users since this is a crowd-sourcing approach. Due to these conflicting objectives it was decided to restrict the trial to a few car parks in the university where spaces would be shared between the trial participants. Most of the users that were recruited had fairly regular working hours, which ensured that users arrived and departed within a certain predictable time window. This was particularly important given that this was a semi-controlled trial. Such a setting helps to shed light on the promise of the solution as heatmap updates from some users (those who arrive early) benefit those who arrive later. In practice, when such a solution goes live with a large number of participants, one may encounter a variety of scenarios:

- No heatmaps in certain places where there is no user activity,
- Up to date heatmaps in places with lots of user activity, and
- Differences between heatmap updates and user arrivals at their destination, which could lead to variation in the usability of the heatmap — timely and useful when a user arrives at the destination after updates have been made by other users in this area, and less useful in other cases due to stale information resulting from no recent updates in the area of interest.

In the worst case scenario, where heatmaps do not provide any useful information due to lack of updates, the outcome would be similar to that of the status quo (not using any parking availability information whatsoever) and in the best case, where up-to-date parking availability information does exist, this will improve park search times and therefore, reduce unnecessary CO_2 emissions, wastage of fuel, time and money. In summary, there is nothing to lose from participating in using the app. In terms of parameters to be evaluated, we were specifically interested in the following:

- F1 scores, a measure of precision and recall of the cruise detection algorithm, that highlight its generalization capability,

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- The average cruising time with and without heatmap data, and
- Qualitative metrics concerning the use and usability of the app.

Experimental Setup and Datasets

In this trial, all the participants recruited were employees of UWE who commuted by car to a campus on the outskirts of the city of Bristol. They installed the ParkUs app on their personal smartphones and used it during the trial period. Each participant drove to the UWE campus and parked in one of the several on-campus car parks. One of the objectives of the trial was to help users find a parking space quickly without having to cruise through unavailable car park areas. The trial was conducted over a period of six weeks, and various statistics from the dataset have been summarized in Table 1.

In total 117 journeys were collected out of which 66 had a valid cruising behavior. This validity is mainly based on the time spent after the chosen destination is passed in the user journey (i.e., when parking was found within 30 sec of reaching the destination, it was deemed as a non-cruising journey). By this definition 51 journeys did not have any cruising, however these are still useful journeys in the context of the machine learning engine that can be improved with both positive and negative examples of the cruising behavior. Out of the 66 cruising journeys, we distinguished between two categories, i.e., 1) journeys in which a parking heatmap was shown at the beginning of the journey with at least one road segment marked with parking occupancy level, and 2) journeys in which the initial heatmap had no information about parking occupancy.

As illustrated in Figure 3 most commutes were around the U.K. average, and the majority of drivers had what they self-assessed as medium sized cars. Although this latter point might not have any bearing on the cruising behavior for the University car park scenario, it is still an important factor to consider for on-street parking spaces where parking bays are of limited size and may impact the decision of users parking in tight spots.

TABLE 1. Dataset summary.

Metric	Data Value
Total number of journeys	117
Total number of journeys with cruising	66
Total number of journeys without cruising	51
Total number of journeys with colored heatmap	35
Total number of journeys with no heatmap information	31
Average cruising time	154 sec
Average distance covered during cruising	402 m
Average time within 400-m radius	218 sec
CO_2 estimate for the trial	10.6 kg

Cruising Analysis

The average cruising time in this dataset was 154 sec (2.56 min), the average distance covered during cruising was about 400 m and the total time spent in the last 400 m radius of the destination was about 218 sec (just over 3.5 min).

Figure 4 shows a histogram of the arrival times of all the journey logs submitted as part of this trial. This follows a roughly normal distribution centered around 8:30 AM-9:00 AM, with a few journeys ending quite early in the morning. We can expect these earlier journeys to have almost no cruising, as the car parks would be nearly empty at these times. Instead, these earlier journeys would be useful to form the parking availability model for users who arrived later. Figure 5 shows the cruising duration with respect to arrival times. There is a clear and expected trend of users spending more time on average looking for parking when they arrived later. During the early hours, most of the car parks were empty so it was easy to find parking and therefore less amount of time was spent looking for parking (almost 100 sec before 8 AM). Post 9 AM when the car parks were busier, an extra 40 sec on average was spent looking for parking. This is where ParkUs can be expected to provide value, presenting roads with a higher likelihood of having a parking space and showing users which roads to avoid.

Figure 6 shows the cruising times in two car parks of different sizes. Car park 1 is of smaller size and therefore, relatively less time is spent looking for parking in this car park. However, there are cases in which a user enters this car park, does not find parking and goes to the next car park, therefore spending more time looking for parking. Cruising times are compared for users who experienced both cases of parking availability heatmap at the beginning of their journeys namely, a) with heatmap data (showing colored road segments) and b) without heatmap data (where users saw a gray heatmap on their devices). In car park 1, which is a relatively smaller car park, the median of cruising duration without a colored initial heatmap is 100 sec, and that drops to 64 sec when the initial heatmap data is available (a 36% drop in cruising time).

On the other hand, in car park 2, a relatively more significant change in cruising durations can be observed. In this case, the median cruising duration was 150 sec when the initial heatmap was gray, and that dropped to 107.5 sec when it was colored.

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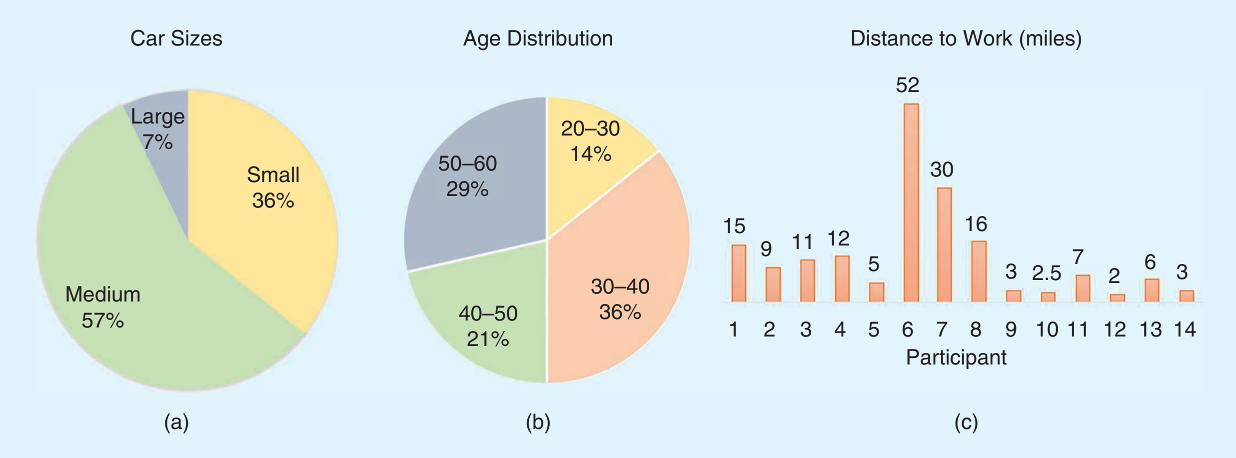

FIGURE 3. (a) Car size distribution, (b) Age distribution, and (c) Distance to work for all participants.

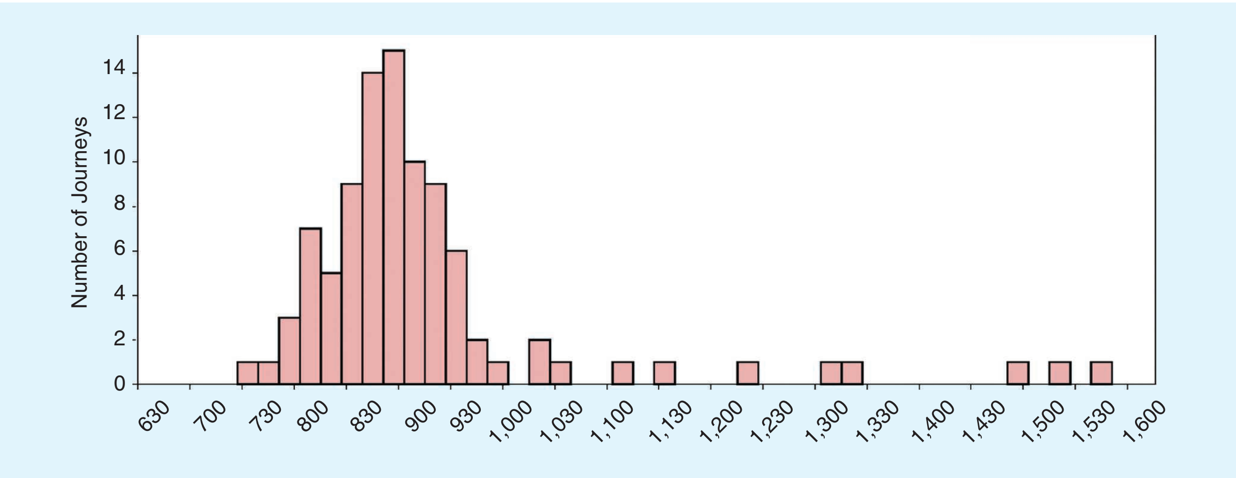

FIGURE 4. Histogram of arrival times in the collected dataset.

Figure 7 shows two cases of cruising in our dataset. In the first use case, a driver using the ParkUs app enters the destination and sees at least one road segment marked with parking availability information close to the destination. Some of the relevant statistics for this journey are also shown in Figure 7. The total cruising time for this journey is 58 sec, the total distance covered is 214 m, while both fuel and CO_2 emissions are estimated at £0.03 (U.S.$0.039) and 53.5 g, respectively.

The second case is a worst-case scenario whereby the user does not have any parking availability information at the beginning of the journey and hence spends a significantly higher amount of time looking for parking. It can be seen that the user first enters one of the car parks but does not find parking. The user then travels to the second followed by the third car park and finally parking in the fourth car park that ends this journey. As expected, the user spent much longer time looking for parking (about seven times more) and covering much more distance in this trip (about four times more). The average

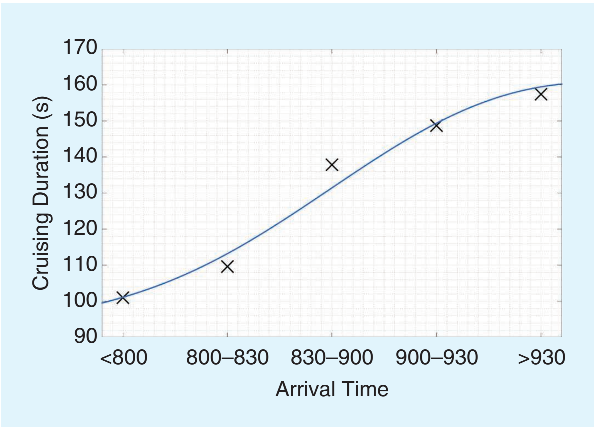

FIGURE 5. Cruising duration with respect to arrival times.

cruising time for this journey's arrival time is close to 150 sec. In this trip, the user spends four times more in both estimated fuel costs and CO_2 emissions. If the second user had known about the parking availability

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beforehand, the total amount of cruising would have been much less; i.e., if the user had known that only the fourth car park had parking available and the first three car parks were all completely occupied then a significant amount of time (and hence, fuel, money, and CO_2 emissions) could have been saved. In an ideal scenario, we envision ParkUs to help users find parking quickly and easily by providing accurate parking availability information at their chosen destinations.

Generalization Performance of Automated Cruising Detection

We also made a comparative and combined analysis of the cruising detection algorithm using the dataset collected in this trial and the one used in earlier ParkUs research [12]. In [12], a leave-one-user-out cross validation method was used to evaluate the performance of the detection algorithm. This is generally the cross-validation method of choice for evaluating the generalization performance as the training and test sets have samples from non-overlapping sources [13]. Table 2 shows the results for the leave-one-user-out cross validation method in terms of the class weighted F1-score (an accuracy measure considering both precision and recall of a test). Here Trial 1 refers to the dataset collected in [12]. Combined datasets include all the journeys collected in both the trials. It can be seen that SVMs consistently performed the best across all data sets. In particular, for Trial 1, an F1-score of 0.81 was achieved, while for the dataset collected as a part of the trial in this paper, the performance goes up to 0.84. When both datasets are combined, the overall F1-score is 0.77, highlighting the promising generalization capability of the automated cruise detection algorithm.

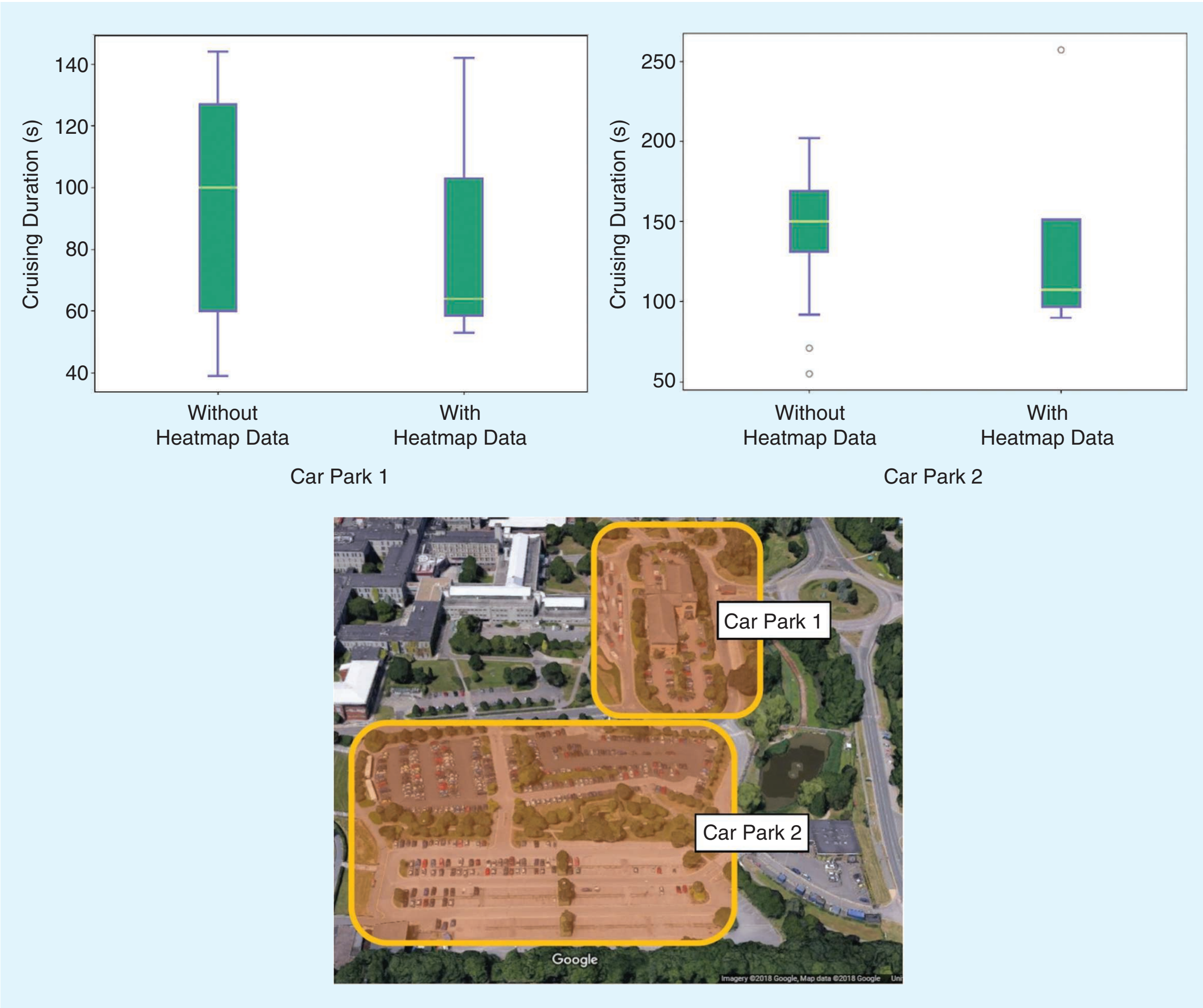

FIGURE 6. Two car parks and their associated cruising durations filtered by the availability of heatmap data at the beginning of user journeys.

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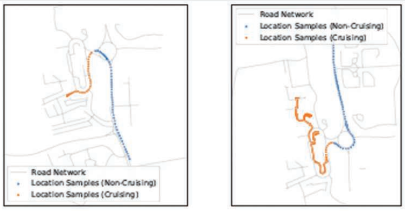
Qualitative Study of the Trial

Additionally, qualitative work was undertaken with trial participants after the study period, with the objective of gathering information about the attitudes and perceptions of the users involved in the trial. The key results from this activity are discussed below, and displayed in Tables 3, 4, and 5.

Some initial questions asked participants to reflect on their environmental impact, and how they might reduce this. Responses illustrated that people were aware of the negative aspects of car use, and how to reduce them, but were not so confident they knew how to reduce their impact more generally. Over 20% of the sample admitted to using a car when they could walk — a group that might be dissuaded perhaps with accurate information about parking availability.



Cruising Time	58 s	392 s
Cruising Distance	214 m	791 m
Initial Heatmap	Colored	Gray
Arrival Time	8:32 a.m.	8:59 a.m.
Est. Fuel Cost	£0.03	£0.13
Est. CO_2 Emissions	53.5 grams	198 grams

FIGURE 7. Two use cases of journeys in this trial, one with no cruising and the other with cruising. Various statistics related to both journeys are also shown. It is worth noting that while fuel cost saving and CO_2 emission reduction appear to be small, the percentage reduction is substantial (close to 75%) and that the overall reductions will be big (cumulative effect) when large number of people adopt the solution and experience a reduction in cruising time.

It is useful to understand whether people are already using apps, and whether they are now seen as part of life, as this could potentially impact their decision to use a parking app. The sample users here were unanimous in disagreeing with the notion that apps were not part of their lifestyle. There was also clear support for using a parking app to reduce environmental impacts, even if this involved some "hassle." A note of caution should perhaps be raised here, as the sample were people who had volunteered to trial a parking app so may well have been better disposed towards it.

More specific questions about how participants might use a parking app were also asked, and the top three answers from these questions are presented in Table 4. Most people were not using existing parking apps, although some were using proprietary apps to pay for parking. For those using them, they were seen to be beneficial in speeding up the parking process, consistent with other research on use of parking apps that finds parking time important [21].

Trial participants were likely to be users of other apps that offered personalized services, and many were already checking traffic conditions before leaving home. Other key messages about the use of parking apps were that some people might consider changing mode if they knew parking availability was restricted, but there were concerns that this app might encourage some people to drive — as they would know they might be able to park at their destination (or somewhere nearby). This was an attitude commonly seen in some members of staff at the University, who preferred to see alternatives (cycling and public transport for example) to the car developed, as well as with representatives of civic authorities (who are encouraging people to use public transport more often) who perceive an app that simplifies parking as one that encourages driving. This doesn't portray the true picture, and it was essential to clarify that the objective was to create an intervention that could help to minimize the impact of cars on the environment as taking them off the roads is not currently a practical solution. When the potential air-quality, emission, and congestion benefits of ParkUs were explained to people, the majority of users agreed with this perspective.

TABLE 2. Leave-one-user-out cross validation results using datasets collected in trial 1 [12] and trial 2 (This study).

Method	Trial 1 Dataset	Trial 2 Dataset	Combined Dataset
k-NN	0.75	0.65	0.61
DT	0.72	0.66	0.67
SVM	0.81	0.84	0.77

While encouraging responses were received with respect to the usability (user interface aspects) of the app, mixed responses were received with regards to the usefulness of the app. The mixed responses mostly pointed to limited heatmap data and that the app seemingly didn't reduce park search time, a primary expectation of the participants. As was shown earlier, although the reduction in park search times was substantial, it was not

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TABLE 3. Survey questionnaire 1 (Attitude and perceptions).

Question	Top Response	Percentage
I can easily reduce my environmental impact/carbon footprint	No	64.3%
I think it is realistic to reduce my environmental impact/carbon footprint	Yes	57.1%
I know how I can minimize my impact on the environment resulting from my car use	Yes	85.7%
I usually drive when I could potentially walk	No	78.6%
Using smartphone apps in general doesn't fit into my lifestyle	No	100%
Using a parking app could help reduce the environmental impact of cars	Yes	85.7%
Generally use apps but using a parking app is too much hassle	No	71.4%
I am willing to go through the hassle of using a parking app for the greater good	Yes	85.7%

TABLE 4. Survey questionnaire 2 (Parking apps).

	Top 3 Responses		
Question	First	Second	Third
Do you currently use other parking apps on your phone?	No	Ringo (parking and payment app for managed car parks)	—
What is your main motivation for using these apps?	Reduce parking time	Check for spaces	Reduce Stress
Do you use any other apps that provide a personalised service?	Yes	No	Health apps
Do you usually check traffic/parking availability information before starting on a journey?	Yes - Traffic	No	—
If you knew parking availability information beforehand, would you consider changing the mode of transport?	No	Yes – if available	—
Do you see a parking app that aims to simplify parking as one that encourages driving?	No	Yes	Possibly

significantly perceivable, e.g., for someone who takes two minutes to find parking, a reduction of half a minute may not be noticeable. Other than this, users suggested adding new features to improve the app, e.g., integration with a navigation system and voice-based activation of the app.

Key Lessons from the Trial

The key benefit of ParkUs is that it provides the user with an accurate representation of parking availability at their destination. This requires sufficient users to populate the map with data, users who are not attracted to use the app if there is no data available. This was addressed in the trial by restricting the sample to a small number of car parks at the university campus, but the issue of how to recruit sufficient users to make a wide-scale deployment work remains an important issue to address.

Aspects of parking behavior have been confirmed in this trial, For example, those who arrive later in the morning will spend more time cruising, as spaces are harder to find, and further away from campus buildings. Later arrivals would have benefitted from the app, and could have avoided wasting time and fuel. An important point to note here for wider deployment is that local "peaks" in parking need may vary depending on location and time of day. For example residential areas may see a peak early evening as people return from work.

Small differences in cruising time were unlikely to register strongly with drivers, as they were focused on their journey and parking. More widely of course these small differences will accumulate to create more significant savings across a city. In terms of the accuracy of the cruising detection algorithm itself, it was found to show promising generalization capability achieving an average F1-score of 0.77 as highlighted in an earlier section. The F1-score represents a model's classification accuracy and is a harmonic mean of precision and recall.

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TABLE 5. Parkus survey questionnaire 3 (Parkus usability feedback).

Was ParkUs easy to use?	Yes	Reasonably	—
Did you encounter any problems using it?	No	Gray Heatmap	Yes (Various)
What were your expectations from the app?	Park close to office	None	See Heatmap
Were these expectations satisfied?	No	Yes	—
Did the app help to reduce your park time? Why/Why not?	No (No Data)	No (Arrive early)	—
How long does it take (on average) for you to find parking?	Quick (1-2 mins)	5 mins	—
What's the feature in the app you liked the most?	Heatmap	Interface	Previous Searches
What's the feature in the app you'd rather not prefer to have?	None	Arrival questions	—
Would you suggest any new features for improving the app?	Add satellite navigation	Automatic Activation	—
How likely would you be to continue using ParkUs?	Likely	No	Maybe (More users)
What could encourage you to use ParkUs?	More useful data	More features	—
Do you have any privacy/other concerns about this sort of technology?	No	—	—

The trial participants were conscious that car use had an environmental impact, and were willing to use a parking management app as a way of potentially addressing some of the negative impacts. This would suggest merit in pursuing the ParkUs approach.

People were willing to engage with and use travel apps but were less sure about swapping their car for another mode of transport even if there was no available parking showing on the heatmap. This is a key element in promoting ParkUs to local authorities, and consideration will need to be given to how this might be addressed for widescale deployment.

The ParkUs app was seen to be a usable tool, and people liked the heatmap display (especially if it was populated). Several suggestions were made with respect to improving the app, with integration with satellite navigation and voice activation and control popular suggestions. There are likely to be several benefits from integrating ParkUs functionality into wider travel information services either onboard in vehicle systems, or in a multi-function app. Key among these would be the ability to achieve critical mass in user numbers, and thus accurate and current parking data.

Discussion

We have described the approach taken with ParkUs, and the results from the pilot user trial conducted at UWE. While this study was relatively small, it does provide evidence pointing towards the potential for such a system to be deployed at larger city-wide scale.

Based on the observations from the trial described in this paper, ParkUs was able to reasonably reduce median cruise times from 150 sec to just over 100 sec when users had data available in the form of parking occupancy heatmap. While the impact of this was negligible for an individual user, the cumulative impacts for a city might be significant. For example, using publicly available U.K. census data on daily work commutes it is estimated that the total number of daily work trips made by vehicles into the city center of Bristol (the city in which the trial described in this paper was conducted), was approximately 28 500. Taking into account average EU vehicle engine performance metrics [14] and the distance/time spent searching for parking (as reported in our dataset), it can be estimated that within the city center approximately 240 000 L of extra fuel is consumed when cruising to find vacant parking spaces annually. Bristol, like many other U.K. cities is actively looking to improve air quality in inner-urban areas (i.e., Bristol clean air initiative: https://www.cleanairforbristol.org/), and avoiding this fuel use would be a positive step forward. The additional fuel used for cruising also impacts CO_2 emissions in the city, roughly equating to an annual production of nearly 800 metric tons of CO_2, at a time when the city has declared a climate emergency and has goals to reach carbon neutral status. Estimates from Bristol City Council indicate that around 300 deaths a year in Bristol could be attributed to air pollution [15]. ParkUs has shown the potential for being an important tool in modifying parking activity, thereby reducing the associated overhead costs, i.e., leading to burning less fuel, and reducing congestion and air pollution. This will contribute towards achieving regulatory/governmental targets on emissions.

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Another aim of ParkUs was to test the ability of the app to influence drivers not to use their vehicles unnecessarily; since there's little benefit to drive a short distance only to spend an equal amount of time searching for a parking space at the destination end. We posited that the latter might be achieved if users note that there is no parking near their destination and consequently decide to walk or use public transport instead. Using ParkUs to achieve this outcome might be considered a voluntary travel behavior change (VTBC) program, an approach widely used by authorities looking to encourage more sustainable mobility behavior. Policymakers have also shown interest in how collaborative apps built on knowledge sharing — as in ParkUs, might work in this context, although it is acknowledged that a critical mass of users is essential for these to work well [16]. More widely with respect to driving behaviors, apps have been trialed that look at nudging drivers with behavioral feedback [17], [18], but have encountered problems with persuading people to use the apps every day, and note that incentives only work while they are active. In response it is suggested that the app functionality is built into vehicle systems [17], and that the benefits of the behavior change should be sufficient on their own [18]. How to achieve the latter is a challenge beyond this trial, but an important factor to consider in future trials or deployment. More broadly, there is little evidence of long-term positive effects in travel mode change from nudging techniques, nor of nudging being effective against more habitual behaviors — such as commuting. Incentives are however seen as effective in encouraging travel behavior change [19], and this may prove to be the necessary route to reach sufficient user numbers to make the ParkUs app self-sustaining in respect to parking data.

Participants in this trial were reticent to consider changing from their car, although some conceded they might walk if the distance was short, for example to a convenience store. Offering information on alternatives through the app when there is no parking may be one way to encourage this change. This could be achieved through integration with a source that provides multi-modal transportation information. As an example, the Travelwest journey planner (https://journeyplanner.travelwest.info/) in Bristol, U.K. and the Transport for London (TFL) (https://tfl.gov.uk/) applications provide a way for users to explore different transportation options for a journey. If the ParkUs app were to be integrated with such applications, the user could then begin by entering their destination details in this application. This would then show parking availability at the destination as well as other modes of transport available including the park and ride option (one that entails parking the car in a dedicated parking lot at the periphery of the city from where buses ferry people to destinations in the inner city areas). The user could then make a more informed choice, and this could perhaps act as a nudge to opt for the public transportation. Exploring such interventions could make an interesting study. This is however outside of the scope of this article.

This study was conducted in one location, with a broadly heterogeneous sample. Other drivers might exhibit different behaviors as a consequence of their socio-economic characteristics, or existing travel habits, attitudinal factors, etc. Thus, there may be a diversity of behavioral responses, and it will be important to consider this when promoting ParkUs as a VTBC tool [20]. It will also be important to consider factors such as the cost of parking. In simulator-based research in the U.S., it was found that information provision (availability displayed on an app as in ParkUs) decreased circulation, or cruising time significantly, but also that drivers would take into account the cost of parking in any particular location [22]. Parking was free at the point of use in this trial.

Promise of a Crowdsourced Smart Parking Solution

In this article, we presented a smart parking solution (ParkUs) developed and deployed using smartphones with a built-in functionality of providing parking availability information at the user's chosen destination. It is a crowdsourced approach that relies on mobile sensing and automatically labeling parts of a user journey with cruising/non-cruising events. In order to evaluate the solution, we conducted a semi-controlled trial with participants sharing parking spaces at a large university campus. In this, we successfully showed that parking search times are reduced when the app showed some information about parking availability at the beginning of their journeys. We also performed qualitative analysis of parking behaviors through the use of participant surveys focusing on both usability and performance of ParkUs. Findings from this study have demonstrated the promise of a crowdsourcing based smart parking solution. There is no doubt that cutting the park search time by even a few seconds will yield air quality improvements as well as big reductions in CO_2 emissions (cumulative savings). This makes a case for using ParkUs. In summary, when a large number of people adopt ParkUs they will help to reduce not only the impact of vehicles on the environment but also perhaps, do their bit in helping towards accomplishing governmental/regulatory targets for emissions reduction.

It is also evident from this study, that the key factor to be considered in deploying ParkUs more widely is the critical mass required to populate parking availability. It will be important to explore a range of options (in-built to vehicle systems, integrated with journey planners, etc.) in future trials and research to better understand the optimum use of the functionality developed here.

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