A High-level Category Survey of Dial-a-Ride Problems

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Abstract: Dial-a-Ride Problem (DARP) is an active research field since 1980. Many on-demand transport concepts like Dial-a-Ride (DAR) services, Demand-Responsive Transport (DRT) and ride-sharing share the common objective of solving DARP. Along with its application areas changing over the years, the problem continues to draw increasing attention with growing diversity of requirements, constraints and features. This paper examines the research on DARP with respect to the feature categories the solutions consider in order to discover DARP variants that most works focus on.

1 INTRODUCTION

Personal transport can be divided into two basic groups: Private and public. Both forms have their advantages and disadvantages. While private transport is flexible (w. r. t. time and location) and therefore convenient, public transport utilizes fixed routes, schedules and stops. Since public transport is based on predetermined network and infrastructure, it can achieve a higher throughput (i. e. bringing a larger number of people from *A* to *B* in a period of time) and therefore be more cost-efficient. On the other hand, its quality of service can be poor in rural communities and off-peak times. Much attention has been given to developing transport services that can combine the advantages of both groups. On-demand transport or DAR services pick up their customers at their desired time and bring them from any location to any location. In this sense, from a convenience perspective, they are similar to private transport. They also resemble public transportation, since passengers with similar journeys may share the vehicle, which contributes to their cost-efficiency.

The initial applications included door-to-door transportation of elderly/disabled people and transportation at night and in rural areas to complement public transport. However, with technological advancements like smartphones with Global Positioning System (GPS) and Internet capabilities, it became apparent that these applications can be broadened. This gave rise to ride-sharing (i. e. carpooling, taxi-sharing) and companies like Uber[1] and Lyft[2].

1.1 Motivation

The underlying problem that DAR services address, namely DARP, can be summarized as follows. According to (Cordeau and Laporte, 2007), DARP considers designing vehicle routes and schedules for

- m users who specify trip requests between origins and destinations,
- where there are n vehicles based at k depot(s),
- while minimizing vehicle route costs and accepting as many requests as possible
- under a set of constraints.

DARP generalizes Pick-up and Delivery Problem (PDP) and Vehicle Routing Problem with Time Windows (VRPTW) which are prominent problems dealt with in logistics and operations research.

Many real-world practices necessitate various requirements and variants of DARP. In this paper, we identify the feature categories that are derived from the requirements and give a high-level overview of the DARP landscape over the last 40 years w. r. t. feature categories the solutions consider. By doing so, we aim to unlock aspects that get more attention from the scientific community. In this paper, the following terminology is used:

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

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Feature Category. DARP studies address multiple problem dimensions that are orthogonal to each other. A feature category corresponds to a problem dimension. For example, the decision about the number of vehicles a DARP study makes constitutes a feature category.

Category Aspect. In our analysis, each feature category is three-valued. The values correspond to category aspects. The special value NULL is used to express that a study does not address the feature category. For example, the feature category about the number of vehicles contains two *aspects*, namely single- and multi-vehicle.

DARP Variant. A DARP variant is a combination of aspects from all feature categories, fully describing the study w. r. t. decisions it makes about the problem dimensions.

2 TAXONOMY

This section gives an overview of different feature categories that can be found in DARP studies:

- Static/dynamic (i. e. offline/online): In static variants all trip requests are known a priori. The decisions about vehicle-trip assignment and routes are made before operation. In dynamic solutions, the trip requests are revealed while the vehicles are in operation. Such variants process requests as they appear in real-time without knowledge about the future and constantly update the decisions.
- Deterministic/stochastic: In deterministic variants, it is assumed that all necessary information to solve the problem is known with certainty. However, practical applications have to work around unexpected events, such as some customer demands being only revealed when they are visited or potential customers not showing up. Such solutions have to deal with information uncertainty or imperfectness when decisions are made. They, therefore, fall into the category of stochastic variants.
- Single/multi vehicle: Solving multi-vehicle DARP increases the problem complexity, since trip-vehicle assignment optimality has to be considered.
- Single/multi depot: In single-depot variants, the vehicles start their routes at the same depot and, if backhauls are wanted, return to the same depot after servicing all requests. With multi-depot variants, the vehicles are initially located at multiple depots. The cost-effectiveness of the first (and last, if backhauls are wanted) route leg has to be considered. In addition to that, a vehicle might start at one depot and return to another depot, which adds another level of complexity.
- With/without time constraints: Earlier DARP solutions derive from PDP and therefore have no time constraints. Recent works employ time constraints for customer pick-up/drop-off events, even though their definitions vary. Most works explicitly use the concept of *time windows*, which enforces an event to happen between an earliest and latest time. The concepts like *maximum waiting time*, *maximum ride time* and *maximum travel delay* are also in use. Basically, they all describe the temporal boundaries to ensure customer convenience. Moreover, some works use *soft* time windows, where violation is allowed to some degree.
- Homogeneous/heterogeneous vehicles: Most multi-vehicle DARP studies consider a homogeneous fleet and the vehicle capacity as the only constraint. However, some real-world use cases (e. g. transferring patients or elderly) require vehicles with heterogeneous features and constraints (e. g. vehicle type, equipment, capacity).
- With/without backhauls: Solutions with backhauls require the vehicles returning to a depot after servicing all requests.
- With/without transfers: Classical DARP solutions transport a customer from a pick-up to a drop-off location in one vehicle. Some recent works started to investigate the possibility of vehicle transfers in order to reduce travel costs.
- With/without Electric Vehicles (EVs): The utilization of electric vehicles introduces the challenge of considering the state of charge of the battery and service pauses for battery charging when planning the routes and schedules. This variant seems to get a lot of attention in the context of Vehicle Routing Problem (VRP), but not DARP.
- With/without meeting points (location flexibility): In DARP variants with arbitrary locations, vehicles are typically routed via the exact locations that the customers specify. This might cause inefficiency due to high number of small detours or multiple unnecessary stops if locations are nearby. In such situations, it is desirable to combine a vehicle's nearby location visits (whether for pick-up or drop-off) into one (i. e. meeting points between customers). A variation of the same idea

is the meeting point between the driver and a customer, which might reduce the overall costs, even if there are no nearby location visits. The latter is an active research area in the context of *carpooling*, where a driver has a specific journey and accepts to make detours and extra stops to pick-up and drop-off riders with similar journeys in order to divide the travel expenses.

- With/without user preferences: Solutions can consider user preferences, if users can influence the decision making process (w. r. t. vehicle-trip assignments and route calculation) by providing extra constraints. Traditionally, a trip request model consists of a pick-up and drop-off location, a pick-up or drop-off time, time constraints and the number of passengers. A model extending this definition can be considered as a trip request with user preferences. Some examples are as follows: Fastest or cheapest ride, riding alone (i. e. no ride-sharing), intermediate stops, vehicle type, seating preference, baggage allowance. Since some preferences directly imply selection of vehicle features (which is already expressed by heterogeneity of vehicles category), herein we consider preferences that are not covered by heterogeneous vehicles in order to minimize the functional overlap between the two.

3 RELATED WORK

A comprehensive survey and analysis of DARP landscape (i. e. models and solutions) up to 2007 and thereafter can be found in (Cordeau and Laporte, 2007) and (Ho et al., 2018), respectively. The review in (Cordeau and Laporte, 2007) categorizes the solutions according to the single/multi vehicle and static/dynamic variants and annotates whether a solution incorporates additional constraints like time windows and vehicle capacity. The survey in (Ho et al., 2018) categorizes the solutions according to static/dynamic and deterministic/dynamic variants and annotates whether a solution considers single/multi depots, single/multi vehicles, homogeneous/heterogeneous vehicles, time windows and vehicle capacity. Unfortunately, both works fall short of giving a complete overview of the DARP taxonomy, for example as the work in (Psaraftis et al., 2016) does for VRP.

In recent years, *ride-sharing* started to emerge as a new form of transportation with the rise of services like Uber and Lyft. The authors of (Czioska et al., 2017) differentiate ride-sharing from DARP with regard to ride-sharing drivers having unique origins and destinations whereas DARP utilizes depots. Nevertheless, ride-sharing can be modeled as DARP, where every vehicle starts at one unique depot and returns to another unique depot (similar to multi-depot and backhauls). Due to this close relationship between the two domains, we include works addressing ride-sharing as part of our study.

Table 1: DRT stop visit types according to (Ambrosino et al., 2004). The higher the level, the higher the flexibility.

Level	Location	Visit time	Required visit?
1	predetermined	predetermined	yes
2	predetermined	predetermined	no
3	predetermined	flexible	no
4	arbitrary	flexible	no

Some variants of DRT services can be considered as another application of DARP. Table 1 illustrates the four types of DRT stop visits identified by (Ambrosino et al., 2004). Based on this observation, we can determine five groups of DRT services:

- Fixed routes and schedules consisting of only Level-1 stop visits (e. g. a conventional bus service)
- Free routes and schedules consisting of only Level-3 stop visits (e. g. DARP with pretermined locations)
- Free routes and schedules consisting of only Level-4 stop visits (e. g. taxi service, DARP with arbitrary locations)
- Fixed routes and schedules with divergence/deviation: In this group, the routes are only partially defined (Level-1) and can contain stop visits of remaining levels. It is allowed to deviate from the route based on customer demand.
- Other mixed forms

4 CATEGORIZATION

Section 2 gave an overview of descriptions of different DARP feature categories *in isolation*. However, solutions almost never consider only one category but a combination thereof. In order to recognize some major trends, this section provides statistics about studies addressing different combinations.

4.1 Research Methodology

We used Google Scholar[3] as the database to search for the keywords *dial-a-ride* and *ride-sharing*. We

[3] https://scholar.google.com

Table 2: Analysis about the percentage of papers that address different feature categories (without combinations).

Category	Percentage of papers
Multi-vehicle	86%
Deterministic	86%
With time constraints	82%
Homogeneous vehicles	68%
Single-depot	64%
Static	64%
With backhauls	63%
With transfers	8%
With electric vehicles	5%
With user preferences	4%
With meeting points	3%

considered only the results of which the full text was accessible from our organization network. Many variants mentioned in Section 2 are studied in related problem domains as well, e. g. (Shang and Cuff, 1996) addresses Pick-up and Delivery Problem with Transfers (PDP-T). Even though problem models and solution approaches are similar and adaptable to our examined domain, we intentionally leave such research out of our scope. In total, we analyzed 154 publications between 1980 and 2019 with regards to DARP categories they consider. Due to the high number of publications, we have made the paper references only publicly available[4], along with our analysis of each paper for all categories.

4.2 Results and Discussion

Figure 1 depicts the distribution of number of DARP papers over the years. We can see that it started to get more attention from the scientific community since 2000. Table 2 summarizes the percentage of papers which consider different feature categories. We can recognize 3 groups of percentages: Category aspects above 80% that most papers consider, aspects in 60-70% band where the complementary aspect receives non-negligible attention and aspects with less than 10% percentage. DARP with transfers, electric vehicles, user preferences and meeting points only gained momentum in the recent years. Due to the low number of papers in these categories we omit them from further inspection.

Figures 2a to 2g visualize the distribution of number of papers for each category over the years. As we can see from Figures 2a to 2d, one category aspect received continuous attention from the community over the years and dominates its complementary aspect. On the other hand, Figures 2e to 2g illustrate that the aspects dynamic, multi-depot and backhauls started to receive increasing attention (arguably due to the rise of ride-sharing).

Moreover, we wanted to analyze which combinations of category aspects are addressed the most in DARP landscape and what their percentages are. In order to achieve this, we calculated the power set of 7 remaining categories to find out the subsets with 2 to 7 categories. Table 3 summarizes the combinations with the highest percentage in their respective subsets with up to 6 categories. One interesting observation is that the most popular n-combination builds upon the most popular $n-1$-combination.

Finally, Table 4 depicts most popular 4 combinations in the subset with 7 categories. They all have in common that they build upon the multi-vehicle, deterministic, static DARP with time constraints and backhauls. We conclude our analysis with the following results: The most popular DARP variant with 19% percentage of papers considers single-depots and homogeneous vehicles aspects, additionally. Moreover, the dynamic DARP variant with the highest percentage has only 5% share and addresses multi-vehicle, deterministic, multi-depot DARP with time constraints and homogeneous vehicles without backhauls.

5 CONCLUSION

In this work, we analyzed the research on DARP since 1980 w. r. t. various feature categories the studies consider. We provided a taxonomy of the variants and labelled DARP publications accordingly. In doing so, we were able to discover some new trends and that some feature category aspects remained focal points over the years. Finally, we can derive that *multi-vehicle, single-depot, deterministic, static DARP with time constraints, backhauls and homogeneous vehicles* is the most studied DARP variant.

5.1 Outlook

We envision that DARPs with electric vehicles, user preferences and meeting points will receive increasing attention in the forthcoming years. For example, one real-world application of meeting points is already introduced by Uber as *Express POOL (Stock, 2018)*. The service reduces detours by having the customer walk to/from a location nearby the start/endpoint of the initial request. The so-called *Express spots* change based on popular routes at the time of request.

[4]https://github.com/goekay/DARP-variants/tree/54422a1

Table 3: Most popular combinations with 2 to 6 categories. Each row represents the combination with the highest percentage of papers in its respective subset.

Category combinations	Percentage of papers
Multi-vehicle & deterministic	75%
Multi-vehicle & deterministic & time constraints	67%
Multi-vehicle & deterministic & time constraints & backhauls	51%
Multi-vehicle & deterministic & time constraints & backhauls & static	43%
Multi-vehicle & deterministic & time constraints & backhauls & static & homogeneous vehicles	27%

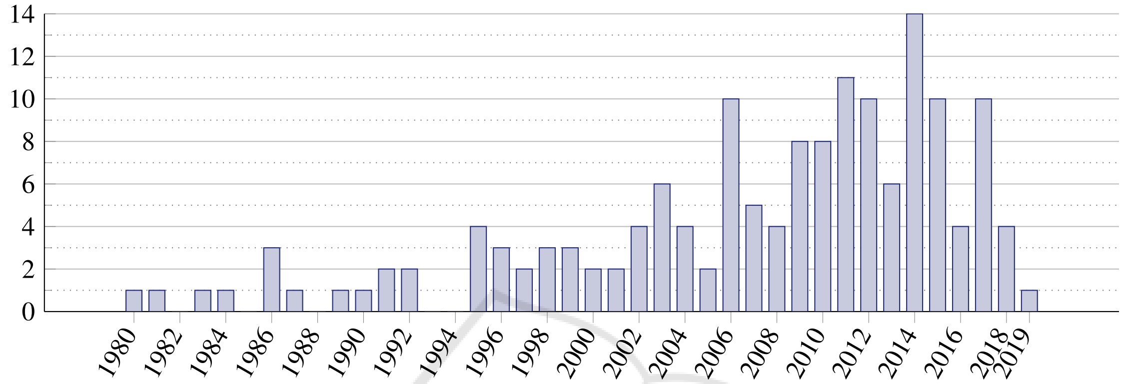

Figure 1: Number of DARP papers per year.

Table 4: Most popular 4 combinations with 7 categories. All papers commonly consider the multi-vehicle, deterministic, static DARP with time constraints and backhauls. They differ from each other in 2 categories which are depicted.

Category combinations	Percentage of papers
Homogeneous vehicles & single-depot	19%
Heterogeneous vehicles & multi-depot	10%
Homogeneous vehicles & multi-depot	9%
Heterogeneous vehicles & single-depot	6%

Autonomous Vehicles (AVs) are a research area that is in experimental stages, but may be considered by the DARP research community in future. Classical DARP concentrates on calculating optimal schedules and routes, but not on who executes them or how they are executed. Therefore, the entity that moves the vehicle (i. e. a computer in case of AVs or a human) is mostly orthogonal to DARP. However, taking into account additional constraints like crew scheduling (e. g. work shifts) is only applicable in variants with human drivers. Similarly, it is possible that specific constraints arise with the advent of AVs.

Most DARP solutions assume that shortest path information between origins and destinations exists, and that the lookup of shortest paths between two locations is fast and therefore negligible. Consequently, they focus on the multi-criteria combinatorial optimization aspect of DARP. Fast shortest path lookup is possible, if a shortest path matrix between *all* locations can be pre-calculated and cached. This is feasible either in *static* variants or in variants with *predetermined* locations. With the popularity of on-demand real-time ride-sharing, the research focus will shift from static to dynamic DARP solutions. A predetermined set of locations for pick-up and drop-off reduces the flexibility to Level-3 (see Table 1) and forces the customers to walk to/from a pick-up/drop-off location. However, real door-to-door mobility is provided by DARP solutions with *arbitrary* locations. In these variants, the number of locations is virtually infinite (depends on the underlying map), which prevents pre-calculation[5] and makes path calculations a performance bottleneck. This is an issue that needs to be addressed by DARP research community.

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[5] Or is only possible with extraordinary computing resources.

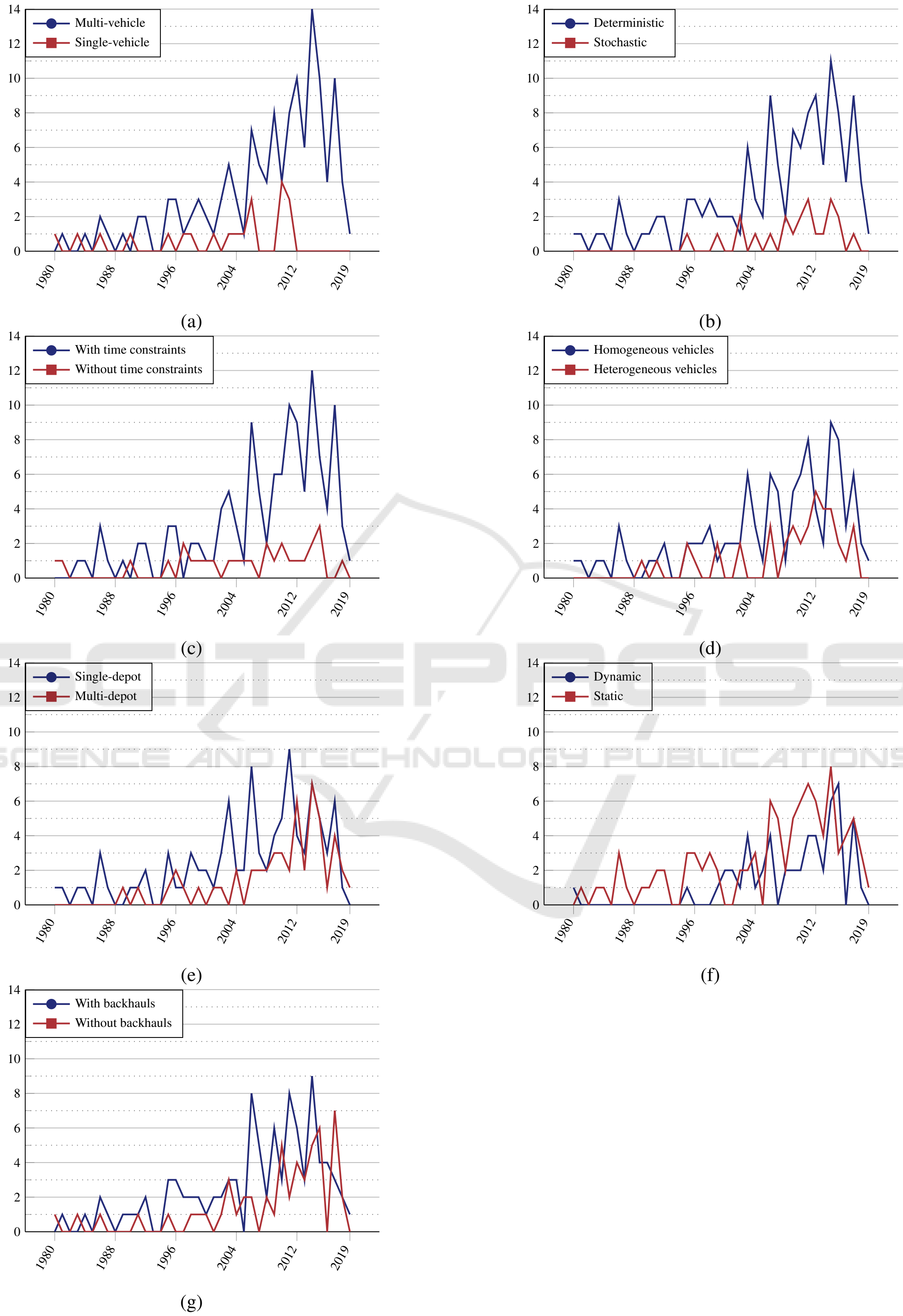

Figure 2: Number of papers over the years considering different DARP categories.

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