An opportunistic client user interface to support centralized ride share planning

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ABSTRACT

Existing ride sharing systems for commuting in urban environments are rigid. They rely on the communication of discrete, spatio-temporal constraints from both vehicle and client to perform ride-matching. From a client user perspective these approaches are problematic, leading to location-privacy issues and the use of additional communication channels for ad-hoc negotiation which cannot be immediately quantified. To account for these important aspects, we develop a dynamic, intuitive interface technique called launch pads and a centralized system architecture, which together simplify the ride-matching process whilst preserving location-privacy. The results of two experiments reveal the latent potential existing within ride sharing systems if vehicle flexibility is quantified and incorporated into a representation of accessibility. The communication via launch pads provides a client with means to fully exploit this potential.

Categories and Subject Descriptors

H.4.0 [**Information Systems Applications**]: General; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces

Keywords

Human-computer interaction, time geography, ad-hoc ride sharing, demand-responsive transport

1. INTRODUCTION

The concept of ride sharing promises solutions to many problems we face in urban transportation today. By pooling the mobility intentions of people and developing software systems to exploit this potential using spatial technologies, it may be easier for drivers to offer rides and riders to discover suitable opportunities. These systems have the potential to significantly reduce the amount of traffic on city roads, reduce overall travel times and the amount of congestion. By providing links to existing (e.g. public transportation) and novel (e.g. autonomic shuttle services) modes of transportation, ride sharing systems could dramatically reduce the overall economic and environmental costs of urban transportation [5]. However, despite these clear benefits, ride sharing concepts have not been implemented at large scales and initial trials have not been successful enough to justify further roll-outs. Researchers have addressed the potential reasons for this failure (e.g. [18]) and have identified a spectrum of reasons, the most prominent being: fear of traveling with strangers, related privacy concerns, and lacking flexibility to offer and catch rides on short notice. The first reasons can potentially be addressed by combining ride share systems with social networking platforms (e.g. Facebook) and many commercial providers offer such services (refer Section 2). However, the second two problems (privacy and flexibility) have not been addressed convincingly so far and will be the focus of this paper.

We are proposing a novel type of user interface and visualization, which does neither reveal the location and identity of someone who wants to catch a ride (called *client* from here on) and an entity which offers a ride (called *vehicle* from here on) until a valid *contract* between the two has been established. By a contract we refer to an agreement which includes a pick-up location and time for the client and a respective drop-off location, which the vehicle will reach before heading towards its own next (or final) destination. Furthermore the proposed user interface aims to improve the flexibility of clients and vehicles to make ad-hoc arrangements while the vehicles are already on the road and heading towards their destinations. By relying on concepts of time geography [7, 11, 13] the core idea is to incorporate into the user interface a visualization of possible pick-up locations potentially serviceable by several vehicles. One of the main motivations is to enable the client to quickly explore the possible pick-up choices offered, thus facilitating ad-hoc ride sharing arrangements.

We hypothesize that our proposed architecture provides an effective user interface for use in ride sharing applications. We define an effective, opportunistic client user interface as one communicating all available rides satisfying the client's spatio-temporal constraints, whilst protecting the location privacy of both the client and vehicles involved.

In this paper we present a centralized ride sharing architecture that preserves, as a trusted entity, the identity and

*This research was done during a visit of this author at the University of Melbourne.

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locations of clients and vehicles alike. In the proposed user interface, vehicle locations are protected by only visualizing their potential pick-up locations in the future—both the vehicle's current location and plan are not disclosed. During the client's interactions to discover suitable rides, their own current location also needs not be revealed at any time, only their chosen destination is required for the purposes of ride matching. Only once the client selects a corresponding pick-up option and establishes a contract with an individual vehicle, location information is shared between both parties. During this process the client can freely choose from a set of spatio-temporal options, resulting in choices which may reflect any matter of private intention, e.g., physical exercise or deliberate obfuscation of location.

The concepts have been implemented and successfully tested in a grid-based simulation environment for a scenario with one client and multiple vehicles. We use the results as proof of concept and illustrate that an opportunistic client user interface which is simplified (purely graphical), privacy preserving (until contracts are made) and flexible, is feasible. By dynamically updating such an interface, opportunistic, ad-hoc planning can be realized.

The paper is organized as follows. We review related work in the next section, discussing human-computer-interaction related literature and existing ride share systems. In Section 3 we present the main visualization idea based on concepts of time geography. Section 4 explains in detail the centralized ride sharing architecture and its privacy preserving properties within the context of our experiment design. Section 5 discusses results from a grid-based simulation and shows visualization examples as well as a quantitative discussion. In Section 6 we conclude the paper and detail a set of future required works.

2. RELATED WORK

Surprisingly relatively little work has been carried out on how a user interface should be designed in order to facilitate opportunistic ride sharing. Research in Human Computer Interaction has mainly investigated the obstacles connected to ride sharing in terms of trust and security and technical design decisions. Earlier projects, e.g. the RideNow project [24], focused on email and web forms to offer or request rides and to share additional information on drivers and clients. Later approaches rely on map visualization and in order to improve trust amongst participants also on social networks, such as Facebook to help drivers and clients to feel more comfortable traveling with strangers. The interesting question on how much information should be disclosed to whom has also been addressed. Radke et al. [19] highlight the need for users to only disclose "as much information as needed" to improve the usability of an agile ride sharing system. While they discuss this issue for the disclosure of profile information, they do not extend these thoughts to the disclosure of clients' pick-up and drop-off locations.

Furuhata et al. [6] describe matching agencies as the centralized authority facilitating the "double-sided" ride matching of client-vehicle, seeking to satisfy the constraints (e.g., spatio-temporal and social) of both parties. Spatially, the authors classify ride matching into four categories: identical, inclusive, partial and detour. These techniques operate at various scales and granularities, e.g., city or suburb level for long distance ride matching. All these techniques rely on both client and vehicle sharing their explicit origin and destination information. Within this context the authors discuss the importance of privacy in ride sharing from two respects: the disclosure of private information to third parties, and the systematic collection and storage of this information in systems. They also describe one major challenge as the design of "concierge like ride-arrangement", i.e., a smart agent, facilitating the ride-matching process. Here their focus however is on matching user preferences and profiles rather than a specific human-computer interface.

A system design that allows for spontaneity has been proposed by Brereton and Sunil [4]. Their system relies on unstructured instant messaging. However participants need to be already known to each other to overcome trust and spam issues. Some work has looked in depth at the motivations and intentions of both drivers and clients and how ride sharing can be promoted, e.g., within organizations. Ozenc et al. [18] investigated commuting choices and different ride share scenarios in a large study. They highlight the importance of flexibility to most of the participants, i.e. the possibility to quickly make up their mind. Their results also demonstrate that users want to be able to select amongst several possible alternatives and their reservations towards fully automated matching of rides.

Morese et al. [17] have explored the use of web sites and public display systems to promote ride sharing within organizations and display possible rides on a large map, highlighting the savings obtained by sharing rides. However, they report problems related to flexibility, i.e. how much time drivers were willing to delay their own plans to pick-up additional passengers. Commercial approaches such as CoWaG[1], flinc[2], Avego[3] and Zimride[4] require precise information about start and destination points of vehicles and clients and then either apply heuristics to find good matches in terms of routes and user profiles (e.g., CoWag and Zimride) or rely on additional communication channels, such as text messaging or voice communications to fix the details of a pick-up (e.g., flinc and Avego). Often they also require some sort of user profile from a social network (such as Facebook) or additional information (e.g., age, telephone number, first and last name) to finalize the contract. The visualization usually relies on digital maps (often mash-ups using 3rd party mapping services mostly Google Maps). Pick-up and drop-off locations are conventionally marked with push-pins and colored lines are used to highlight routes.

Visualization of dynamic spatio-temporal phenomena has been studied extensively by Andrienko and Andrienko. In visualizing trajectories within an interactive space-time cube [1], the authors examine the complexity of data overlapping in space-time. The authors develop a method to interactively filter results using time windows to reduce display clutter in three dimensional (x,y,t) space. Such an interface technique is pertinent in ride sharing given multiple vehicles can provide overlapping services at a single location. However use of such a technique by a client within a mobile context requires careful attention, particularly in regards to affordances.

While map-based user interfaces are familiar to clients, they are very limited in their support regarding spatio-temporal

[1]http://www.cowag.de
[2]http://www.flinc.org
[3]http://www.avego.com
[4]http://www.zimride.com

options. With existing systems the user has no possibility to understand to what degree drivers of vehicles are willing to detour. This is often arranged ad-hoc in later communication which is difficult to quantify in space-time. Furthermore all discussed approaches assume that clients and drivers reveal their discrete origin and destinations for ride matching purposes.

Given that intentions as plans can be considered as being inherently partial [3], due to, e.g., the dynamism and complexity of any day, the rigid requirement of a client's origin and destination in ride matching may (under certain circumstances) constrain their use of a ride sharing application. By providing a client with a set of mobility options, other levels of their intention hierarchy [8], e.g., collection of a coffee or newspaper, might materialize, particularly when presented within a familiar, geographic context. Exploiting such a perspective in a map based environment, GoCatch[5] allows clients to discover available private taxis in their local area. Such an interactive, location-based approach has significant potential in public ride sharing.

In this paper we will present an approach which allows the client to explore their pick-up options without revealing their current location and without knowing the current locations and destinations of vehicles. Such a system would allow for ride sharing of autonomous vehicles where decisions must be wholly quantitative, rather than ad-hoc and qualitative.

3. USING TIME GEOGRAPHY TO VISUALIZE RIDE SHARE OPPORTUNITIES

This paper will suggest a novel approach enabling clients to find vehicles without either party revealing their current locations or plans to each other, and yet understanding transport demand and supply via a visual interface. This visualization is based on dynamic time geography.

3.1 Time geography basics

Time geography provides a framework to describe and analyze the location of mobile individuals over time [7, 11, 13]. In particular it allows to characterize the uncertainty about an individual's location some time after or before it was encountered last time (a *space-time cone*), or between two encounters (a *space-time prism*).

Originally, time geography partitioned space-time in a binary manner: locations accessible to a mobile individual considering all physical constraints versus the locations inaccessible to this individual. Among the physical constraints considered are maximum speed [7], a network [12, 28, 9], or the kinetics of a vehicle [10]. Accordingly, all analysis based on this representation is qualitative; for example, two individuals can have met only if (i.e., where and when) their space-time volumes intersect.

What has been a qualitative description—delineating potential locations or potential paths—has recently been refined by probabilistic time geography, facilitating quantitative statements about the likelihood of encounters at particular locations [25, 16, 27, 26].

Time geography has already been suggested to support the planning of ride sharing [22, 21]. In that context time geography was used to limit the spread of messages in the negotiation protocol, and thus was concerned with efficient communication in a peer-to-peer network. In this paper we will apply time geography concepts and analytics for a visual interface. Time geography becomes relevant for visual communication because vehicles and clients in ride sharing have some flexibility: their willingness to add detours to their route or to accept waiting times in any demand-responsive transport mode. This allows vehicles to hide their current location and plans to only communicate or share the locations within their reach. We will further make use of this idea to design and manage the negotiation process between clients and vehicles in a novel and intuitive manner.

[5]http://www.gocatch.com

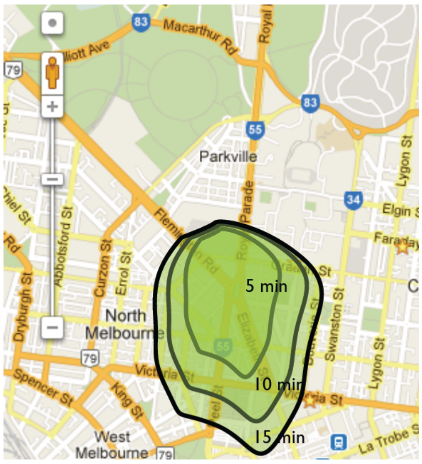

Figure 1: The areas that can be served within the given time intervals by vehicles that can serve the user's destination within their time budget.

3.2 Visualizing possible pick-up locations

In order to design a user interface for clients in a demand responsive transportation system, the concepts of time geography will be transformed into a dynamic visualization of travel opportunities. For this purpose the element of interest is the projection of a time slice of the space-time volume of a vehicle with some flexibility in their time budget onto the map plane (Fig. 1). It visualizes the area that a particular vehicle can serve within the next time interval(s) (in the figure, within 5, 10, and 15 minutes). It does not reveal the current location of the vehicle, and hence, preserves the privacy of drivers contributing to demand-responsive transport. Even if the clients will not see the vehicle's location, in order to generate the time slices the central ride sharing service needs to know the vehicle's current location, destination and time flexibility.

Still, this vehicle can head to any location and thus might not be relevant for a particular client. To filter out only those vehicles that are relevant, i.e., vehicles that would be able to serve the client's destination within their time budget, the service also needs to know the client's destination. However, the client's current location can remain hidden, and thus, the client's privacy remains preserved as well.

Accordingly, the set of filtered vehicles consists now of all vehicles on their way in current traffic (i.e., registered with a central service) that can reach a particular client's destination within their space-time volume. The time slices of their space-time volume for the next time interval can be shown on a map. These slices can be all over, can overlap, and the vehicles can be close to the client's destination or far away. In case of overlapping time slices the interface would show the earliest service times first. The interface could also indicate, e.g., by a heat map, the number of vehicles serving particular locations.

Again only a subset of these vehicles is relevant for the client: those that are nearby or more precisely, those whose time slices intersect with the space-time volume of the client. For example, to be picked up by a vehicle somewhere in the vehicle's 15-minute time horizon the client must be able to reach this location within 15 minutes as well. This last decision—where to meet and to be picked-up—can be left to the client, who can choose a pick-up location in the visual interface. The only condition is that this location must be inside of one of the highlighted *launch pads*, i.e., is within the service area of at least one vehicle. This user interaction would form a request to the system.

3.3 Vehicle accessibility

Within anisotropic network space, the set of potential paths a vehicle can travel between vertices origin O and destination D within a defined time budget t_{budget} can be described using the time geography concept of a *network time prism* (NTP) [14].

The NTP is an application of classical time geography: a three dimensional (x,y,t) space-time prism, constrained to transportation network space. In network space we define a graph G consisting of vertices V and edges E, abstracting the transportation network's intersections connected by roads. Here vehicle movement is constrained by various sets of capability, coupling and authority constraints [7], unique to the network's environment, e.g., speed limits.

In this paper we construct the NTP by calculating the complete set of *kNN* shortest paths within a search space partitioned using a simple heuristic [23]. During each shortest path calculation, vertices are attributed with the times they are accessible. Following creation of the NTP, a discretized *potential path tree* (PPT) can be derived. The PPT describes those vertices of the transportation network accessible by the vehicle within its time budget constraints [11].

Typically the NTP is constructed using a time budget equal to the time required to traverse the shortest path OD, $t_{shortest}$. However if the vehicle's available time budget is greater than this, we deem the vehicle to have some *flexibility* in time; expressed formally as $t_{flex} = t_{budget}$ - $t_{shortest}$. For vehicles with $t_{flex} > 0$ and with an intention to operate as a public ride sharing service, we assume they possess a willingness to compromise, which may be considered a type of cooperative behavior [15]. Flexibility may be used by the vehicle in various ways e.g., waiting for a client (forming a space-time station in terms of time geography [20]), or trading time for space, e.g., a diversion from their shortest path to pick-up or drop-off a client—both of which result in an expansion of the NTP. In Fig. 2, for example, a vehicle can take the shortest path from O to D and arrive early, choose to stay at O for the duration of its flexibility and then travel the shortest path to D, or trade time for space and make a detour through P before heading onto D.

Facilitating the service provisioning process client-vehicle, the centralized authority is responsible for computing each vehicle's NTP with complete (accurate and timely) knowledge of the transportation network. Aggregating the NTPs of all vehicles, the authority can then determine the predicted service potential within the transportation network

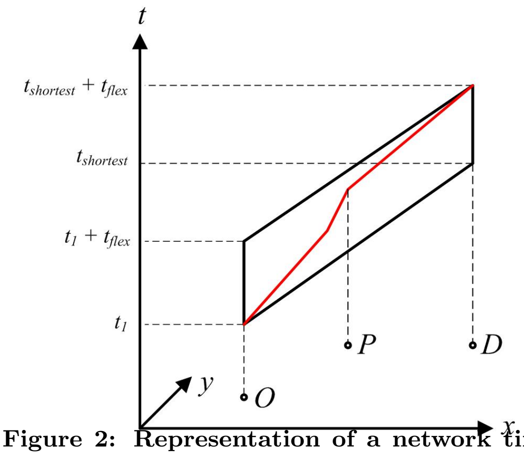

Figure 2: Representation of a network time prism (NTP) for travel at constant velocity from origin O at time t_1 to destination D with the potential of flexibility, t_{flex}. The prism contains the path OPD (shown in red) of a vehicle diverting from its shortest path OD within the constraints of t_{flex} to pick-up a client at P

over time. Using a discretized approach, this measure is calculated by counting the number of occurrences when each vertex is accessible by vehicles per time step. In those cases where a single vehicle can access a vertex multiple times, e.g., from different paths, only the unique occurrences in time are counted. Each vertex's counts are then aggregated into a *service coverage map* for the purposes of both assessing the overall quality of the ride sharing service and the later provisioning of rides client-vehicle. To maintain relevance this map must be updated regularly, e.g., in real-time. Note for reasons of simplicity we have referred to accessibility in regards to space-time constraints only, e.g., weighting edges according to their Euclidean distance. However this perspective can be broadened to include additional measures of utility [2, 12], which may be dynamic and uncertain.

In this paper we assume flexibility to be a dynamic and finite resource. Flexibility is the potential for a vehicle to become more accessible without leading to invalidation of its own mobility intentions or those of the client(s). To handle this spatio-temporal balance we develop the general concept of a *flexibility bank* in which flexibility is stored. The bank's balance ultimately constrains a vehicle within its NTP used to communicate its potential movement, e.g., drop-off within 5 minutes. Further, flexibility can be exhausted by the transportation network itself, e.g., road congestion, or other factors, e.g., weather conditions, however further consideration of this is beyond the scope of this paper. The bank metaphor also allows future scope to consider negotiated travel fares as time is traded between vehicle and clients.

Depending upon the transportation network's geometry, flexibility may mean a single vehicle has the potential to visit a vertex multiple discrete times or continuously over a time period (see space-time stations). With such an expanded NTP, a vehicle's potential to intersect with the mobility intentions of a client can increase. To communicate a vehicle's potential service offering to a client, we now formally develop the *launch pads* concept.

3.4 Launch pads

In this section we describe the base case scenario of a single client's interaction with our user interface. In this scenario the client interacts with launch pads to investigate and choose a mobility option from the set of all available rides satisfying their spatio-temporal constraints. The system architecture proposed protects the location privacy of both the client and the vehicles.

Launch pads form the basis of our opportunistic client user interface, communicating the full service offering of active vehicles within the ride sharing system. The concept abstracts a client's future physical pick-up and drop-off locations to virtual space in the form of interactive, graphical icons. We develop the launch pads concept to assist clients to fully exploit vehicles' potential in a simple manner.

Launch pads are calculated from a vehicle's accessibility at any point along its path OD with a specified time window. We define the PPT between t_{now} and t_d as PPT_{nd}. Querying an NTP described with flexibility can yield either a discrete or continuous representation and in this paper we will consider the discretized case only. Next is to determine which vertices within PPT_{nd} can be reached by the vehicle sometime in the future, i.e., t_{n+1}. To achieve this we derive a subset of this product, PPT_{local}, describing the vehicle's *local accessibility*. This product can be derived from PPT_{nd} using a simple spatio-temporal query.

We now describe the base case scenario of a client's interaction with our user interface. Using a digital map representation of the transportation network, the client selects their intended destination d and then using some interface, e.g., a slider, selects an arrival time t_d, which may also be expressed in the form of a continuous time window. This selection forms a new *mobility request* which is submitted to the centralized ride sharing authority to discover suitable rides. With visibility of all vehicles, the authority queries its service coverage map with the client's specified destination constraints in order to discover those vehicles which might be able to offer rides. If a vehicle's local accessibility intersects this query, the centralized authority then creates a unique *mobility contract* at every remaining vertex accessible by the vehicle prior to the client's selected arrival time. In cases where multiple vehicles overlap at vertices, only unique contracts are counted and aggregated, with the total number of contracts used as a measure of the vertex's service *stability* over time.

Contracts are then consolidated into launch pads and then revealed within the client's user interface overlaid on a digital map. Each launch pad is represented in the form of an icon abstracting a network vertex and is visualized according to the vertex's stability using a theme, e.g., a color ramp, refer Fig. 3. The client then uses the interface to find a suitable launch pad, i.e., one accessible to them. If one is found, the client queries (opens) it to discover the set of contract(s) being offered from potentially multiple vehicles. Each contract is described according to the vehicle's estimated time of arrival, e.g., 5 minutes, refer Fig. 4 and the client may also choose to describe them in other ways, e.g., carbon emissions. Note given our discretization, we can exchange time and space, thus ignore differentiation between the two in our descriptions.

The launch pads interface allows the client to explore and choose a contract which suits their private intentions. Throughout this process the current location of the vehicle remains concealed within the user interface. Once a mobility contract is accepted by a client, the centralized authority issues the vehicle with new route directions to pick-up the client at the agreed point and the vehicle's real-time position is revealed to the client for any other decision-making, e.g., walking to or waiting at the agreed location. If the client does not reach the location by the agreed time, the client forfeits its mobility contract and the vehicle continues towards its own next (or final) destination.

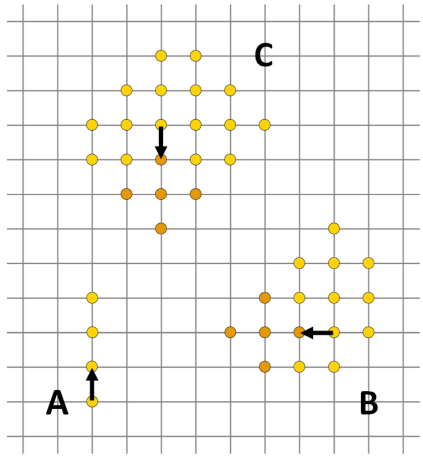

Figure 3: Example launch pads of three vehicles with varying flexibility for the time window [t_0, t_2]. Vehicle A has no flexibility, Vehicle B has flexibility 3000 units and vehicle C has flexibility one third of its path length (approximately 5000 units). Arrows describe each vehicle's direction of travel OD, colors denote stability (yellow = low, orange = medium.

In the base case scenario the client first selects their destination within the digital map user interface, and then sees the launch pads available. However if this location is either (1) unserviceable by vehicles, or (2) vehicles for some reason are unavailable, then the centralized authority may further present the client with an alternative choice set of *landing pads* from which to re-select their destination near their original request. This process may require additional constraints, e.g., maximum walking distance, to reflect the client's preferences.

We will now observe the potential effectiveness of communicating vehicles' accessibility in our proposed opportunistic client user interface using two independent experiments.

4. A SYSTEM ARCHITECTURE TO FACILITATE OPPORTUNISTIC RIDE SHARING

This section provides an overview of the *OppRide* system architecture from the perspective of two independent experiments: *service coverage* and *probability of pick-up*. Our aim is to examine the communication of ride share potential satisfying some level of service through space-time.

4.1 Overview

The OppRide system consists of three key levels: the *client* with mobility needs, the *vehicle* operating a mobility service and a *centralized authority* facilitating the service matching process client-vehicle.

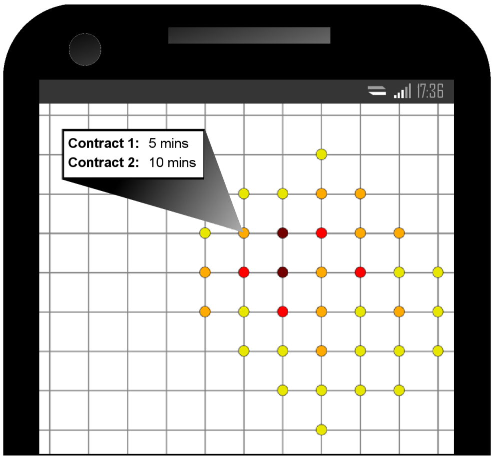

Figure 4: Realization of launch pads for two vehicles with overlapping local accessibilities within an example environment. Example contracts for a client's selected vertex are shown. Colors denote stability (yellow = low, orange = medium, red = high).

To test this interaction we design two experiments using the multi-agent simulation toolkit Repast[6]. Repast is ideal for testing OppRide as it allows us to observe the provisioning process client-vehicle over both space and time. In both experiments we abstract clients and vehicles to agents of different type. Each type is characterized by a set of attributes and functions unique to their ride sharing role: the client agent requests a mobility service and vehicle agents respond to the client agent's request via the centralized authority. All agents are assumed equipped with a mobile device, are location-aware and are capable of communicating with the centralized authority. Upon instantiation in the transportation network, agents use the OppRide system from either a client or vehicle perspective.

In our experiments we define the transportation network as a regular grid of 15 $\times$ 15 vertices connected by edges weighted according to their length, abstracting a Manhattan style urban environment. For simplicity we set each edge length to 1000 units. To balance the distribution of agents we divide the network into 9 equal *zones* each containing 5 $\times$ 5 vertices, and number each zone 1-9, (Fig. 5). We define the central zone 5 as containing the *service area* within which the client agent will seek to move between their origin o and destination d. This experiment design allows us to observe client-vehicle interactions without boundary effects from network geometry.

In this environment, vehicles' local accessibility over time will be examined in regards to service coverage (Section 4.2) and communication of this potential using launch pads for a client's probability of pick-up (Section 4.3). In these experiments local accessibility is realized in the form of discretized vertices and launch pads according to the base case scenario described in Section 3.4 and visualized above in Fig. 4.

[6]Repast Simphony 2.0, http://repast.sourceforge.net

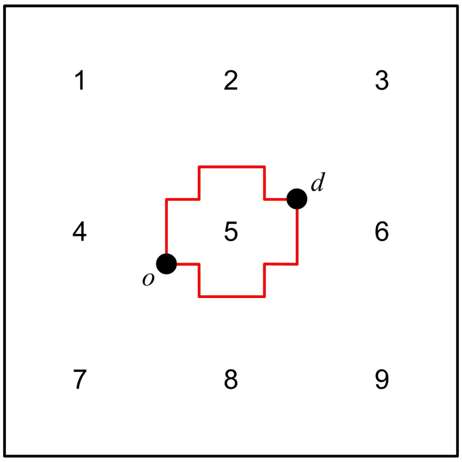

Figure 5: Transportation network space, showing the central zone 5 and the service area; an inscribed, discretized circle (visualized in bold red).

4.2 Service coverage

In a first experiment, we consider the concept of vehicle service coverage. Introduced in Section 3.4 in the form of a service coverage map, this measure is used by the centralized authority to determine the operational potential of OppRide at any time. We will investigate service coverage by varying the population size of vehicle agents and record the vehicle *diversity* and *counts* observed at each vertex per time step. We define:

- Vehicle diversity: The mean number of different vehicle agents observed per vertex per time step,
- Vehicle counts: The mean number of potential unique vehicle agent visits per vertex per time step.

Populating the transportation network with n vehicle agents, we assign each a random origin O and destination D vertex[7] from a uniform distribution within different zones surrounding the service area, zones 1-4, 6-9. Without clients each vehicle agent uses OppRide to plan their movements according to their own intentions, calculating their shortest path OD, setting $t_{shortest}$ and defining their flexibility, t_{flex}. We set a minimum shortest path length to ensure that vehicles have potential to cross the entire service area if their random origin and destination allows it. Each vehicle agent then submits their plans to the centralized authority which determines the vehicle's accessibility in the form of an NTP (Section 3.3). Following this the authority dynamically derives the vehicle agent's local accessibility (from which launch pads may be later derived) at each time step as it moves through the transportation network. By aggregating each vehicle agent's local accessibility representations over time and combining them with those of other vehicle agents, we form the centralized authority's service coverage map. Using this map the centralized authority can observe the level of service saturation at each vertex, independent from demand.

[7]Uppercase OD for vehicles, lowercase od for clients

4.3 Probability of pick-up

In a second experiment we examine the variables affecting a client's *probability of pick-up* using launch pads. The introduction of a client's destination constraints and subsequently its origin constraints, can be thought of as forming a coupling constraint in space-time [7], limiting the set of vehicles (and subsequently launch pads) available to the client to only those which satisfy both.

The client agent's origin o and destination d vertices are chosen at random from a uniform distribution on the boundary of the transportation network's service area (Fig. 5). We constrain the choice of an opposing destination to ensure that the shortest path od has some significant length. We then set the client's $t_{shortest}$ as the time to traverse the shortest path od and set the client's flexibility, t_{flex}.

In this experiment we will automate the client agent's interaction with our user interface in the following way. At instantiation, the client agent creates a *mobility request* detailing its constraints: setting its intended destination point d and arrival time $t_d = t_{now} + t_{shortest}$ and t_{flex} to be flexible with their request. The client agent will persist in the transportation network with its request until its t_{flex} is exhausted. If a vehicle agent is able to satisfy the client agent's constraints, the centralized authority issues the client with launch pads consisting of mobility contract(s) for pick-up. Then filtering the launch pads to only those available at its current location o, the client automatically chooses the next available service—thus short-circuiting the client-vehicle interaction process detailed in Section 3.4.

Upon receiving any mobility contract we deem the client agent's mobility request to be successful. If however the client agent is not offered a contract before exhaustion of its t_{flex}, we deem its mobility request to be unsuccessful. The client agent's probability of pick-up is calculated from this measure of success. Following exhaustion of t_{flex}, the client agent is removed from the environment and a new client agent is added to maintain a constant client agent population. This reiteration process is the same for all vehicle agents upon reaching their destination.

To quantify the client agent's probability of pick-up in the transportation network, we will observe the effects of varying the vehicle agent *population size* and *flexibility*.

In this experiment we will consider a single client agent only for simplicity. If multiple client agents were introduced, the centralized authority must provide vehicle agents within the constraints (including the flexibilities) of a broader client pool. Here the vehicle agent's flexibility bank can be thought of as a resource to be used for, e.g., diversions or waiting for new clients. Such increased complexity however is outside the scope of this paper yet will be considered in future work.

5. SIMULATION RESULTS

From the experiments described in Section 4, we will report on observations of service coverage (Section 5.1) and probability of pick-up (Section 5.2). These two factors directly impact on the visual communication of service potential within our proposed user interface. We aim to demonstrate that by communicating vehicles' full accessibilities to clients using launch pads, works towards proving the effectiveness of our approach.

Example effects relating to these two factors might include the dynamism of the client-vehicle interaction, the management and impact of vehicle flexibility and also the management and resolution of multiple vehicles' overlapping launch pads. In this paper only service coverage and probability of pick-up are studied for this purpose. The fact that they themselves are critical factors of user satisfaction with any ride sharing system is irrelevant for this paper.

5.1 Service coverage

To observe service coverage the movements of a population of vehicle agents were recorded. These movements were observed over a total of 3000 time steps. We set the minimum shortest path length of vehicles agents to 14 edges and for simplicity agents traverse each edge in a single time step. Each agent's flexibility has been set to one third of its path length OD, which we estimate to be a fair measure of potential deviation in time for most urban travel.

The observations of vehicle agent diversity and counts per vertex were recorded to create service coverage maps each time step (Section 4.2), which may be aggregated, e.g., Fig. 6. Table 1 presents the average service coverage results within our specific area of interest, the service area. By randomly assigning vehicles' OD from a uniform distribution we can compare results without other bias.

Table 1: Service coverage results: Average vehicle agent diversity and counts per vertex over 3000 time steps.

Population Size	Diversity	Counts
1	0.11	0.25
5	0.55	1.22
10	1.11	2.52
20	2.21	4.96
40	4.47	10.07

Results in Table 1 show that as vehicle agent population size increases, logically so does vehicle agent diversity and counts per vertex per time step. This increase is linear and the relationship between vehicle diversity and counts is a constant multiple of approximately 2.25. Moderate-high levels of both vehicle diversity and counts are observed for 10 or more vehicles (approximately 5% of the vertices in our

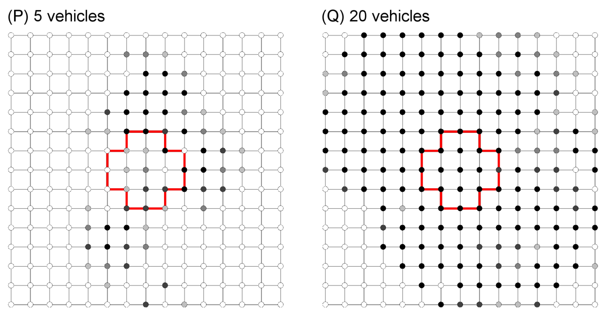

Figure 6: Aggregated service coverage maps for a time window showing comparatively low (P) and high (Q) levels of service for different vehicle populations (flexibility of one third of their path length). Vertices are visualized according to their average vehicle counts using a grey scale color ramp. The service area (Fig. 5) is shown in bold red.

15 × 15 grid network). Such level of service coverage is due to both the chosen level of vehicle agent flexibility and the grid network used; factors which both increase each vehicle agent's local accessibility.

Recall that service coverage is calculated by the centralized authority from vehicles' aggregated local accessibilities, irrespective of any client constraints. The average results of service coverage shown in Table 1 can be used an general indicator of service supply within the service area. This is of considerable interest to any ride sharing system designer, whose role it is to determine what levels of vehicle diversity and counts can create and sustain demand from clients.

For example, for a vehicle population size of 20 vehicle agents (refer to Table 1 and Fig. 6), a high level of vehicle agent diversity and counts indicate a high level of service coverage. These results illustrate the full potential service offering of vehicle agents currently active within OppRide. When communicated using our launch pads concept, clients can fully exploit this potential in space-time. Conversely however, a low level of service coverage from, e.g., 5 vehicle agents, may not provide sufficient service coverage to elicit demand from clients. This reveals the system designer's delicate role of balancing supply against demand. Note, within networks of less regular geometry, coverage maps may be even more valuable to the designer for such analysis.

Within this context we now discuss the results of a client agent's probability of pick-up.

5.2 Probability of pick-up

We now observe a client agent's probability of pick-up within the service area. Recall that a client agent can only be offered a mobility contract if all of its space-time constraints for *od* can be met by a vehicle. Again we set the minimum shortest path length of vehicle agents to 14 edges, so as to offer them potential to fulfill client agents' mobility requests.

First, we observe the effects of varying the vehicle agent population size. We again choose a fixed vehicle agent flexibility of one third based on our earlier assumption and similarly choose a client agent flexibility of one third. Then we calculate the client agent's probability of pick-up from the cumulative average of their mobility request's success over time. After observing convergence we delimit our results to 300 client agent mobility requests (iterations). The effect of increasing population on probability of pick-up is clearly evident in Fig. 7. For our grid network of 15 × 15 vertices, a population of 40 vehicles results in approximately a 96% probability of pick-up.

Second, to test the effects of varying vehicle flexibility we choose a vehicle agent population of 5, allowing us scope to sufficiently test a range of flexibility values: from zero flexibility up to half of the longest possible path. Results in Fig. 8 show that as flexibility increases so too does a client's probability of pick-up. Here the larger the flexibility, the larger the potential launch pads, increasing a client's probability of pick-up.

Referring back to results of service coverage in Table 1, 5 vehicles with flexibility of one third of their path length, yields an average vehicle diversity of 0.55 and vehicle counts of 1.22 per vertex per time step. Examining Fig. 7 for the corresponding vehicle population size, a client's probability of pick-up is approximately 35%. A comparison of all vehicle population sizes reveals a logarithmic style relationship (Fig. 9), indicating that whilst a client's probability of pick-up can never be wholly guaranteed, a system designer can expect a minimum service level for a defined set of variables.

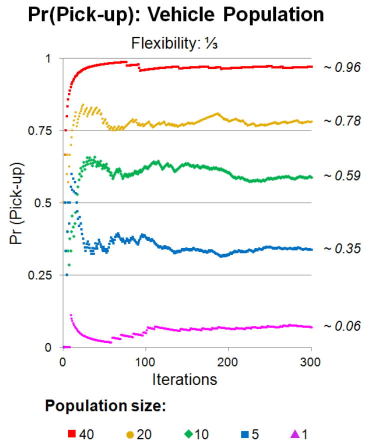

Figure 7: Probability of pick-up: Varying vehicle agent population size. Average probability in italics.

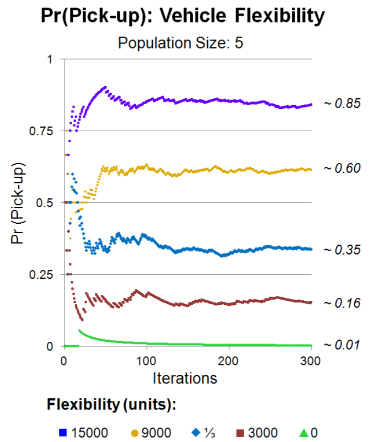

Figure 8: Probability of pick-up: Varying vehicle agent flexibility. Average probability in italics.

Relating these results to our client user interface reveals the complex spatio-temporal task of matching a client's constraints with the vehicle's local accessibility. With higher levels of vehicle counts, a client's probability of pick-up at a fixed point may be higher, but still not guaranteed. The observed results reflect the behavior seen in the real world between different transport modalities. For instance, an on-demand private taxi has unlimited flexibility (roughly corresponding to a flexibility of 15000 units in Fig. 8) and using larger corresponding launch pads (Fig. 3), can satisfy the client agent's mobility request to a very high probability. In contrast, a bus service following a fixed route has no flexibility and as such the probability of pick-up is virtually none—relying on the perchance coincidence of the vehicle exactly intersecting the client's constraints.

5.3 Proof of concept

In this paper we hypothesize that our proposed architecture provides an effective user interface for use in ride sharing applications. Recall that our definition of an effective

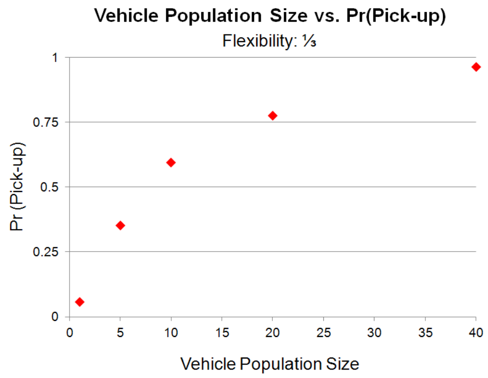

Figure 9: Vehicle agent population size vs. probability of pick-up

opportunistic client user interface is one capable of communicating all available rides satisfying the client's spatio-temporal constraints, whilst protecting the location privacy of both the client and vehicles involved.

It is clear from results shown in Figures 7 and 8 that there needs to be sufficient balance between vehicle population and flexibility in order to offer clients' a moderate-high probability of pick-up. This is the chief responsibility of a ride sharing system designer. Our results illustrate that potential exists for exploitation of vehicle diversity and counts within a spatio-temporal context, if flexibility is quantified and incorporated. Once a desired level of service coverage is attained, the accessibility of vehicles may be exploited in the form of mobility options by clients. This potential is explicitly communicated using launch pads within the proposed client user interface.

However the introduction of a client's constraints to find matching vehicles might not necessarily guarantee the client a ride. Ride-matching is a complex spatio-temporal task for the centralized authority, however a client does not need to know about this—what matters to them is a means of accessing mobility services on-demand. The OppRide architecture relaxes the rigid constraints by offering clients choice within the vehicles' pool of potential. By working backwards from their intended destination and arrival time, the centralized authority can propose the corresponding options available. From here the client may choose an option nearby, e.g., their current location, or an option further afield by, e.g., walking or using a shuttle service. This further allows the client to protect their location privacy in regards to places of residence, work or other social activity.

We argue that proof of concept of our interface technique and architecture lies explicitly in this offering. By communicating the full accessibilities of matched vehicles using the launch pads concept, we determine our user interface to be effective for several reasons. First, launch pads provide an accurate representation of vehicle accessibility using quantitative methods (which ultimately can be trusted and relied upon by clients—essential for any mobility service). Second, launch pads overlaid on a digital map clearly demark the options offered within the transportation network, assisting clients' travel planning. Third, multiple contracts are intuitively visualized according to the vertex's stability using, e.g., a color ramp, providing clients with an interface which can be easily understood and utilized. Fourth, the use of launch pads protects the location privacy of both client and vehicle, when used with architecture described in our base scenario.

6. CONCLUSION AND FUTURE WORK

This paper has explored the development of an opportunistic client user interface for ride sharing applications which is effective in regards to communicating options whilst protecting privacy. The design is grounded in quantitative methods of vehicle accessibility and provides clients with choice in an intuitive manner.

Using this design a client can search for and potentially discover mobility contracts satisfying their intentions, without revealing the current locations of the individuals involved. The results of this paper provide proof of concept for our client user interface which we deem to be effective for use in ride sharing applications.

The novel contributions of this paper include the quantification of vehicle flexibility and its incorporation into a representation of vehicle accessibility, the creation of the launch (and landing) pad concept to communicate a client's potential pick-up (and drop-off) locations in space-time, and the design of a ride sharing application architecture which protects the location privacy of both client and vehicle, until a formal contract is created.

The experiments in this paper are based on a grid style transportation network, which despite quantitatively demonstrating the need for balance between vehicle population and flexibility is simplistic. Further experimentation using a real street network with, e.g., greater spatio-temporal constraints or degrees of centrality, is required to more rigorously determine the effectiveness of launch pads and the OppRide architecture.

Future experiments are also needed to examine the effects of multiple clients and vehicle capacity constraints, where a pool of clients (and their constraints) ultimately dictate the vehicle's overall flexibility (otherwise clients themselves may have to compromise their intentions in space-time, e.g., walking). Tied to any such increased complexity from heterogeneous flexibility, the development and effect of fare mechanisms must be examined, particularly in regards to contract modification, cancellation and refund.

In this paper we consider the simple case of launch and landing pads discretized at vertices only. However if a continuous representation visualized in Fig. 1 is derived from the representation of a vehicle's accessibility, discrete points needs to be determined for pick-up and drop-off within these continuous features of geometry type line, polygon or volume. In future work we will consider the client-vehicle negotiation processes to determine such points.

The art of choosing spatio-temporal options in ride sharing requires further attention. Any ride sharing system within an urban environment must be capable of facilitating demand and supply fast enough to ensure that contracts remain valid. Here the architecture may need to be adapted to cater for all possible interaction scenarios. In this same vein, the behavior of human clients using the OppRide architecture needs to be tested to ensure its real-world viability. Usability extensions to OppRide, e.g., preferences and custom queries, may further motivate this behavior. From here various social and environmental costs and benefits could be incorporated into the user interface.

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