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Abstract

This paper proposes an unconventional carpool-matching system concept that is different from existing systems with four innovative operational features: (F1) The proposed matching system will be used by members of an association and sponsored by the association, e.g., the employees of a company, members of a homeowner association, employees of a shopping center. This expands the scope beyond commute trips. Such associations can also voluntarily form alliances to increase the number of possible carpool partners and geographical reach. (F2) Service provided by a driver or received by a rider incurs credit or debt to a bank centrally and fairly managed by the association, rather than to each other. This removes requirement for service reciprocation by the rider(s) of a carpool to the driver of a carpool and hence frees partners of a carpool from long-term commitment; it also removes requirement for payment. (F3) Together with new security-inspired real-time information technologies, the common affiliation with an association can significantly alleviate the insecurity factor. (F4) When a rider belongs to two such associations, e.g., employee and homeowner associations, a rider's trip can be completed with a transfer by two drivers, one from each association. The service-system concept was motivated by an exclusive focus on human needs for convenience, fairness, security and user-friendliness, to maximize the potential of carpooling. We report on a software prototype already developed to demonstrate (F1) and (F2) and also suggest future enhancements. We also illustrate the complexity of the mathematical problems with a brief specification of an optimal matching problem.

Keywords: Carpool; Matching; Routing; Convenience; Security; Fairness; Online rating/review

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Table 1. Means of Transportation to Work by Workers 16 Years and Over: 2009-2013 Average (Source: U.S. Census Bureau, 2009-2013 5-Year American Community Survey).

	United States	
	Estimate	Margin of Error
Total:	139,786,639	+/-142,773
Car, truck, or van:	120,356,737	+/-161,792
Drove alone	106,725,474	+/-111,405
Carpooled:	13,631,263	+/-60,703
In 2-person carpool	10,522,671	+/-43,709
In 3-person carpool	1,818,712	+/-18,975
In 4-person carpool	669,623	+/-8,590
In 5- or 6-person carpool	350,218	+/-5,115
In 7-or-more-person carpool	270,039	+/-5,187
Public transportation (excluding taxicab):	7,000,722	+/-21,139
Bus or trolley bus	3,670,204	+/-15,845
Streetcar or trolley car (carro publico in Puerto Rico)	84,019	+/-2,063
Subway or elevated	2,441,478	+/-12,996
Railroad	763,025	+/-7,141
Ferryboat	41,996	+/-1,660
Taxicab	158,124	+/-3,682
Motorcycle	295,469	+/-4,474
Bicycle	802,450	+/-7,657
Walked	3,922,801	+/-16,357
Other means	1,203,951	+/-11,935
Worked at home	6,046,385	+/-21,247

1. Introduction

Current predominantly automobile-based personal mobility in U.S. urban sprawls will not be environmentally sustainable. Public transportation alone may not be able to solve the entire problem, and a significant increase in carpooling may be necessary. Carpools have accounted for a very small fraction of (home-to-work) commute trips, and carpools for non-commute trips mostly involve family members engaged in family activities. Between 2009 and 2013, approximately 9.7% of the commute trips were made in carpools [21]; see Table 1 for details. Most of the commute carpools, however, were actually so-called "household pools" or "fampools," in which carpooling partners are all family members (including either adults or children). Regarding this, Li et al. [13] stated, "A nationwide estimate of all work-commute carpools chronicled an increase of fampools from 75.5% to 83% for 1990 to 2001. In addition, two of these studies estimated just 2% and 8% of the type of work carpools between strangers that the HOV policies supposedly encourage. The results in this paper support these earlier findings." In this paper, we propose an unconventional carpool-matching system to maximize the potential of carpooling, in an attempt to help achieve environmental sustainability of modern human living in the US and around the world.

Fulfilling the potential of carpooling requires design and operation developed with a systems-engineering approach and supported by human-factors research, modern information technology and innovative operation. Major issues associated with conventional carpooling include inconvenience of long-term commitment to fixed schedules with friends and a focus on commute trips, which account for about 20% of all personal trips. Modern real-time web-based carpool matching circumvents these issues but must contend with the insecurity factor involved in partnering with a stranger and the necessity for payment.

The proposed system differs from existing systems with four innovative operational features: (F1) The proposed matching system will be used by members of an association and sponsored by the association, e.g., the employees of a company, members of a homeowner association, employees of a shopping center. This expands the scope beyond commute trips. Such associations can also voluntarily form alliances to increase the number of possible carpool partners and geographical reach. (F2) Service provided by a driver or received by a rider incurs credit or debt to a bank centrally and fairly managed by the association, rather than to each other. This removes requirement for service reciprocation by the rider(s) of a carpool to the driver of a carpool and hence frees partners of a carpool from long-

term commitment; it also removes requirement for payment. (F3) Together with new security-inspired real-time information technologies, the common affiliation with an association can significantly alleviate the insecurity factor. (F4) When a rider belongs to two such associations, e.g., employee and homeowner associations, a rider's trip can be completed with a transfer by two drivers, one from each association. With (F1) – (F4), we propose a new mode of carpool operations, which enables a new business model. Concepts similar to (but not the same as) some of the four innovations have been proposed before, but it is the unique combination of the four that constitutes the transformation. We report on a software prototype already developed to demonstrate (F1) and (F2) and also suggest future enhancements. New mathematical problems associated with matching multiple drivers and multiple riders for their mutual selection, including fairness, optimization and ranking problems, will be addressed separately; we illustrate the complexity of the problems with a brief specification of an optimal matching problem.

The rest of the paper is organized as follows. Section 2 reviews the literature. Section 3 describes in detail the four innovative features of the proposed system. Section 4 explains the novelty of the system, including how the proposed system achieves fairness to all carpool partners. Section 5 briefly describes a prototype system. Section 6 briefly describes an optimal matching problem. Concluding remarks are given in Section 7.

2. Literature review

Carpooling has been promoted by governmental and some private organizations as a means to reduce traffic demand, in an attempt to reduce traffic congestion and environmental impact in urban areas. It is imperative for such organizations to understanding commuters' propensity to carpool. Based on the 1977 – 1978 Nationwide Personal Transportation Survey, Teal [20] defines a carpooler to be "anyone who shares transportation to work in a private vehicle with another worker". He then analyzes commuters according to six different transportation and household characteristics and identifies salient characteristics of carpoolers. The six characteristics can be grouped in two categories: characteristics motivating a commuter to carpool (i.e., trip distance, household income, drive-alone out-of-pocket commuting cost, number of household vehicles per worker, number of workers in household) and demographical characteristics (i.e., gender and marital status). The scope of Teal's study did not include barriers for a commuter to carpool (e.g., inconvenience of arranging and scheduling a carpool, fear of carpooling with strangers, etc.). We refer to the three groups of factors as motivating factors, demographical factors and barrier factors.

Ferguson [10] reported, "According to Census journal to work data, carpooling declined from 19.7% of all US work trips in 1980 to just 13.4 in 1990." and attributed the decline to unfavorable changes in the motivating factors and demographical factors. In 2000 and 2010, the percentages fell continuously to 12.2% and 9.7%, respectively [1]. They have not improved since [21]. Ferguson did not address the barrier factors either. Both Teal [20] and Ferguson [10] focused on traditional carpooling. Buliung et al. [3], however, focus on internet-based carpool matching, particularly the Carpool Zone service provided by Smart Commute in the Greater Toronto and Hamilton are of Canada. In addition, they focused on active Carpool Zone users and attempted to identify driving factors behind their successes and failures in forming carpools. The factors they considered are similar to those considered by Teal [20] and hence are again motivating factors and demographical factors. Again, they did not consider barrier factors.

Teal [20], Ferguson [10] and Buliung et al. [3] all used only survey data in their studies. Arning et al. [2] adopted a much more human-centered approach – a "user-centered approach"; they used focus groups to develop both user requirements and user-interface design guidelines for a commuter carpooling internet website. Because of the user-centered approach, they are able to deal with the levels of details required for developing the user requirements and user-interface design guidelines. In developing user requirements, they considered not just demographical factors and motivating factors (including fuel cost savings, conversation and company, ecological reasons, and professional exchange) but also the barrier factors (including coordination with others, unwillingness to accept detours, lateness and unreliability, danger from strangers, data privacy concerns). Although Arning [2] considered the barrier factors, they, like Teal [20], Ferguson [10] and Buliung et al. [3], did not offer any suggestion to help overcome the barriers.

The research community seems to have resigned to the inconvenience and insecurity of either the traditional carpooling and internet-based carpool matching systems and seems to have treated the operating rules used in carpooling as fixed and cannot be changed, except Correia and Viegas [5]. Correia and Viegas [5] proposed a club structure for managing carpooling groups in a metropolitan area. Such a carpool club screens club members for

establishing a base trust level. More precisely, they "proposed studying a carpooling club model with two main new features: establishing a base trust level for carpoolers to find compatible matches for traditional groups and at the same time allowing to search for a ride in an alternative group when the pool member has a trip schedule different from the usual one." The system does not have the concept of association and alliance of associations, "credit-banking" or rider transfer.

In the proposed system, there exist at least two types of service: service involved in the conduct of a carpool, co-created by the partners, and service by the system to match carpool partners. The latter falls in the "do it for me" type of service, which has already been defined in [19]. The former can be regarded as a "do it with me" type of service, and this new type of service may expand the service types defined in [19]: "tell me", "self-service", "show me", "help me", "do it for me" and other more advanced service types.

3. The four innovative features of the proposed carpool-matching system

In this section, we describe the four operational features in more detail.

3.1. (F1) – Association and alliance

In traditional carpooling, carpool service is exchanged between two or few more specific partners for the long term. While secure, the long-term commitment is inconvenient. In the proposed project, any particular carpool ride can be shared with any other member of the same association without the need for long-term commitment. Such associations include employees of a company, workers employed by different stores of a shopping mall, members of a homeowner association, or renters of an apartment complex. With respect to conventional carpooling, it drastically expands the size of partner pool, commonly referred to as pool size in the carpool literature. It also expands the scope of carpooling beyond commute trips. In addition, such associations can also voluntarily form alliances to increase the number of possible carpool partners and the geographical reach. This has the potential of drastically larger trip scope and partner pool.

3.2. (F2) – Centralized credit banking

In the proposed system concept, quantity and quality of carpool service are treated separately. Service quantity is performed exclusively for the association and managed by a credit-banking system sponsored by the association, with neither reciprocal obligation nor long-term commitment between the driver and rider(s). Therefore, service quantity provided by a driver or received by a rider incurs credit or debt to a bank centrally and fairly managed by the association, rather than to each other. (F2), together with (F1), has the potential of drastically improving convenience of carpooling in terms of expansion of carpool opportunities and also in terms of bookkeeping and fairness assurance. The idea of fair credit in carpooling between the same origin-destination pair but different numbers of daily participants proposed by Fagin and Williams [9] and Naor [15] can be extended to fair credit in carpooling among different origin-destination pairs by weighting the credits they proposed with the corresponding origin-destination distances. Service quality is experienced by carpoolers through "co-creation" of the carpool service, and their experiences are recorded on and managed by the credit-banking system in the form of ratings/reviews. The quality of co-created carpool service depends on not only the performance of the driver, e.g., driving skills and habits, on-time arrival, but also that of the rider(s), e.g., on-time readiness, interaction with the driver, etc. Related performance metrics and the participant's personality traits and their preferences regarding other participants are used by the system in matching and ranking, while such quality input is not used at all or used to a very small extent by related existing services such as Uber[1] and Lyft[2] (e.g. rating threshold for matching passengers to drivers).

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[1] http://www.uber.com
[2] http://www.lyft.com

3.3. (F3) – Security through association and technology

Insecurity of taxi or similar services (e.g., Uber) has been reported recently and widely, including tragic incidents that occurred domestically or internationally. In response, some security-oriented technological solutions have been proposed. Examples include installation of on-board cameras. Together with new security-inspired real-time communication and information technologies, the common affiliation with an association or an alliance can significantly alleviate insecurity of carpooling. New security-inspired real-time communication and information technologies that may be considered include an "app" of a direct "panic-button" connection to the system, which relays in real-time the alarm and the exact location of the car to the police. Driver speeding may be a rider concern, and an "app" that uses the CAN Bus protocol to monitor vehicle speed (with respect to the speed limit) during a carpool may also be worth consideration.

3.4. (F4) – Rider transfer

A rider's trip can be completed with a transfer or relay by two drivers. The rider and the two drivers may belong to the same association. When a rider belongs to two or more such associations, e.g., employee and homeowner associations, a trip can be completed with one driver from each of the two associations. This feature is particularly useful for long trips.

4. Novelty enabling the credit-banking system

With (F1) – (F4), we design a new mode of carpool operations, which enables a new business model for a web-based carpool matching system. In (F2) - Centralized Credit Banking, a critical set of quantities is the amount of credit a driver earns from the credit-banking system after completion of a carpool and the amount of debt a rider of the carpool owes to the system. The fairness concept proposed by Fagin and Williams [9] for varying daily carpool participants between a fixed pair of origin and destination is analogous to fairness in sharing taxi fare, except that the driver not only takes the full fare as compensation, he or she must also pay a fair share of the fare, because the driver benefits from the ride equally as any of the other partners. As a result, for each completed trip with n partners (1 driver and n-1 riders), the driver generates a credit of $1-1/n = (n-1)/n$ and each of the n-1 riders generates a debt of 1/n, leading to a zero sum for credit (or debt) of course. A rigorous definition of fairness and a mathematical proof that this credit/debit scheme is fair can be found in [9]. When a partner participates in carpools of different origin-destination pairs, his or her overall credit or debt across multiple trips can be obtained by first weighting the credit or debt incurred for each trip by the distance associated with the origin-destination pair and then summing the weighted credits or debts. This simple scheme is the basis for credit-debt calculation of the credit-banking system, although it may be refined to accommodate the extra distance a driver must travel to pick up riders. In addition to travel distance, travel time is another important factor for the calculation.

Features similar to some of these four transformational innovations have been explored before. However, it is the unique combination of the four that makes them collectively transformational. For example, the concept of a regional carpool club or carpool platform has been proposed and studied before [2, 5]. Screening for club membership has been suggested as a way to improve security, and a subset of the members working or living close-by can form carpools. However, only the work and home locations of club members can be shared with other members to facilitate carpool formation. In the proposed concept of association sponsorship for a matching/management system, the home locations of all the employees of an employer (or all the employers working for different employers collocated in an office complex and belonging voluntarily to a common alliance), but not the identity and other personal information, can be shared with all employees of the employer (or employees of all the allied employers). This will enable an employee to easily discover co-workers living in proximity and even to visualize their home locations. Similarly, the work locations of all the residents of a homeowner association can be shared among all the members. This cannot be done in the club construct. In addition, club members can make claims about their employment or employer, but only a real association can verify and update membership

information truthfully and promptly. Moreover, the stake in membership in an association is much higher than that in a regional club, leading to a much stronger deterrent to misbehavior.

Any system has to deal with the issue of low usage at or just after launch and before reaching a "critical mass" – a chicken-and-egg problem. (A number of such web-based matching systems seem to have come and gone; this problem may have been a cause.) Associations can form an alliance to further increase the number of possible partners. Another advantage of the proposed association sponsorship is that potential partners have at least one end of the trip that is common already, either work destination or home origin, for example. These are among the advantages of (F1). Employer-based or community-based carpool matching systems have been in existence, but they are limited to only large employers or communities with high concentration of activities, whose economy of scale warrants investment of such matching systems [7]. With the advent of software as a service (SaaS) and cloud computing, small employers and homeowner associations can sponsor such systems much more affordably, particularly when the matching service is outsourced to a third party specializing in providing such service to many associations. In addition, such existing systems do not have the flexibility enabled by the fair credit/debit scheme proposed in (F2), etc. In fact, (F1) and (F2) enable a new "association-based SaaS business model" for commercializing a carpool matching system.

Insecurity has been recognized as a key issue for carpool matching, e.g., [6]. However, membership of an association has not been used as a purposeful way to help overcome the insecurity issue in particular and to help build trust in general, as proposed in (F3). Rider transfer has also been considered in the literature [11,4]. However, it was considered only for matching efficiency and hence convenience, without regard to security. Transfer of a rider proposed here can be made only between drivers belonging to the rider's associations, e.g., employee association and homeowner association.

One major differentiation of the proposed system, as compared to existing carpooling and transportation solutions, is the ability to generate driver/passenger recommendations leveraging sophisticated, state-of-the art machine learning and recommendation algorithms [17]. The system has a hybrid matching/recommendation algorithm, that works on two levels: a content-based one, where similarities will be based on explicit profile preferences (e.g. non-smoker, likes jazz, interested in politics) and a collaborative filtering one, where similarities among users will be inferred by the ratings they've given (received) to (by) other users in the past. Once a base algorithm has been designed and evaluated, a natural extension would be the incorporation of aspect-level sentiments in the recommendation process [8], where specific quality traits of the passengers/drivers as inferred by the written reviews/feedback will become part of their profile and similarity-based matching.

5. A prototype software system

We developed a proof-of-concept system prototype, called "CarpoolWorld", and implemented the main functionality of the system, focusing on (F2). The prototype provides the user the opportunity to post and request a ride, rate and review other users (either drivers or passengers) after a ride is completed, and get directions. The credit-banking system described in Section 4 and [9] is the core of the prototype, with the credits maintained centrally in a database that is updated every time a user completes a ride as a passenger or driver. The second important component of the prototype was the recommendation system: based on the ratings of each registered user, as well as their personal preferences provided during sign-up, the system is able to recommend to the user potential riders for the next carpool. We employed the well-known item-based collaborative filtering approach [18], using the Pearson correlation coefficient to calculate similarities between users. A screenshot of the "post/request a ride" page is shown in Figure 1. The technical specifications of this prototype are omitted as they are out of the scope of this paper, but the reader may refer to [12, 14] for more details.
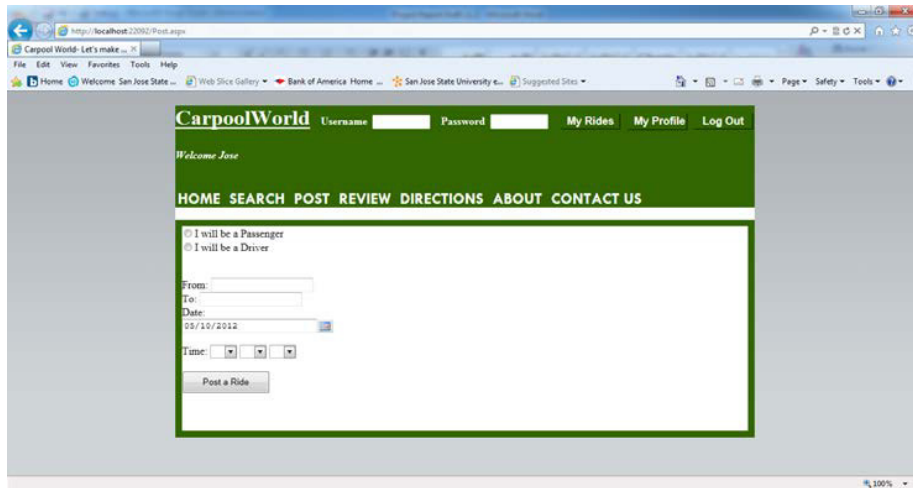
Fig. 1. CarpoolWorld prototype.

6. Mathematical algorithms required for the proposed system: an optimal matching problem

The required algorithmic work can be built on existing discoveries, particularly the recent work of Hou et al. [11] produced by an NSF-funded project [16]. Hou et al.'s work was inspired by the "Store-and-Forward" strategy used in Delay-Tolerant Networks (DTN). They proposed the concept of transfer-allowed-carpooling (TAC) and referred to the traditional carpooling as transfer-incapable-carpooling (TIC). In DTC operations, a message (or a data packet) is sent from its origin node to its destination node, and return of the message back to the origin node is not an issue. As a result, Hou et al.'s algorithm does not support a round trip. But, ours must. We briefly describe the work of Hou et al. [11] and use it to point out the requirements for the mathematical algorithm needed to optimize the proposed carpool matching. Given (i) a set of drivers, their routes, and schedules, (ii) a set of rider requests, their origins and destinations, and the latest departure times from the origins, (iii) the maximum extent of detour from a driver's route necessary for picking up and dropping off a rider, and (iv) the maximum amount of waiting time and the maximum number of transfers for a rider, Hou et al. developed and studied two types of matching strategy and studied their performances.

The proposed system must be able to make sufficient matches to ensure that if a rider is matched for a trip out of the origin, he or she must also be matched for a complete round trip back to the origin. However, Hou et al.'s work deals with a given set of independent rider requests and hence can deal with only either a to-trip or a from-trip but not both, which usually are separated by a significant amount of time. A rider transfer to be accommodated in the proposed system can be made only between drivers belonging to the same associations or alliances the rider belongs to. In other words, a rider can be transported only by those drivers belonging to the same associations or alliances. However, Hou et al.'s work assumes that any driver can transport any rider. The proposed system accommodates those requesters who are indifferent about providing a ride or receiving a ride; however, Hou et al.'s work assumes a set of drivers and another non-overlapping set of riders needing a ride. The proposed system considers several possible preference criteria in recommending matches, e.g., preference toward high quality of carpool service (of a driver or a rider), preference toward carpooling with members of the same association over carpooling with members of allied associations, preferences resulting from peer reviews or recommendations made based on other members' perception of their carpool experiences with a potential partner, preferences about personality traits, etc.

7. Conclusion

A significant increase in carpooling in the US requires a significant change in commuter behaviour. Although all factors contributing to the current low popularity of carpooling must be studied with a systems engineering approach, human factors are among the most important factors. This paper focused on several major human factors issues and proposed an operational concept, with four innovative features, and a companion matching and management software system to overcome the issues. New mathematical problems associated with matching multiple drivers and multiple riders for their mutual selection in such a system arise; they include fairness, optimization and ranking. We illustrated the complexity of the problems with a brief specification of an optimal matching problem. Ongoing efforts on further development of the operating concept, the resulting mathematical algorithms and the companion prototype software will be reported separately.

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