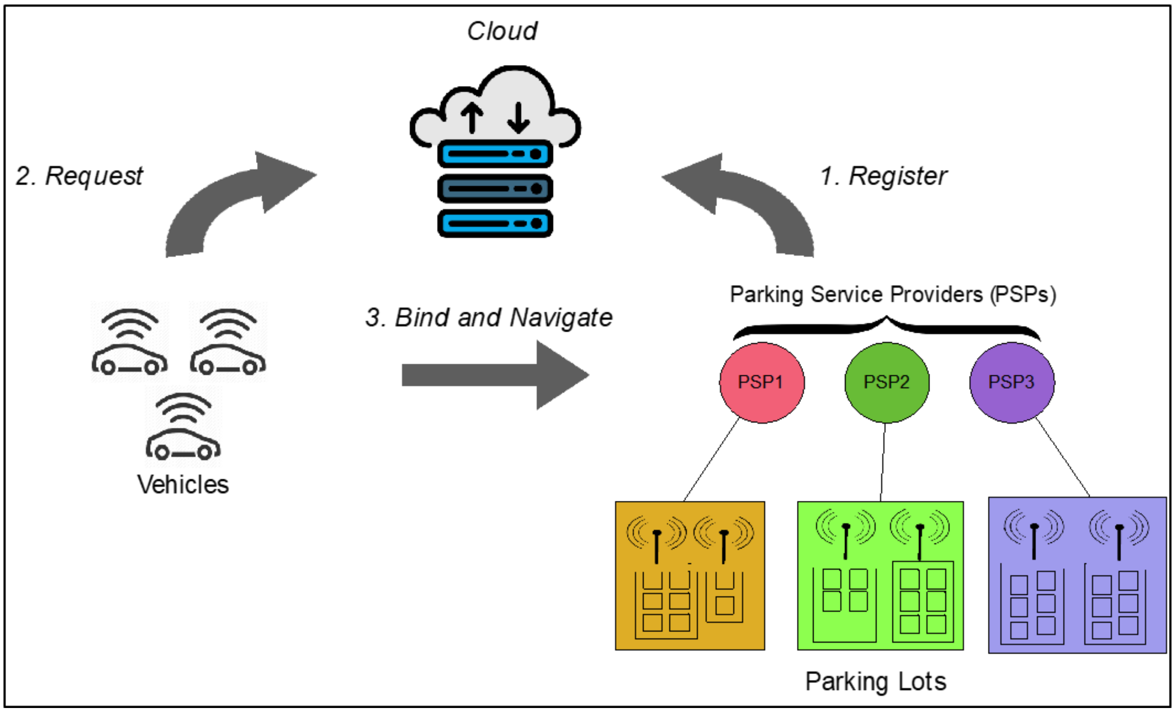
Smart Park

Sustainable traffic of autonomous vehicles in smart-parking management

Public report



Project within Efficient and Connected Transport Systems - FFI

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1. Summary

Traffic induced by parking-spot seekers is a growing challenge and constitutes a considerable portion of the traffic in city centres. However, new opportunities to solve this problem are emerging by connected vehicles and infrastructure. For instance, ultrasonic and magnetic sensors are already mounted on the ceiling of many parking lots to detect the availability of a parking spot. These sensors can provide parking spot availability information in real-time. Further, traffic-aware smart sensors which can detect the movement of individual vehicles are also available in many city and highway areas. This report suggests an algorithm for a cloud-based parking service provider which exploits these streams of data to choose the best parking-lot in a given parking area.

The parking-seeking problem is subject to a range of criteria that may include user, municipality and parking-operator preferences. For example, users may have some preferences with respect to walking distance to destination, municipalities prefer to spread the traffic to reduce congestion in the urban core and parking-operators seek to maximize parking-lots utilization in order to increase profits on real-estate investments. To solve this problem, an optimization algorithm based on multicriteria decision-making process is used.

The proposed Smart-Park algorithm employs a discrete Markov-chain model to demystify the future state of a parking lot. The algorithm features three modular sections. First, a search process is triggered to identify the expected arrival time periods to all parking lots in the targeted parking area. This process utilizes smart pole data streams reporting congestion rates across the parking area. Then, a predictive analytics phase uses consolidated historical data about past parking dynamics to infer a state-transition matrix, showing the transformation of available spots in a parking lot over short periods of time. Finally, this matrix is projected against similar future seasonal periods to predict the actual vacancy of a parking lot at the arrival time.

The performance of the proposed Smart-Park algorithm was simulated and evaluated in Kista district in Stockholm. Additionally, a baseline parking search behaviour, referred to as Blind-Park algorithm, was simulated and compared with the Smart-Park algorithm. In the Blind-Park algorithm, the vehicle was driven to the nearest parking-lot, in the hope of reducing driving-time. Smart-Park and Blind-Park algorithms were simulated and compared with varying number of parking-lots in the parking area, as well as under varying congestion rate situations. The simulation results illustrate a clear advantage of Smart-Park algorithm. The performance of Smart-Park algorithm versus Blind-Park algorithm was also demonstrated in a traffic simulation tool called SUMO (Simulation of Urban Mobility), which confirmed the simulation outcomes.

2. Sammanfattning på svenska

Trafik som består av sökandet efter parkeringsplats är ett växande problem och utgör en avsevärd del av trafiken i stadskärnor. Nya möjligheter att lösa detta problem kommer dock finnas när fordonen är uppkopplade till infrastrukturen. Till exempel, ultraljudsensorer och magnetiska sensorer är redan monterade i taket på många parkeringshus för att detektera tillgängligheten av en parkeringsplats, och dessa sensorer kan ge information om lediga parkeringsplatser i realtid. Vidare, smarta sensorer för trafikmätning som också kan se förflyttning av enskilda fordon finns redan i många städer och på motorvägar. Denna rapport föreslår en algoritm till en molnbaserad parkeringstjänst som använder ovanstående typ av data för att välja den bästa parkeringen i ett visst parkeringsområde.

Lösningen med problemet att välja bästa parkering omfattar en rad kriterier som kan inkludera preferenser från användare, kommuner och parkeringsbolag. Användare kan till exempel ha vissa preferenser med avseende på gångavstånd till destinationen, kommuner kan föredra att sprida trafiken för att minska trafikstockningarna i stadskärnan och parkeringsbolag försöker maximera parkeringars utnyttjandegrad för att öka vinsten på fastighetsinvesteringar. För att lösa detta parkeringsproblem användes en optimeringsalgoritm baserad på en beslutsprocess med flera kriterier.

Den föreslagna Smart-Park algoritmen använder en diskret Markov-kedjemodell för att prognosticera det framtida tillståndet för en parkeringsplats. Algoritmen innehåller tre modulära delar; Först används en sökprocess för att identifiera de förväntade ankomsttiderna till alla parkeringsplatser i det önskade parkeringsområdet. Denna process använder data från smarta stolpar som mäter trafik och trängsel inom parkeringsområdet. Sedan görs en prediktiv analys med hjälp av sammanställd historisk data över tidigare parkeringsanvändning för att skapa en matris som visar förändringen av tillgängliga platser på en parkeringsplats över kortare tidsperioder. Till sist används matrisen tillsammans med data om säsongsvariationer för att prediktera ledigheten av en parkeringsplats vid tiden för den beräknade ankomsten.

Prestandan på den föreslagna Smart-Park algoritmen simulerades och utvärderades i Kistaområdet i Stockholm. Dessutom var ett normalt sökande efter parkering, kallat ”Blind-Park algoritm” också simulerat och jämfördes med Smart-Park algoritmen. I Blind-Park algoritmen kör fordonet till den närmaste parkeringsplatsen i hopp om att erhålla den kortaste körtiden. Smart-Park och blind-Park algoritmerna simulerades och jämfördes med varierande antal parkeringsplatser i parkeringsområdet, samt under varierande trängsel i trafiken. Simuleringsresultaten visar på en klar fördel med Smart Park-algoritmen. Utförandet och prestandan av Smart-Park algoritmen kontra Blind-Park algoritmen visades också i ett trafiksimuleringsverktyg som heter SUMO (simulering av urban rörlighet), som bekräftade simuleringsresultatet.

3. Background

Finding a parking spot in urban areas is a growing challenge because of increasing congestion and scarcity of parking spots in major cities. Parking search traffic constitutes a considerable portion of the traffic in city centers, e.g. in a review by Shoup (2007) it is stated that sixteen studies of cruising behavior were conducted between 1927 and 2001 in the central business districts of eleven cities on four continents, the average time it took to find a curb space was eight minutes, and about thirty percent of the cars in the traffic flow were cruising for parking. A similar study in Paris (Gantelet & Lefauconnier 2006) reports an average time of 10 min spent in search of a parking spot.

However, recent advances in automated driving, data sharing and aggregation among connected vehicles, and in sensor developments embedded within vehicles as well as parking infrastructures may hold a viable solution to this problem. Contemporary developments in these areas have the potential to address parking issues in several ways. One of these is to make better and more efficient utilization of existing parking spots and parking infrastructures, e.g. by providing a real-time direct match between parking spot supply and demand, and, in the longer term, optimizing parking infrastructure and facilities for remotely operated or self-driving vehicles. Such vehicles can be closely packed in dynamically-sized parking areas, or in garages without lighting, with lower ceiling height, where entry and exit routes are optimized for vehicles rather than a combination of vehicles and people. While laying the foundation for these long-term developments, current means for addressing this problem in the case of manually-driven vehicles on the short term consist in providing optimized routing and smart guidance algorithms for multi-criteria objectives. These objectives represent a combination of accessibility, short-travel paths, reduced carbon emission, efficient utilization of parking space, and user convenience. In a slightly more distant future, this approach can be mapped directly to remotely operated or completely automated vehicles capable of higher autonomy levels.

The introduction of smart parking system solutions in congested city centers could lead to several positive effects: it would allow for alternative land use in city planning, by reducing traffic volumes, and shifting traffic to designated lanes or routes leading to and from more distant parking spots or parking complexes, preferably off-street. Through judicious optimization techniques, the total distance covered by vehicles leaving and picking-up individuals can be managed to satisfy both user preferences and city-planning expectation in terms of environmental footprints and traffic fluidity. This latter consideration induces also increased levels of traffic-safety by avoiding pedestrian-crossings involving vulnerable road users, and by coordinating with other transport, e.g. reduced interference with public transport. User preferences such as usability, trust, safety, security, as well as general customer-oriented utility aspects must also be part of the optimization process: for instance the waiting time for re-accessing a parked vehicle must not be too long, or the cost too high, nor must there be a too high perceived risk of vandalism or theft.

Smart parking including routing of this kind has been considered in some recent studies. In (Yoo et al 2008) is a strategy utilizing wireless sensor networks to implement a system for parking guidance. A more recent study in (Rhodes et al. 2014) utilized a strategy to collaborate the path finding to show that this can lead to less congestions through simulations. Earlier attempts can also be found in the literature. The study in (Kurogo 1995), shows an implementation of a full-fledged parking guidance and information system through dedicated signs on the roadside, dated 1995. A review by Idris et. al. (2009) shows that numerous approaches exist. However, none of these utilizes the opportunities of connected infrastructure and smart sensing of traffic flow and parking infrastructure. Ultrasonic and magnetic sensors are already mounted on the ceiling of many parking lots to detect the availability of a parking spot. These sensors convey the parking spot availability information in real-time to a gateway to be processed by a parking system which for instance displays the rate of available spots on screens. The gateway could also communicate this information to a Cloud-based service to be further exploited by third-party parking-service providers. Traffic-aware smart sensors which can detect the movement of individual vehicles are also available in many city and highway areas (Sanguesa et al. 2015, Mustafa et al. 2017, Nellore and Hanke 2016, Soomro et al. 2018). The streams of data that literally "senses the city" is increasingly driving open Cloud-services to stimulate technology and business innovations. Smart parking service providers are potential beneficiaries of this evolution, particularly with the expected progression towards connected and driverless vehicles. Figure 1 illustrates this.

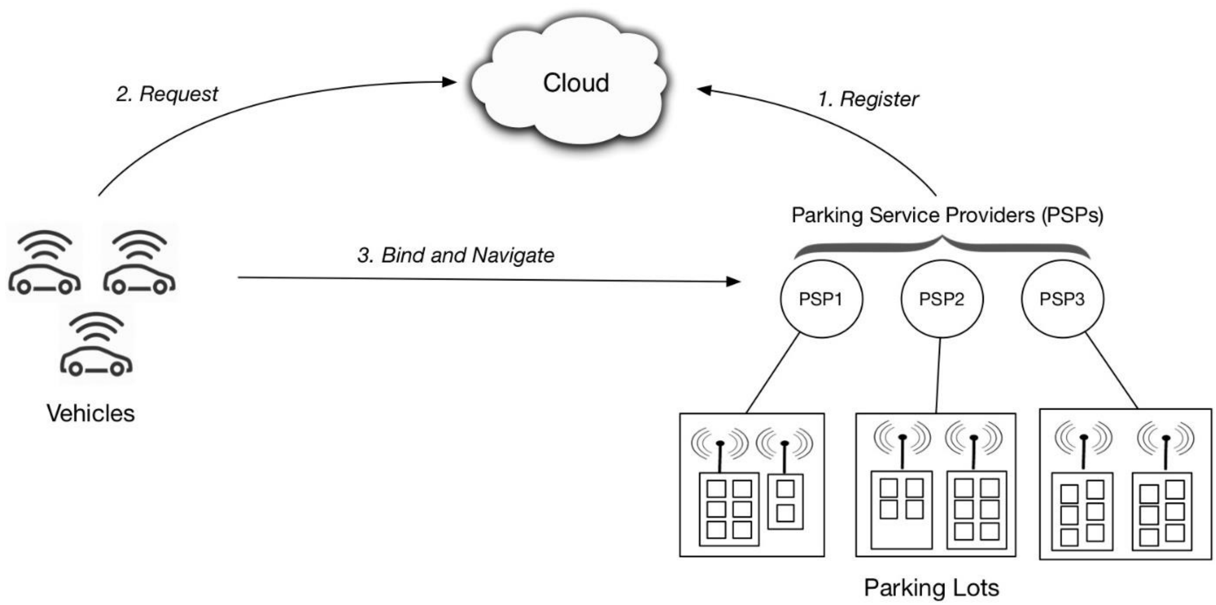

Figure 1. Parking as a service in a smart city

This report presents a research project that utilizes data streams from parking lot gateways and traffic junction smart-poles for development of a Smart-Park algorithm. The algorithm is based on multi-criterion optimization that minimizes the journey duration to the selected parking lot, while maximizing the chances to find an available spot there. The project was financed by Vinnova (grant number 2017-03028) and coordinated by VTI. Other partners in the project are Skövde University of Technology, Stockholm City, Stockholm Parking and Kista Science City. This project consortium brought the expertise, knowledge and insight to the problem through a service provider, a parking company, a city and research organizations.

In the following chapters, first the Smart-Park algorithm is described, which is followed by the achieved results and evaluation of Smart-Park algorithm in Kista district in Stockholm. Metrics used in the evaluation are time to arrive to the parking lot and the success/failure rate to find an available parking spot. Furthermore, the algorithm performance is demonstrated in a traffic simulation tool. The conclusions are provided in chapter 8.

4. Purpose, research questions and method

Smart-Park algorithm

The main problem addressed in this report is how to choose the best parking-lot in a given parking area. This problem is subject to a range of criteria that may include user, municipality and parking-operator preferences. Users may have some preferences with respect to walking distance to destination. Municipalities prefer to spread the traffic to reduce congestion in the urban core. Parking-operators seek to maximize parking-lots utilization in order to increase profits on real-estate investments. To solve such a problem, an optimization algorithm based on multicriteria decision-making process can be used.

Parking lot availability and traffic situation fluctuate across different seasonal periods, raising the need for a data approach to the parking selection problem that learns from past historical seasonal data to predict current parking and traffic-dynamics. Combination of data streams from parking-lot gateways and traffic junction smart-poles provide the historical grounds to engage into predictive analytics to forecast traffic and parking dynamics that tune decision-making processes (Akbar et al. 2017). In the following sections, short descriptions of multicriteria decision-making and predictive analytics are provided.

Multicriteria decision-making

A multicriteria decision-making algorithm maximizes a utility function involving different weighted criteria. In a Smart-Parking algorithm, these criteria can be set by the stakeholders, namely, drivers, parking operators and the municipalities. Figure 2 illustrates such a combined optimization processing involving data sources from stakeholders as input.

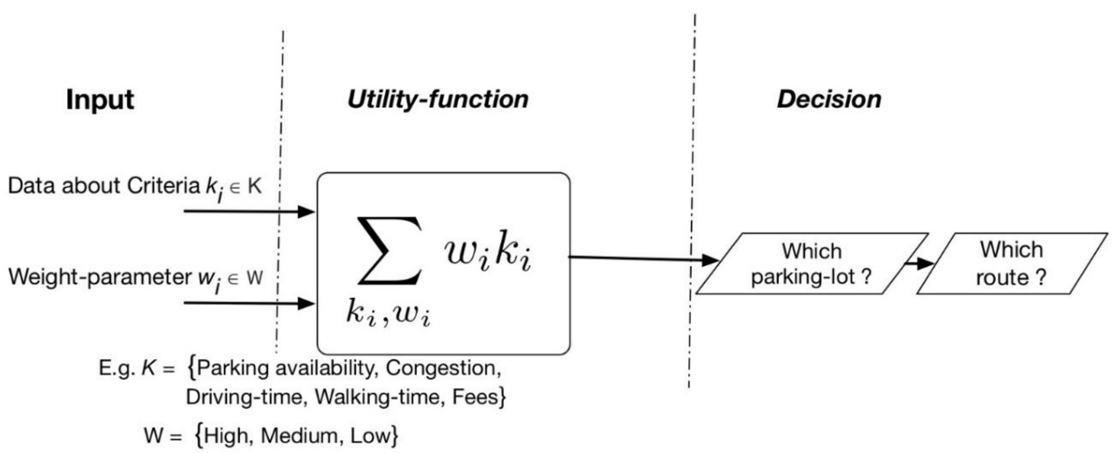

Figure 2. Utility function involving different weighted criteria, set by the stakeholders

Predictive analytics

In Predictive analytics statistical techniques from data mining, predictive modelling, and machine learning are used to make predictions about future outcomes based on historical data. There are two mainstream bodies of literature with respect to representation of state variables of interest for predictive analysis: continuous and discrete models. The difference is in the number of state-variable instances or measurements that need to be collected or represented to perform the predictive analysis. Continuous measurements enable state variables to take any value on a number line, whereas discrete measurements are confined to integer instances. Since predictive analysis is often probabilistic, this distinction results in different distributions.

Both continuous and discrete models have been used in the literature to address parking related issues. Examples of continuous models are queuing-theory approaches (Caliskan et al. 2007, Tilahun & Serugendo 2017) and machine learning approaches (Zheng et al. 2015, Shin et al. 2018, Hog & Jensen 2018), including deep learning (SHoeibi & Shoeibi 2019, Karakaya & Akinci 108). Discrete approaches to the parking-selection problem, like the suggested algorithm in this report, have also been quite extensively investigated, where quantification of uncertainty over future parking-lot states have been addressed as well. Earlier studies focused on the parking-type selection issues such as off-street vs. on-street parking with respect to pricing dynamics (Guan et al. 2005, Bagloee and Asadi 2012). Subsequent research combines travel experience and parking issues, such as park-and-ride optimization practices (Zhiyuan & Meng 2012, Prokop et al. 2016). Most recent research combines navigation and parking information to alleviate congestion-issues associated with the cruising process towards a designated parking lot (Adewumi et al. 2014, Rybarsch et al. 2017, Liu et al. 2017, Rahman et al. 2018). The research project presented in this report is positioned within this last group and investigate decision-making approaches for parking selection, including the routing process. Particularity, the project addresses deficiencies in existing approaches which do not aggregate efficiently the various intervening characteristics to the parking selection problem. These factors include the degree of traffic congestion while navigating to the predicted parking facility. The utility of a chosen parking lot is based on a judicious balance between traffic congestion and parking-lot availability. The project presents an original discrete stochastic approach to optimize this utility.

Algorithm assumptions

The parking-lot selection algorithm proposed in this report involves a vehicle routing approach that maximizes the utility of the selected parking lot considering a multicriteria decision-making process. To achieve this, a few assumptions on the available data are made.

It is assumed that the rate of entering and departing vehicles at a parking-lot are known at any time, as well as the parking-lot occupancy. Such historical data could be supplied by contemporary parking-lot operators or future PSPs seeking to leverage their services quality and increase the utilization rate of owned parking lots.

The proposed algorithm operates within the boundaries of a parking area, and thus any parking-lot within that area is a plausible solution candidate. This allows the algorithm to utilize all parking lots in the parking area as part of the solution domain. It is also assumed that a vehicle's GPS-location is known when entering the parking area. This allows the proposed algorithm to be triggered and use the vehicle's entry point as a navigation startup to the selected parking-lot. Alternatively, motorists may specify the desired parking area entry point and expected entry time into the area offline to trigger the algorithm, as well.
Additionally, it is assumed that smart-poles are available at each junction of the parking-area, recording traffic patterns. This real-time data that can contribute to reduce congestion and carbon emission in the urban core, as influenced by the proposed parking-lot algorithm.

Parking area representation

To solve the parking search problem, the parking area is represented as a directed graph, where nodes represent junctions and edges represent road lanes. Each junction is linked to other junctions or parking lots by a single or a double-lane road. Each smart-pole collects congestion data via traffic-sensors, while parking-lots accessed via dedicated junctions are equipped with sensors detecting and reporting entrances, departures and parking occupancy, see Figure 3. Each smart component of the parking area is managed by an autonomous agent.

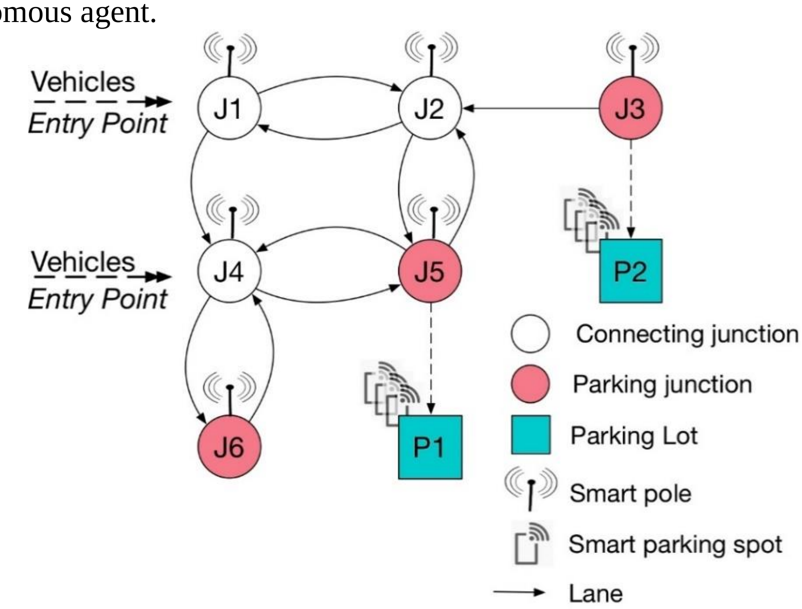

Figure 3. Parking area representation

Vehicle routing

The goal of the search process is to locate a parking junction and then to compute the expected arrival time, considering the traffic congestion from a given entry point. The search is carried out along two processes. A forward search starts from the entry point node which scouts the parking area for an available parking lot. When found, the predicted availability of the corresponding parking is calculated, considering the estimated arrival time. A backtracking process carries back the availability-rate and congestion attributes to the entry node. While doing so, the utility of the parking lot is re-evaluated at each junction point and the maximum utility is relayed back to antecedent node, until it reaches back the vehicle at the entry point node.

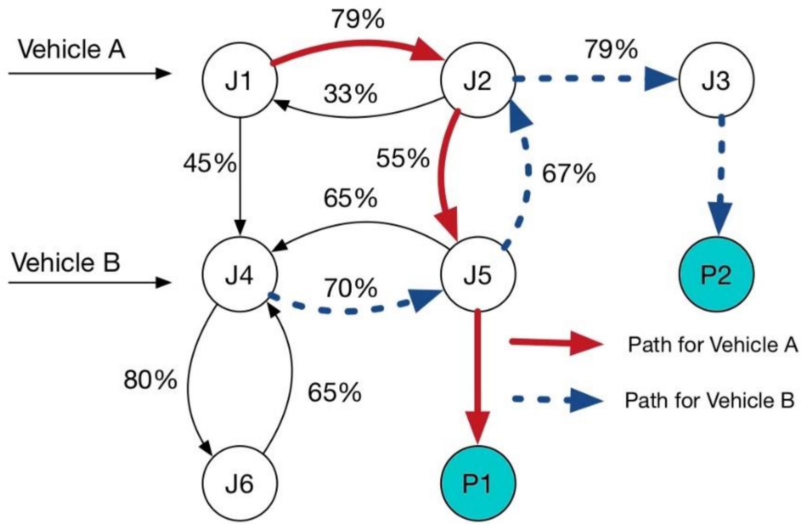

Figure 4. Illustration of an example of routing vehicles to parking-lots

Figure 4 provides an example of the above process, where vehicles are routed to designated parking lots upon entering a congested parking area. A simplified congestion model that is consistent with the conventional traffic flow theory is adopted (Wardrop 1952). Each road edge between two junctions is directed and has a capacity of vehicles driven over the edge lanes. Entering vehicles onto an edge i of the road are captured by junctions' smart poles to determine the density d_i of the traffic, formulated as $d_i = N{=}K_i$,where N is number of vehicles driven over the road edge, and K_i is the maximum number of vehicles that could be accommodated over that edge, expressed as percentages in the graph-based representation of the parking area in Figure 4. This local information is worked out in real time by smart poles and communicated to the search process triggered by a vehicle entering a parking area to figure out a global congestion rate. The congestion model is generalized over the parking area with a global value $C = \sum_{i=1}^{j} {}^{d_i}/_{L}$, where L is the total number of road edges in the parking area. This global congestion rate estimate is used later by the parking-state prediction algorithm to infer parking states, considering expected arrival time.

Given a parking lot, the path-finding problem consists in finding the best path to that lot from a given entry point, in terms of driving time in order to derive the expected arrival time to the parking lot. The search space consists of a graph where the root node represents the entry point, and the nodes at the next level represent all junctions that could be visited first from the entry point, whereas the nodes at the following level represent all junctions that could be visited from outgoing junctions in the previous level, etc. In this tree-like view of the graph traversal, the maximum depth is the number of junctions, and the candidate parking junction occur at this level of depth. Dijkstra algorithm guarantees to find an optimal path which minimizes travelling time to a given parking-lot. It should be noted that multiple vehicles coming through the same entry point and heading for the same parking lot, may not follow the same "shortest" path. This is because a query to smart poles junctions enable the algorithm to work out a new path for each parking request considering the new values of congestion rates returned by smart-poles, resulting in a new shortest path.

Historical data representation and state modeling

Using historical parking occupancy data from parking-lot sensors, a categorization based on seasonal periods across several instances of the historical data can be obtained. This categorization can be used to match current parking considerations with similar historical situations for a given parking-lot. The seasonal classification aims at capturing similar periods, which is chosen to be small enough to reduce variations in parking dynamics. This data representation is meant to model the randomly changing parking's available spots whereby a future state depends only on the current state and does not depend on any event that may have occurred before it. This property is called the Markov property whereby a stochastic model based on a Markov process can be used to describe parking dynamics.

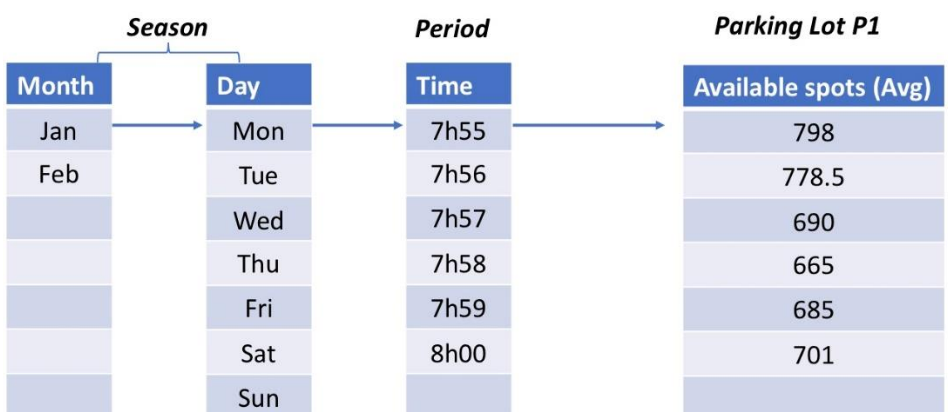

Figure 5. Parking data sample

It is the availability of a certain parking-lot that is the variable of interest here. Figure 5 illustrates an example of such parking data. The parking availability variable is averaged over multiple historical one-minute period observations across similar seasons. The time period is chosen sufficiently small to assume discrete state changes of a parking lot modelled over a time span of 5 minutes during which arrival and departure rates are assumed fixed. The next 5-minutes cycle uses a similar discrete state change model, but with different arrival and departure rate values. The small 5-minutes interval assumes a stationary arrival/departure rates Poisson process with fixed mean value of entering and departing vehicles to/from parking-lot Pi over a single observation period. The Poisson distribution is used in the simulation to represent the arrival process into periods, parking states are derived for each parking lot. A state represents the parking availability range.

Following Kendal’s notation, the classic Markov chain model is used to predict the future availability state of a parking lot Si given that the current state is S_j, denoted as $P(S_i|S_j)$. A fixed arrival/departure rate of vehicles is used for each parking-lot Pi to describe its queueing model over a 5-minutes observation period. Arrival/departure rates variation is handled across observation windows but considered fixed within each observation window, which is deliberately chosen small enough to justify this assumption. Each state corresponds to an availability rate range. The proposed model employs 6 states, ranging from the highly occupied state S_0 to the highly available state S_5 of a parking-lot. A sample is show in Figure 6 for a parking lot with capacity C_i = 1000, where an occurrence frequency matrix is derived for the currently 5-minutes observed period from the historical data. A normalized transition matrix is also depicted in Figure 6, which describes the parking dynamic availability patterns within the observed period in terms of probabilistic weights.

Availability States

State	Available	Percentage
S0	0	0%
S1	1-200	0% - 20%
S2	201-400	20% - 40%
S3	401-600	40% - 60%
S4	601-800	60% - 80%
S5	800-1000	80% - 100%

Occurrence frequency

	S0	S1	S2	S3	S4	S5
S0	40	30	0	0	0	0
S1	10	34	44	0	0	0
S2	0	23	13	32	0	0
S3	…					
S4						
S5						

After normalization

Transition matrix

	S0	S1	S2	S3	S4	S5
S0	0.6	0.4	0	0	0	0
S1	0.1	0.3	0.6	0	0	0
S2	0	0.3	0.2	0.5	0	0
S3	…					
S4						
S5						

Figure 6. Markov state model

The Markov model provides an inference approach through connecting the dependencies of current period information, i.e. parking-lot availability, with historical information of parking availabilities in similar periods. For each parking-lot, a current observation time-window, an arrival rate, a departure rate and a state transition-matrix are established. Under short periods of time which fit within a single observation window size (i.e. 5 minutes), a single states-transition matrix holds the parking dynamics information. However, if the calculated trip time from the entry point to the parking area to the targeted parking-lot exceeds the duration of a single observation-window, the corresponding transition matrices for the calculated time period are multiplied to estimate the state of the targeted parking-lot at time of arrival.

The parking selection process is triggered once a vehicle enters the parking area from a given entry-point. The geographical map of the parking area is an input to the parking selection algorithm as well as the list of parking lots and their related attributes, such as capacity, current availability and transition matrices. The traffic data returned by smart-pole sensors within the parking area is conveyed to the algorithm in the form of congestion rates compiled in a list. Using these inputs, the parking algorithm finds out the parking-lot with the least risk of not having a vacant spot once the vehicle reaches it. The best route to reach each parking lot is searched considering the entry point and the list of current congestion rates for the road edges. More information about the Smart-Park algorithm and its implementation can be found in (Atif et al. 2019).

5. Objective

Objectives as described in the application

The overall aim of the project is to demonstrate how connected vehicles and smart sensing of parking infrastructure can be used to coordinate parking traffic. Optimization of routes and parking lot selection will be utilized to minimize congestions and environmental impact of parking traffic. The benefit of fully automated vehicles will also be analysed in this context.
The project will introduce a new application and knowledge by developing an algorithm based multi-criterion optimization that addresses simultaneously (a) customer utility, (b) user satisfaction, (c) traffic safety, (d) accessibility, (e) parking operation effectiveness and (f) city planning considerations. An important aspect is also to make early investigations into overall user and societal acceptance of the concept and of prototypes illustrating the concept, since it is largely driven by technological enabler development.
The project goals can be summarized as follows,

1. Identify the different aspects of the problem at hand by bringing actors and stakeholders together. Examples of geographical areas in the target municipality (Stockholm, specifically the Drive Sweden Test site locations in Urban ICT Arena in Kista, and the planned expansion in “Slakthusområdet”) will be used as basis for the exploration. Identified aspects will be condensed to parameters of the optimization problem
2. Pooling and ensuring technical availability of parking data and statistics, inventory of APIs and connectivity-based data sources relevant to solving the problems of parking guidance as well as partially or fully automated parking
3. Development of a centralized routing algorithm, suitable as a service innovation or functionality in a cloud.
4. A visual demonstration of the effects of applying such parking routing optimization.
5. Assessment of user and stakeholder attitudes towards the proposed automated and optimized solutions
6. Identification of problems (regarding technology, regulation, business models etc.) in need of further research or other actions to enable automated parking in the long run.

By fulfilling the above goals, the project will contribute to the following general objectives of the FFI programme:
Develop new knowledge in the cross-section between Research Institutes, Academia, City, traffic and environmental planning offices at the municipality level, Business region actors, Car parking operators and Parking Facility technology providers. This contributes to increasing the capacity for R&D and innovation, and developing competitive environments in Sweden, especially by promoting participation of sub-contractors, cooperation between industry and academia, and societal bodies at the municipality level.

Specifically, the project will contribute in the following way to the FFI sub-programme "Efficient and connected transport systems (EUTS)":
Of the priority research areas for EUTS, the proposed project will contribute primarily to

- Infrastructure: technical requirements, data usage and API:s, technical demonstrator based on real data from suppliers participating in the project
- Services: by developing a demonstrator and traffic simulation set-up to illustrate the intended optimization strategy as a cloud-based service
- People/users in the system: by carrying out a survey with potential users and stakeholders
- Business models: by bringing together several of the relevant actors, the project will contribute to a better understanding of future business roles to be expected in the type of connected, traffic control-like setup investigated in the project. However, developed business models are not an explicit deliverable in this project, but could be developed in a parallel or subsequent, adjoining project.

As regards the development trends foreseen in the EUTS road map, the project will cover

- Automatization: the concurrent, top-level rout planning optimization is intended to work with drivers in vehicles as well as with partially or fully automated driving, in mixed-traffic scenarios
- Digitalization: connected vehicles, GPS-based tracking, high-speed mobile connectivity (5G) and data-flows from connected and sensor-equipped parking facilities, which also enable predictive analytics to be performed on historic data, is a fundamental enabler for the project, and will be developed further
- The prototype system developed in the project will contribute to
    - Functions for improved road safety, by avoiding routings that interfere with VRUs
    - Reduced environmental impact by more efficient routing
    - Maintained accessibility in general, as compared to selectively raising parking fees. For certain groups, e.g. the disabled or elderly), accessibility can be considerably improved
    - For municipalities, the environmental aspects, city planning perspective and alternative land use potential go hand in hand with the EUTS goals, and would ultimately benefit their citizens.

Changes during the project

The following are comments on how the objectives above have changed during the project.

- Participating organizations. One project partner had to leave the project (due to internal matters). This had negative impact on the budget, and some of the activities had to be cancelled or modified. A revised project plan was presented and accepted by Vinnova.
- Targeted geographical areas. The project first looked at three areas in Stockholm with different type of challenges regarding parking (Högalid, Slakthuset, Kista). At the end

one area was analyzed (Kista), and the reason for this was that the added value of doing more than one analysis was considered not worth the effort.

- End user aspects and social acceptance. This was one workpackage in the application that had to be taken out due to budget changes.
- Congestion, emissions and traffic safety. The project focused on the primary impact of a Smart Park function – the parking performance perceived by the individual driver and the parking operators. Secondary effects, like congestion, emission and traffic safety are not evaluated in the project. This is proposed to be done in a follow up study. However, the hypothesis is that the Smart Park function leads to less traffic, thus no negative effects on congestion, emissions and safety should be foreseen, rather the opposite.

6. Results and deliverables

Evaluation of the Smart-Park algorithm

To evaluate the developed Smart-Park algorithm, a geographical area in Stockholm was selected as the test parking area. The parking model was parameterized based on sample parking data from Stockholm provided by Stockholm Parking. However, it should be noted that the available data was limited and was complemented with artificially crafted data.

Geographical area selection

Considering the project partners interest and needs, the selection of geographical area for the project was limited to Stockholm. The minimum requirement for this area is that it should allow for enough degrees of freedom to prove the effectiveness of the developed algorithm. At the same time there is also a need to limit the area to get a tractable problem. The selection criteria can be summarized as below:

- A set (larger than 2) of parking-lots with a geographical orientation that have number of available parking lots. Street parking will not be considered in the optimization problem.
- A set of routes leading to the parking-lots. This means that it should be possible to guide a car to a specific parking lot and the choices should ideally have different implications on the output (e.g. travel time, congestions, emissions, etc.)
- The areas should be large enough to include the parking-lots and the route possibilities with the above-mentioned properties. However, the areas need to be well limited in size. Too large areas can overcomplicate the problem at hand without gaining or adding to the generality of the solutions.
- It should be possible to parameterize the traffic and parking models from relevant data.

Considering the above criteria, part of Kista district in Stockholm was chosen as the geographical area for simulation and demonstration of the developed algorithm. Kista is a busy hub with variety of business and shopping stores, as well as a booming science and innovation centre. A map of the selected area is provided in Figure 7.

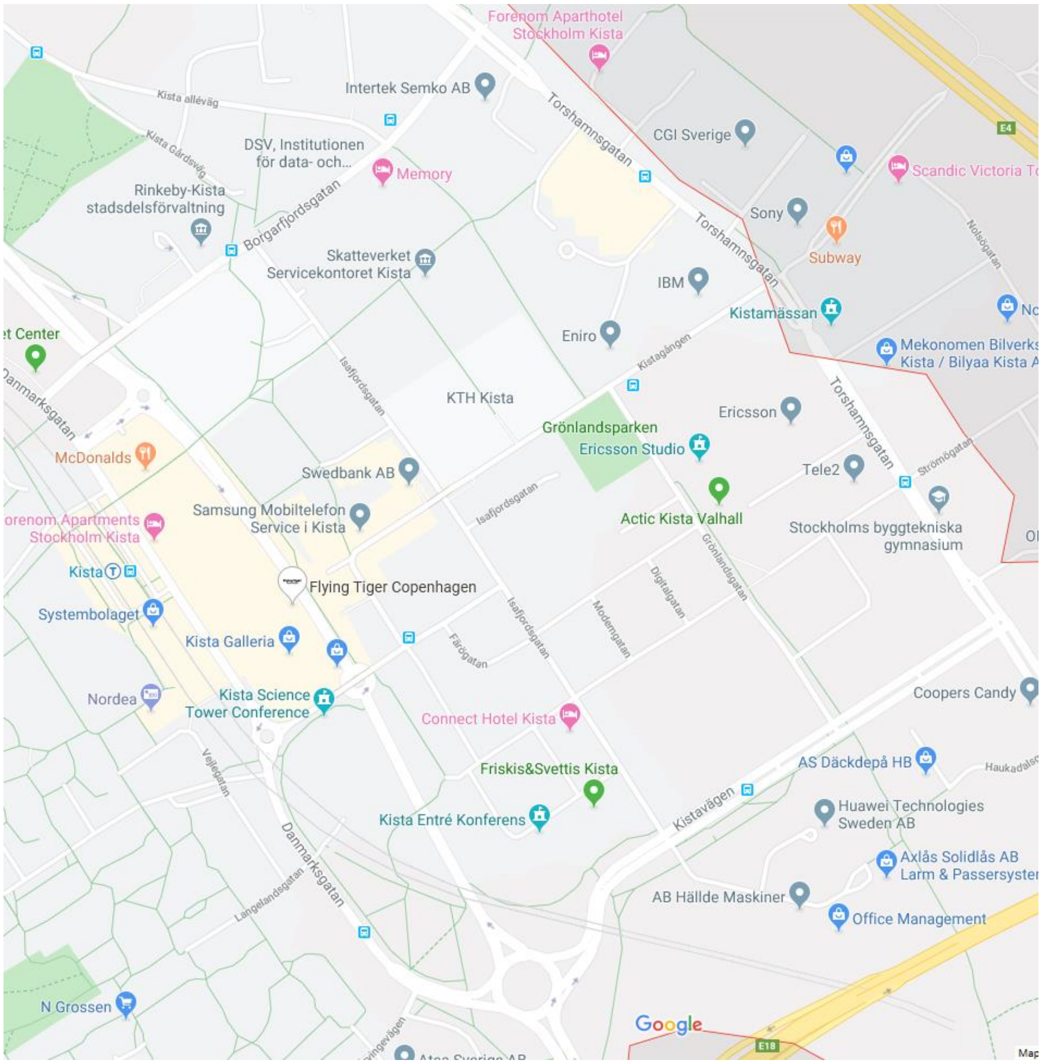

Figure 7. Selected geographical area, part of Kista district in Stockholm

Simulation set-up

A simplified version of the selected parking area is used in the simulations with parking-lots randomly situated at junctions. Parking data provided by Stockholm Parking from Kista district and other parts of Stockholm is used as a base in the simulations and complemented with artificially crafted data. A maximum capacity of 200 parking spots is considered for each parking-lot, with arrival and departure rates of 10 and 5 vehicles per minute. The initial availability of the parking-lots are randomly generated following a uniform distribution, but upper-bounded by 90% maximum initial availability A parking-lot is deemed full if its occupancy threshold exceeds 80%. A varying degree of traffic density was injected into the simulation to evaluate the performance of the proposed Smart-Park algorithm under different traffic considerations.

In addition to the Smart-Park algorithm, a baseline parking search behaviour, referred to as blind-Park algorithm, is also simulated and compared with the Smart-Park algorithm. In the Blind-Park algorithm, the vehicle is driven to the nearest parking-lot, in the hope of reducing driving-time. However, the parking-lot may turn out to be full, and thus the vehicle path is augmented with a new segment leading to the following nearest parking-lot, starting from the current vehicle location. This procedure will continue until a parking-lot with available spot is found.
Smart-Park and Blind-Park algorithms are simulated and compared with varying number of parking-lots in the parking area, as well as under varying congestion rate situations. The vehicle entry point to the parking area is fixed to create a controlled experimental environment to be able to study the scalability of the candidate algorithms when parking resources increase and the ability to adjust to varying traffic considerations.
Two performance metrics are use in the proposed experimental setup. The failure rate and arrival time. The failure rate reflects the blocking probability, which is the risk that a vehicle finds a designated parking-lot, suggested by the candidate algorithm, full. This metric reveals the rate by which the algorithm fails to lead vehicles to a parking-lot with available spots. The parking dynamics model described earlier, is used to determine the available spots in the designated lot. Subsequently, the blocking probability or failure rate for each parking lot is obtained from the availability rate, as follows:

$$FailureRate = 1 - AvailibilityRate = 1 - \frac{VacatSpots}{TotalSpots}$$

VacantSpots is retrieved from the corresponding state at which the parking-lot is found upon arrival of the vehicle controlled by the candidate algorithms, and *TotalSpots* is the parking lot capacity.
The arrival-time metric measures the time duration a vehicle controlled by candidate algorithms, spends within the parking-area since entry until it reaches a parking-lot with available spot. Vehicles may pass through full parking lots until a successful one is found. A clock is maintained throughout the simulation to pick vehicles' arrival time to a parking-lot, which availability rate falls below the defined threshold (i.e. 80%).

Evaluation results

In the first experiment, the scalability performance of the candidate algorithms to decrease the failure rate when taking advantage of an increasing instances of parking lots in the parking area, is investigated. The injected traffic in this experiment is fixed at a high rate of 0.8, while number of parking-lots range from 1 to 9. Figure 8 shows the average result of 20 simulation runs, with error-bars showing the deviation of the sample means. The figure shows that Smart-Park algorithm takes better advantage of the available parking-lots in the parking area, scaling down gracefully the failure rate as more parking-lots are provided. The Smart-Park algorithm outperforms the greedy Blind-Park, which routes vehicles naively to the nearest parking lots, while facing consistently high failure probabilities. It should be noted that in this experiment, only the first parking-lot chosen by the candidate algorithms are used in the evaluation. Otherwise, each algorithm can continue to guide the vehicle to other parking-lots unless an available spot is found.

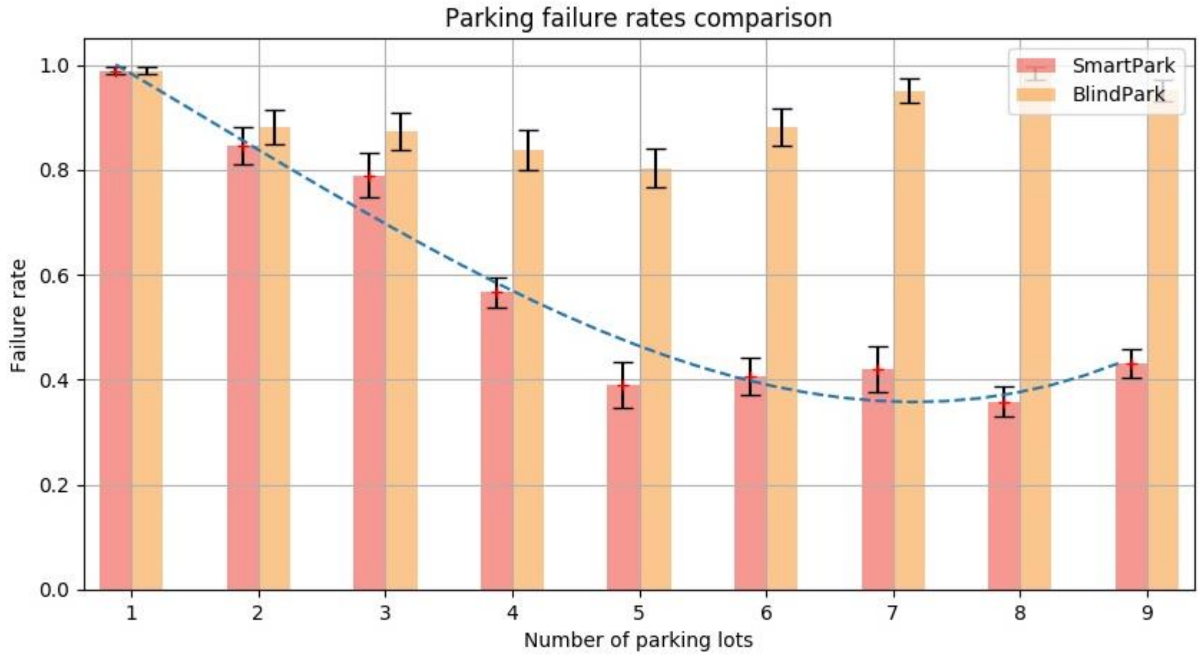

Figure 8. Parking scalability performance with congestion rate fixed at 0.8

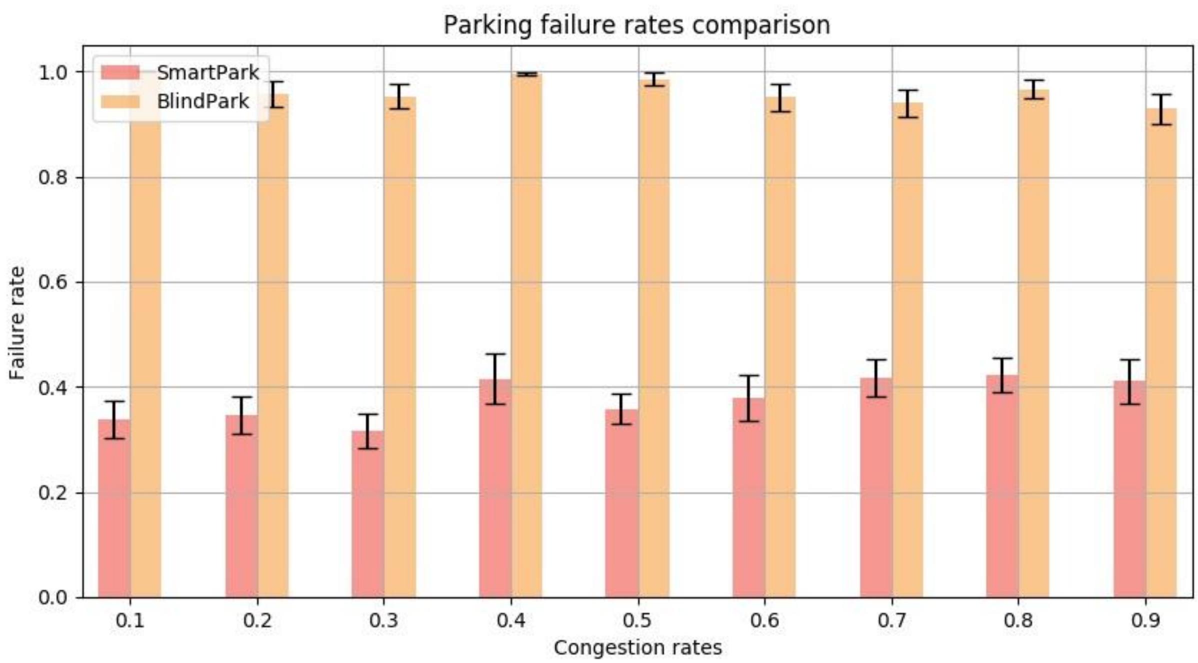

Figure 9. Routes congestion performance with parking-lot instances fixed at 8

In the second experiment, Smart-Park and Blind-Park failure rates are compared in simulations with a varying degree of congestion rates in the parking area. Hence, the performance metric is still the probability to find an available spot in the designated parking-lot when the vehicle controlled by the candidate algorithms reach it. In this experiment, the number of parking lots is fixed to 8. Figure 9 shows the average result of 20 simulation runs, with error-bars showing the deviation of the sample means. The figure shows that Smart-Park is not sensitive to congestion fluctuations due to its ability to use real-time traffic data from smart-poles across the parking area. Blind-Park algorithm on the other hand, is unaware of the traffic situation, driving cars to the nearest which are highly occupied.

Next, the above experiments are repeated and the arrival time to a designated parking-lot with available spot are compared. Thus, in this case the simulation continues to run until an available spot is found by the candidate algorithms. Figure 10 illustrates that for the experiment with varying numbers of parking-lots and fixed congestion rate of 0.8, the Smart-Park algorithm has a lower arrival time for all cases, compared with the Blind-Park. The figure reveals the arrival times in seconds since entering the parking area, while the dots in the curves show the failure-rate of the parking-lot, once the vehicle arrives there. Smart-Park consistently leads vehicles to a parking lot with lower failure rates, yet those vehicles arrive earlier than the ones led by the Blind-Park algorithm. With only one parking-lot in the parking area, both algorithms have no choice but to lead vehicles to the same parking-lot, but the arrival-times gap expands as more parking lots are made available. Eventually, as parking resources increase, chances to blindly fall into an available parking lot increase too, allowing Blind-Park to lower arrival times, after a peak of about 20 minutes delay difference compared to Smart-Park. The arrival times gap narrows as further parking-lots are provided, yet Smart-Park always keeps a lower failure rate, which means even-though arrival times converge with increasing parking lots, the probability to find available spots in a lot chosen by Smart-Park is always higher than Blind-Park. Smart-Park cars consistently arrive earlier to the designated lot, yet with a lower failure rate (at most 0.42).

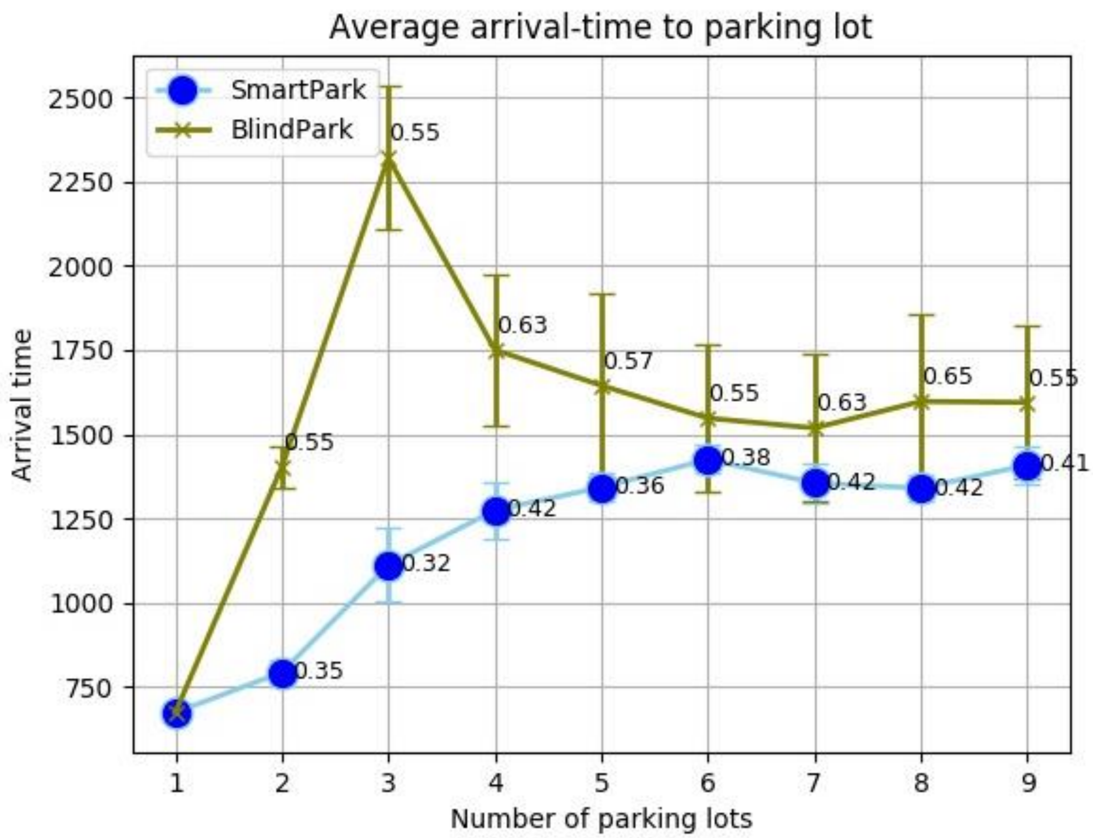

Figure 10. Arrival time to a parking-lot with available spot, congestion rate is fixed at 0.8

The figure shows the average result of 20 runs, with error-bars showing the deviation of the sample means. Blind-Park error-bars are much wider than Smart-Park ones, which indicates that Smart-Park is more predictive ensuring the arrival-time remains within a narrower interval.

In the other experiment, the influence of congestion rates on the arrival time is studied. Figure 11 shows that the arrival times generally increase within an increasingly congested parking area. Traffic congestion data are captured by real-time sensors in junction smart-poles and are used by Smart-Park search algorithm to choose an optimal parking-lot. Smart-Park's integration of traffic data trades routing and parking-allocation problems in a way that vehicles reach a highly promising parking lot with failure rates ranging from 0.34 to 0.41. However, Blind-Park vehicles arrive later to parking lots with failure rates ranging from 0.5 to 0.65. While parking-availability chances are always in the advantage of Smart-Park-led vehicles, the arrival-time gap narrows further with congestion rates, making it difficult for both algorithms to move vehicles at a higher-speed as the parking area becomes packed.

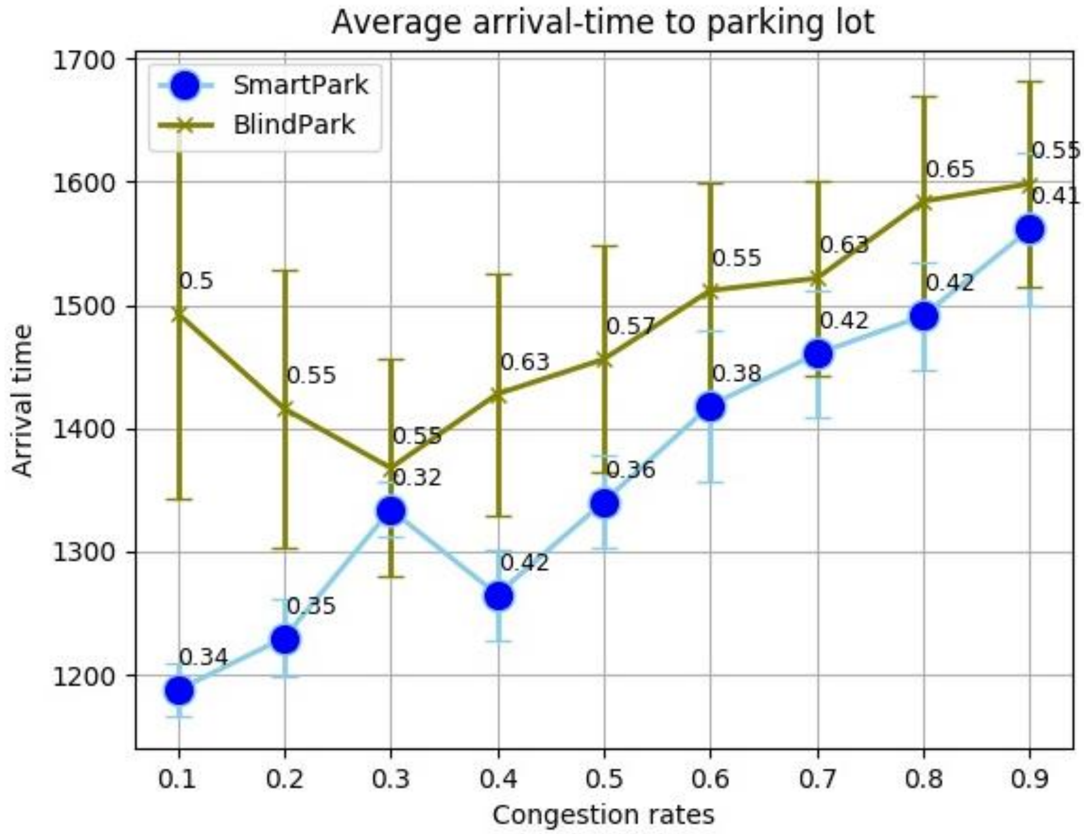

Figure 11. Arrival time to a parking-lot with available spot, number of parking-lots is fixed at 8

Demonstration in SUMO

The Smart-Park algorithm performance was also demonstrated in a traffic simulation tool called SUMO, which stands for Simulation of Urban Mobility. SUMO is a free and open source traffic simulation package, in which each vehicle is defined explicitly and has a defined route through the network. A type can be assigned to each vehicle to describe the vehicle's physical properties and the variables of the behavioural sub-models (Behrisch, et.al. 2011). The default behavioural model in SUMO is a modification of the model defined by Krauß (1998) which let vehicles drive as fast as possible while maintaining perfect safety.
To demonstrate the Smart-Park algorithm performance versus Blind-Park, the selected part of the Kista district was modelled in SMO. To create the parking area, the road network data was imported to SUMO from OpenStreetMap and simplified. Eight parking-lots was considered at random junctions in the area, see Figure 12. A random traffic was generated in the road network and two vehicles, one controlled by the Smart-Park algorithm and the other one by the Blind-Park, were added to the traffic simulation at the same entry point. The SUMO demonstration confirmed the previously described simulation results and a significant difference was demonstrated in the time it takes to find a parking-lot with an available spot with each algorithm.

Figure 12. Modelled Kista map in SUMO

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Primarily the result will be used within the participating organizations. Also two publications (one scientific paper and oner project report) will be available to the public. Presentations has been held at FFI/EUTS Resultatkonferens, SAFER competence Center and Transportforum (VTI).
Be passed on to other advanced technological development projects	X	A follow-up project is proposed by some of the project partners. To be decided.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

Atif, Y., Kharrazi, S., Jianguo, D., Andler, S.F. (2019). *Internet of Things data analytics for parking availability prediction and guidance.* Transactions on Emerging Telecommunications Technologies. https://doi.org/10.1002/ett.3862.

Kharrazi, S., Yacine A. (2020). *Sustainable smart-parking management for connected and autonomous vehicles*. VTI report (to be published). Swedish National Road and Transport research institute (VTI).

8. Conclusions and future research

Conclusions

Smart-Park and Blind-Park algorithms are simulated and compared with varying number of parking-lots, as well as under varying traffic situations. Smart-Park always keeps a lower failure rate compared with Blind-Park. Further, the probability to find available spots in a lot chosen by Smart-Park is always higher than Blind-Park. In other words, Smart-Park cars consistently arrive earlier to the designated lot, yet with a lower failure rate. The evaluation results show an increased scalability of Smart-Park algorithm when further parking resources are made available.

The Smart-Park algorithm performance versus Blind-Park was also demonstrated in a traffic simulation tool called SUMO (Simulation of Urban Mobility). The SUMO demonstration confirmed the simulation results and a significant difference was demonstrated in the time it takes to find a parking-lot with an available spot with each algorithm.

The outcomes of this project illustrate how recent advances in data sharing and aggregation among connected vehicles, and in sensor developments embedded within vehicles as well as parking infrastructures holds a viable solution to the parking seeking problem.

Future research

Future research should aim at studying the effect on traffic flow under different penetration rates of a Smart Park service, ranging from just a few vehicles using the service up to all vehicles. Simultaneously there should also be studied if there will be any emission benefits when introducing a Smart Park service.

This virtual study may be followed by a pilot study where operational matters and user aspects can be further tested and evaluated.

More items that need attention in connection with a Smart Park service are for example to find the most important actors, explore business models and identify legal- and regulatory aspects.

9. Participating parties and contact persons

Participating party	Contact person
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