

Dynamic Ridesharing Practice and Future Directions

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Abstract Although ridesharing can provide a wealth of benefits, such as reduced travel costs, congestion, and consequently also less pollution, there are a number of challenges that have prevented its widespread use. In fact, even at a time when our improving communication systems provide real-time detailed information that could be used to facilitate ridesharing, the share of work trips that use ridesharing has decreased by almost 10% in the past 30 years.

In this paper we present a survey and taxonomy to understand the key aspects of ridesharing and existing ridesharing systems. The objective is to present a framework that can help identify key challenges in the widespread use of ridesharing and thus foster the development of effective formal ridesharing mechanisms that would overcome these challenges and promote its massification.

Keywords Dynamic Ridesharing · Carpooling · Industry survey · Sustainable transportation · On-demand

1 Introduction

The success of given transportation options depend on it being selected by the individual travelers. Some of the reasons that help users decide on a transportation mode are its cost, the resulting travel time, the flexibility to adapt to changes in schedule, the convenience to users (such as the ability to listen to music or its privacy), reliability, and the user perception of security. To illustrate, consider first fixed line systems (such as buses or subways) that provide a fixed travel option at a small cost with long travel times and little convenience. At the other end, there are private cars or taxi service which at a higher cost provide a faster, flexible and convenient option. Ridesharing, sometimes referred to as carpooling, can aim at combining the fast travel time

and flexibility of private vehicles, at the expense of convenience, in a way that reduces costs both to drivers and passengers.

Ridesharing occurs when individuals share a personal vehicle for a trip and split travel costs such as gas, toll, and parking fees, with others that have similar itineraries and time schedules. Advantages of ridesharing for participants, to society, and to the environment include saving travel cost, reducing travel time, mitigating traffic congestions, conserving fuel, and reducing air pollution [25,37,44,17]. However, the requirement that itineraries and schedules are coordinated between the participants in ridesharing and the lack of efficient methods to encourage participation in ridesharing has made a wide adoption of ridesharing difficult. Any system that aims to popularize ridesharing must have at its heart an efficient mechanism to assign riders to vehicles [1]. In addition successful ridesharing systems have to implement efficient ways of distributing the cost benefits of ridesharing to its participants and address concerns on security and inconvenience. Unfortunately, the transportation research community has largely ignored this research area [1]. There are several examples of systems that facilitate ridesharing coordination, however to date there is no industry standard method to coordinate travelers.

For the most part, ridesharing coordination is an informal and disorganized activity and only in certain cases can travelers make use of ridesharing as a regular transportation alternative. In the history of ridesharing, there are several attempts where practitioners have overcome inhibitors of ridesharing and developed usable ridesharing services by enhancing implementation of innovative technologies (see [17,28,6,31]). A better understanding for these attempts is essential to generate the methodological background to enable the development of successful ridesharing in more generic conditions.

The first organized ridesharing, Car-Sharing Club, was led by the government as a regulation policy in order to conserve fuel during WWII. Similar to how financial institutions operated at that time, ridesharing was arranged on bulletin boards at local matching institutions. Then in the 1970s several ridesharing methods emerged as a consequence of the oil crisis. The first employer vanpool programs were established by 3M and Chrysler, which provided vans for commuting of employees working at the same location [47]. Employers also support the formation of carpools, in which drivers take turns driving a vehicle to take a group of employees. *Carpooling* is a regular, advanced, and cost effective means of transportation [25,44], but it is inflexible for unexpected changes of schedule. In addition, semi-organized ridesharing services have also emerged spontaneously. Individuals arrange ridesharing automatically and without previous planning to travel specific roads which provide a precise benefit for the driver such as access to faster HOV (High-Occupancy Vehicle) lanes or reduced toll. In such systems drivers and passengers meet at predetermined locations on a first-come first-service basis. *Slugging* formed in the Washington D.C. area free of charge to the participants is one example [40, 52]. *Casual carpooling* formed in the San Francisco Bay Area and Houston with a fixed-price for each rideshare route is another example [14,37]. A major advantage of these spontaneous ridesharing examples is the flexibility for the

participants, which is harder to achieve in regular carpooling or vanpooling. Unfortunately, these examples require a large number of participants in continuous use and thus they are limited to specific locations or circumstances and are difficult to replicate elsewhere.

With the advent of the Internet age, a number of private matching agencies emerged to provide diverse ridesharing services for travelers [22]. These internet-based matching agencies have focused on two types of demands: *commute* trips and *long-distance* trips. While the target population for commute trips has been carpoolers, the demand for long-distance ridesharing tends to be one-shot travelers with schedules defined well in advance and that allow some itinerary flexibility. Typical matching agencies do not charge any commission fees and the sources of revenue are advertisement fees and government subsidies.

The New York Times (Jan 29 2011) however recently reported that ridesharing has continued to decline reaching only 10% of work trips in 2009, from 19.7% of work trips in 1980 [25]. This indicates that Internet-based matching agencies have not caused a fundamental transportation mode shift and innovative systems and services are necessary to overcome inhibitors of ridesharing. One of the significant challenges is the ability to satisfy *on-demand* requests, typically due to casual one-time demands for short distances that are known only shortly before the pick-up time. This includes irregular commute trips. Ridesharing services for such trips may overcome some of the barriers that limit conventional ridesharing whereby participants must schedule a roundtrip ride in advance [23]. For this type of demands, a few matching agencies implemented *real-time* ridesharing systems based on mobile technologies enhanced by smart phones with global positioning systems (GPS) that enables matching agencies to detect the current location of car providers and communicate with drivers. In such a system, a casual request of a user can be matched with a car provider currently driving close to the pick-up location. Systems like these are currently used by taxi services and shared ride vans. However, they still face the challenge of motivating independent drivers to participate.

The objective of this work is to help bridge current industrial practice and research contributing to the development of effective formal ridesharing mechanisms that could service large shares of travelers and be replicated nationwide. For this we present the state-of-the-art in ridesharing literature and applications, focusing on a function of rideshare matching to identify ridesharing specific issues and open questions that can help address the industry's current needs and promote activities of matching agencies working as connecting hubs between unknown individual travelers.

The rest of this article is organized as follows: In the next section we outline the main characteristics and develop a taxonomy of ridesharing systems in terms of their geographical and time structures. Section 3 presents a review of current industry practice in ridesharing, classifying existing systems into six classes depending on their matching search criteria and demand target segments. Section 4 describes additional concerns regarding how to motivate participation and concerns on convenience. In particular we discuss how chal-

allenges of fair distribution of benefits, security, and government participation have been addressed so far. We provide some final conclusions in Section 5.

2 Background

2.1 Basic Definitions

Seattle Smart Traveler, which is a Federal Highway Administration field operational test, defines a *trip* as a single instance of travel from one geographic location to another [22]. Ridesharing is a joint-trip of more than two ridesharing participants that share a vehicle and requires coordination with respect to itineraries. Some participants have concerns with several factors including travel cost, compensation for alternative ride provision, gender, and reputation of drivers and passengers. Nowadays, several different service providers assist such coordination activities which are the topic of the next section. In this section we describe the characteristics of ridesharing in general.

Unorganized ridesharing that involves spouse, family, colleagues, neighbors, and friends has a long history. Even without such a personal relationship, ad-hoc ridesharing has occurred occasionally, e.g., hitchhiking. These types of ridesharing activities, however, do not scale well.

Organized ridesharing is operated by agencies that provide ride-matching opportunities for participants without regard to any previous historical involvements [22]. Due to this, organized ridesharing has great potential as a scalable service. *Prearrangement* by service providers is a key characteristic of organized ridesharing unlike hailing a taxi or hitchhiking which are sought on the street.

For the ride arrangement, the requests are submitted through the Internet or telephone to the service providers, and then the supply and demand is matched by service providers. These service providers can be classified into two types:

- *matching agencies* focusing on facilitation services of rideshare matching between individual car drivers and passengers
- *service operators* focusing on rideshare operations using their own vehicles and drivers.

Representative practices of service operators are vanpooling and airport shuttle transportation services. Typical service operators accept requests from passengers only and assign these ride requests to vehicles. This matching process is called *one-sided matching* in economics and *centralized transportation management* in management science and operations research. A notable characteristic is that most of the decisions are made by service operators and participants decide whether to take it or leave it. In general, pick-up and drop-off locations are tailored for participants but pick-up and drop-off time sometimes require some amount of spare time. Moreover, service areas are often times restricted and advanced requests are required by service operators.

Alternatively, matching agencies focus on facilitation services of ride-matching between individual car drivers and passengers. Unlike service operators, matching agencies do not provide vehicles and drivers. Instead, individual participants provide their unoccupied seats for passengers. Both car drivers and passengers submit their offers and requests to matching agencies and ride-matching is executed by the matching agency. This is what is called *two-sided matching* which involves network externalities. For example, the value of a matching agency for a car provider relates to the number of requests of passengers that can be matched through the matching agency, while the value for a passenger depends on how efficiently a car provider can be found at the matching agency. As a result, the nature of matching agencies gives rise to a chicken-and-egg problem [15]: in order to attract car providers, a matching agency should have a large number of requests, but these will indeed be willing to offer rides only if they expect many passengers to show up at the matching agency. Thus, a central issue of matching agencies is to design market mechanisms that are attractive enough for both car providers and passengers to participate into a market. In addition, drivers offer rides in order to share travel costs and they do not provide tailored rides for passengers. Therefore, it is important for matching agencies to provide highly effective ride arrangement services for both sides.

2.2 Geographical Structure of Rideshare

Ridesharing led by matching agencies and service operators have different matching problems. The differences are highlighted according to geographical characteristics of ridesharing. As mentioned above, each service operator provides tailored services with respect to pick-up and drop-off locations for the passengers. Thus, service operators receive requests from passengers (a single-sided matching) and then they allocate requests to vehicles (optimal vehicle routing). In contrast, matching agencies arrange ridesharing in a double-sided matching where both drivers and passengers submit their offers and requests and the trip can be formed if participants agree on the conditions of the ride. Therefore, a fundamental problem is how efficiently matching agencies can assist ride-arrangement for both sides. In practice, matching agencies provide potential ridesharing opportunities based on several different matching criteria that are characterized by a geographical structure of formed ridesharing. In the literature, Morency [44] classified geographical structures of carpooling focusing on trips for commuters. We extend her classification to extract how these structural differences influence rideshare matching in general.

Each individual has a demand for their trip consisting of the *origin* and the *destination*. In ridesharing, a car driver *picks up* a passenger and drives to a *drop-off* location. We call an original route of a driver if he or she drives alone; otherwise we call it a ridesharing route. Notice that the origin of a passenger and their pick-up location can be different; the same is true for the destination and drop-off location. We classify these differences with the

following notation. Let us denote a as a driver, and b as a passenger. Each driver and passenger has their origin o and destination d . We denote u as a pick-up location and v as a drop-off location. We assume that each driver a has his original route $R(a)$. The route of ridesharing formed by driver a and a set of passengers B is denoted as $R(a, B)$.

We classify ridesharing patterns into four that are illustrated in Figure 1. Notice that we distinguish between single passenger case and multiple passengers cases. In the following, we describe the pattern for the single passenger case.

- **Pattern 1 (identical rideshare)**: Both the origin and destination of driver a and passenger b are identical, i.e., $o_a = o_b = u_b$ and $d_a = d_b = v_b$. All the identical trips are accomplished by ridesharing.
- **Pattern 2 (inclusive rideshare)**: Both the origin o_b and destination d_b of passenger b is on the way of an original route $R(a)$ of driver a , i.e., $o_b, d_b \in R(a)$. All the trips are accomplished by a single driver, but a passenger does not have an identical trip with a driver.
- **Pattern 3 (partial rideshare)**: Both the pick-up location u_b and drop-off location v_b of passenger b are on the way of an original route $R(a)$ of driver a , but either the origin or the destination of the passenger is not on the way, i.e., $u_b, v_b \in R(a)$ and $\neg(o_b = u_b \text{ and } d_b = v_b)$. A rideshare is a partial part of the entire trip of passenger b .
- **Pattern 4 (detour rideshare)**: Both the pick-up location u_b and drop-off location v_b of passenger b are not on the way of an original route $R(a)$ of driver a . Thus, taking a detour, rideshare route $R(a, b)$ covers both the pick-up and drop-off locations.

In traditional matching agencies, these four patterns are not well distinguished. Instead, rides are matched in accordance with the level of regional areas rather than exact locations. In the-state-of-the-art matching agencies, recognition of these differences is used for a *routing* of ridesharing that supports instantaneous ride-matching, in particular for pricing, and geographical and time decision makings. Among these four ridesharing patterns, detour ridesharing (pattern 4) has difficulties on instantaneous decision making, since the additional travel costs and time for the driver is not usually paid by the passengers.

We now emphasize the difficulties of rideshare matching in the multiple passengers' cases. In Figure 1, the multiple passengers' cases of the four ridesharing patterns are illustrated. Patterns 1, 2, and 3 are simple extensions from the single passenger cases but detour rideshare (pattern 4) is complex. There are two scenarios: (1) detour is beneficial for both passengers and (2) detour is beneficial for one of the passengers and not for another passenger. In the latter case, permutations of the rideshare agreement have a significant impact on the overall agreement. In this example, passenger b has an identical trip with driver a ; passenger b' requires detour for driver a . If passenger b' agrees on ridesharing with passenger a first, these parties form detour ridesharing. Then, whether to form ridesharing with passenger b is based on the detour ridesharing. In contrast, if passenger b agrees on ridesharing with passenger a

	Single Passenger	Multiple Passengers				
Pattern 1 (Identical Ridesharing)	$o_a = o_b = u_b$ $d_a = d_b = v_b$ 	$o_a = o_b = o_{b'}$ $d_a = d_b = d_{b'}$ 				
Pattern 2 (Inclusive Ridesharing)	$o_b, d_b \in R(a)$ 	$o_b, d_b, o_{b'}, d_{b'} \in R(a)$ 				
Pattern 3 (Partial Ridesharing)	$u_b, v_b \in R(a)$ $\neg(o_a = u_b \ \& \ d_a = v_b)$ 	$u_b, v_b, u_{b'}, v_{b'} \in R(a)$ $\neg(o_a = u_b \ \& \ d_a = v_b)$ $\neg(o_a = u_{b'} \ \& \ d_a = v_{b'})$ 				
Pattern 4 (Detour Ridesharing)	$\neg(u_b \in R(a) \ \& \ v_b \in R(a))$ 	(1) $\neg(u_b \in R(a) \ \& \ v_b \in R(a))$ $\neg(u_{b'} \in R(a) \ \& \ v_{b'} \in R(a))$ $u_b, v_b, u_{b'}, v_{b'} \in R(a, B)$ (2) $u_b, v_b \in R(a)$ $\neg(u_{b'} \in R(a) \ \& \ v_{b'} \in R(a))$ $u_b, v_b, u_{b'}, v_{b'} \in R(a, B)$				
Legend	Origin o	Destination d	Pick-up u	Drop-off v	RS Path	Joint RS Path
Driver a						
Passenger b						
Passenger b'						

Fig. 1 Classification of Rideshare Structures in Geographical View

first, these parties form identical ridesharing. Then, whether to form ridesharing with passenger b' requires the joint agreement with passengers a and b , since both parties incur additional costs of travel for the detour. Moreover, there is a pricing problem in the multiple passengers' case. We will discuss this problem in Section 4.1.

2.3 Time Structure of Rideshare

In addition to geographical coordination, rideshare participants need successful coordination in time as well. Some matching agencies support such coordination according to a scheduling function of ridesharing. The prerequisite of the scheduling function is a routing of ridesharing based on the input of detailed geographic information from drivers and passengers.

First, a driver and a passenger need to agree on the pick-up and the drop-off time. The simplest case is identical ridesharing (pattern 1) in which it is easy to determine the pick-up and drop-off time while satisfying demands for the driver and passenger. However, in the rest of three ridesharing patterns, the determination of the pick-up and drop-off times is not simply obtained, since a driver does not indicate when he or she is expected to pass all possible pick-up locations. Thus, an assistance of feasible ride-matching due to scheduling has a significant value for participants. Moreover, finding a feasible ridesharing for multiple passengers increases the difficulty. We will discuss this problem in Section 4.

In addition to the agreement for the pick-up time and drop-off time, the decisions are necessary to be made prior to the latest notification of time which is typically the departure time for a driver and the pick-up time for a passenger. The matching cannot be made prior to the listing of one-side. We call the time period between the listed time and the latest notification time as the matching time window similarly to Agatz et al. [1]. Usability of rideshare participants rely on an easiness to a rideshare agreement. Therefore, it is important for matching agencies to define their business processes that enable participants to utilize their matching time windows in the optimal way. We detail these business processes and their business functions in Section 3.

2.4 Strategic Consolidations

Ridesharing matching agencies undertake certain strategies to consolidate diverse offers and requests for the assistance of ridesharing coordination. The most common consolidation method of a matching agency is to organize information flow, in particular the process of listing and searching.

Some providers propose methods to consolidate demands physically. They set ridesharing routes and major stops as landmarks of pick-up and drop-off locations, typically major streets, park-and-ride lots, and transit centers. According to physical consolidations, detour ridesharing (pattern 4) can be transformed into partial ridesharing (patterns 3) with consolidated pick-up and drop-off locations.

Another approach to alleviate difficulties of rideshare matching is to extend matching time windows by tracking the location information of the car drivers according to GPS and mobile technologies. Ridesharing systems implementing such technologies enable notifying drivers rideshare matching even after a departure from their origin. This type of ridesharing is sometimes referred

to as *dynamic* or *real-time* ridesharing. A primary advantage of these services enjoyed by ridesharing participants that do not share the origins of drivers and passengers such as inclusive ridesharing (pattern 2), partial ridesharing (pattern 3), and detour ridesharing (pattern 4) is due to the extension of the matching time windows.

3 Ridesharing Matching Agencies

In this section, we present our survey results of current industry practices in ridesharing matching agencies. The survey is conducted in the second half of 2011. We classify matching agencies according to their main characteristics focusing on the ride-matching aspect unlike existing surveys that provide a list of matching agencies with short descriptions as seen in [45,13,28]. First, we classify matching agencies into six classes according to their primary search criteria and target segment. Then, we focus on how matching agencies implement their business processes and functions.

3.1 Overview of Classification

We have investigated characteristics of 33 major matching agencies in the world, and we have identified two major taxonomic criteria to characterize them: *primary search criteria* and *target segment*. First, we describe the following four primary search criteria:

- **Route and time:** a request and an offer are matched by route and time. The necessary input is addresses of the origin and the destination of respective participants. A routing function is necessary for this criterion.
- **OD pair and time:** a request and an offer are matched by their OD-pairs and time. Cities, regions, districts, and user-specified areas are used as locations.
- **Keywords/lists:** a request and an offer are searched by keywords (such as city names) or lists (including bulletin boards).
- **OD pair and first-come first-service:** a request and an offer are not prearranged. Instead, drivers and passengers are matched at predetermined meeting spots in a first-come first-service basis.

The three target segments are:

- **On-demand:** a casual, one-time, and irregular trip for relatively short distances requiring almost a real-time response.
- **Commute:** ridesharing for commuters with regular work schedule and long-term relationships. Participants often provide their vehicles in turns.
- **Long-distance:** ridesharing for a long-distance trip including inter-state, inter-city, and inter-country trips with advanced scheduling and with less restrictive accordance of meeting time and place.

In addition to these target segments, there are a few other types of trips. *Event* trips are formed among travelers that share a type of occasional reasons such as going to concerts, ski resorts, beach, and going home during school breaks. In our survey, we put event trips in the long-distance category. Amey [6] defined *occasional* trips in which drivers and passengers are reminded daily at a fixed time (e.g., 11am) to post their offers and requests for trips in the afternoon. Occasional trips are casual, flexible, and moderate size of matching time window. Even though this function has not been implemented in practice, a similar function is described in Section 3.2.1.

According to the combinations of these two types of taxonomic criteria, we classify matching agencies into the following six classes:

- **Dynamic real-time ridesharing** [30,1,23,3]: providing an automated process of ride-matching (routing, scheduling, and pricing) between drivers and passengers on very short notice or even en-route.
- **Carpooling** [53,25,44]: serving for commuters that share transportation to work in a private vehicle with another worker.
- **Long-distance ride-match**: serving for travelers of long-distance trips to share rides.
- **Carpooling and one-shot ride-match**: a hybrid of carpooling and one-shot ride-match.
- **Bulletin-board** [10]: providing ridesharing opportunities (information) based on notice boards.
- **Flexible carpooling** [40,52,14,37]: providing ridesharing opportunities without prearrangement in advance but coordinated on the spot. Ridesharing is matched spontaneously based on a first-come first-service basis at the meeting sites.

In Figure 2, we demonstrate how target segment of matching agencies and the search criteria that are provided by them are correlated; we illustrate these six classes and relevant names of matching agencies (or service types for flexible carpooling) in each class. First, dynamic real-time ridesharing is the most emerging class among these. While there are several different definitions of this class [30,1,23,3], we focus on three automation functions, routing, scheduling and pricing in order to achieve instantaneous ride-matching for satisfying demands for on-demand trips. Since the matching time-window can be very short, the system makes an automated rideshare matching including a routing of ridesharing specifying pick-up and drop-off locations and times based on the simple input of participants’ itineraries and schedules. Notice that a passenger’s pick-up and drop-off locations are not needed to be the same as the OD-pair of the car driver as long as they are on the route of the driver’s original trip. In addition, we consider the automated pricing system as a necessary function in this class.

Second, carpooling matching agencies serve for commuters that place importance on their home and work places, start and end times of work. Typically, matched participants have a similar OD-pair and prefer long-term and regular carpooling.

Third, matching agencies in the class of long-distance ride-match are targeting long-distance travelers in particular inter-city, inter-state, and inter-country. One type of search criteria is the OD-pair and the departure time, similar to carpooling matching agencies. However, long-distance travelers frequently have more flexible travel schedules, and thus some matching agencies provide an alternative search choice which is a list-based search. First users specify the departure region, and then they search for the candidates in the list.

Fourth, some matching agencies aim to satisfy demands for both commuters and travelers of one-time trips. Matching agencies in the class of carpooling and one-shot ride-match provide multiple search methods according to an OD-pair matching or searching from lists. Some agencies in this class are capable of matching based on a route matching, while they do not provide an automated pricing function.

Fifth, some matching agencies in the class of bulletin board aim to provide the places to notify ridesharing offers and requests as flexible as possible. They delegate to the users what kind of information they include in their offers and requests. Thus, users search methods are based on the keywords/lists.

Finally, typical flexible carpooling is a semi-organized service, i.e., usually no matching agencies. There is no prearrangement, but the destination, the meeting place and time are all predetermined and publicly known among participants. Drivers and passengers are matched on a first-come first-service basis. A meeting spot is a reasonable parking spot (for passengers who may drive to the site and leave their cars) and proximity to major transportation corridors that provide HOV lanes [37].

A rising trend in ridesharing industry is to provide the general services that cover multiple target segments like the class of dynamic real-time ridesharing, and carpooling and one-shot ride-match rather than specific services. In order to identify opportunities and challenges in industry, we describe business functions of each matching agency, in particular matching systems in the next section.

3.2 Business Functions

In the early nineties, Beroldo [10] identified five fundamental components of successful ride-matching systems: a storage system for trip information, a matching system, an information dissemination method, a database update and validation system, and an evaluation system. By contrast, from the user-side, we identify the following five key business functions as fundamental services for ridesharing matching agencies: listing, prearrangement, pricing, assistance of pick-up and drop-off, and payment.

Search Criteria	Target Segments		
	On-Demand	Commute	Long-Distance
Route & Time	(1) Dynamic Real-time ridesharing Avego (US) Zebigo (US) flinc(DE)		
OD Pair & Time	(2) Carpooling 511 SF Bay Area (US) Carpool Crew (US) Carpool Wozid (US) Ridesearch (US) Carpool Zone	(4) Carpooling and One-shot ride-match Participate (US) Carriva (DE) GoLoco (US) iCarpool (US) JayRide (NZ) NuRide (US) ride 4 cents (EU)	(3) Long-distance ride-match amovens (FR) GishiGo (US) Nottoko (JP) Pinchela (CN) ZimRide (US) Covoiturage (FR) Mitfahrgeleg enheit(DE) PickupPal RideshareList (US)
Lists/Keywords		(5) Bulletin board AlterNetRides (US) Craigslist (US) Is any one going to (UK)	Commuter Connections(US) eRideshare (US) RideBuzz(US)
OD Pair & FCFS		(6) Flexible Carpooling Casual Carpooling (US) Slugging(US) Raspberry Express (NZ)	

Fig. 2 Classification of ridesharing matching agencies

3.2.1 Listing

To list offers and requests of ridesharing is the most fundamental function of the matching agencies. With respect to geographical information, there are several different levels such as exact addresses, intersections, regions, ZIP codes, cities, and landmarks. We group these geographic levels into two: *address* which is able to refer in the street level and *region* which corresponds to the higher level of geographic information. While address is used in real-time ridesharing matching agencies, region is used in long-distance ridesharing matching agencies. Regarding the time, the expected departure time for a car provider or the preferred pick-up time for a passenger is specified in matching agencies targeting for on-demand trips and long-distance trips. In order to reduce the effort of input, some matching agencies implement a function that enables to submit offers and requests repetitively in a regular frequency (daily or weekly) in an automated way. We will denote this function as “rep” in a classification of matching agencies in Section 3.4. In contrast, work days and schedule with start and finish times are usually specified for listings of commuting trips. In addition, allowances for time differences are commonly specified within 15 minutes of the time interval. For long-distance trips, participants tend to accept wider time differences for the departure.

At the time of listing, an active matching enables finding potential partners while listing offers or requests. Contrary, a passive matching does not deal

with any matching at the listing in this case; filtering and keywords search are necessary functions to find potential partners.

3.2.2 *Prearrangement*

Prearrangement is the heart of matching agencies. If potential car drivers or passengers do not have a good experience within the first three attempts of search at a certain matching agency, they will not return to the matching agency. No matching result is a case where matching agencies are concerned to avoid, whereas too many unrelated opportunities are meaningless for users. The prearrangement function of matching agencies consist of two-stages: search of potential partners within the system and negotiation of ridesharing with potential partners. In addition, users are likely to find appropriate search results by designing matching methods, in particular geographic and time aspects of matching. In the geographic aspect, there are three criteria: route, OD-pair, and keywords/lists. A matching by route requires the input of geographic information in detail and matching agencies are necessary to have a routing function. A matching by OD-pair has two types of geographic matching levels: an address level and a region level. The former typically uses radius to specify an allowance of difference, while the latter uses exact matches of regional names registered in the system. Finally, in a matching by keywords/lists, users search from non-customized lists of offers and requests.

Regarding matched by time, many matching agencies ask users to specify their preferred time within a list of matched results according to geographical matching. Other agencies ask users to specify the departure date and matched by date, while some other agencies require users to specify the departure time and matched by the feasibility of the pick-up time. The latter often includes matching with moving vehicles. Some other matching agencies propose pick-up time according to the scheduling function.

In addition to geographic and time matching, some ridesharing participants consider additional search criteria to find potential partners which is described in Section 4.

3.2.3 *Pricing*

Pricing specifies the amount of transfer money between the involved parties including how to share the costs of gas, toll, and parking amongst the rideshare participants, and how to charge transaction fees by the matching agencies. In industry, the following three types of pricing rules are used:

- **Catalog price:** drivers or passengers specify their least preferable price while listing. Therefore, the owners of listing determine their price.
- **Rule-based pricing:** a price is determined by a cost calculation formula specified by a matching agency. Typically, a formula is a predetermined standard rate per distance times a computed distance between the pick-up and drop-off locations.

- **Negotiation-based pricing:** a matching agency is not involved in pricing. It is negotiated between potential partners while they determine pick-up and drop-off locations.

Some matching agencies allow to choose pricing between catalog price and rule-based pricing in order to deal with both pricing automation and user specific situations. Notice that most matching agencies have issues in pricing for multiple passengers. In addition, rule-based pricing for detour ridesharing (pattern 4) has not been implemented. These issues will be discussed in Section 4.

3.2.4 Assistance of Actual Pick-up and Drop-off

Whereas business functions of service providers described above are relevant to rideshare planning, we now describe the business functions of the actual ridesharing trip. Regarding this, there are two types of service providers: real-time tracking of actual execution of ridesharing, or no involvement of actual ridesharing. They assist rendezvous by providing information of current vehicle locations. While service providers of the former type charge transaction fees for ridesharing thus requiring tracking of the actual ridesharing, the rest of the service providers leave all the decisions to the ridesharing participants. A typical way of tracking is asking participants to notify their status according to sending text messages with secret codes that are used for authentication.

3.2.5 Payment

The following two payment methods are used by ridesharing matching agencies in practice:

- **Direct payment:** a passenger makes direct payment to a driver.
- **Payment via third party:** payment from a passenger to a driver is made via a third party such as Paypal (an online clearing service provider).

While payment via third party avoids the problem with direct payment such as no-show, lack of cash in hand, and lack of change, it is necessary to pay commission fees to online clearing service providers. Ridesharing service providers charge a transaction fee using payment via a third party. In addition, participants are required to register their payment accounts on an online clearing service providers prior to ridesharing.

3.3 Business Process

Each matching agency has a different focus on their businesses and we present the following four types of processes that we have observed:

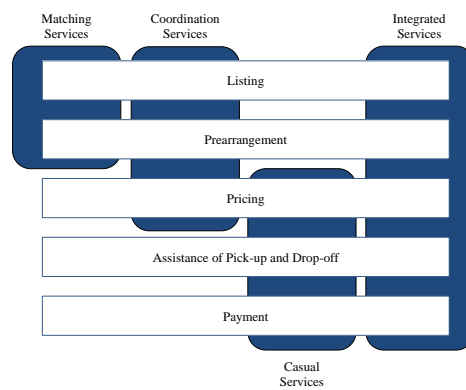


Fig. 3 Business Process of Service Providers

- **Matching services:** only involves listing and prearrangement functions. Instead of including the pricing function, matching agencies leave pricing for the participants to negotiate. Legacy bulletin-board and some carpooling are in this category.
- **Coordination services:** involves listing, prearrangement, and pricing function to promote the coordinated behavior among participants.
- **Casual services:** does not deal with prearrangement. Instead, they pre-determine routes, meeting places and time, and prices of ridesharing. Matching is based on a first-come first-service basis. Flexible carpooling is in this category.
- **Integrated services:** involves all the five business functions in order to deal with instantaneous ridesharing. Dynamic real-time ridesharing is in this category.

We summarize these business processes in Figure 3.

Business processes are relevant to the transaction fee charging scheme of the matching agencies. Matching agencies that include the payment function as their services only charge from the participants. Otherwise, they run their businesses based on the revenue of advertisement and government subsidy.

3.4 Classification of Ridesharing Service Providers

We now present a result of our investigation regarding business processes and functions of matching agencies in practice. We observe that matching agencies in the same class have similarities in these aspect and we present a list of 33 major matching agencies in Table 1 that indicates several key characteristics of their ridesharing processes and functions introduced in this section.

First, dynamic real-time ridesharing matching agencies provide integrated services that are capable of automated rideshare matching including routing, scheduling, and pricing based on the input of the participants' itineraries in

the street level and departure times. The use of a GPS function is a standard method to input the current location in offers and requests. Moreover, the system assists in the meeting using real-time location information. Regarding the payment, they use online payment systems with charging transaction fees. Most matching agencies in the rest of classes do not charge any transaction fees for their services.

Second, typical carpooling matching agencies focus on ride-matching based on similarities of locations and work schedule between car drivers and passengers, whereas the departure time of home is not considered in matching. Most negotiation items are delegated to individuals to negotiate by themselves. Car-pool Zone is an exception that is capable of ride-matching based on routing with a pricing function.

Third, matching agencies in the class of long-distance focus on ride-matching based on similarities of locations and the departure times between car drivers and passengers. Typical matching criteria are according to city or region names and the departure dates. Some of matching agencies allow participants to list their preferred prices.

Fourth, matching agencies in the class of carpooling and one-shot ride-match serve as ridesharing department stores that cover demands of multiple target segments. They offer a few choices for a ride-matching method according to trip types. Each matching method is similar to ones used in carpooling and long-distance ridesharing. Even though one-shot ride-match is covered, they focus on a matching function.

Fifth, matching agencies in the class of bulletin board have a simple passive matching system based on the information of locations. Most ridesharing conditions are determined by negotiation among participants.

Finally, flexible carpooling does not deal with a prearrangement of ridesharing. Raspberry Express is a unique private company that serves flexible carpooling.

Dynamic real-time ridesharing matching agencies, Avego, Zebigo, and flinc have distinctive characteristics that are the ability to provide detailed ride-matching including pricing, routing and scheduling in an automated way. However, only simple ridesharing can be arranged according to the current pricing rule. A matching agency specifies the standard mileage cost (cost-per-distance) and a passenger pays the amount of the cost for the distance between the pick-up and drop-off locations. Two major limitations are: (1) matching is limited for a pair of a single car provider and passenger; (2) detour ridesharing is not matched. A recent survey result on dynamic ridesharing finds that participants are not inclined to commit for rides in advance but they do not trust that rides can be arranged in the last-minute [23]. These findings show that users expect for only limited usages for dynamic ridesharing, which needs to be improved. To deal with this issue, matching agencies need to implement mechanisms that satisfy the following conflicting matters on ride-matching: advantages for early posting, flexibility to schedule changes, and adaptability to traffic environmental changes.

Matching agencies targeting for commuters implement a function that is able to filter geographical differences between their origins and destinations. This function is aligned with a tendency of users found in a survey for Carpool Zone users: partners are found mostly within a 1km radius of their residential locations [12]. In reality, filter by estimated time to pick-up increases the usability of the ride-matching process, since congestion in certain directions is critical in peak-time. In order to compute such a time, carpooling matching agencies need to have functions of routing and scheduling for ridesharing arrangement.

Another important opportunity is a periodic reallocation for carpoolers. In current matching agencies, potential carpoolers post their offers and requests, whereas formed carpoolers disappear from the system even though their partners may not be the best partner as a whole. Therefore, a periodic reallocation enables carpoolers to swap their partners in an efficient way. This swap function brings flexibility in carpool formation and mitigates barriers for carpoolers.

In many matching agencies in the class of carpooling, long-distance, and bulletin board, the determination of meeting spot, time, and sometimes pricing are not detailed during the matching. Thus, current service levels are said to be highly dependent on a case-by-case basis.

Table 1 Business Functions of Matching Agencies

Name	Business Process	Activity Level		Listing		Matched by		Pricing	Assistance of Meeting	Payment
		Address	Level	Location	Time	Location	Time			
Dynamic Real-Time Ridesharing										
Avego	Integrated	Address	Active	Address	Dep. Time (Rep.)	Route	Pick-up	Rule	Yes	Third
Zebigo	Integrated	Address	Active	Address	Dep. Time (Rep.)	Route, OD (address)	Pick-up	Rule	Yes	Third
fhnc	Coordination	Address	Active	Address	Dep. Time (Rep.)	Route, OD (address)	Pick-up	Rule, List	No	Direct
Carpooling										
511 SF Bay Area	Matching	Address	Active	Address	Work Sched.	OD/Work (address)		Negotiation	No	Direct
Carpool Crew	Matching	Address	Passive	Address	Work Sched.	OD (region)		Negotiation	No	Direct
Carpool World	Matching	Address	Active	Address	Work Sched.	OD (address)		Negotiation	No	Direct
Carpool Zone	Information	Address	Active	Address	Work Sched.	Route, OD (address)		Negotiation (Rule)	No	Direct
RideSearch	Matching	Address	Active	Address	Work Sched.	OD (address)		Negotiation	No	Direct
Long-Distance Ride-Match										
amovens	Coordination	Region	Active	Region	Dep. Time	OD (region)	Date	List	No	Direct
Covoiturage	Coordination	Region	Passive	Region	Dep. Time	OD (address)	Date	List	No	Direct
GishiGo	Coordination	Region	Active	Region	Dep. Date	OD (region)	Date	List	No	Direct
Mitfahrgelegenheit	Coordination	Region	Active	Region	Dep. Time	OD (region)	Date	List	No	Direct
Nottreco	Matching	Region	Passive	Region	Dep. Time	OD (region), List	Date	Negotiation	No	Direct
PickupPal	Matching	Address	Active	Address	Dep. Date	OD (address)	Date	Negotiation	No	Direct
Pinchela	Matching	Region	Passive	Region	Dep. Time	Region, List	Date	Negotiation	No	Direct
RideshareList	Matching	Region	Passive	Region	Dep. Time	Region, List	Date	Negotiation	No	Direct
ZimRide	Matching	Address	Active	Address	Dep. Date	Route, OD (address)	Date	List	No	Direct
Carpooling and one-Shot ride-match										
Participate	Matching	Address	Active	Address	Dep. Time	OD (address)		Negotiation	No	Direct
Carriva	Matching	Region	Active	Region	Dep. Time	Route, OD (address)		Negotiation	No	Direct
GoLoco	Comprehensive	Address	Active	Address	Work Sched.	OD (address)		List	No	Third
iCarpool	Matching	Address	Active	Address	Dep. Time			Negotiation	No	Direct
JayRide	Coordination	Address	Passive	Address	Dep. Time (Rep.)	Route, OD (address)		Negotiation	No	Direct
NuRide	Matching	Address	Passive	Address	Dep. Time (Rep.)	OD (region), List		List	No	Direct
ride 4 cents	Matching	Region	Active	Region	Dep. Date	OD (address)	Date	Negotiation	No	Direct
Bulletin Board										
AlternetRide	Matching	Address	Passive	Address	Dep. Time (Rep.)	List		Negotiation	No	Direct
Commuter Connections	Matching	Any	Passive	Any	Any	List		Negotiation	No	Direct
Craigslist	Matching	Any	Passive	Any	Any	List		Negotiation	No	Direct
eRideshare	Matching	Region	Passive	Region	Any	List		Negotiation	No	Direct
in anyone going to	Matching	Region	Passive	Region	Any	List		Negotiation	No	Direct
RideBuzz	Matching	Region	Passive	Region	Dep. Time (Rep.)	OD (region), List	Date	Negotiation	No	Direct
Flexible Carpooling										
Casual Carpooling	Casual	NA	NA	NA	NA	NA	NA	Fixed	No	Direct
Raspberry Express	Casual	NA	NA	NA	NA	NA	NA	Fixed	No	Third
Slugging	Casual	NA	NA	NA	NA	NA	NA	Free	No	Direct

3.5 Comparison with Other Transportation Systems

We now present some primary characteristics of ridesharing services by comparison with popular shared vehicle transportation services in the US, which is an extension of the classification by Amey [6]. As mentioned, a unique characteristic of ridesharing is that individual car drivers provide their unoccupied seats for other passengers including unknown travelers motivated by cost-sharing unlike other shared vehicle transportation services that are motivated by gaining profits. This is from a car provider's perspective. Another criterion that characterizes matching agencies is the prospecting services that passengers can be offered from service providers. This is from a passenger's view. Some service providers can offer a tailored trip for a passenger, while others require passengers to align to predetermined routes and schedules. Typical ridesharing falls in between these two extremes, since they require the coordination between a car driver and passengers. This criterion is different from the study of Amey [6] which focuses on who has initiative to determine routes, while we focus on how ridesharing can contribute to the most preferred trip plan for each passenger. According to these two criteria (the degree of tailored trip in the horizontal axis and motive of services in the vertical axis), we illustrate the six classes of matching agencies and five popular shared vehicle transportation services (taxi, vanpooling, airport shuttle services, dial-a-ride, and fixed-route transit services) in Figure 4.

Passengers in these five types of transportation services increase the benefit of sharing costs with other passengers, whereas decrease flexibility of their trips. First, a taxi provides a tailored trip for a passenger at the highest cost. Second, dial-a-ride is an advanced reservation transportation service tailored to the elderly and persons with disabilities that allows passengers to request any pick-up and drop-off locations as long as they are in the service coverage area. Third, in airport shuttle services, each passenger can specify a single location for either the pick-up or drop-off, but the opposite end of the trip (i.e., an airport) is fixed. Fourth, vanpool can provide a trip from the specified pick-up and drop-off locations by a passenger, whereas the travel time includes the time to pick-up and drop-off other passengers. Finally, operations of fixed-route transportation services are fixed regarding route and schedule. Passengers are forced to align to the offered services. By contrast, prospecting ridesharing services for passengers offered by matching agencies fill extensively with respect to the service level, in particular most matching agencies in the classes of dynamic real-time ridesharing, long-distance ride-match, carpooling and one-shot ride-match, and bulletin board. It is highly depended on an individual situation. For instance, in current dynamic real-time ridesharing, a passenger sometimes needs to specify the pick-up and drop-off locations on the route of a car provider. In the future, they intend to provide tailored services like a taxi which requires a detour for a car driver. As for carpooling, the service level can be contrasted with service operators (vanpooling and airport shuttle services). In carpooling, a work place corresponds to an airport in the shuttle service. Finally, passengers are required to go to the meeting spot in

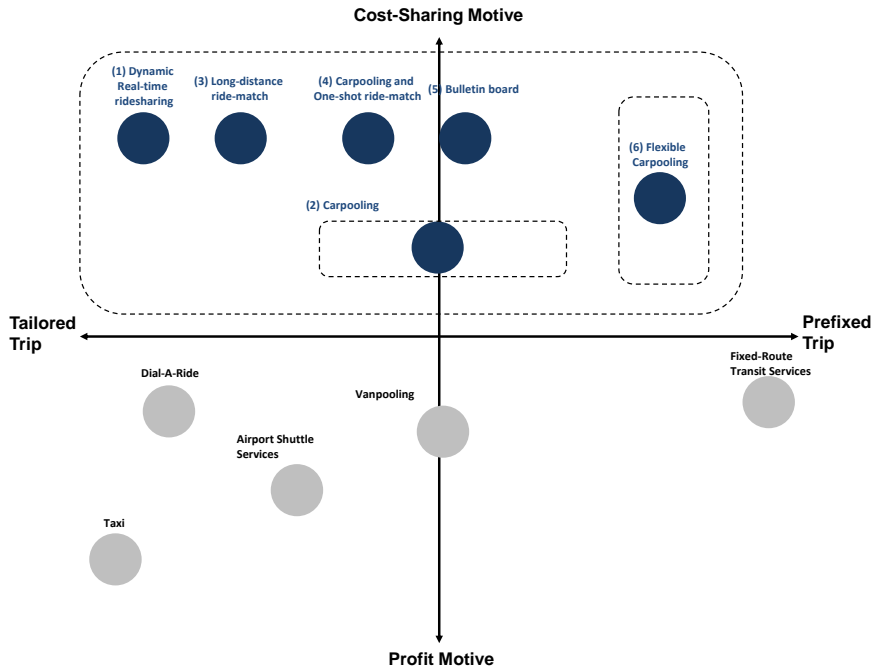


Fig. 4 Comparison between Matching Agencies and Other Shared Vehicle Transportation Services

flexible carpooling. The typical drop-off location is not the final destination of each passenger. As mentioned above, slugging is free of charge and casual carpooling shares the incurred cost among ridesharing participants.

These differences are not known in general. Ridesharing participants have to know these characteristics in order to choose the most appropriate matching agencies in order to form ideal ridesharing for each participant. Moreover, it is important to establish ridesharing services that can offer consistent services. To achieve this point, matching agencies are necessary to attract enough participants consistently and persistently that exceeds the critical mass. In the following section, we investigate some challenges to establishing attractive matching agencies.

4 Desirable Services of Matching Agencies

In the previous section, we described how matching agencies offer diversified ridesharing services. However, at this time, none of these services is considered as an ordinary means of transportation. In other words, there are some barriers for people to use current ridesharing services offered by matching agencies. In this section, we investigate attractive markets and identify ridesharing specific problems.

4.1 Instantaneous Ride-Matching

The development of algorithms for optimally matching drivers and passengers in real-time is at the heart of the ride-sharing concept [1]. All matching agencies in the class of dynamic real-time ridesharing presented in this paper had launched services in 2010 or 2011, and their services are still limited to simple ridesharing services like identical, inclusive, and partial ridesharing for a single passenger as mentioned in Section 3.1. In this section, we highlight issues in complex dynamic real-time ridesharing in order to clarify opportunities and challenges.

In academia, there are a limited number of papers that deal with issues of complex ride-matching and pricing. In transportation planning, optimization techniques to minimize the overall travel distance are typically considered, while the pricing aspect has not been considered well. Agatz [1] describe a method for the optimal ridesharing arrangement considering detour based on linear programming. While this method is able to find a feasible ridesharing considering constraints for upper-limits of travel time, various costs for different car providers are not taken into account. Instead, they assume that the center is able to obtain truthful cost information of car providers and simply applies proportional cost-sharing for pricing. There are some similar researches that deal with the constraints of to-work and return-from-work [8] and multiple network travel times at different times [16]. More recently, the problem of ride-matching with a price discovery is studied in the AI community, typically using a market-based approach where the ride arrangement and price are determined by the interaction of supply and demand. Kamar and Horwitz [36] proposed a methodology to generate ridesharing plans using a Vickrey payment scheme [54] that induces truthful prices. A key idea of payment to the system is to compute the contribution of a participant to the system which is the difference between the surplus from the value-maximizing ridesharing plans without the value of the participant and the value of the value-maximizing ridesharing plans when the participant is excluded from the system. In their mechanism, detour is not considered. Kleiner et al. [38] proposed an auction mechanism using a Vickrey payment scheme that takes into account the effect of detour for pricing. However, the proposed mechanism only works for a single passenger case.

A market clearing cycle is an important factor to design market mechanisms. In a periodic clearing market, participants have to wait to be notified the auction results until the clearing time. This waiting time can be a crucial disadvantage for time sensitive participants like travelers seeking dynamic real-time ridesharing. In a continuous clearing market, participants are notified of the ridesharing arrangement in real-time. However, an efficient price discovery requires a large number of competing participants. A small market results in volatile prices and thus participants have to play a game of the market arrival time known as *online mechanism design* problems [48, 34, 50, 27]. Typical solution mechanisms postpone the determination of the final price as much as possible by providing some options for participants. However, the assump-

tion of those mechanisms is limited for independent valuation of players. In other words, existing online mechanisms may not work for ridesharing, since dynamic arrival of passengers gives an impact on the cost for existing passengers, which can be decreased in identical, inclusive, and partial ridesharing, or can be increased in detour ridesharing.

We point out that the combination of the following three aspects characterize complex dynamic real-time ridesharing:

- **Collection:** The final form of ridesharing is derived from a collection of offers and requests, and it is only realized at the end. Car providers and passengers do not simply exchange empty seats.
- **Complex cost:** A different combination of offers and requests incurs different costs. The additional cost that is incurred due to taking an additional passenger in ridesharing has different impacts on existing participants either in a positive or negative way.
- **Dynamic decision-making:** Each participant realizes their demands and submits their offer or request sequentially and possibly updates them.

Unlike trading items in typical exchange markets, ridesharing is not directly exchanged between car providers and passengers in dynamic real-time matching agencies. Instead, car providers and passengers notify their preferred trips and ridesharing is formed by the consequence of negotiations between these two-sides. While matching between car providers and passengers involves combinatorics similarly to combinatorial auction [21], matching agencies consider routing, scheduling, and pricing during ride-matching in order to reduce difficulties for participants to specify the willingness-to-pay for all combinations.

A notable aspect of ridesharing is involvement of both competition and cooperation among participants. Each participant behaves as a self-interested player, whereas it is important to split ridesharing costs cooperatively to motivate players to participate into ridesharing, which is relevant to a cost-sharing study [46, 56, 11]. In addition, ridesharing involves both *subadditive* and *super-additive* cost functions. In a single passenger case, it is simple to distinguish these two costs. The former is observed in detour ridesharing, while the latter is observed in identical, inclusive, and partial ridesharing.

Car drivers and passengers submit their offers and requests sequentially. In general, the time to notification of ridesharing has an important meaning to choose ridesharing as an alternative transportation means for people. A key issue here is to notify the cost for each passenger instantaneously even though the final form of ridesharing is not determined, i.e., the total ridesharing cost is not determined. Another issue is to give proper incentives for participants to declare their demands as soon as possible. This issue is relevant to online mechanism design. In a context of ridesharing, a truthful online mechanism satisfies that participants declare their offers and requests as early as possible and they allow the notifications of ridesharing as late as possible.

To the best of our knowledge, there are no attractive mechanisms that deal with these three aspects simultaneously (instantaneous price quote, incentives

for participants, truthfulness). To illustrate these issues as a complex dynamic real-time ridesharing problem, we provide an example scenario.

Example 1 Consider four connected locations L_1, L_2, L_3 , and L_4 , two car drivers D_1 and D_2 , and three passengers P_1, P_2 , and P_3 having demands for trips as illustrated in Figure 5. They have their own OD-pairs, the realization times of demands, and the preferred departure times, and the travel cost of drivers, and the stand-alone costs of passengers. Let us assume the unit cost for car drivers and passengers is \$1 per distance, and the speed of each vehicle is 1 unit of distance per minute. Suppose participants submit their offers and requests truthfully as shown in Table 2. How should we arrange ridesharing dealing with routing, scheduling, and pricing?

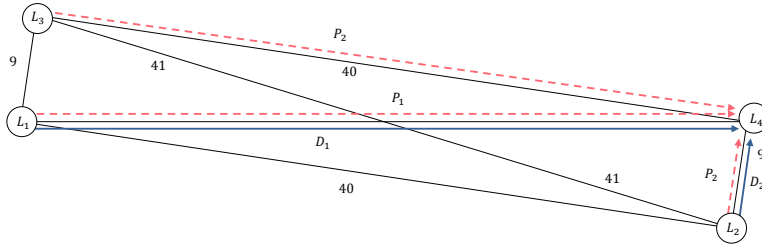


Fig. 5 An Example of Ridesharing

Table 2 An Example of Truthful Offers and Requests

Participants	OD-Pairs	Distances	Submission Time	Preferred Departure Time
D_1	$L_1 \rightarrow L_4$	41	7 : 12	7 : 15 – 7 : 30
D_2	$L_2 \rightarrow L_4$	9	7 : 50	8 : 00 – 8 : 30
P_1	$L_1 \rightarrow L_4$	41	7 : 13	7 : 15 – 7 : 30
P_2	$L_2 \rightarrow L_4$	9	7 : 20	7 : 30 – 8 : 30
P_3	$L_3 \rightarrow L_4$	40	7 : 28	7 : 30 – 7 : 45

There are several ways to allocate passengers to car drivers and to evaluate mechanisms. In an ex-post analysis in an offline setting, a formation of two ridesharing groups such as $\langle D_1, P_1, P_3 \rangle$ and driver $\langle D_2, P_2 \rangle$ optimizes the total required trip distances for the participants at the minimum cost. However, in a dynamic environment with partial information, there are several obstacles to achieve such a consequence. Thus, mechanisms are frequently evaluated by *competitive ratio* which is a comparison between the solution quality in an online setting and the optimal solution in an offline setting. In the following, we present some desired properties of mechanisms in a fragmented manner in order to focus on some important perspectives to design mechanisms for complex real-time ridesharing.

Truthfulness is frequently considered as an evaluation criterion in the literature, because participants do not need to game their behaviors and the stable outcome can be generated. In this example, the submission time of an offer or a request, a declared cost or willingness-to-pay, and the earliest and latest departure time are the components to be truthful. Suppose car driver D_1 submits their offer truthfully at 7:12 with a specification of the latest departure at 7:30. The cost for driver D_1 is \$41.

If passenger P_1 submits their request at 7:13 whose trip is equivalent to driver D_1 , two properties should be satisfied are an *instant notification* of availability and the cost, and a *fair division* [56] of the total cost, i.e., \$20.5(= \$51/2). While this notion of *fairness* is that a cost is proportional to a trip distance, it cannot be simply applied to detour ridesharing. For instance, if passenger P_2 submits a request at 7:20, driver D_1 does not allow passenger P_2 into their ridesharing under proportional cost-sharing. This is because to add passenger P_2 incurs an additional cost \$8(= \$49 - \$41), whereas this additional cost is proportionally shared with the existing participants and the cost of passenger P_1 would be increased from the notified price of \$20.5. Therefore, for detour ridesharing, an incremented cost of a participation should be assigned to passenger P_2 similarly to incremental cost-sharing method [46]. In other words, the fairness property should be hold as long as participants that have submitted their offers and requests earlier have some advantages. Since this additional cost exceeds the stand-alone cost of passenger P_2 (\$9), passenger P_2 can not take this offer, which satisfies *individual rationality*, i.e., a participant would not incur any loss by a participation. Let us consider a case where passenger P_3 submits a request at 7:28.

To add passenger P_3 into ridesharing requires detour with the following path $L_1 \rightarrow L_3 \rightarrow L_2 \rightarrow L_4$, which satisfies all the conditions of requirements of existing trips, and incurs an additional cost \$10(= \$59 - \$49). Even though this is detour ridesharing, proportional cost sharing is beneficial for all existing participants, i.e., \$18.46, \$18.46, \$4.05, \$18.03 for D_1, P_1, P_2, P_3 , respectively. Thus, detour ridesharing with multiple passengers involves a complex notion of fairness.

At 7:30, driver D_1 departs location L_1 with passenger P_1 toward location L_2 in order to pick up passenger P_3 . At 7:39, driver D_1 picks up passenger P_3 at location L_3 and drives to location L_2 in order to pick up passenger P_2 .

At 7:50, suppose driver D_2 submits a truthful offer specifying their cost is \$10 which satisfies the requirement of passenger P_2 . A key issue here is whether a system deals with reallocation, even though driver D_1 is currently moving toward location L_2 in order to pick up passenger P_2 . If passenger P_2 is reassigned to driver D_2 instead of currently assigned to driver D_1 , driver D_1 is able to change their route at the middle point between location L_2 and L_3 toward the final destination L_4 in order to reduce their travel distance, which results in reducing the overall travel distance (driver D_1 and D_2) from 68(= 59 + 9) to 59(= 50 + 9). This reassignment is beneficial for all participants as long as their payments are not increased from their notified prices. In a Vickrey scheme, the costs for driver D_1 and D_2 are \$50 and \$9, respectively. If the trip

cost of driver D_1 is \$50, and the costs for each participant under proportional cost sharing can be decreased \$16.8, \$16.8, \$16.4 for D_1, P_1, P_3 , respectively. Even though a fair division between driver D_2 and passenger P_2 is \$4.5 each, passenger P_2 should not pay more than \$4.05 in order not to increase their prior notified price. Thus, driver D_2 takes passenger P_2 to location L_a at \$4.05.

In the above example, we pointed out several unique characteristics in the complex real-time ridesharing problem focused on the cost sharing aspect and supposed truthful behaviors of the participants. An interesting question is to design specific mechanisms that satisfy the above desirable properties. Morris [45] also provides several scenarios to deal with issues of multiple passengers, detour ridesharing, changing schedules, pricing and routing. In the following section, we describe additional characteristics of dynamic real-time ridesharing.

4.2 High-Dimensional Matching

The screening of ridesharing partners grows in importance if there are many potential partners. For instance, in carpool formation, gender may play a role [18]. Even though participants frequently require various conditions for ridesharing partners, a screening function is limited in practice. While most matching agencies (in dynamic real-time ridesharing, carpooling, and long-distance ride-matching) have functions to store profiles of participants including photos, gender, short descriptions, car make, model, and year, screening according to profiles is conducted manually by participants. In addition, ratings from other participants are stored in the reputation systems (which will be discussed in the following section). In this section, we focus on the issues regarding ride-matching. A key challenge to include preferences regarding profiles of potential partners in a systematic ride-matching is efficient methods to specify complex preferences and search results. Elicitation of precise priorities among screening items can be complex even for experienced users. While some screening items treated as hard constraints are easy to set, tuning parameters for soft constraints requires some skill. From a systems point of view, higher-dimension makes it harder to compute a feasible and optimal ride-matching in real-time.

Another challenge for a high-dimension ride-matching is a complex recommendation system. Gruebele [30] lists and specifies some desired functions to be implemented in the future: multiple routes option for ride-matching, recommendation of route settings that have higher chances to be accepted, and multiple rides to accomplish a single request from the origin to the destination (conditional commitments for ride-matching). Potential transfer points should be transportation hubs having large parking spaces such as public transport terminals, park-and-ride spots, and large shopping centers.

A great number of choices for participants increases the importance of assistance by software agents that enable personalized travel planning and

execution. For instance, a car driver wonders which route at which time she or he should drive in order to maximize the opportunity of ride-matching. For the development of smart agents for ridesharing, simulation systems and analysis play a central role, but there are a limited number of researches. For instance, Agatz et al. [2] developed a simulation system to test some matching rules for dynamic real-time ridesharing using work trips data in the Atlanta metropolitan region. In an offline environment, Amey [7] carried out simulation analysis on efficient ride-matching algorithms using MIT's survey data. Herbawi and Weber [32] investigated in more complex settings dealing with multi-objective route planning including multi-hop ridesharing. While these studies deal with the optimization problems including matching and routing, their studies lack the analysis on pricing mechanisms and strategic decisions for users.

4.3 Trust and Reputation

Since most matching agencies leave the physical part of ridesharing services to individual car providers, a main concern of matching agencies is to provide consistent ridesharing services with a variety of individuals and even more to convince individuals to participate in ridesharing services. While a guideline and etiquette that ridesharing participants should follow plays a prominent role to share the standard of ridesharing activities, it is not just sufficient for participants to build trust with a stranger as a ridesharing partner. This is not a specific issue just for matching agencies, but it is common in informational intermediation service providers that delegate individuals to provide actual services.

While a direct experience is the most reliable foundation of trust, some intermediation service providers mitigate the limitation of users' direct experiences according to an implementation of a large-scale word-of-mouth network, which is known as reputation systems [24, 33]. For instance, e-Bay's feedback mechanism supports buyers to build trust to unknown sellers and elicits honest behavior [49]. Typical reputation systems use a feedback report that is filled by users who have experienced services or providers who have offered services; the collected feedback is shared among the community members in order to evaluate other individuals whether they are trustworthy to exchange services in the future. This well-established e-Bay like reputation system is implemented in some ridesharing matching agencies: Avego, Zebigo, Carpool World, Golco, etc.

In academia, e-Bay like reputation systems are well-studied and the most critical issue is how to ensure that it is in the best interest of a rational agent to actually report reputation information truthfully [35]:

- Reporting positive feedback can lead to increased competition with others in the future [35, 24],
- Fake negative feedback can cause scarce resources to exit the competition [35, 24],

- There is a bias towards a positive report in order to protect against a retaliation of a negative report by a counter partner [49],
- It is easy to create a new ID to wipe out past records [24,33,58],
- All service providers are not around long enough to be incentivized by future returns that are dependent on today’s feedback [24,33,58].

Recently, Witkowski et al. [58] proposed *escrow mechanisms* to deal with these issues instead of using reputation systems. The main idea is to install a trusted intermediary that forwards the payment from the buyer to the seller only if the buyer reports that she or he has received the good in the promised condition. In a ridesharing example, escrow mechanisms work as follows. At the time of ridesharing arrangement, the passenger sends her payment to the center (the trusted third party) which holds it in escrow. The center then acknowledges receipt of payment to the car provider, who then provides his or her sharing, but in some cases may fail to do so. Once the car provider has taken a passenger to the drop-off location, the passenger is asked by the center what signal she or he received. Only if the passenger reports a high signal does the center forward the passenger’s payment to the car provider. Currently, this function has been implemented by several ridesharing service providers as mentioned in Section 3.2.5. However, currently used escrow procedures in practice do not satisfy some desirable properties such as incentive compatibility (sending the truthful signal is the best behavior for participants), efficient (the winning price is the highest bidding price of the rational passenger), individual rational (no negative utility), and budget-balance (no subsidy required) simultaneously. Their proposed escrow mechanism does not simply reimburse every passenger who reports a low signal. The main idea is whether or not a passenger receives a rebate (equal to her escrow payment) depends on the report of another passenger which may not necessarily be in the same ride. Essentially, by a passenger reporting a signal, she or he enters into a lottery for receiving a rebate back from the escrow mechanism. It remains the case that the center forwards the payment to the car provider if and only if the respective passenger reports a high signal.

There are some challenges in applying escrow mechanism in ridesharing practice. The main issue is an identification of causality of failure. Indeed, difficulties increase in the multiple passengers’ case, since realized ridesharing is determined by the interactions of the ridesharing participants. For instance, a dishonest activity (such as delaying to show up at the pick-up location) of the second passenger can lead to dishonest activity by the first passenger (such as delaying to take her or him to the drop-off location), even though the car driver behaves honestly. How should passengers evaluate their experiences? At the opposite end, a delay of the first passenger can result in a delay of the pick-up for the second passenger. A question is whether the second passenger has to identify the causality of the delay due to the driver, the first passenger, or something else. Another issue is transfer of perceptions. Different people have different perceptions of received services. For instance, different people have different tastes for driving skills of others, cleanness, and conversations. More-

over, required service levels between carpoolers and long-distance riders are significantly different and a question is whether signals from these two should be mixed or not. Thus, there remain some obstacles to use this mechanism in practice.

A ridesharing survey for students in a university [19] indicates that a close relationship is a key factor of successful ride-matching: 7% would accept rides from strangers, whereas 98% and 69% would accept rides from a friend and the friend of a friend, respectively. Thus, another way to build trust is to associate acquaintances in efficient ways. Recently, social network sites (SNSs) play important roles in this point. Regarding advantages of using SNSs for ridesharing, Wessels [57] explains that participants can get information about other participants by simply checking the profile on their social network; they can evaluate the profile and decide if the other traveler seems trustworthy and friendly. In industry, some matching agencies, such as ZimRide, Avego, and Carticipate, offer services in conjunction with SNSs in order to find acquaintances in efficient ways, to increase the transparency of rideshare individual information, and to share common interests in a community. Indeed, ZimRide also provides an option to search from a limited community such as a university. While there are some potential for successful ridesharing services, we mention one important characteristic of SNSs: users can closely communicate with each other online, but they are sensitive to meet physically if they have not met before. Thus, it is interesting to identify the relationship between preferences as ridesharing partners, closeness of acquaintances, and ridesharing trip types. Better understanding of this point should help to develop successful ride-matching systems.

4.4 Institutional Design

A fundamental question is how many matching agencies should coexist in a certain region. A greater number of matching agencies leads to a fragmentation effect that can cause a failure of matching in a matching agency, even though an offer or request can be matched by a different matching agency. In contrast, a monopoly frequently sets back investment on innovative technology and increases costs. In financial markets, this controversial issue has been discussed for many years [20]. Increasing liquidity in fragmented markets can be achieved using a smart order routing system that aims at maximizing the opportunities of matching. This system would use technology that consolidates offers in different markets and routes orders accordingly, [26]. It is a challenging task to extend such a system to the ridesharing industry.

Travelers of dynamic real-time ridesharing may not complete their trips by ridesharing. Therefore a ridesharing system with information of alternate and complementary transportation methods increases usability of ridesharing for participants [23]. For instance, the optimal trip planning integrated with other transportation methods is a valuable function for participants. One of the largest obstacles to greater multi-modal integration has been a lack of

availability of travel information in a consistent format [5]. Recently, Google's Transit Feed Specification has become the unofficial industry standard for coding transit data [4]. However, current specification focuses mainly on simply data exchange. A key challenge is to define specifications for business processes in order to deal with dynamically changing data which is necessary to be considered for dynamic real-time matching agencies. Dycapo protocol [29] proposed by the Dynamic Carpooling Project considers this aspect in their specification.

The use of High-Occupancy Vehicle (HOV) lanes opened in 1969 is one of the main reasons to shift from other transportation means to ridesharing. More recently, High-Occupancy and Toll (HOT) lanes have been adopted by several metropolitan areas in order to apply effective pricing rules for congestion mitigation and off-peak usability, and to allow single occupancy vehicle drivers who are willing to pay. As pointed out by Konishi and Mun [39], there are a limited number of papers that analyze the effect of congestion pricing on ridesharing formation from a social welfare point of view such as [59, 51, 55] that analyzed the effect of a few congestion pricing mechanisms for carpoolers. An interesting extension is to analyze the effect of congestion pricing on dynamic real-time ridesharing involving routing, scheduling, and pricing. In addition, this is relevant to traffic assignment study that deals with a prediction of travelers' behaviors to choose routes over a road network [9].

5 Conclusion

In this paper, we presented both survey results of existing ridesharing systems and open questions with the establishment of relevant existing research in order to identify ridesharing specific challenges and opportunities. With advances in technological innovation such as smart phones integrated with GPS, we are seeing the early days of a new ridesharing industry such as dynamic real-time ridesharing. However, there are only a few agencies today and their service areas are strictly limited. We pointed out the difficulty of such ridesharing systems stems from the requirement of the successful coordination instantaneously with respect to itineraries, schedules, and cost-sharing among the participants that may not be known to each other and decisions must be made in a dynamic sense. Three major challenges for agencies are: design of attractive mechanisms (instantaneous price quote, incentives for participants, and truthfulness), a concierge like ride-arrangement (preferences of profiles in detail, multi-hop rides, and a consolidation with other transportation means), and building of trust in online.

There are many other challenges to overcome inhibitors of ridesharing. Privacy is one major concern for individuals. While the risk of exchanging private information for ridesharing is a one end [19], the opposite end is the risk of loss of personal privacy due to systematic data collection of detailed private information involved in real-time ridesharing [3]. Another concern is uncertainty of legal liability of ridesharing services. Leibson et al. [41] identified potential legal

risks in traditional ridesharing programs. Among existing ridesharing services, NuRide has a unique challenge which aims to stimulate regional economy according to ridesharing and its commuter rewards program [43]. The core idea is similar to complementary currency developed by Gesell in the 1930s that gives incentive for people to circulate money by demurrage systems [42].

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